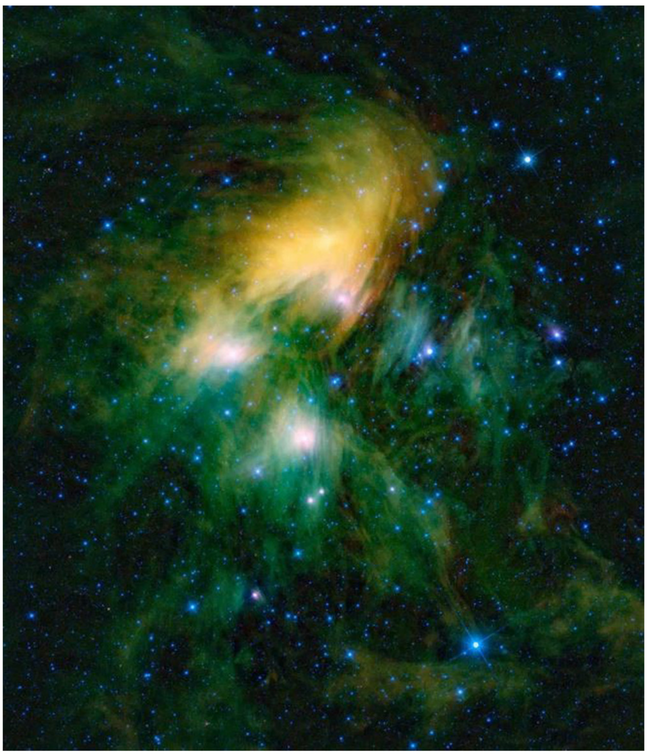
THE EVOLUTION OF STARS

From Birth to Death



Graham Hill

The Evolution of Stars

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From Birth to Death

By

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Cambridge Scholars Publishing

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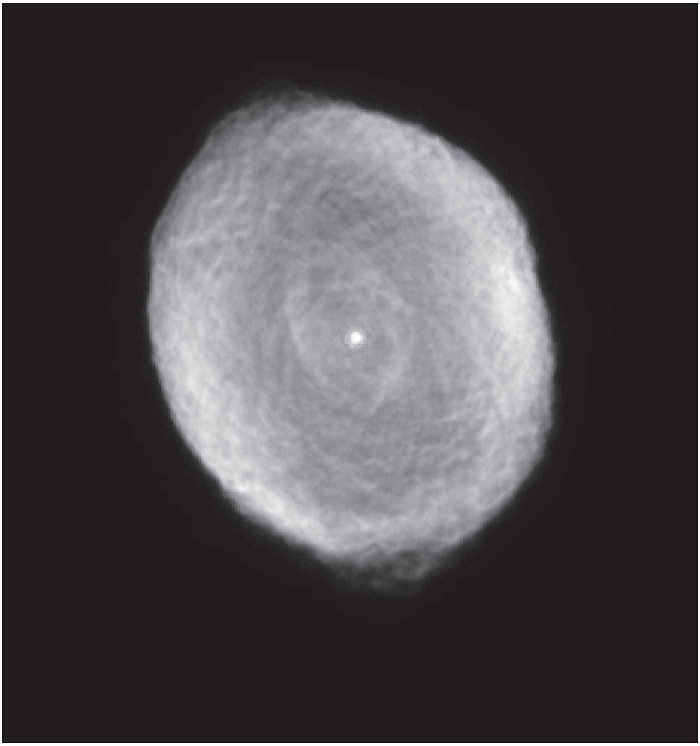
To Willem J Luyten who gave me the opportunity to become a professional astronomer and who, each day, demonstrated that age is no barrier to imagination and innovation.

And to my wife Joanie, who has been my rock over many years, particularly over this last year.



Frontispiece. See Centrefold. The Spirograph Nebula. Credit: NASA and The Hubble Heritage Team/(STScI/AURA)

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Preface

"Twinkle, twinkle, little star
How I wonder what you are
Up above the world so high
Like a diamond in the sky
Twinkle, twinkle little star
How I wonder what you are"

This book had its genesis more than sixty years ago when I read W. M. Smart's book "Some Famous Stars". It was, and still is, a wonderfully informative book on astronomy and was influential in setting me on my path to becoming an astronomer. Now, in my mature years, I've responded to the heeding of my wife who has long urged me to write about astronomy though not in a technical manner for I have authored and co-authored many papers on the subject. Her drive, and that of our children and close friends, was for me to write a popular book about the stars that might interest a public who have long been fascinated by astronomy. This is an interest only whetted further by the flow of results from the Hubble Space Telescope, the huge ten-metre-class ground-based telescopes such as the Keck twins on Mauna Kea, the quartet of eight-metre European telescopes in northern Chile and other more esoteric observatories currently in space.

Unlike Smart who wrote about a few specific stars, I have chosen to write the story of the evolution of stars from birth to death, but not just of single stars. About 50% of the stars in the sky come in pairs that are gravitationally linked, just as the Earth and Moon are linked, as is the Earth-Moon system to the Sun. Because of this physical connection between stars, the possibilities involved in their evolution take some curious and very interesting paths, much as in our own lives which are more complex when lived with a partner.

Most people know little about those little points of light out there we call the stars. Many don't even realise that the Sun is a star and differentiating between a star and a planet is often in the too hard basket. I hope that folk may find this book a stimulus that will entice them into this untouchable world, and further, heighten an interest in our Earth, both in its current form—damaged as it is—and also into its past, both physically and historically.

Astronomy, like all sciences, builds on the past from which much of its language is derived. Rather than present the past as a continuous historical survey I've chosen to interleave it with the narrative to introduce some of the underlying principles of astronomy. Additionally, I attempt to honour in a small way some of the early astronomer's accomplishments that were often based on rudimentary measurement but often capped by brilliant insight.

I've also appended a glossary to further aid the reader in understanding the language of astronomy. Words included in the glossary are initially written in boldface type. Further, I use the metric units of measurement along with the US definition of the billion.

Graham. Hill
Auckland
New Zealand
1 November 2019

PROLOGUE

To set the stage, what follows is an outline of the birth, life and death of our solar system.

And then there was **light**. A gigantic point of energy bursts forth out of nowhere (the **Big Bang)** and in its bursting comes expansion and space. Where there was nothing expansion creates space within a universe that expands into nothingness. Amid the high-energy soup of **radiation** there is little matter and what there is, continues to be annihilated into energy and subsequently renewed as matter. With its expansion, the fireball cools. Atomic **nuclei** form out of the radiation, creating Nature's building blocks—**electrons**, **neutrons** and **protons**. Minutes pass—time as measured one day by the motion of a rotating planet revolving around a yellow star called the Sun—and more and more radiation converts into matter. Cooling further, protons and neutrons are thrust together past the repulsive forces that keep them apart to form the **nuclei** of light elements known in their time as **hydrogen**, **deuterium**, **tritium**, **helium**, **lithium** and **beryllium**. Dominant among these elements are hydrogen and helium, with hydrogen contributing three times the total mass of helium to the stew of radiation and matter, with the remaining elements being inconsequential contributors. In this process of element building, only a few simple stable combinations of protons and neutrons result, for conditions are limited in the cooling high-pressure furnace that is the early universe. As these atoms form, radiation lessens.

After a few million years, temperatures are cool enough so the positively charged nuclei can capture the negatively charged electrons. **Atoms** form, allowing a world previously opaque to sight to become more visible for matter now dominates rather than radiation. Gigantic clouds of gaseous hydrogen and helium become visible, linked by long filaments of matter, and dominate a universe bathed in the primal radiation which slowly ebbs away as the universe expands.

Over millions of years, within this expanding universe, clouds of matter clump together under **gravity**, collapsing and forming giant flattened pinwheels of rotating gas. Within these pinwheels—these embryo

galaxies—smaller clumps of gas collapse to form brightly shining objects called **stars**. The pinwheels gain form, rotating and trailing three or four spiralling arms defined by hot, blue, young stars. Overlaying this image are myriads of stars that are cool and red but their light is hard to see against the glorious overwhelming light of these young stars and the remains of the clouds from which they sprung. Small numbers of spherical objects containing hundreds of thousands of stars orbit these galaxies; dipping in and out of the flattened disks, which are rich in stars, but not sharing the general motion of the spiral arms and their attendant stars and gas.

The universe is a crowded place amid these gigantic pinwheels or **spiral galaxies** as they will be known one day. Collisions occur, for the universe is small and the galaxies are large. Galaxies collide and merge. Their gases intermingle, forming even more stars which interact with each other creating diverse orbits as the colliding galaxies go through a huge mixing process. At its end, the mixing may result in an oval shaped object vastly different from the parent spiral galaxies. In this way **elliptical galaxies** form, which are notably different from their progenitors in their shape and in the absence of gas. Other galaxies brush by each other drawing matter away in vast, long tendrils of stars and gas.

But as the universe expands, these galaxies gain more space in which to move. There are fewer collisions. **Billions** of years pass. A pattern emerges, revealing a vast latticework of matter linking the galaxies and surrounded by enormous holes of empty space. The galaxies also clump together under mutually felt gravity to form giant rotating conglomerations, themselves part of even higher groupings. Long-born galaxies grow dim with the passage of time. New galaxies form from gaseous material that slowly clumps together over the eons. Within these giant rotating spirals, stars continually form while others die away. Some stars die in such a blaze of glory that the light from the explosion drowns the light of the galaxy's other 100 billion stars.

Within one of a spiral galaxy's arms there is a star ripe for destruction. It is huge, so large that light takes tens of minutes to traverse it. And it is red and bloated, its density a billionth of what it was when its **nuclear furnaces** started only 10 million years ago. Suddenly, with not a tremor of forewarning, it explodes in a blaze of light that would in time be seen clearly at the outer reaches of the universe. Once the glare subsides, a shell of gases moving at unbelievable speeds expands outwards from where the star ***had*** been. For it is no more. Well, almost no more, for a tiny object remains, it too racing outwards as if to keep in touch with the other remnants of its parent. This object, this dead star, a **neutron star**, contains only a fraction of its parent's mass. It is almost as dense as an atomic **nucleus** and spins as it races through space emitting a narrow beam of light from its polar regions as it rotates. When viewed it is called a **pulsar**. Even then it is hard to detect because it flickers on and off in thousandths of a second. This neutron star keeps on its path inside a gaseous shell that expands rapidly into interstellar space and is soon lost to view.

At speeds of many millions of kilometres/hour (km/hr) the debris races outward with little to impede its motion. The debris is not just hydrogen and helium but oxygen, iron, silicon, carbon… elements which were created in the blazing cauldron that resulted from the star's detonation. Over millennia the cloud crosses the spaces between the stars until it collides with a similar random giant cloud of gas and dust. The cloud itself, the product of long dead stars or part of the enormous gaseous residue from the universe's formation nine billion years previously. Within the merged cloud, the balance between natural internal motions of the individual atoms and the force of gravity wanting to collapse the system is sundered as the impacting gas increases the local density of gas. Now this denser material acts as a gravitational magnet that pulls the cloud together in one huge gaseous mass **trillions** of kilometres across. The cloud collapses under the effects of gravity, and, over time, motions that might be only metres/second (m/s) are accelerated into speeds of 100s of km/s. Because of asymmetries in the way that the cloud collapses, it begins to rotate. With this rotation it flattens, swirling into a planet-forming pinwheel with a compact mass of gas at its centre. The centre compresses more under the inexorable force of gravity, and, consequently, it heats up and begins to glow, first a dull red then a more brilliant red. But initially, not much can be seen for the pinwheel is shrouded in gas and dust. Outside the central mass of gas, rotating material collides, often sticking under the local effects of gravity. Nodes of matter form. Under gravity, the nodes grow and they too begin to rotate. These nodes, later to be known as planets, sweep around the embryo star—our Sun—colliding with any material in their path. Sometimes other nodes of material are captured. Most often the material falls onto an existing host but some go into orbit about the host providing a seed upon which other material may accumulate.

Amid this mayhem the central star shrinks and shrinks under gravity's relentless imperative, getting hotter and hotter until it is decidedly yellow in colour. This radiation slowly drives the gases out of the embryo **solar system**. By now the central star is a nuclear furnace, fuelled by converting hydrogen gas into helium, a process switched on by the enormous temperatures and pressures in its central core. Its fuel will burn for billions of years. But out of this seeming chaos order comes. Over time, the Sun and its retinue of planets, many with moons and rings, emerge from the gaseous remnants of their creation. Eight planets, among a plethora of debris, remain. All these planets start out surrounded by massive atmospheres of hydrogen and helium, either in liquid or gaseous form, the very building blocks of the Sun. A tug-of-war occurs between the planet's own gravitational pull and that of the heating, vaporising radiation from the Sun. The innermost planet loses the fight and slowly its heated atmosphere evaporates. The other nearby planets fare better in retaining their atmospheres, except the fourth one whose atmosphere is thin because its gravity is not as strong as the two planets immediately interior to it. The moons, associated with many of the planets, fare less well too but four moons, orbiting the outer planets, retain cold, gaseous atmospheres.

The four inner planets are small rocky places, one hosting a giant moon, and another with two tiny moons probably captured in the early days of formation. The innermost one is scarred by **impact craters**; a permanent reminder of the history of the planet as it did its part in sweeping the flotsam and jetsam remaining from the birthing of the solar system. The surface of the second planet is totally obscured by a white veil of clouds that traps the heat from the Sun, creating an arid place of enormous pressure and heat. Its surface is pockmarked by volcanoes and covered in magma flows. The third planet is brilliant blue and white with seas starting to teem with life, its moon a carbon copy of the innermost planet. The fourth planet is red, coloured by iron oxides, a reminder of the fact that iron provides a critical pathway in the way stars live and end their lives. There may be large masses of water still there but hidden underneath the polar ice caps. Its thin atmosphere is revealed by clouds and gigantic dust storms that sweep across the planet's surface, making the surface detail all but invisible for many of this planet's days. Other planets are huge rotating spheres of hydrogen and helium modified by the presence of carbon compounds. All have moons and rings though one is particularly spectacular. One moon reveals intense volcanic activity caused by a "push-me pull-me" gravitational effect from its giant master and another nearby moon. The original ninth and outermost planet-like object is different from the rest. It is really two objects of almost comparable size moving in a path that loops inside the orbit of its immediate interior planetary neighbour. Another more remote and smaller object takes its place as the ninth planet. More are out there.

The solar system revolves under the immutable laws of physics, and interlopers, arising from the vast reaches of space beyond the last planet, sweep in towards the Sun. At first, their motion is slight, but the Sun's gravity accelerates them, and in time, as they approach closer to the Sun, its heat begins to evaporate the cold gaseous envelope that encapsulates these objects. Ices turn to gas and the pressure of radiation—the same force that expelled the last of the gases from the solar system billions of years earlier—creates a bright reflecting gaseous tail that always points away from the Sun. But the Sun pours out more than radiation, it accelerates nuclei of its own material into space. Hydrogen, helium, **iron** and other nuclei beat on the onrushing interloper driving forth the dust that is mixed with the evaporated gases into another tail. The **comets**, for that is what they are, increase speed the closer they get to the Sun, quickly curving around it then racing outwards, slowing as they go back to the place from where their journey began tens, hundreds, or thousands of years earlier. From this place they will return, for they are in the immutable grip of gravity that holds them in their orbit. Occasionally, they don't make a return to the unfathomable cold of the outer solar system, but are captured by the gas planets, in particular, the giant one, either claiming it as another satellite or more likely gobbling it up in the seas of liquid **hydrocarbon compounds**. Sometimes the Sun's gravity breaks up the interloper so that it exits the Sun's environs trailing material. Occasionally these parts will strike the third planet shrouding it in dust for millennia. Within that shrouding cloud, species die, notably the dinosaurs, but upon its inevitable dissipation life reasserts itself.

Eons pass until other interplanetary interlopers are seen. All arise from the third planet—our Earth—which seems to be producing its own version of what had previously been seen arising in the outer reaches of the solar system. These new interlopers circle and perhaps pass by each of the planets at times, sometimes disappearing outward into **interstellar space**—the space between the stars. A number of these objects land on the Earth's moon and the fourth planet, or circle two of the next outer planets.

Over billions of years the Sun gets larger and slightly cooler. Though its growth is slow, it is steady and inexorable. Its outer atmosphere enlarges until the radiation melts and evaporates the inner planet and clears the atmosphere of the cloud-shrouded second planet. Then its evaporation begins. The seas boil on the third planet and then it too meets its fate. The fourth planet follows. After ten billion years from their formation these planets are finally consumed by the source that birthed them. Yet the process is not yet over…

The foregoing outlines the birth, life and death of our solar system. We must deal with the fact that Earth is doomed. Our present notion that we can't travel between the stars because of the distances involved is false. Many science fiction writers have dealt with the imperative for us to reach the stars. We have no choice in the matter. Yes, the Earth's destruction is billions of years into the future and how we get to the stars is unknown, but we will have to accomplish the leap. Currently, telescopes are investigating our stellar neighbours looking for evidence of life. Given its discovery, maybe we'll find our future home, or 'life" will find us!

In this book I'll finish the story of our Sun and other stars too, for the stars come in all sizes, chemical compositions and associations—single and double or more. These factors mean that their evolution is all different. Don't think for a moment that the story is clear-cut—it isn't. This can be seen from the confessions, contradictions and the omissions in this narrative. I'll talk about the way astronomers practice their science, the tools they use and the general limitations of the process, from the point of view of someone who has had the marvellous good fortune to be still doing research after more than five decades.

CHAPTER 1

BACKGROUND

1.1 What's with astronomy? Who cares?

The world of the astronomer, which I call the night-time world, is one of mystery and excitement. Regardless, whether one is a stellar astronomer (one who studies stars) or a cosmologist (one who studies galaxies and the structure of the universe), we view this world with the same wonder. The mystery is easy, for we have all looked up at the sky at some time or another and wondered "What is out there?" The list of queries I've encountered from the public about the night-time sky is endless and the answers are as interesting as they are diverse. What are those points of light we call stars? And those streaks we see burning across the sky—the shooting stars (**meteors**), are they stars? What about the comet things that are played up in the newspapers as promising to be spectacular to look at and, upon viewing, always seem to let us down? Is the Sun a star? Where does the Sun, and the storms that erupt on its surface that somehow disrupt communication here on Earth, fit in the scheme of things? How do events taking place within the Sun affect the long-term climate on Earth, producing ice ages and more recently a mini-ice age within the last five centuries? How come barley was grown in Greenland a thousand years ago? Why is the Moon bright? What is the difference between a planet and a star? For some, this latter question is ridiculously easy and yet there is a real issue about what a planet is and what is a star! What about life out there? And of course, what about UFOs? What we ***don't*** know is endless. At other times I've had a different point of view expressed. "Why should we waste our money on studies that have no relevance to me? The stars don't affect me one bit." True. One cannot justify the case for studying astronomy based on utility. But there is one exception. As we will discover, there is a strong case for us to study the Sun for what happens around and on it, impinges directly on Earth and some of its effects can be mitigated if we receive enough warning. I'm talking here about global warming and catastrophic communication failures caused by particles emitted from the Sun running down the magnetic lines of force in the polar regions. But my real answer is buried in the responses people make when, in my adult education classes, I ask them why they enrolled in the course.

Are we alone? There is a deep drive within us that wants an answer to this question. "Is the Sun and its planets simply an accident of fate?" In coming to grips with an answer, we first must find planets circling other stars. Thousands of planets are now known to orbit stars (we call these objects **exoplanets**). Some planets have been found in the "**Goldilocks zones**", orbiting in places where the temperature is neither too hot nor too cold to preclude life as we know it. Given this, the likelihood of an answer to the larger question increases, such that one day we will know for sure.

There is the wonder involved when looking into the heavens on a moonless night out in the country that is totally absorbing. Everyone who has done so has, at one time or another, wondered about Life, our existence, whether the universe is endless or not, whether sentient beings are out there and whether these beings are already among us or spying on us in some way. Just as if we ever learn to travel forward and backward in time, we'll have those beings with us right now. These cogitations feed the human spirit. When I look upon the images from the **Hubble Space Telescope (HST)**, I recognise their beauty and am moved. The images in Figure 1-1 are two of many in the Hubble website that take my breath away.

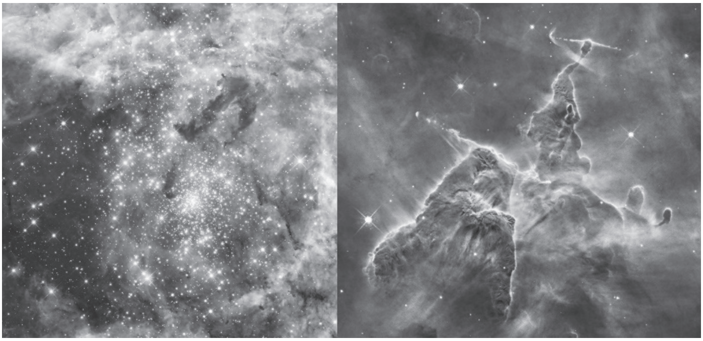

Figure 1-1. See Centrefold. Left panel. The star cluster, 30 Doradus, an **open or galactic cluster** made up of young, hot blue stars with an age in the millions of years. The right panel shows a star-forming region with the unlikely name Mystic Mountain. Credit: Left panel. NASA, **ESA**/Sabbi (ESA/**STScI**). Right panel. NASA, ESA/Livio, and the Hubble 20th Anniversary Team (STScI).

To answer the question about **extra-terrestrials,** we need to discover their base or realise the potential that they could already be here. And how can astronomy help in this regard? Believe it or not there is a branch of astronomy where questions are posed and conclusions reached about the feasibility that sentient beings could populate the galaxy even when limited by the speed of light, the maximum velocity a spaceship can attain. People suggest that in the billions of years available—remember the Sun has been around for 4.5 billion years—even at sub-light speeds sentient beings could have explored the whole of our Milky Way Galaxy! If so, perhaps they have reached our solar system, leading to the question, "Where are they?" In turn, this leads one to wondering about the places where their listening posts might be set up. The backside of the Moon? Maybe in the **asteroid belt**, the space between Mars and Jupiter where debris called **asteroids** are found. We have investigated the backside of the Moon and find no trace of some far-flung outpost. Investigating the asteroids is another issue—there are thousands of them. Perhaps they are under the sea in its deepest reaches. When the Viking Explorer took a picture on Mars that appeared to show a sculpted face, it generated immense interest and an excessive over-interpretation of the limited data available. Unfortunately, follow-up data showed that the face was a chance illumination and the unseen side of the mesa was quite different from Viking's original view. The point of all this is that the practicalities of another race exploring the galaxy lead to a consequence, a listening post of some sort—at least in the way ***our*** minds work. This is the essence of the **scientific method**. Reach a conclusion and make a prediction. Your theory then rises or falls on the prediction being found correct or not. The lack of evidence does not negate the possibility that such beings have visited us, establishing a lookout amongst the jumble of the asteroids or hidden within our moon's surface. There is a surfeit of potential hiding places. Related to this is the ever-intriguing notion of time travel, because, if it is ever possible, then those beings, our distant descendants, could be here now—our neighbours perhaps. And if one of the travellers told you that they were from the future, even if they ***could*** prove it, would you believe them?

When you glimpse the heavens on that starlit night in the country you become aware of what we have lost in the cities. Just as looking at a flower brings a sense of joy, looking at the sky engenders similar awe. Environmental issues are now front and centre in our consciousness as the days of mindlessly raping our Earth are slowly becoming limited. We rape our night sky with notions of placing huge reflectors that will illuminate the icy, northern latitudes of our planet in winter. Do we want to live on an Earth where day follows day follows day…? Think about your neighbour's security lights that blaze throughout the night, or the light spilling over into neighbourhoods from sports field, malls and business security lighting.

Mulling over the night sky brings the notion that perhaps we may be able to give ourselves downward-oriented lighting that does the job yet is less intrusive in our lives and will save a dwindling resource—energy!

Contemplating the night sky should give us a proper perspective on our importance, putting our tribal tribulations and pomposity into humble perspective. This is summed up for me in Shelley's poem Ozymandias:

> "…And on the pedestal these words appear:
> 'I am Ozymandias, King of Kings.
> Look on my Works, ye Mighty, and despair!'
> Nothing beside remains. Round the decay
> Of that colossal Wreck, boundless and bare
> The lone and level sands stretch far away."

A more contemporary view is offered by Hobbes, in response to Calvin's observation about the Universe.

> "Look at all the stars! The Universe just goes on forever and ever!"
>
> "It kind of makes you wonder why man considers himself such a big screaming deal."

Thank you, Waterson!

By our study of the stars and galaxies we may learn there was a beginning to our universe, about 14 billion or so years in the past. Naturally, we ponder about this beginning and why the universe came into being and hence to the question "Is there a God behind all this?" My science has made me a believer, but what we believe is highly personal and we aren't going to change our belief because some scientist comes to a particular conclusion. But we can talk about what appears to be the fate of the universe and our uniqueness.

Looking at our lives here on Earth we are like grubs looking at the ground underfoot as we grasp and seek sustenance. It is a hard life for most of Earth's inhabitants, only made bearable by our children succeeding where we failed. For us, it is to be able to roll over onto our backs on a magical night where the sky is black and the stars and the Milky Way burn into our consciousness, and be reminded that out there perhaps, there is a world untrammelled by lust and greed and hate; that for the pain and penury we may, and do, experience here on Earth, there is indeed a larger world, unknown for sure, that is beautiful beyond description and imagination. For me, the gaze and the dream are of the symbolic craft that took a mortal

Arthur to the promised land, a place in which we all deserve to be. When I am observing, I look up at the night sky with wonderment and never more so when I was in Chile where the sky was clear and the firmament gloriously exposed above me. A photograph from the **European Southern Observatory (ESO)** at Cerro Paranal in the Atacama Desert in northern Chile included here (Figure 1-2) might remind you, the reader, a feeling that everyone has experienced who has seen the **Milky Way** in all its splendour from outside a city's environs.

Figure 1-2. See Centrefold. A view of the Milky Way from Cerro Paranal, Chile. The Magellanic clouds, the smaller (**SMC**) and larger (**LMC**), are our nearest galaxy neighbours, identified by Magellan on his circumnavigation of the globe in the early 1500s, are to the right of the dome. The galactic centre is down to the left of the dome. Credit: ESO/Tafreshi.

If the previous comments regarding astronomy feeding the human spirit are unconvincing, let me take another tack. There are two answers I give to those who think that astronomy, and by extension, pure research, is of no value. The first is the **calculus** that Isaac Newton (1643-1727) developed independently with Leibnitz (1646-1716) and which Newton later used in his theory of gravitation. The calculus was developed as an academic exercise and yet no modern aircraft flies and no skyscraper stands without it. The second is the notion of imaginary numbers, which are based on exploring what might happen if you ***can*** take the square root of a negative number, which is impossible. Consider this example. Four is the square root of 16—the number when multiplied by itself gives 16—the square root of -16 does not exist as -4 times -4 is 16! Despite this impossibility, our communication system depends entirely on an analysis that has imaginary numbers at its heart. Both practical examples are entirely based on pure or "**blue sky research**" embarked on centuries ago. As I write these words, I'm reminded of a subject that I took at university and gave up on, writing the final exam on only two of the three subjects required. I was a "**flat-earther**" with respect to projective geometry which is based on the question, "What happens if parallel lines ***can*** meet?" We see this fact all around us, the railway track and roads that come to a point in the distance. Well, I don't know, but I guess that theorems from those mathematics are at the heart of the gaming of which our kids are enamoured.

Lastly, we want to explore the universe with our **telescopes** and space probes because of sheer inquisitiveness, just as the early explorers carried out expeditions to explore the Earth with wide-eyed interest and amazement and so catalogued the Earth's fauna and flora. One of the greatest of the western world's navigators Captain Cook, travelled to Tahiti to observe, of all things, Venus traversing the face of the Sun! We want to investigate because it is there and because knowledge of one thing leads to another! The same with space, and further abroad—the universe.

The newspapers routinely report that astronomers have observed the most distant galaxies yet (again). Their light has taken thirteen billion years to get here. How do astronomers know this and what has time got to do with distance? We see pictures of a star that has suddenly appeared in a distant galaxy and it is referred to as an exploding star—a **supernova** (super new star)—well, how do astronomers know this and what does it signify? What about these black holes from which not even light can escape? How do we examine them when they prevent light from reaching our eyes? Other reports tell us that the universe is expanding, but even more, it is accelerating as it expands—itself a major problem for those who try to explain the universe and its evolution since the acceleration requires a force. Where, and what is it? They say supernovae tell us this. What does this mean and why are exploding stars useful in this regard?

Beginning to answer these questions gets to the heart of astronomy which has its origins thousands of years ago when the first measurements of distance and size were made. Then, the world was pristine and life was hard. Ideas of democracy and great thoughts were in flower but what was known then was lost for more than two millennia. I often think back and imagine those people living before the advent of telescopes, trying to get a handle on the strange world out there. Knowledge has come to us incrementally over the centuries because the ancient scientists were limited by their equipment and hence their acquisition of data. But they were not limited by their imagination, as a study of the ancients and the diverse ways they gained insight soon reveals.

What are data? What sort of things did the ancients measure? What do we measure today? It is easier to start the discussion by talking about the ancients. Data are compilations of measurements. The early Greeks measured angles of the Sun, stars, and planets against some reference line, maybe a vertical plumb bob or against the horizon, recording the seasonal changing positions of these celestial objects. They recorded times and places of eclipses, times of the rising and setting of the Sun, Moon, planets, and selected stars. In the process they learned to predict the seasons and long-term cycles of solar and lunar eclipses. Note that a solar eclipse occurs when the Moon blocks out the light of the Sun and a lunar eclipse is when the Earth blocks out the Sun illuminating the Moon. Other peoples distilled similar information and presented it in the form of stone circles used as observatories to give them practical information regarding the seasons and their onset. They measured the period of revolution of the planets known to them—Mercury out to Saturn. They measured the brightness of stars, admittedly crudely, but their system of measurement we call **magnitudes** we still use today—and they recorded it. Libraries of data ***must*** have been available so that predictions using these data could be made. Given these data, Hipparchus (190-120 BCE) then tried to make sense of these observations and in doing so, discovered the **precession** of the equinoxes. or the rate at which the Earth‘s rotational axis **precesses** about the North-South axis—precession is what we see when we spin a top onto the ground. The period of this precession is about 26,000 years and was derived by Hipparchus in the second century BCE! The early names, positions and brightness of prominent stars were recorded by Hipparchus and later reproduced by Ptolemy (100-170 CE) in the Almagest in the second century CE and later developed by Arab astronomers.

Like us, they needed a framework upon which to interpret their observations. Initially, they would have interpreted the motions of the planets, a word that means “wandering star”, in terms of the Sun and planets moving around the Earth. Wise in the use of geometry, they understood that the Moon got its light from the Sun because it was the simplest explanation for the phases we see. And so, their interpretations went on, culminating in the notion that their data were best served if the Sun was at the centre of our solar system and that the Earth and planets revolved about it. The Greeks knew this more than a thousand years before Copernicus (1473-1543) proved it, yet it was Aristotle’s acolytes who shot down this notion of the

Earth revolving around the Sun because seasonal shifts in stellar positions are predicted by this assertion. This was early science in action, the logic being, that if the Earth revolves around the Sun, the closer stars should move backwards and forwards over six months with respect to more distant stars. This was not observed. The prediction failed, so the assertion was false. But nobody had any idea just how far away the stars were.

To this day, we measure positions of objects in the sky with ever-increasing accuracy and note any positional changes with time. We draw maps of the sky showing the positions of stars and the gas clouds in our galaxy. Satellites detect **X-rays** and **gamma rays** from space, recording, for each object, the picture or image, the time of the observation and the location of the source, comparing these data against objects at the same position in order to identify them. We time the moments when we make our observations. We measure the brightness of stars and galaxies, often recording times and brightness of thousands of stars at a time. We spread out the light from stars and galaxies into rainbows and measure the strength and positions of the features in these so-called **spectra**. The colours of celestial objects are measured and so it goes on. But, as with the ancients, we still need a framework—a model—with which to interpret what we see, but more of this later.

Nowadays, we are limited because of too much information. Knowledge is expanding **exponentially**, like our debts did when the mortgage rates were up at 18% or so. Under these financial circumstances, managing a debt was (thank heaven it is in the past) difficult and so it is when I try to assimilate the exciting information about the stars that are flooding across the Internet from the Hubble Space Telescope (HST) and other groups pushing the boundaries of astronomy and astrophysics. A book like this cannot keep up with the exponential flow of data and results that are currently flooding the literature. A glance at Figure 1-3 illustrates this through the output of many observatories. The numbers of paper include results for engineering, optical, electronic and astronomical research because the designers and builders of these wonderful telescopes and instruments are forever breaking new ground, just as astronomers are now breaking new ground as the universe is being plumbed by new technology in an ever-expanding subject. I'll talk more about this in Chapter 15. I can't nibble at the material as it flows by but periodically take large chunks to digest and hope that I haven't missed some juicy morsel. But in interpreting what is going on in the sky, specifically among the stars, I take a long-view knowing that this plethora of information will have its chaff, for winnowing is a natural process when these exciting front-page discoveries are critically examined on their way into print in an astronomical journal. Trying to navigate within this material

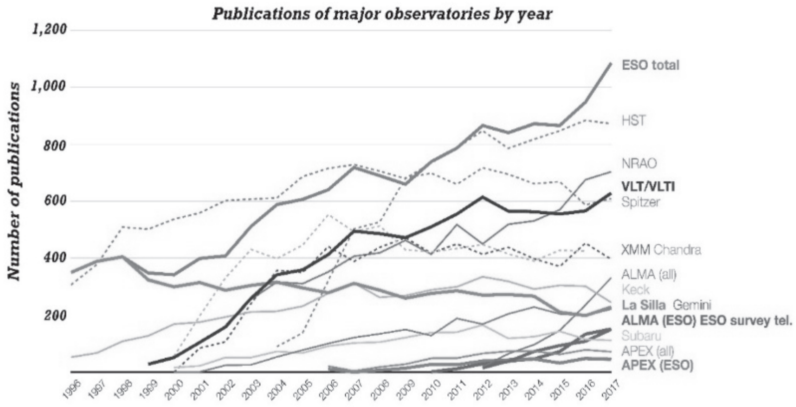

Figure 1-3. This graph shows the difficulty in being current with the science and I make no excuse for failing in this regard. The codes along the side refer to the various major observatories producing papers. Most of the abbreviations, are described in the glossary. Credit: ESO.

is like getting lost in some strange city where contradictory information is fed to you from imperfect street signs and inadequate maps. My caution therefore is to go “ooh”, “ahh”, but take the first announcements with a grain of salt. Like good wine, knowledge will mature with age. If the same story is around a year from now then chances are it is more than an astronomer’s fanciful theory, but sometimes the stories are unfortunately aimed at getting an individual a moment’s instant fame. What is included in this book however should give the reader some worthwhile framework within which the inevitable new discoveries may be understood and evaluated.

While words might be suspect—extravagant even—the images coming from the HST and the **Very Large Telescope (VLT)** cannot be ignored. Universally stunning, they are the fast food of astronomy, totally satisfying but also intriguing in what they are depicting. The words come by way of explanation and it is those words that may throw the eager viewer for a loop for the language of astronomy is strange.

My scientific interest has been the study of stars, young, extremely hot stars mostly, but also I've been interested in stars that are born in pairs (**binary stars**) or as triples. Sometimes, when binary stars evolve, they grow old in their way without interacting with their companion, but most often they interact dramatically with each other. Under these circumstances one star may get **cannibalised**, that is the companion consumes part of it, but perhaps it gets its material back; maybe it gets heated and evaporated to a central core. Sometimes binary stars appear in a form like dumbbells we cannot explain. The possibilities are endless. It is a strange, mostly unknown world out there. From a study of these stars and single stars using theoretical models, once generated laboriously by hand but now in an instant by a computer, we have gotten a good grasp of the way stars are born, live and die. Sometimes they end like embers, gently snuffing out, or explosively leaving in their wake bizarre remnants. Binary stars often die by convoluted pathways making them an even more interesting topic for the discussion that follows on the way stars evolve.

But, as one reads in the newspapers, astronomy is much more than the study of stars. The European and American space programs are uniting at times to explore our solar neighbourhood as well as out to the boundaries of our universe. A new space telescope—**Gaia**—has been launched and is currently observing at a **critical point**, called **L2**, 1.5 million km from the Earth, beyond the Moon, where gravity from Moon, Earth and Sun are balanced by the spacecraft's orbital centrifugal force (see Figure 1-4). It is a good place to park a telescope because you are well away from the Earth which takes up a fair bit of the sky when you are in an Earth-based orbit. At L2 you are further away but still, with some gentle orbital changes, able to affect the direct connection needed to download data while the Sun, needed to charge the solar panels, is visible.

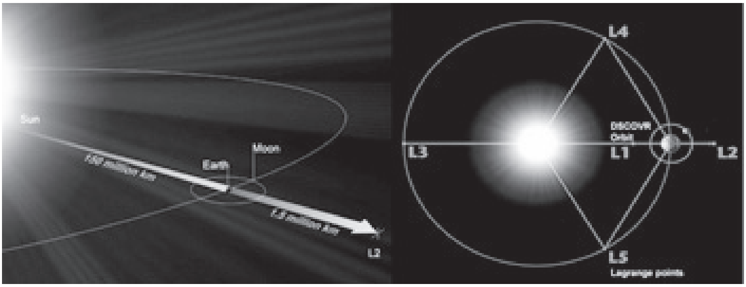

Figure 1-4. L2, the favourite location for orbiting observatories is shown on both panels. Other points of zero gravity are shown in the right-hand panel. They are located at the points where the orbital centrifugal force balances the joint attraction of the Sun and the Earth. Credit: **European Space Agency (ESA).**

The search for **extrasolar planets**, or planets going around other stars, is going at full throttle as well as cosmological research aimed at understanding the first moments of creation. "Why the universe looks like it does, and its long-term fate?" **Stellar astronomy** finds itself between the study of our solar system and the only star we can see close-up, and the study of galaxies, those "island universes" as they were described in the early part of the twentieth century. Galaxies are made up of countless stars. When we look at blank spots of sky and make deep time exposures, we find the blank space filled with distant galaxies indicating that there are as many galaxies as stars in our own Milky Way (see Figure 1-5) and with each galaxy containing perhaps a trillion stars! Just think about it. A trillion galaxies, each containing a trillion stars! These galaxies take our interest because they race away from us and by their motion promise to give us both a time of creation and an end. But these galaxies are filled with stars. Who

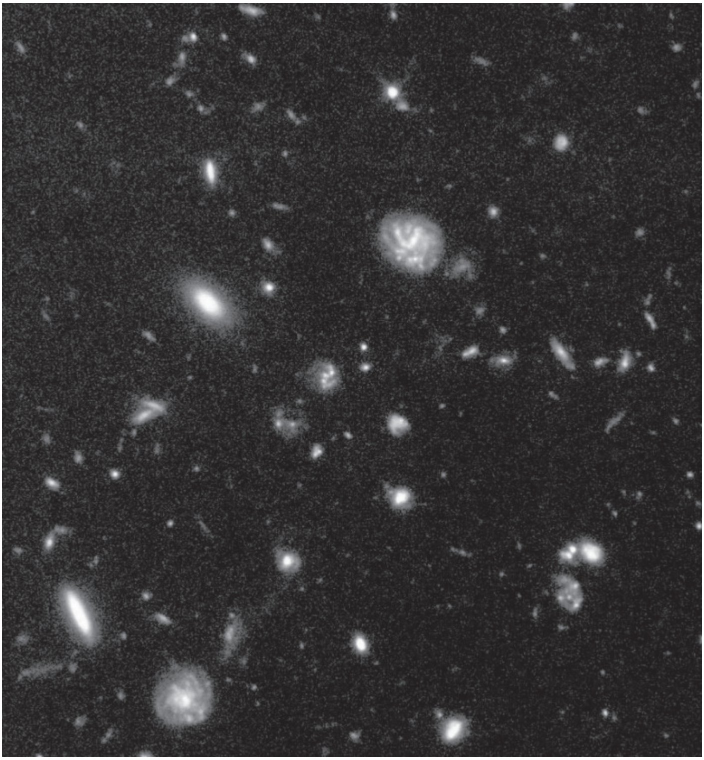

Figure 1-5. See Centrefold. A scene 13 billion years ago, less than a billion years after the Big Bang. This exposure, taken piecemeal over 11 days by the HST, reveals galaxies soon after matter "condensed" out of energy at the dawn of galaxy formation. There is no "empty space". The images of galaxies displayed here are undefined or long, like toothpicks, just as we are undefined in the womb in the early months of our mother's pregnancy. Credit: NASA/HST

would look at a distant city and not wonder what its people were like? This is my interest.

I'm a stellar astronomer working with single or binary stars. Strangely enough, this latter specialized topic spills over into the galaxy domain because of our growing capacity to measure the distances to binary stars in nearby galaxies. Thus, we contribute to the task of establishing a reliable means of measuring distances to nearby galaxies and hence play a role in working out the distances to the oldest galaxies we see. These stars are part of creating a reliable distance scale which begins with measuring the distance to the Sun, thence to nearby stars and outward to the galaxies. These series of measures define what is called the **extragalactic distance scale** which is crucial to the determination of the age and future of the universe.

In this book I'll try to deal with the questions I've posed above while telling the story of **stellar evolution**, that is the story of how stars are born, live and die. On the way, we'll learn more about the astronomer's world, the way they do their science, how science may be done in the future and our debt to the past dating back two and a half millennia to the ancient Greeks. I've structured the book to give a brief overview of some of the science before talking about stellar evolution. In doing so, the reader is introduced to the language of astronomy and the fundamental techniques mankind has slowly developed to understand the larger world we live in. I use the discussion of some binary systems to amplify some aspect of stellar evolution. Many of these systems I've worked on and I view the work with some affection and must be careful to avoid getting bogged down in too much detail.

1.2 The nature of astronomy

Astronomy is different from the other physical sciences in that we cannot conduct experiments on the objects we wish to study. Aside from the Sun, our nearest stellar neighbour, the stars are at vast distances from us and all we can do is to observe them as faint points of light. Not only by looking through telescopes with our eyes, as people often mistakenly believe, but by observing them with sophisticated instruments that are always at the leading edge of every aspect of technology. Technology in astronomy is continually pressed, not only in the detection of faint signals from space but in designing and making the **optics** that we use in our various instruments. It is also critical in the design of the huge buildings housing the behemoths that are the present-day telescopes and in constructing the delicate drives that track the stars and galaxies in the face of the Earth's rotation. Computers that deal with collecting and analysing data are challenged in their response time (how fast they can process information), storage capacities and in the memory needed for us to create theoretical models of various observed phenomena in the hope of understanding an increasingly quixotic universe.

Astronomy is **remote sensing**, a term that appeared in the 60s describing the task of observing the Earth from satellites to see what riches it holds. Remote sensing by orbiting detectors, pointing down instead of up, are mapping the Earth's resources whether they be mineral or forest, grassland, ocean and so on, as well as providing the military with the capacity to spy. But not only do these satellites look for these resources, they check on the well-being of our plant growth and that of our rivers and seas and the ever-shrinking sea-ice. The basis for this work mirrors what has been done in astronomy through the twentieth century when astronomers mapped the sky using various colour filters—variations of coloured glass—to expose a hidden world. The Sun is a good example, where, in the light we see, it has a benign appearance, but when the light is restricted to a narrow range in colour, which we term **wavelength**, a whole new picture is revealed (see Figure 1-6).

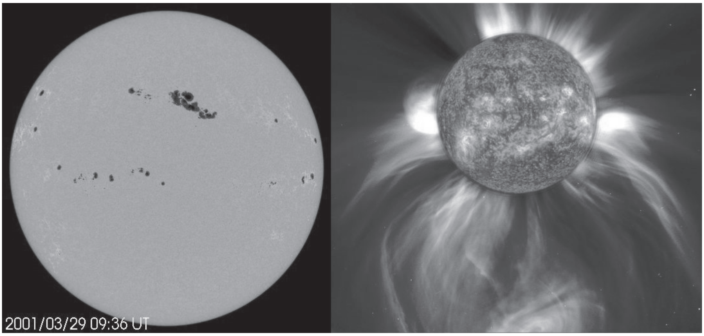

Figure 1-6. See Centrefold. Two images illustrating how our benign-appearing Sun seen through a piece of yellow glass (left panel) is different when we look at it through hydrogen light (right panel). Notice the vast plume of hydrogen, termed a **solar prominence**, erupting from the edge of the Sun while the left-hand panel reveals a Sun spotted with **sunspots.** Credit: NASA/HST.

Also, we look at the stars with **spectrographs** (see Figure 1-7), instruments that spread the light out into all its colours (wavelengths)—rainbows if you will—that enable us to judge the chemical composition of stars, and we map

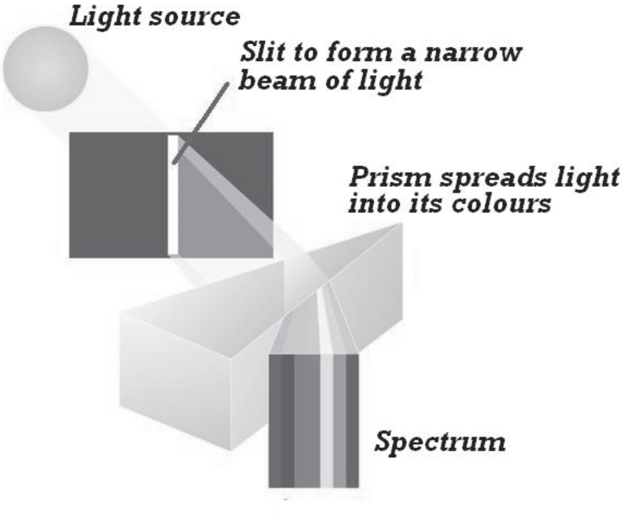

Figure 1-7. See Centrefold. An example of a spectrograph using a **prism** to spread the light out into its colours. Credit: ESO. Modified by the author.

the resources of the Earth, and also Mars with the **Mars Reconnaissance Orbiter (MRO)** currently beaming back high-resolution images of the planet. Working with things one cannot touch is the world of astronomy, so it is therefore no accident that astronomers looking for jobs, find a ready home in the field of remote sensing and surprisingly, because of their capacity to handle large amounts of data, in the arcane labyrinthine banking industry! (And that ignores the home we find in the defence industry.) Not only do we deal with technology but also on Earth we live with the weather, the single most severe difficulty astronomers (and farmers) face on the Earth's surface—ignoring funding of course! For this reason, we have seen much energy expended in the 20^{th} century in finding places free from the limiting aspects of our comforting atmosphere. Remember, the astronomer's ideal location is one where the skies are clear and the normal winking and flickering of the faint starlight caused by the atmosphere is at a minimum. It is no surprise that observatories are found on the top of a mountain in the mid-Pacific where the atmospheric flow caused by the large-scale motion in our atmosphere—wind if you wish—is largely lamina, or smooth. It is why observatories are in northern Chile in the fringes of, and within, the Atacama Desert where there is little moisture and 330 days or more in a year are free from rain and clouds amid a relentlessly static atmosphere. In this context the polar regions of the Moon would be ideal since it has no atmosphere and one can work unimpeded, aside from the periodically encroaching Sun, but communications might be complicated. The side facing us is no good since the Earth blocks out more of the sky than the Sun. The discovery of the perfect observing site has long been the holy grail of astronomy. For this reason, the pioneers have been willing to endure any hardship to find the best place to establish an observatory. I've visited sites where astronomers have been checking the sky for months, if not years, monitoring the cloud cover and measuring the degree that stars **twinkle,** while living under primitive conditions. I can't imagine anything worse than living alone in a shed or trailer, eating poorly and generally getting cabin fever in the hope that the site will be ***the*** one. Nowadays, this drudgery is bypassed in part since it is easy to check the cloud cover from weather satellite records. But measuring the twinkle of a star is best done on site and for astronomers, the smaller the twinkle means the more stable the atmosphere and the more the stars look like tiny points of light. Compacting the light into a pinpoint means that the detector will respond quicker to the light just like it is easier to clear a driveway with a focussed stream of water than one spread out.

In perfect conditions, an astronomer's world is one of wonder and joy where the **photons**, the smallest elements of light we can detect, illuminate our detectors with maximum efficiency bringing in their wake the likelihood of yet another discovery. The nights of greatest pleasure I have ever experienced as an astronomer were when the skies were dark in the absence of the Moon and when the Milky Way burned down over a still, starlit mountain landscape, with the Andes towering beyond me. These were the nights when I have felt close to my maker and in wonderment at the firmament gloriously exposed above. Those are the nights when I am subsumed in the world I try to understand in but the smallest measure. Astronomy, in this viewer's eyes, is not a world of hard-nosed observers trying dispassionately to unravel a piece of Nature's unfathomable puzzle, but a mixture where the observer attempts in some small way to become one with what he or she observes. Thus, on a lonely hilltop in distant Chile, or on a peak ridiculously high on the big island of Hawaii, the effects on my psyche are the same. Often, I've interrupted my observing to go outside to stretch out on the ground and look up at the glorious Milky Way (Figure 1-8), gazing upon the universe with but one thought—to feel the joy of discovery

Figure 1-8. See Centrefold. The Milky Way forms an arc high above the radio antennas of the **Atacama Large Millimetre/submillimetre Array (ALMA)** located in northern Chile. This arc is caused by the panoramic view of the camera. Credit: ESO/Duro.

—but equally, to know that beyond that wee success is exposed more potential successes and with that realisation I know the unbounded nature of the universe.

I will talk about what we might hope to learn about stars in our own galaxy—or those in nearby ones—and outline some of the methods we use to investigate them and what astronomers have done in the past. What strikes me as remarkable about the subject is the range of ideas and techniques astronomers use in their attempts to unravel the secrets of the universe—from using the Moon's passage to block the light from an interesting star existing in a universe about 14 or so billion years old, or to detect and analyse **microwave** radiation emitted when the universe was only a "young" 380,000 years old!

1.3 The Window to the Universe: The Electromagnetic Spectrum

When we think of observing the universe we implicitly think of light and the world it displays. But light is only part of a spectrum of radiation, termed the **electromagnetic spectrum** (see Figure 1-9). It is called the electromagnetic spectrum because the radiation is created by a changing **electric field** which itself creates a **magnetic field**, itself creating an electric field and so on. This cycle of action and reaction creates a wave that propagates or moves through space at a speed of 300,000 km/s, which we term the speed of light, Einstein (1879-1955) pointed out the duality of light, the fact that light is both a wave and a corpuscle—a packet of energy we call a photon. Thus, we can characterize the electromagnetic spectrum by the energy contained

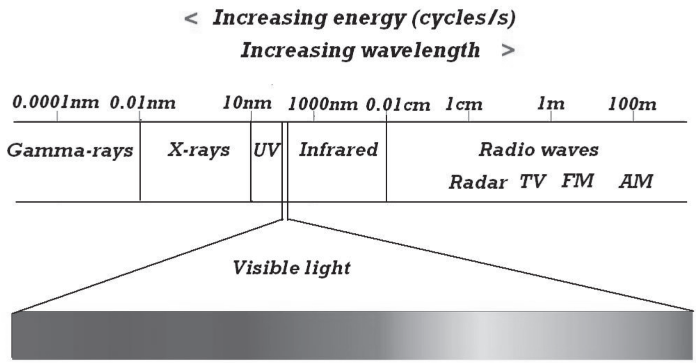

Figure 1-9. See Centrefold. The electromagnetic spectrum. Note the narrow band of wavelengths through which we view the universe. Now observations with new detectors launched on satellites allow us to observe the whole of the displayed spectral range (see Figure 1-10 also). Note that the wavelength scale is displayed in **nanometres** (**nm** or 10^{-9} m) rather than astronomy's traditional Angstroms (10 A is 1 nm). Credit: Image from the Web. Redrawn and modified by the author.

in these photons or by the wavelength (or frequency) of the wave—the distance between the wave peaks or troughs. We are all familiar with waves, for at the beach we'll likely watch the breakers crashing onto the shore, or if we're body surfing, we stand there and watch the wave crests come by until the one that is the right height and just beginning to break arrives to carry us to shore. Thus, the surfer watches the wavelength, the distance between the wave crests ***and*** the frequency, thinking, "How long do I have to wait for the next right wave?" In terms of wavelength, we may be talking about 50 metres between the wave crests whereas in terms of the electromagnetic spectrum the wavelengths are unbelievably smaller. Yellow light is at a wavelength of about 550 nanometres (nm) or 550 billionths of a metre! When waiting for waves on the beach we might record one passing every minute or so. In contrast, the frequency of yellow light is 600 trillion cycles/sec corresponding to 6×10^{14} waves (1 followed by 14 zeros) or photons passing every second!

Heat is motion. Increase heat and motion is increased, whether it is the molecules of water in a pot coming to the boil or the atoms comprising an iron bar being heated in a furnace. Thus, where there is motion there is temperature, and with temperature there is electromagnetic radiation. Everything that has a temperature emits electromagnetic radiation, from the unreal temperatures in the centre of the Sun, to the liquid nitrogen or ethane seas of Saturn's moon Titan. But there is a temperature where all motion ceases. This temperature, which we call absolute zero, is reached at –273 **Celsius** (water freezes at 0°C and boils at 100°C). In astronomy we measure temperatures in terms of degrees above absolute zero in a temperature scale named the **Kelvin (K)**. In this scale, water freezes at 273 K and boils at 373 K. In terms of stars where we measure temperatures in thousands of degrees the distinction between Kelvin and Celsius is not that great so you might as well think of the temperatures in terms you are familiar with—Celsius.

We usually think of the electromagnetic spectrum as light but the radiation we see occupies only a small window within the breadth of the total spectrum. Photons are intrinsic to the whole electromagnetic spectrum and they move energy from one place to another and through our eyes reacting to these photons we have sight. Despite these strange sounding words, we are familiar with the electromagnetic spectrum for we've all been X-rayed, used a microwave oven, felt heat from the Sun or a fire or listened to the radio. These varied categories of radiation are only differentiated by the amount of energy contained in these packets of radiation.

Prior to us being able to get our detectors above the limiting effects of the Earth's atmosphere, astronomers were limited to what we call the visible region of the electromagnetic spectrum and the radio spectrum (see Figure 1-10) but now the whole of this realm is available to us. Today, we observe the universe across the whole range of the electromagnetic spectrum with detectors and telescopes seemingly only limited by imagination and precious dollars. In this realm, the most energetic radiation is from the gamma rays, usually produced on Earth in nuclear explosions, which are lethal to us. The next most energetic form are the X-rays which we are all familiar with and which too are lethal when absorbed massively in one dose, or incrementally over a long period of time—hence the lead aprons technicians use when our teeth are X-rayed! The next region of the spectrum is that of the **ultraviolet rays (UV)** which cause sunburn. Additionally, in the extreme, we have become increasingly aware of the harmful effects of UV radiation caused by excess radiation flowing through the hole in the ozone layer and the widespread danger of melanomas or skin cancers all too prevalent today. The next part of the spectrum is the **visible**, or light, a small range of frequencies that our eyes respond to and which reveal the magical beauty of our beloved Earth and the distant cosmos. At even lower frequencies, we move into the world of heat or the **infrared (IR)**, an area opened by the Hubble Space Telescope in its privileged position above the Earth's atmosphere. IR detectors, sensitive to body heat, are routinely used to locate people lost in the woods. We are all familiar with the effects of microwaves in our ovens, and the lower frequencies in the FM and AM parts of the **radio domain**. Electromagnetic radiation is ubiquitous. Remember next time you switch on your cell phone and wait for it to connect; it is connecting to radiation that is around us and ***in*** us every moment. We are continuously bathed in electromagnetic radiation.

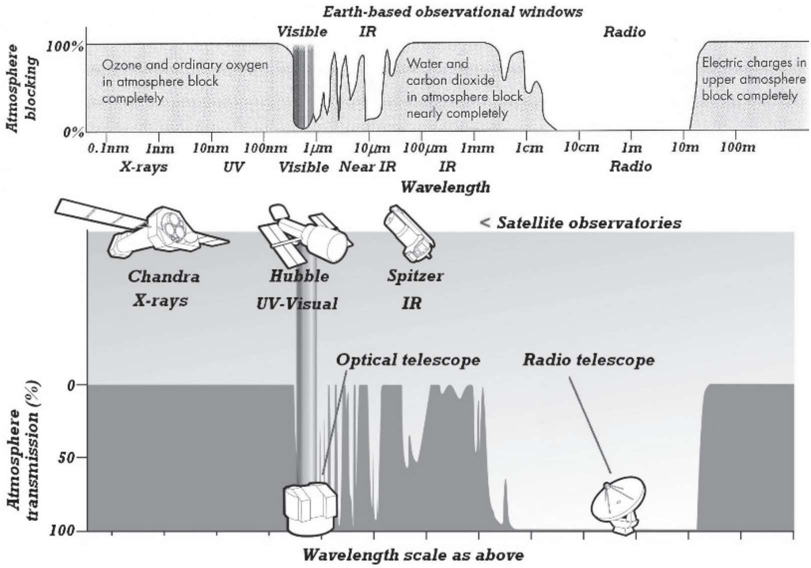

Figure 1-10. See Centrefold. The electromagnetic spectrum and the Earth's blocking atmosphere. The upper panel shows the blocking effect of the Earth's atmosphere on the electromagnetic spectrum. A glance at the lower panel reveals that our view of the universe, if limited to the visible and radio regions, leaves out most of the electromagnetic spectrum. Airborne observatories fly at high altitudes to reach part of the IR. Radio telescopes "see" right through the Earth's atmosphere. It is not surprising that since space-borne telescopes have opened the whole of the spectrum, a picture of the universe is forming that contains many surprises. Credit: NASA/ESA Modified by the author.

But the electromagnetic spectrum tells us more. It has a shape that we call a **blackbody spectrum** whose peak depends on the temperature of the source. The electromagnetic spectrum emitted by the human body peaks in the IR. The Sun's electromagnetic spectrum peaks in the yellow part of the spectrum. **Sirius**, the next brightest star (temperature ~12,000 K, ~ means approximately), peaks in the UV (Figure 1-11). The hotter the source, the

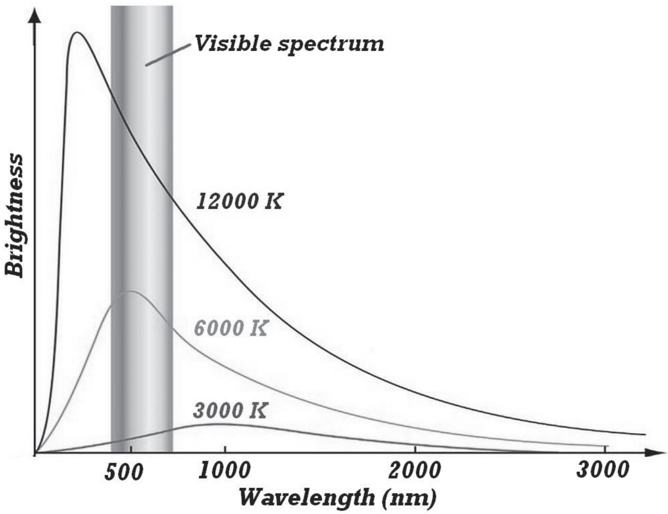

Figure 1-11. See Centrefold. The distribution of energy within a heated body is shown for three temperatures. As the temperature increases, the peak of the energy moves to shorter and shorter wavelengths, or to higher frequencies. Our eyes are attuned to the region of the spectrum peaking near 6000 K, which is the approximate temperature of the Sun's surface. The wavelength scale is given in units of a billionth of a metre. Credit: Unknown source. Modified from the Web by the author.

more the radiation peaks towards higher and higher energy and towards shorter wavelengths. This fact enables us to measure the temperature of stars, at least in principle, for nothing is ever simple.

To demonstrate how bizarre the astronomical world is, consider the fact that we get a snapshot of the universe only 380,000 years into its existence. How come? Well, at that age, the universe was expanding and hot, about 3000 K. At this temperature, the peak of the electromagnetic radiation was at about one millionth of a metre (see Figure 1-11). Over the intervening 14 billion years, space itself has expanded along with the wavelength of all radiation. With the universe's expansion, the peak has shifted to longer wavelengths and has therefore cooled. Now the original peak of the 3000 K remnant corresponds to only 2.7 K, that is 2.7 degrees above absolute zero—and we can measure the temperature of this (Figure 1-12)!

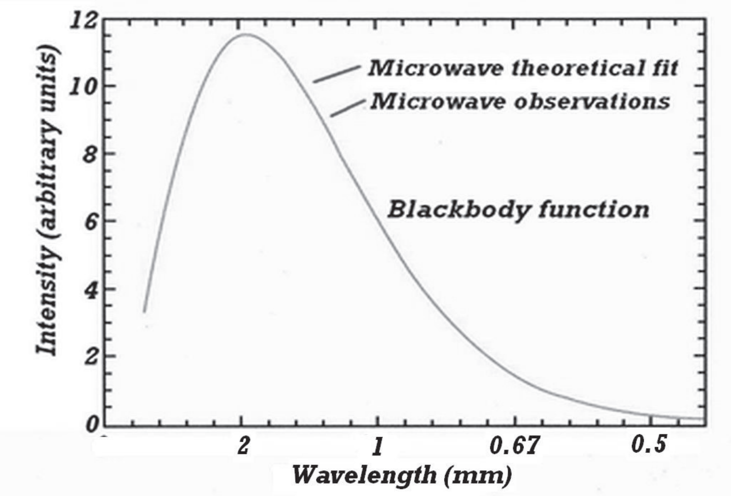

Figure 1-12. The shape of the theoretical electromagnetic spectrum (called a blackbody function) at 2.7 K compared with the observed microwave data. The fit is so perfect that the observations are under the theoretical line! I can't recall ever seeing data so beautifully represented by theory. Credit: NASA.

1.4 Neutrinos

Our bodies are continually bombarded by neutral, massless particles called **neutrinos** that are produced in the nuclear furnace in the centre of our Sun and from the larger universe surrounding us. In fact, the detection of these particles is necessary to prove the theories about how stars are powered since they are a natural consequence of the **nuclear reactions** taking place in a star's core. Neutrinos are produced in every star that is experiencing nuclear reactions, they whisper through us, the Earth and out to the furthest reaches of the universe barely reacting with matter. Once we can detect these wraiths more effectively, we'll have opened another window in which to investigate the universe.

1.5 Gravity waves (GWs)

Just a bit into the future we may anticipate achieving a new look at the universe through the "eyes" of the gravitational distortion of our surrounds caused by catastrophic events in the life, but in fact, the death of stars. These are the so-called **gravity waves (GWs)** that arise when gravity is affected by some catastrophe involving unbelievably dense stars or by the awesome explosions when stars blow up. They are created when space is deformed by gravitation changing the curvature of space. Best explained by saying that if there was no curvature of space there would be no bending of light caused by the gravitational effects of the Sun on the space around it. Something that Einstein predicted and Eddington (1882-1944) verified. Binary, or orbiting stars massive enough to bend space, create gravitational waves, losing energy in the process. Because of this energy loss they slowly spiral into each other and ultimately coalesce, exploding and shaking the fabric of space. Since I penned these words years ago, gravity waves ***have*** been detected in 2015 using detectors located in Washington State and Louisiana State. Subsequently, a third has been added in Georgia. Other detections have now been recorded. The original detection is shown in Figure 1-13 and if you have any scepticism about their reality these observations should remove them. Later in Chapter 14, I'll show a few more events involving merging black holes or neutron stars. The detection is daunting, because the vibrations are so weak, and verification depends on two independent events being simultaneously recorded with similar shapes

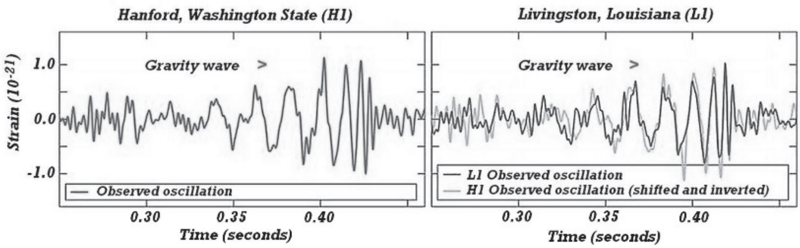

Figure 1-13. See Centrefold. The original wobbles of gravity that confirmed the existence of gravity waves. The two sites, one in an old nuclear facility in Washington State and another in Louisiana, recorded the same signal with a 7-millisecond delay in Washington State. Gravity travels at the speed of light so we'd expect—and get-- a perfect coincidence in time as well as the "wobbles" to be in perfect tune (excuse the pun!). I can't describe the vertical axis called "strain", but whatever it is it is unbelievably small! The final few vibrations are called "chirps". Credit: Abbott et al., 2016, PRL 116, 061102-1. Modified by the author.

(called chirps) within a second of each other. David Reitze of Caltech is quoted as saying that the detection was equivalent to measuring the varying distance to the nearest star α Centauri wobbling by a hair's breadth!! Gravity waves offer astronomers the opportunity to detect the shaking of space produced by some cataclysmic event involving orbiting neutron stars merging or orbiting black holes merging. It has been suggested that up to a thousand of these events may be detected per year. At the moment, there is limited directional information associated with the detections, but now that there are three locations in the US which are integrated into a world-wide network of detectors, there is an expectation that more coincidences will yield more directional information (a site on the Moon would be great!). In this respect, now all we currently know is that an event has occurred, though theoreticians somehow reverse engineer the happening to identify the objects that caused the observed GW (see Chapter 14).

1.6 Cosmic Rays

Atomic nuclei streak through space and react with our atmosphere colliding with the atoms and molecules, producing what we call a **cosmic ray** shower. The particles from these showers are penetrating our bodies all the time. Astronauts see flashes before their eyes at times, caused by particles passing through their retinas. They are ubiquitous. These nuclei come from across the galaxy, accelerated by the galactic magnetic field or in physics-speak are considered high energy particles, that is, the energies of motion they have can only be replicated in the most powerful particle accelerators on Earth. Some come from the Sun, though these are not travelling fast. Some come from interactions with what is called the **heliopause**, the junction of the Sun's influence with the gas between the stars commonly called the **interstellar medium**. The **Voyager 2** spacecraft, that provided the first close-up glimpse of all the gas planets nearly forty years ago, has finally reached the heliopause while its twin, **Voyager 1**, has already passed through it and will now drift amongst the stars forever! The distribution of the incoming particles from interstellar space is from all over—isotropic—that is, no direction is favoured over another. The abundance of the elements producing these showers appears to be like that found in the Earth and the Sun. We'd anticipate this from the cosmic rays emanating from the Sun but what about interstellar space? Because the nuclei come from all over, they present a puzzle because, if the cosmic rays came from the disk or plane of the Milky Way (the **galactic plane**), we'd expect to detect more cosmic rays in this direction, but we don't. In contrast, when radio waves were first discovered and mapped in the 40s and 50s it was found that most of the radiation was limited to the galactic plane or the disk of our galaxy. A schematic of the Milky Way is shown in Figure 1-14. In contrast to the radio emanations from the **interstellar gas**, it is not easy to determine the origin(s) of the high-energy particles and therefore we cannot use them to probe the universe.

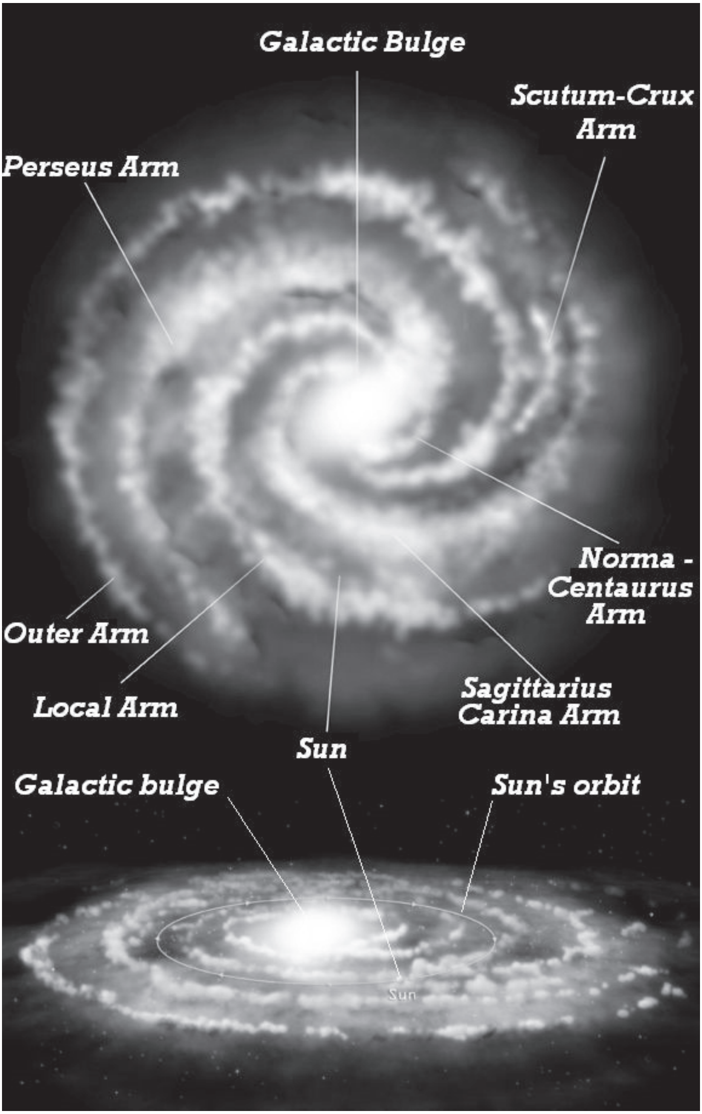

Figure 1-14. Upper panel. The Milky Way from above, showing the spiral arms which have been mapped using radiation from neutral hydrogen gas within the arms. Lower panel. The Milky Way is like a giant pinwheel. The Sun’s orbit is indicated and it takes about 250 million years to orbit the galactic centre 25,000 LYs away. Credit: NASA/Chandra. Modified by the author.

1.7 A brief reflection

I turn now from how we might observe the universe to the way we do, by talking about the astronomical limitations of the environment we live in, and it is not always caused by the weather. The Earth can be a very limiting place from which to work, even when we've had the good fortune to get observing time on a large telescope. Most observers have had their time extinguished by rain, snow, or clouds. Some will have lost out to forest fires as I did once in New South Wales. On the Big Island of Hawaii, astronomers have had access to their telescopes denied them by activists protesting the construction of the **Thirty Metre Telescope (TMT)** on the peak of Mauna Kea. In 1966 I lost out to the **Leonid** meteor shower that presented me with an unimaginable display of celestial fireworks, which memory keeps me awestruck in recall! And, if I am asked about the most memorable thing I have ever seen, it must be this shower that had every astronomer on **Kitt Peak** in southern Arizona gazing in wonder at a sky continually lit by thousands upon thousands of meteor trails from midnight to sunrise (amply demonstrated by Figure 1-15). I suspect that this little group of people were

Figure 1-15. Early lithographs depicting the Leonid meteor showers in 1799 and 1833. These are accurate depictions of what I saw in 1966. Credit: In the public domain.

the only ones privileged to witness this recurring event, showing the glorious effects of the Earth crossing some ancient comet's remnants. I wonder what will be recorded the next time we cross the Leonid's path in 2032.

But remember that not every observational astronomer just observes, they may also work on a theory, picking a topic and investigating what the observations are trying to reveal. I see that in my work, for my world is also one of pen, paper, computers and a brain that ticks over all the time trying to make sense of data that has often been hard fought to obtain. Answers don't often come quickly and when they do, as likely as not, they lead to more observations and more predictions or problems. I like that, because then my work is never done.

CHAPTER 2

THE SKY AND HOW WE VIEW IT

2.1 Twinkles

Earthbound, we look at the sky where the light from the firmament is distorted by the atmosphere which makes the stars twinkle and dance about. The air above us is in motion with streams of rapid flow (the **jet stream**) moving around the Earth along with upward flows of air caused by the heat released at the Earth's surface. The most dramatic of these upward, or convective flows, are seen in thunderheads commonly seen in the centre of the US. These various motions are what cause the stars to twinkle. The best example we see during the day is along a hot highway where distant hills dance and shift through the hot air shimmering above the road's surface. At night, the heating effects are much less as the Earth cools off but they still cause the stars to appear larger than they are and to twinkle. Some of the most innovative recent technical developments in astronomical optics have been aimed at negating the dynamic distortion caused by the Earth's atmosphere. The notion that we can compensate for atmospheric turbulence is at the heart of the controversy that swirled around the construction of the HST decades ago. The arguments then centred on the extreme cost of a spacecraft needing to be maintained in space against a much cheaper and larger telescope constructed on the Earth where the atmospheric effects could be largely nullified by new developing optical technology. At the time it was envisaged that the twinkling of the stars could be counteracted using optics that could instantaneously respond to and correct the anticipated changes in the stars flickering light. The creation of such optics, called **adaptive optics (AO),** was anticipated to be realisable dream. Now, years later, the technology is robust and is routinely used to counter the effects of the atmosphere's motion. But the whole argument is irrelevant now in the aftermath of the stunning pictures continually being beamed back to Earth from the HST. Only now are images being obtained with ground-based telescopes employing adaptive optics that have superior clarity (**resolution**) than obtained by the HST. You can judge the effectiveness of adaptive optics by looking at Figure 2-1.

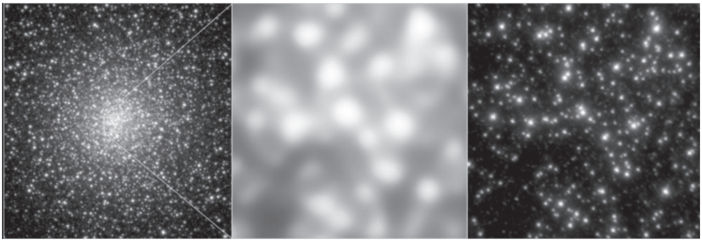

Figure 2-1. An observation of the **globular cluster** NGC 6388 showing the effectiveness of adaptive objects. The centre panel shows a blow-up of the central region of the globular cluster (seen in the left panel) and the rightmost panel shows the same image taken with adaptive optics. The size of these images is comparable to those achieved in space. Credit: ESO.

2.2 Attenuation of starlight

When we look at the stars their brightness is altered by the Earth's atmosphere. Seen overhead, a star is brighter than when we see it low down towards the horizon. We see this effect with the Sun as it slowly sinks towards the horizon, its brilliance all but extinguished. In this situation, the sunlight (or starlight) must pass through more of the atmosphere to get to us and so the intervening air dims the light. The dimming of starlight by the atmosphere is called **attenuation** or **extinction** and in the extreme, completely blocks some dangerous radiation from us. I'm thinking here of ultraviolet radiation (UV) and harmful X-rays and gamma rays. The geometry of the situation allows us to calculate the physical extent of the atmosphere with respect to the atmosphere overhead and allows us to measure the effect of the atmosphere on a star's brightness. Tracking a star's brightness change with position in the sky enables us to remove the effects of the atmosphere from our observations. Typically, during a night, we monitor a small number of stars we call **standard stars** known to be reliable in terms of their brightness—you can't monitor the atmosphere's effect on starlight if you do not have a stable source of light. These so-called standard stars fulfill this role. When clouds are about, this whole scenario goes out the window for obvious reasons, hence the desire to locate an observatory in places that are almost cloud free. In the continental US, in my own experience, we may rarely see a series of perfectly clear nights (or days for that matter) for clear skies are generally found in the driest of places. Northern Chile is wondrously clear and that is why the Europeans have established a massive astronomical facility there (ESO). Incidentally, part of that observatory is featured in a James Bond movie.

Starlight is also attenuated differently with the colour, or frequency, of the radiation coming to Earth. Taken in the extreme, we all know this because the Earth's atmosphere, specifically the molecule O_3, or ozone, shields us from much of the destructive effects of ultraviolet radiation; but not all, as we must be careful of sunburn and the melanomas that result from prolonged exposure of tissue to UV radiation. In the Southern Hemisphere it is particularly dangerous because the "ozone hole" is approximately centred over the South Pole and extends over New Zealand and Australia. It is no accident that melanomas are most prevalent in these two countries.

The amount of attenuation of starlight also varies with altitude. The higher we go, the less the light is affected by the atmosphere and hence more UV comes through. Notice the sunburn on skiers and mountaineers! The reason is straightforward. As we go higher there is less atmosphere between us and the star to cause a twinkle. Hence the fact that most major observatories are located at high altitudes, typically at 1800 m (6000 feet), though Mauna Kea on the big island of Hawaii boasts five major observatories at 4200 m (14,000 feet). At sea level, the atmosphere absorbs sunlight quite dramatically in the UV and in the far infrared. As we go to higher altitudes, the atmosphere has less effect on the starlight, finally disappearing when the telescope is satellite-borne.

We are fortunate in that water and carbon dioxide molecules trap heat radiating away from the Earth making our world warmer than it should be if we only consider the amount of radiation coming to us from the Sun. This is the greenhouse effect that concerns all of us when we talk about global warming. Global warming results when additional molecules are released into the atmosphere that absorb and hence contain even more of the Earth's heat. This is a problem that will affect our grandchildren unless we limit the emissions that will shroud and heat the Earth, raising the sea level and changing our climatic patterns. None of this is good news. The Earth maintains an average temperature of about 10°C, about 25°C hotter than it would be without our blanketing atmosphere. An extreme case of the greenhouse effect is seen in the cloud-shrouded planet Venus, the Earth's twin in terms of size and mass, which has a surface temperature of about 480°C!! much hotter than the 25°C it would be if its atmosphere was like the Earth's.

2.3 Constellations: Not the only legacy from ancient times

When the ancients observed the night sky, they placed their myths amid the star patterns we call **constellations**. To this day we have the constellations Taurus, Gemini, etc that we know as the signs of the zodiac. Most of the bright stars still retain names based on these patterns. But not only did the ancients delineate the various constellations, they also set up a system of judging a star's brightness. The brighter stars in each constellation were lettered brightest to faintest, with the brightest stars called alpha (α) from the Greek alphabet, beta (β) for the second brightest and so on. We still use this nomenclature, augmented by other names given to bright stars by Arab observers a thousand years ago and, more recently, names associated with someone who made a major study of a star. One of the binary stars I'll discuss later, the most famous of all, is β Persei, known to most astronomers by its Arabic name **Algol** (El Ghoul). Algol was named the demon star by Arab astronomers because of its changing brightness. It is in fact three stars, one pair orbiting a distant third, and each "group" orbiting about a common centre called the **centre of mass**. Perhaps the Arabs knew something because the close pair has undergone a strange evolution where one of the close pair is slowly cannibalising the other.

The greatest of all ancient astronomers, Hipparchus (circa 134 BCE), bequeathed us a legacy in the magnitude system by which we measure the brightness of stars (some might call it a curse). He divided the stars into groups ranging over what he termed magnitudes, stars of first magnitude, second magnitude through to stars barely visible to the naked eye at sixth magnitude and published a catalogue of a thousand objects giving their positions and magnitudes. Hipparchus' original catalogue was lost, but we are beholden to Ptolemy who is thought to have been responsible for its reconstruction and who also listed the significant accomplishments of Hipparchus that would have otherwise been lost. These magnitude divisions started to be rationalized in the mid-1800s when it was discovered that these ancient brightness divisions corresponded to a brightness ratio of approximately 2.5 between first magnitude and second magnitude stars as there was between the second and third magnitude stars and so on. Soon after, our present-day system was established, based on the definition that 5 magnitudes span a range of brightness of 100, leading to a ratio between each magnitude band of 2.512. The brightness ratio between a first and third magnitude star is 2.512×2.512 or 6.31 and the ratio of brightness between a 1st and 6th magnitude star is a 100. The scale is one where the large number corresponds to the fainter star and the smaller number the brighter!

It was fortuitous that Hipparchus set it up this way because the scale for fainter stars is open-ended—simply increase the numbers for fainter and fainter objects.

To get an idea of the brightness scale, the Sun's magnitude (or **apparent magnitude**) is –27 and the faintest star we can see in a very dark sky with the naked eye is about 7th magnitude. This corresponds to a brightness ratio of about 40 trillion to one. The faintest stars examined by the largest telescopes are about magnitude 22. At this limit, a telescope can detect objects a million times fainter than the faintest star the human eye can see! No wonder telescopes are so useful! We can also calculate the brightness between the Sun and the brightest star we can see (Sirius). The Sun's magnitude is approximately –27 and the brightest star about magnitude -1. The range in magnitudes is then 26 or 5 lots of 5 with one left over. Each 5 magnitudes correspond to a factor of 100 so the 5 lots of 5 amount to 100 × 100 five times or 10^{10} in our shorthand notation. The one magnitude left over amounts to 2.5 and so the total range in brightness is approximately 25 × 10^9 or 25 billion!! Similarly, the difference in brightness between the brightest and faintest star is 22 – (-1) = 23 or 4 lots of 5 magnitudes with three left over. This corresponds to 2.5 × 2.5 × 2.5 × (100 × 100 four times) or about 1.6 billion.

These results are another indication of the size or scale of the numbers encountered in astronomy. For example, densities inside a **white dwarf** are a million times denser than water. A sugar-cubed size of its material weighs 1000 kilogram (kg) or close enough to an Imperial ton! In ultra-compact stars called **neutron stars** we have the situation where a mass, equivalent to that of the Sun, is contained in a sphere approximately 20 km across! But more! At the beginning of the Big Bang, ***the whole mass of the universe was contained in a space infinitely smaller than a pinhead*** until it burst its bonds and exploded into something where distances are measured in terms of how far light travels in a year! Pause and think about this! However, astronomical objects are not only bigger or denser but they can be tenuous beyond belief. The average density of the universe is such that it is best imagined as having a tenth of an atom of hydrogen in one cubic metre of volume. Or further quoting Martin Rees in his book "Before the Beginning", "one snowflake spread through the entire volume of the Earth". We are looking at a universe approximately 14 billion years old, or the light we see coming from its outermost limits, has been travelling for this time at a speed of 300,000 km/sec or 9.5 trillion km/year. The reader will need to get used somehow to the scale of things or simply do as I do and figure that the numbers are so big as to be incomprehensible.

2.4 Telescopes: What does a telescope do?

We all think we know what a telescope is. It is a long optical thing that you put to your eye to make distant objects look closer. Typical are those instruments we see pirates use in movies to track down some hapless prey. That instrument is what is called a refracting telescope. Light comes in the front end and is focussed at the back where we look at it through an **eyepiece**. True. But that is not the whole picture. The real value of a telescope in studying the sky is its ability to collect more light than the human eye. Larger and larger telescopes gather more and more light and allow for more magnification, which is another way of saying that the object we look at appears more spread out than it would be with the naked eye. With our little telescope we might get a magnification of 200. Just think of binoculars compared with what our eyes can see. With larger telescopes the magnification could be a thousand-fold. Thus, we might imagine we could get unprecedented views of the Moon’s craters. Unfortunately, the Earth's atmosphere hinders unlimited magnification. As it is, whatever the telescope’s size, the image will be dancing around in front of us, hence the astronomer's quest for a site where the atmosphere is stable, which is another way of saying that the image will move just a little. It is like the situation that arises when we listen to a weak radio station affected by static (we call this noise whether of optical or of sound origin). Boosting the volume on the affected station also boosts the static and makes it just as difficult to hear. That is also a recurring problem with some hearing aids that amplify both the background sounds and the voice, largely destroying the effectiveness of the aid. Hence the cost of the late models that selectively attempt to reduce the background before amplifying the signal from the voice.

But while we can't get unlimited magnification—I’m ignoring adaptive optics here—by increasing the size of a telescope we ***can*** increase the “**light-gathering power**” in order to see to fainter and fainter limits. The only constraints are being able to build a large telescope ***and*** pay for it. Just think of it, the bigger the area to collect the light—a light bucket in effect—the more light you collect and the fainter you can see. Size in this case is everything! To get an idea of what a telescope can do for you, consider the following numbers. The diameter of the pupil of the dark-adapted human eye, that is one that takes about 20 minutes to become fully dilated, is about

0.7 cm in diameter (the size ranges between 0.5 and 0.9 cm and is a function of age). The amount of light we detect is related to the area of our eye and a telescope is a very big “eye”. With the 8-metre-class of telescopes that are commonplace today we can see more than a million times fainter than our eyes, about (800 / 0.7) × (800 / 0.7) or in shorthand $(800 / 0.7)^2$. If we convert this number to our weird magnitude scale this amounts to 15 magnitudes fainter than the faintest star we can see (7th magnitude). Thus, if we look through an 8-m telescope, we’d see down to ~22nd magnitude.

But what I’ve just described ignores the fact we can expose images for long periods of time on our **digital detectors (CCD)** in a process called integration, and which camera buffs call a time exposure. These time exposures may take milliseconds if what we are observing “does its thing” rapidly. Typically, depending on the instrument you are using, a time-exposures could go on for hours. Our eyes can’t make time-exposures so the numbers quoted above are lower limits. The faintest magnitude a telescope can detect is termed a **limiting magnitude**. To illustrate this point with an extreme example, consider that the HST took a series of images focused on one part of the sky in order to see back about 14 billion years in time (Figure 1-5). Over many orbits, the telescope accumulated an exposure of a million seconds, or 11 days, demonstrating that it is possible to reach new boundaries by stacking image upon image in a way that was impossible with a photographic plate. In this way, it reached a limiting magnitude of 31! In this case the HST observed objects about 4 billion times fainter than that of the human eye. Other judgement is required. Not all data needs to be crisp and noise free. There is such a thing as overkill and if you observe longer than is necessary, then you may not complete your observing program and perhaps not get any more time to do it in the competitive hothouse that is observational astronomy.

But before we talk any more about pictures we need to talk about **pixels** or picture elements. After all these are what we’re looking at when we have this long-desired image displayed on a screen in front of us. Don’t go squirrelly on me, we’ve been looking at picture elements for years. Every time we view the TV, we are looking at picture elements. Turn on your TV and look closely at the image. The picture is cut up into small pieces and each small piece is one of these picture elements or pixels. What is a better image? An image which is crisper-looking or clearer. Now we are starting to deal with what astronomers face when they are trying to judge how good the picture is that they’ve laboured so hard to get. Each picture element has a number associated with it related to how much light it has “soaked up”; the larger the number the better the signal, and the lower the number the poorer the signal. Low numbers in TV pixels correspond to times when you have poor reception and the screen looks blurry or washed out.

Sometimes we need data where the inter-agreement between the pixels will be high (accurate to better than 1%, perhaps even 1 part in 10,000), or maybe poor or noisy to use the TV analogy (only one part in 10). This latter requirement obviously demands a shorter exposure time than one where you need high accuracy. What I'm doing here is describing astronomical requirements in terms of your TV. We deal with something called **signal-to-noise**. A high signal and low noise are good whereas both high noise and high signal will be bad. The TV equivalent of high or low signal-to-noise is the difference between good and bad reception. Bypassing a technical discussion of signal-to-noise, think of it in terms of sampling—say for an election. If you want a poor poll prediction good to 10% or worse, sample a 100 people. The normal polling number is near a 1000 giving an uncertainty of about 3%. To get a poll result good to 1% then requires about 10,000 responses. The time taken to acquire 10,000 responses is 10 times that for 1000 and so on. So it is with observing. For accurate results you need to spend more time than you need for less accurate results. But, unlike polling, perhaps you can get perfectly good results with an exposure time equivalent to polling only a 100 people. It all depends on the program or project you are engaged in.

As noted previously, the whole of the electromagnetic spectrum is available to astronomers, but our eyes are only sensitive to a narrow wavelength range. Our bodies react to IR radiation because we feel heat even though we can't see the pot-bellied stove glow! Alternatively, we "feel" UV radiation ***after*** the event when we discover our bodies have been burnt by the Sun. Though sometimes when I got out into an ultra-violet dominated day, I swear I can feel my skin burning long before the mandatory 20-minute cut-off! Therefore, the concept of a limiting magnitude depends on the part of the spectrum being observed. The IR is more problematic than the visual region because the sky is bright in the IR and against this brighter background you can't reach faint levels. Also, the IR detection devices aren't as efficient as they are in the visual. These factors govern how faint you can observe. To make things more complicated, it depends on the instrument you are using. A spectrograph, which spreads the light out into all its colours, only looks at a narrow range of wavelengths, and for a given exposure time, cannot go to as faint a limit as direct images which usually cover a larger wavelength range, thus dealing with more light. Therefore, how faint you can observe depends on how accurate you want your observations and the derived measures to be, which in turn depends on which instrument you are using (spectrograph or picture camera), which wavelength region you need to observe in (visual or IR) and the sensitivity of the detector.

Telescopes may also be combined in groups. At the end of the twentieth century enormous projects involving larger and larger telescopes have been undertaken. Not only are these **optical telescopes** large (8-12 metres, with 30-metre-class telescopes soon to come online), but they are being linked together effectively increasing their **aperture** or light collecting area. These telescopes are already having a profound effect on our understanding of the universe. When used together, two 8-metre telescopes separated by say 100 metres can resolve or see detail more than ten-fold better than any of their individual 8-m components. If our eyes were separated by twice the amount they currently are, we would be able to see twice as much detail. For the telescopes, the combination works as if there was only one telescope but with a diameter of 100 m, though the light-gathering power (the size of the telescope's eyeball) would be equivalent to adding the collecting area of each telescope. This process, termed **aperture synthesis**, has long been used in **radio telescopes** where, combining them together, is a lot simpler because of the longer wavelength of the radio waves compared with visible light (the factor is > 200 million times). Using this approach in the optical domain now comes with a cost because of the severe technical constraints it puts on us. Only recently has it been successful, but more of this later in Section 2.8.

2.5 Refracting telescopes

The traditional telescope, favoured by cartoonists who love depicting astronomers as weird longhairs, is the refracting telescope. Unlike the cartoon image, these telescopes do not stick out through the portals of the dome but sit inside the dome, where they are safely protected from the weather—you can't observe in the rain! The traditional telescope is the **refracting telescope**, seen in Figure 2-2, similar in principle to the first telescope invented by a Dutch spectacle-maker in about 1600 and later used by Galileo (1564-1642) in his ground-breaking investigation of the solar system. I just can't imagine what went through his mind when he first saw the mountains on the Moon, the phases of Venus, and the very indistinct rings of Saturn as it would have challenged the dogma of the time. The principle of light collection and magnification involves the bending and focusing of light as it passes through the curved glass of a lens. A practical example of a lenses ability to focus light is to use a magnifying glass to set

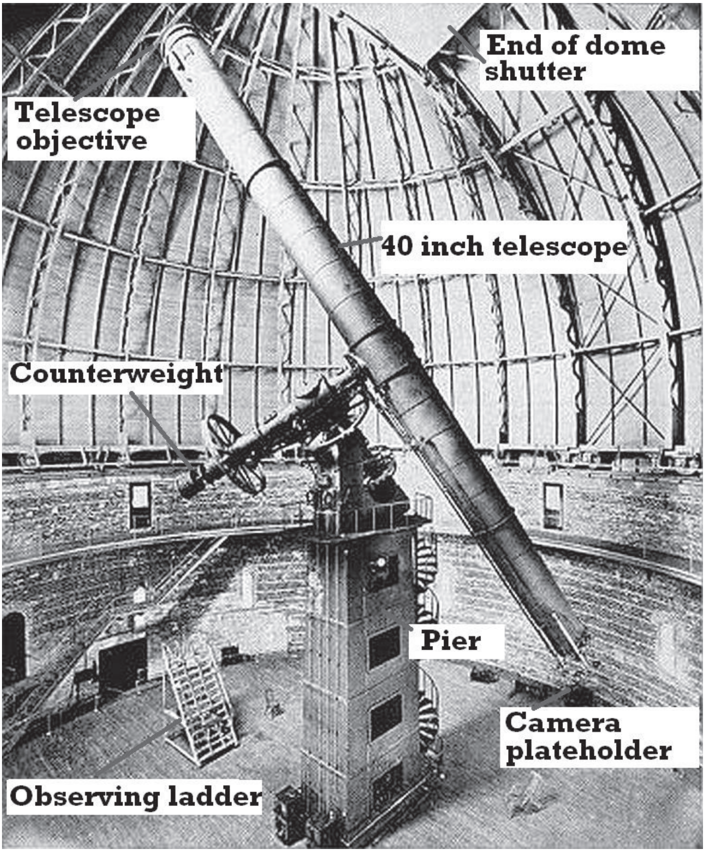

Figure 2-2. The Yerkes telescope, the largest refracting telescope ever built. A hundred years ago, the observers used a ladder to reach the camera and a small guide telescope used to maintain the guiding star under the crosshairs. My experience, observing while standing on the top stair of a similar ladder with nothing but my balance to rely on, was a necessary part of being an observational astronomer. Nowadays, the observer rides upwards and downwards on a movable floor or works in the comfort of a heated observing room. Credit: Yerkes Observatory photograph, 1897. Annotated by the author.

wood or paper on fire. In astronomy, the telescopes invert the image of the object being examined. It is a problem when we use the telescope to examine a terrestrial object because the image is upside down, but we don't care which way is up when we observe the sky. When the inverted image formed by the lens is looked at with a magnifying glass—we term an eyepiece—it magnifies the image. You can take off your spectacles (or I can with mine) and use one of the elements (both of mine are corrected quite differently) to magnify things. I use it regularly as a loupe when examining jewellery or to read a page when my eyes are bleary. The optical layout is shown in Figure 2-3. When a telescope is used for looking at objects on Earth rather than the sky an additional lens is inserted which brings the image upright. Such a telescope is called a **terrestrial telescope**.

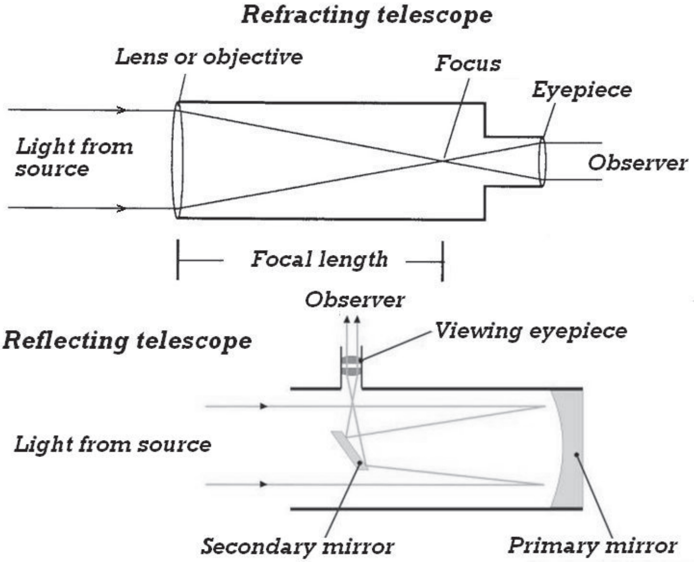

Figure 2-3. The optical layout of refracting and **reflecting telescopes**. Credit: Source unknown. Modified by the author.

There is a basic problem when light passes through a lens because it results in a **spectrum**. Look at Figure 1-7 again. When this refracted light is focused, the red light focuses at a different point than say the blue light. This is called **chromatic aberration** or colour distortion. To defeat this in a large refracting telescope, the **objective,** or main lens, may be made of two pieces of different sorts of glass combined in such a way as to create the fewest chromatic distortions in a focused image. By combining various types of glass, it is possible to minimize these differences in focal length. We know this problem has been solved in our single-lens reflex cameras because we see no colour haze when we look closely at an expanded image. But there is no simple fix in a telescope's camera for it requires many glass elements to correct the colour distortions and we can't afford the light loss as the rays pass through all that glass. These many elements are also the reason why our auxiliary camera lenses are so heavy. In addition, each time a light beam reflects off a glass surface there is a loss of light and there are also losses in its passage through the glass. Minimising this latter loss sets the standard for purity in the fibre optics used in communications, notably to our homes. We hardly notice these effects in a camera because, at least in daylight, there is ample light to register an image on the detector. These reflection losses are mitigated by using anti-reflection coatings which are ubiquitous in telescope optics and in our camera lenses. In addition, they are used in the art world because we hardly want to be looking at our reflection superimposed on some masterpiece.

The largest lens ever used in a telescope is 1 metre across (Yerkes Observatory in Williams Bay, Wisconsin, see Figure 2-2). The reason for this limitation is that the glass sags under its own weight thus distorting the focusing ability of the glass. Even though the glass changes shape with the changing position of the telescope, with modern optical technology the **aberrations** or optical imperfections resulting from the sagging glass can easily be corrected as they happen. While no longer relevant to refracting telescopes—no more lenses of this size have been made—sagging mirrors have, and are, being made that sag under their own weight necessitating such corrections (see next section).

Most photographs show telescopes pointing upward but when observing stars, we prefer to find them anywhere within about 60° of the vertical. Most of the time we are trying to squeeze out a final observation close to the horizon before the march of the seasons takes a star or galaxy from our ken. Remember, the constellations change as the months roll by. Under these circumstances, if you are desperate and really need this observation, the base of the telescope is tilted high in the air necessitating the use of high ladders, or perhaps a modified forklift, or, in later years, in the case of the Yerkes telescope, a rising floor. Nowadays, with the use of digital detectors there is no need to be physically at the telescope and we can observe the stars from the comfort of a warmed room, termed an observing room, unaffected by the extreme positions of the telescope. In the past, there was no such luxury, and the observer needed to be with the telescope to focus on a star and sit with it until the exposure was over. Then, they would remove the plateholder from the camera to go to the darkroom to change the plateholders. Perhaps to store the exposed plate and load another glass plate in the plateholder. The routine was rigid: move the telescope, climb the ladder, focus or set on a new star and begin the observing cycle again. Up and down the ladder, into the darkroom and back to the telescope. Now we work in front of a bank of TV screens that gives information about the telescope and its position: the appearance of the sky, the instrument being used to observe the stars and perhaps another screen or workstation processing the data as it is acquired. Or maybe the local late-night TV if exposures are long and boredom is setting in! Observing can be tedious, sometimes a night might span fourteen hours of tedium interspersed with a few moments of excitement when you get that image you desire, and it is perfect. Many years ago, when I was in Chile, the only observer on the mountain, I spent six weeks with clear nights and a radio that could only pick up static-riven horse-racing results from Australia. No wonder observational astronomers from my era are a little bit strange!

2.6 Reflecting telescopes

The other form of the telescope is the reflecting telescope, the type of telescope conceived by Gregory (1638-1675) in 1663 and first built by Newton in 1668. Here, concave mirrors focus the light without the optical aberrations or defects of a lens for the light does not pass through the glass but bounces off it. The characteristics of mirrors are superior to lenses and currently all major telescopes, whether they are radio or optical, use reflection optics. The optical layout for the simplest configuration is shown in Figure 2-3 along with that for the refracting telescope.

Here the light is reflected off surfaces that are shaped as **paraboloids** since this configuration focusses all the parallel rays of incoming light at one place called the **prime focus**. This system also produces an inverted image that is looked at with a magnifying glass. There are many variants of the reflecting telescope, derived from a series of configurations outlined by Gregory in 1663, but the one most common to the public are the dishes we use to get satellite TV. On the roofs of our homes we have small paraboloidal dishes with a detector between the dish and the radio source located at the prime focus which collects and feeds the signal to our TV. Though, if you have a good look at the dish, you will see that the detector is off-centre (off-axis) so it does not block the signal from the satellite. Alternatively, if the detector is small enough, it can be placed at the focus of the main mirror (on-axis). Both these designs are used in radio telescopes depending whether they are movable (steerable is the technical term) or fixed. The huge stationary radio telescope located in a caldera in Puerto Rico at Arecibo is off-axis and the massive steerable radio telescope in New South Wales used in the movie “The Dish” is on-axis.

For optical work, this configuration is generally no good because the telescopes are smaller and an observer at the upper focus would get in the way of the signal. If the telescope is large enough to have an “observer's cage” at the upper end, where an astronomer rides while the telescope tracks the stars, this configuration would work. The Palomar 5-metre telescope was the first to have someone ride around in the observer’s cage at the upper end. I don’t like to think of the discomfort associated with this and the necessary “calls of nature”.

If you go out on an observing night with amateur astronomers, you will use the configuration first used by Newton (lower panel, Figure 2-3) where the light is deflected to the side at the upper end and where you may get a view of Saturn’s rings or the wonderful lunar mountains amongst the myriad of other celestial sights. This works well for smaller reflecting telescopes. There are exceptions. Five decades ago I used the Newtonian configuration on the 2.1-m telescope at Mt Locke in West Texas where I had to clamber up the inside of the dome to get to the pulpit (a moveable extension jutting out inside the dome from which to observe and which really does look like a pulpit) 18 metres or 60 feet above the observatory floor, to load a plateholder containing photographic film, into a holder while leaning out balanced on a protective railing. All I can say is that I was lucky it was dark because I could never have done it in daylight! My night was spent trying to guide the telescope on a galaxy seen only very faintly through the viewing eyepiece. Ten hours up there, exposed to the elements, was not something that endeared me to this form of observing and undoubtedly served to bend me away from the study of galaxies and towards the stars where I could observe from the **Cassegrain focus** (see Figure 2-4, lower left panel). Now technology has removed the necessity to physically being at the upper end of the telescope because the detectors are small enough to be placed there without obscuring much of the beam. All I can say is, “Thank God!” Related to the telescope on Mt Locke and the prime focus cage, is this story. In 1963, the newly appointed director of the observatory wanted to see if the 2.1-m telescope could carry a person in a cage. He was discussing this high above the observing floor in the observing pulpit. To our surprise, he decided to test his theory and promptly climbed out over the railing of the pulpit onto the end of the telescope. His weight overwhelmed the clutch that normally stopped the telescope from slumping in extreme positions. Whereupon it immediately started to sink towards the floor, forcing two of us to scramble and frantically help our new boss to safety! I was impressed that my professor—a tiny man—and the chief competitor for the director's role, strenuously helped also!

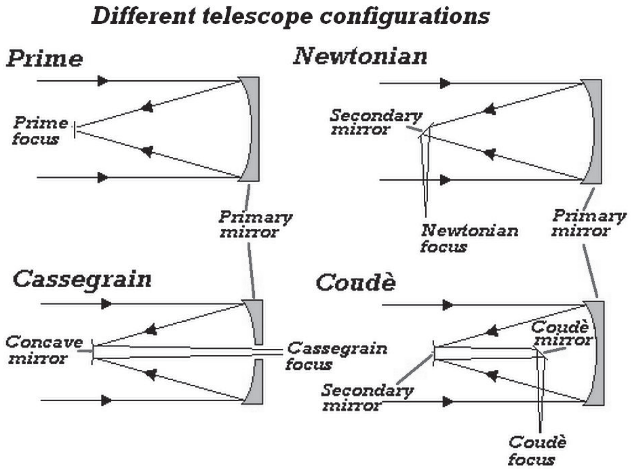

Figure 2-4. Depending on the task, a reflecting telescope is configured differently. In the upper left panel, a detector is placed at the prime focus and digital data are fed down to the observer's room. In the past, telescopes such as the Palomar 200-inch, could carry an observer inside the telescope in a cage located at the prime focus. The configuration in the upper right panel is popular among amateurs. Spectrographs are usually carried at the Cassegrain focus while the **Coudè focus** feeds light into a laboratory setting below the observing floor housing the **Coudè spectrograph**. Credit: Unknown source. Adapted by the author.

When looking at a very faint object, perhaps a galaxy at the limit of the telescope's range, the instrument, either a spectrograph or a camera, will be carried in or on the telescope. On the other hand, the spectrograph may be on the observing floor or in the Coudè laboratory in the building somewhere where light is piped to it either by mirrors or by fibre optics—the latter, an expensive refinement of the same cable that feeds the Internet to your home.

2.7 The current crop of behemoths

The moving parts of the Palomar 200-inch telescope (5 m) weigh 530 tons or 540 tonnes and it was surmised that this would limit a telescope's size unless new technology came into play. The mirror of the 5-m telescope is made of one piece of glass, honeycombed at its back to keep down the weight and strong enough to keep its shape as it points around the sky. Despite this remarkable telescope's success, there are several reasons for ***not*** building telescopes with strong monolithic mirrors, not that they had a choice at the time! One is the problem of casting the mirror and cooling it so it doesn't crack. Another is in the amount of glass having to be removed during the shaping of the mirror. Another is the weight of the mirror and the size of the support housing it and then being able to drive the weighty telescope in order to compensate for the Earth's rotation. However, despite the known difficulties, the Russians built a 6-m telescope that has had only limited success because of the poor quality of the observing site and the poor images it produced. If the conditions had not changed—namely technology in all its forms—the Russian effort would likely have been the pinnacle of telescope construction and the ultimate folly!

In attempting to build larger and larger telescopes these difficulties have been addressed in different ways. The four telescopes of the European Southern Observatory (Figure 2-5) have been made of very thin glass that

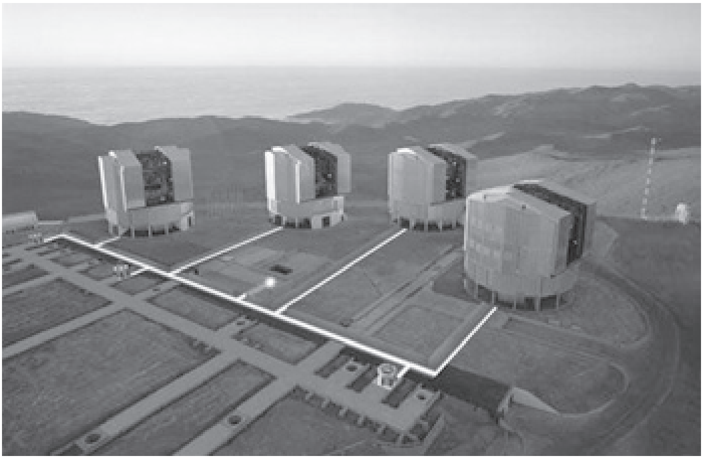

Figure 2-5. ESO's Very Large Telescope (VLT) is comprised of four 8-m-class telescopes. Each telescope can work independently or when used in concert with the rest as an **interferometer** creates a single telescope with the resolution of a 100-m telescope. Credit: ESO.

is not strong enough to keep its shape as it tilts when the telescope moves. Imagine a piece of glass 8 metres in diameter and only 17.5 centimetres (7 inches!) thick where the shape is maintained by 450 computer-operated pads that support the mirror at 152 points across its back. The shape is continually monitored and automatically corrected as it deforms under the varying effects of gravity (see Figure 2-6). This is termed **active optics**. In this case the restrictions involving excessive weight are bypassed, but at the cost of expensive technology. The glass that makes large mirrors like this is melted and spun to create a paraboloidal shape that can be immediately polished without the need to "dig out" lots of glass. Other large telescopes like the Keck twins atop Mauna Kea have been constructed from many hexagonal pieces that are shaped independently and later assembled in a mosaic to form a paraboloidal dish. Each element is then under computer control and focused together to produce the smallest possible image.

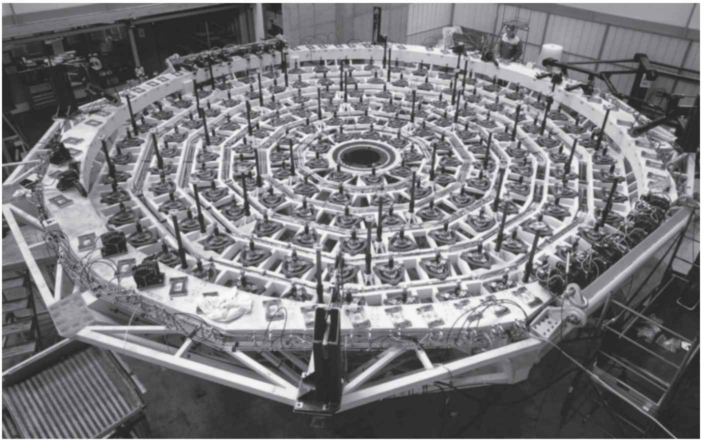

Figure 2-6. The **primary mirrors** of the four telescopes each weigh 22 tonnes, measure 8.2 metres across and are only 17.5 centimetres thick. Each of them rests on computer-controlled supports that are installed in an exceedingly rigid cell that weighs about 11 tonnes. The supports are an integral part of the VLT Active Optics system which ensures that the large mirrors always have the optimal shape. Comment and Credit: ESO.

In a cost-conscious world, telescopes don't need to be movable in two directions. These types of telescopes are called **transit telescopes** and in their original incarnation hundreds of years ago were used to time the stars as they passed by. The time then gave a position relative to other stars whose times were also measured. Some of these telescopes have but limited motion in the east-west direction but can be moved north-south. With this configuration the telescope can be moved in azimuth (east-west) using the limited motion to track the stars as the Earth's rotation sweeps the stars across the sky. Examples of this transit instrument are the 10-m **Hobby-**

Eberly Telescope (HET) in West Texas made of hexagonal segments and another 11-m telescope completed in 2005, the **South African Large Telescope (SALT**). The HET can track an object for 3/4 to 2.5 hours depending on its location in the sky. The advantage of this type of telescope is its relatively low cost which is typically about 20% of the cost of a fully "steerable" telescope. This mode of observing, which is very efficient in that one is not **slewing**, or moving, a telescope over the sky, has obvious limitations in that only part of the sky normally accessible from the site can be observed. The largest single-dish radio telescope in the world, located in the crater of a volcano at Arecibo in Puerto Rico, is a variant of this type. The main mirror, a metal mesh, cannot move and all tracking is done by the detector moving on cables across the volcano. Another extreme form of creating a mirror, is to take a huge "puddle" of mercury and spin it. Under centrifugal force, the mercury banks up around the edges to form a paraboloidal shape. While the mercury spins, one has a telescope that can be used to observe stars transiting overhead. This form of telescope (6-metre class), the **Large Zenith Telescope**, was a joint project between the University of British Columbia and the University of Laval in Quebec. Because the main mirror is fixed, the detector at the upper end of the telescope at the prime focus, must be moved to follow the targets as they transit the instrument. In addition, the detector has a little north-south movement to allow a strip of sky as wide as half of the full moon to be scanned. Despite its apparent limitations, several million galaxies were within its range. However, while a good idea, this telescope was decommissioned because the weather at the site was too poor.

2.8 Interferometers: Getting much more for your bucks

Since the pioneering work of Canadian radio astronomers, radio telescopes have been linked together to act as one gigantic aperture. What started as the linking of two telescopes continent-wide has developed into a **"Whole-Earth Radio Telescope"** capable of mapping radio features with greater detail than the largest of the optical telescopes—those telescopes we traditionally "look" through. Alternatively, arrays of smaller telescopes are linked together to increase the resolution and map fine detail of the sky. The largest array of this sort—**The Very Large Array (VLA)**—operated by the National Radio Astronomy Observatory—is in the New Mexico desert. When operated as a group, these telescopes form an interferometer, a detector that creates a pattern of brightness and shadows that can only be reconstructed in a computer and which lead to maps with a resolution equal to a single telescope the size of the whole array. The VLA is made up individual telescopes, dishes 25 m across, laid out in a huge Y-shaped pattern extending across 36 km of desert! The resolution of this combination of telescopes is equivalent to having a single telescope 36 km in diameter! This technique was only made practical in radio astronomy because the long wavelength of the electromagnetic radiation (ranging from centimetres to metres) made the method technically feasible at that time. The difficulty with interferometry is that when the various telescopes collect the "light" they must combine radiation from the same wavefront, or light that emanated from the source at the same time. The geometry of the size of the array, along with the location of the source is in the sky, means that the same wavefront arrives at differing times to each of the telescopes. Think of this in terms of a long wave coming onto the shore, splashing in at one end of the beach and slowly working its way along. That beach-long wave, forms what we term a wavefront in astronomy. The second wave will be a little different from the first. For an interferometer to work, each instrument must sample the same wavefront. The technique in radio astronomy is now routine, but in the optical region where the wavelengths are millions of times smaller, it is a huge challenge to delay the various arrival times so the waves are properly combined.

The technique in radio astronomy is to link together all the individual signals from the various telescopes with timing from an atomic clock and combine them later in a computer. For the method to work, the time needs to be measured to about 3 parts in 10^{-14}s or 3 parts of a hundred trillionth of a second! Caesium atomic clocks can be synchronized to times of 2-3 parts in 10^{-14} thus allowing this method to work. Alternatively, if the signal can be delayed in some way, the need to record the times along with the signal can be removed. The delay method is what is used with optical telescopes since the times involved are about 6 million times smaller than those encountered in radio astronomy and we can't measure time that accurately! It means that when successfully combined, the radiation falling on each of the dishes interferes with each other forming patterns varying in brightness over the sky (interference patterns) where the telescopes are pointing. As the Earth rotates a complex image is formed which is later analysed by computers to produce a detailed map of the sky. The VLA referred to above can draw maps with a resolution of about 0.04 **arcseconds (arcsec)** when operated at a wavelength of 0.7 cm. Another way of saying it is that the VLA could separate two radio emitting golf balls held together in one hand and seen at 150 km!

What ***is*** 0.04 of an arcsecond? We measure angles in terms of parts of a circle. There are 360 degrees in a circle, 60 minutes of arc in a degree and 60 seconds of arc in a minute. Therefore, 1 arcsecond is 1 part in 360 × 60 × 60 of a circle. Think of it as the angle defined by an object 1 m high being viewed at 206,000 m or 206 km! The theoretical image size in say a 10-m telescope is about 0.01 arcseconds but after the atmosphere degrades the image it is about 0.4 arcseconds, hence astronomers desire to beat the seeing—and they do as shown earlier in Figure 2-1.

In another historic first, radio astronomers linked the VLA to radio telescopes across the continental USA forming the **Very Long Baseline Array (VLBA)** together with a 100-metre telescope in Germany. The aim of the experiment was to show how fast gravity acts! In this experiment, the astronomers used the bending effect on radio waves from a distant radio source being occulted by the planet Jupiter. The bending produced a small shift in Jupiter's position; a result similar in principle to the observations made in 1919 that showed that the Sun bent the light from the stars that were seen close-by its limb during the total eclipse. Observational proof of this, due to Eddington, the foremost astrophysicist of his time, was a key verification of Einstein's theory of relatively. Getting back to Jupiter. To get a measurement of this type required that the position of Jupiter be known very precisely and that it passes almost in front of the distant radio source, a **quasar**, a point-like source billions of **light-years (LY**) from us—the distance light travels in one year. The results, limited by the small deflections involved, appeared to show that the effect of gravity is propagated with a speed exactly like light. They found a value with an accuracy of 20% close to the speed of light. Thus, if we replaced the Sun with an object twice as massive, it would still take 8 minutes—the time for gravity to travel the 150 million km to Earth at 300,000 km/s—for the increased gravitational field to affect the Earth's orbit. In making the observation, the radio astronomers achieved accuracy three times more than what had been done before, the precision equivalent to detecting the width of a human hair at 400 km (250 miles)! Though, while the experiment, which one person has described as a tour de force, stands up, there followed a considerable debate about whether the observation actually measured the speed of gravity or that of light. But the point is, when linked together over vast distances, radio telescopes can make observations of remarkable precision.

Optical telescopes are now being linked together, even though the difficulty of matching arrival times is more difficult than in the radio domain. In this context, the **Very Large Telescope Interferometer (VLTI)** in Chile has achieved success working in the IR where the experiment is less demanding (wavelengths are longer). Other instruments with adaptive optics are also coming online at different wavelengths that will improve a telescope's resolution and observing efficiency many-fold, as well as producing pictures of unprecedented sharpness. The process used at ESO is described in their website and already the first images have been released of observations made in the IR with a resolution of about 80 **microarcsec**, or 80 millionths of an arcsecond. This is roughly equivalent to seeing a dime at 45,000 km—about ten percent of the distance to the Moon! As with the huge numbers experienced in this science, I have great difficulty in comprehending such a tiny measurement.

2.9 The astronomer's night-time world

The picture I've painted here is of astronomers looking at the heavens but in reality, professionals hardly ever do this, unless it is while wandering the catwalk outside the dome in order to check for clouds, or simply to take a break or to enjoy the view. The images from the main mirror are projected onto some sort of digital detector and examined in the comfort of a warm observing room away from the ladders and the cold. Most of my observing has been outside in the ambient temperature where boredom is the norm interspersed with intense activity. The routine is the same whether you are an amateur observing with a fancy new CCD (digital camera in essence) attached to the end of a small reflecting telescope, or a professional. You open the dome by uncovering a slit at sunset to give the building interior and the telescope optics a chance to cool down and reach equilibrium with their surrounds. Perhaps the dome environs have been refrigerated to match the outside air throughout the day so that the, telescope optics and supports are in tune with the ambient air. It is necessary to do this to avoid a draught either into or out of the dome's slit caused by temperature difference between the air outside the dome and that inside. Any draught disturbs the air and creates what we call *"***seeing***"*. Seeing is the motion and flickering of the stars, the twinkles I've talked about. Many an observatory has been built in a place where the seeing is excellent, but often when the site is developed, the telescopes experience seeing worse than what was anticipated. In other words, the building, telescope, and environs degrade the hope of those who laboured long and hard testing the site prior to the decision to build. This is called "dome seeing" and engineers go to great lengths to defeat it. This difficulty has led to extensive research about what causes seeing in and around buildings.

You switch on the telescope drive system and check that the electronics needed to move the telescope and to record the data are operational. You have also cooled down the detector several hours earlier which can, depending on the type of instrument you are using, be located in or on the telescope or “piped” down through a complex light path to the Coudè room, a laboratory setting in which you have a detector. Perhaps your detector is being “fed" from the telescope down bundles of optical fibres (the fibre optics that give us rapid broadband access across the Internet) to an instrument on the floor. The instrument is cooled by liquid nitrogen, nitrogen gas cooled to –196°C where it has condensed into a liquid. These are the temperatures of the “seas” of Titan, a satellite of Saturn and one of the four moons in the solar system known to have an atmosphere—some more tenuous than the others. You might have seen the images of Titan’s surface from the NASA/ESA spacecraft **Cassini’s probe** which recently dropped into Titan’s atmosphere. Back to observing preparations. After you check your observing lists or the files within a computer that will allow the telescope to be set automatically, you wait for sunset. Without going into details, there is a point of intense activity just before you begin observing when you gather calibration material necessary to get the most out of your detector. I guess the calibration is akin to a pilot setting the plane’s barometer to the pressure at the destination airport or checking the coordinates of the Global Positioning System, or GPS system, used on the plane. An error in the pre-flight calibration of a plane can have catastrophic effects as the air crash on Mt Erebus in Antarctica demonstrated.

Finally, the night begins. It may go like a dream where you set on star after star, making exposures much like a time-exposures on a camera, and recording the data until daybreak. Occasionally the night turns sour, either because of problems with a detector which has started to warm up giving you the equivalent of “bad reception”, or maybe you make a blunder. The bumper sticker “s… happens” is as true in a telescope's observing room as anywhere else. I can recall a night when I passed over the telescope to another astronomer who was starting the next shift and was almost immediately frightened out of my wits by loud shouts followed by a huge grinding noise. When I burst out of the darkroom, where I was developing my photographic observations, it was to see the telescope with its upper end hooked into the pulpit jutting from the dome and the lower end carrying the spectrograph—the most delicate part of the whole system—jammed hard against the massive concrete pier that supported the telescope's moving parts! Fortunately, the spectrograph was not damaged.

We have problems with our egos. Working at the Anglo-Australian Telescope (AAT) in Northern New South Wales my colleague and I had screwed up with a finding chart. Yes, in astronomy we need to be able to find the stars or galaxies and so must prepare charts ahead of time and do our own version of a global positioning system on the sky. The pressure is on under those circumstances since at that time a telescope of this class required about $30,000/night to keep it going and observing time, the actual chance you get to carry out your plans, is very hard to come by. And this is ignoring the fact that groping around looking for a star amid zillions is totally unprofessional and humiliating, especially when the telescope operator, seated at the telescope console replete with dials and computer screens, may be watching and judging you unfavourably against others who have sat in your seat. All observers are required to give an appraisal of their observing run, saying what works and what doesn’t, so I expect the telescope operators report on us also.

A great night is when you get underway observing: selecting the stars, getting calibration data, recording the images, checking they're okay and keeping on going like a metronome or an automaton until daybreak. Often, it is your only chance to carry out your program and weather, bad weather—forest fires even—may deny you another chance. In fact, one observing run at the AAT was terminated by nearby forest fires. But it was not the first time I’ve observed where I could smell the smoke and watch the water bombers sweeping down over the lower slopes of the mountain to drop water or fire retardant! Awarding time is a ruthless process and we never got more time to complete the project, though I noticed in researching this book that my colleagues did indeed finish that AAT project ten years later!

On some occasions you are so busy as to have little time to feel fatigued, these are the occasions when each observation takes a few minutes and the telescope is being moved to the next object while you update records. At other times, when the exposures are long, maybe an hour or so, the night at times begins to drag. Perhaps you begin to work on the data you have acquired, though I can’t handle anything except the observing. Perhaps a colleague back home is also logged on to your computer and is checking how things are going and, in some cases, suggesting how you might function better! In these circumstances it is embarrassing to get ***that*** phone call. But despite the fatigue there is no better feeling than when the telescope is behaving, the detector is working well, and you are ”in the zone”. I first experienced that in Chile, alone on a mountaintop, sleeping in an eight by eight shed under primitive conditions, using a small telescope but with a sky as clear and steady as could ever be hoped for with the observations coming steadily in. As I've mentioned earlier the only flaw in the picture was a radio that could only get horse-racing results from Australia but more—the smell from a cooling agent for my equipment obtained from the local brewery. At the end of such an evening you are elated, but the buzz from using a behemoth is even better and at night's end you are hardly ready for bed—a place you need to be as quickly as possible because the hours available are limited and after you sleep you must eat, check your material for the night's observing and ready the instrument. The worst observing regimen I ever experienced was successive days of 16 hour observing on the **International Ultraviolet Explorer (IUE)** at the **Goddard Space Flight Centre (GSFC).** At least the instrument didn't need to be prepped but the days(?) or nights(?) were challenging, sitting in the observing room trying to stay awake and selecting the next object to be observed that required the satellite operator to move the telescope as efficiently as possible to preserve the propellant fuelling the jets used to position the telescope, and also to avoid moving the telescope across the face of the Moon, Earth or Sun. In addition, trying to judge the exposure time to give a well-exposed image was difficult, because it was all new ground. Prior to the IUE, the only observations made in the UV were limited to those few who had experiments on rockets regularly shot into the atmosphere to get but a glimpse of the UV spectrum of stars. Now these varied decisions are computerized with no need for the astronomer to be anywhere else than his office or at home asleep because he can download his data the next day. This is the tenor of all observing whether using the behemoths on the ground or the dedicated spacecraft regularly being launched into space.

When an astronomer says they are going observing, they do not sit glued to the end of a telescope looking at the heavens. The eye is replaced by some sort of digital detector that records the data in a fashion the eye could never emulate since our eyes have no long-term retention of images—just imagine the problem ***that*** would cause! As noted above, with the large telescopes, the observer may not even go to the telescope because the observing is done for you. In this case, observations that people have requested are classified according to the instrument needed: position in the sky, length of exposure, whether they'd be affected by the Moon, Sun or Earth or not, and then they are queued. This means that some clever bit of software organizes everyone's observations according to these criteria and then makes the observation. As I recall, my first exposure to queue theory (developed in the 20s to handle telephone switchboards) was in the 60s when computer jobs were submitted in a batch (one after the other) to a mainframe—every computer in those days was a mainframe!—and the machine had to choose the best order to run the jobs. Nowadays, with the huge speeds available to us, we can ignore queue theory in the processing of jobs, but it has left a legacy for us in ordering our observations in the most efficient manner possible. This hands-off process is a very efficient way of observing but it takes away the pleasure some of us have in making the observations and being able sometimes to change what we're doing in mid-flight to correct for some of the weather conditions. Thinking about queue theory, we could do with a healthy dose of it to help manage the unmanageable traffic flows on our streets and poorly integrated traffic-light cycles!

2.10 Detectors: The astronomer's eyes

2.10.1 The photographic plate

The photographic plate revolutionized astronomy in the same way that digital detectors have created a second revolution now, but in terms of storing information the photographic plate is still unsurpassed. The problem with it is the lack of sensitivity and the poor accuracy with which we can determine stellar brightness. The sensitivity of the photographic plate is about 100 times less than a CCD. In this case, when 100 photons strike a photographic emulsion only one registers by blackening the silver compound whereas a CCD will detect 80 or more of those 100 photons. In addition, the repeatability of a photographic observation may be good to only ~10% whereas the repeatability of a CCD can be at least 1000 times better.

2.10.2 The photoelectric photometer

A major development involving what is called the photoelectric effect, for which Einstein won the Nobel Prize, was pioneered in the early 20th century and came to fruition in the 50s and 60s, the time when I began my career in astronomy. If light falls on a certain light-sensitive material called a **photocathode** then electrons are released, ultimately producing a flow of electrons constituting an electric current that can be measured. No light, no current, and the device, called a **photomultiplier**, found a ready use as a burglar alarm. Shine a light beam across to a detector and get an electric current. Interrupt the light and no current flows, triggering an alarm. In its modern incarnation, lasers produce the light beam. The current produced by starlight is small and requires electronics that will amplify it and hence allow us to measure the signal. The development of stable amplifiers capable of always responding in the same way to small currents was as critical to the advancement of astronomy as was the detector itself. In the

60s, with this development, we suddenly had the ability to measure the brightness and colours of stars to 0.5%--a value hardly surpassed today. The process of measuring brightness and colour is called **photometry**. While the precision was excellent, the downside was that only one object could be observed at a time, in contrast to a photographic plate that could record thousands of images in one shot.

2.10.3 The CCD

The CCD is a digital detector with an array of pixels sensitive to light. Don't ask me how it works, I can deal with a photomultiplier but a CCD is out of my league. We are getting familiar with pixels or picture elements when we look at digital cameras and we've been looking at pixels long enough in our TV! Think of each of the 12 million or so pixels in a digital camera (**megapixels MPs**) as buckets that gather light and then the amount of light in each bucket is measured as it is read out and displayed. The more pixels, the better detail you will see in your photographs. So not only are CCDs more sensitive than traditional devices (you can often avoid a flash when the light levels are low), they also give a number for each pixel. You use these numbers when you process your images with Photoshop, Lightroom, or some similar image-processing software. Having a number at your disposal makes a tremendous difference to your labour since you can take your data directly from the instrument to a computer thus bypassing the need to scan a photographic plate, a document, or pictures to get numbers. In pre-CCD days, this was always a difficult intermediate step needed for us to get loose on the numbers in a computer.

But digital detectors are small. Think of your camera with 5 megapixels compared to a photographic plate that could be 35 cm square and contain a staggering 30 billion (30 Gb) picture elements depending on the size of a pixel. In using a digital detector, you are trading off the expansive spatial coverage that a photographic plate has, against the sensitivity and inherent accuracy of a CCD. With a CCD we can only look at small pieces of the sky or small sections of a spectrum compared with a photographic plate (gelatin on glass) but the CCD can see five magnitudes fainter, the equivalent of being able to detect an object ten times further away and get inter-agreement between the measurements a hundredfold better. What you lose on the swings, you gain on the roundabouts. The ideal detector would be a CCD the size of a photographic plate. But great as this would be, even this would have its problems. It takes time to read the numbers contained in a CCD. If it was ever possible to create a CCD 35 cm square, the size of a photographic plate in the Palomar 48-inch Schmidt Survey, it would contain, depending on the size of a pixel, about ~30 billion pixels or 30 Gigabyte of data—it now exists, see Figure 15-5. An image that size takes time to read and imagine if you made a hundred observations in one night, you'd need to store 3 Terabytes (one Terabyte is 1000 billion) of data each night. Disk storage would soon be at a premium. The pictures obtained this way could not be moved across the Net and our computers would choke on the material if we ever got our hands on it. Having written that, I see that the **Large Synodic Survey Telescope (LSST)** under construction in Chile is dealing with these issues (see Chapter 15).

While it is not without its problems, particularly in its calibration, the development of the CCD has had a huge effect in astronomy, not only in the quality of data it yields but in the time it saves in both gathering and processing observations, but even more importantly, it allows astronomers to observe much fainter objects. This latter comment is the driver in astronomy and a researcher will endure observing and processing problems to get ***that*** exposure which always eluded them.

2.11 Advances in optics

2.11.1 Optical design

Optical design has become very sophisticated over the last 40 years because of the increased use of specialised computer programs, coupled with complex optimization software (see what follows). We see the effects of this in the camera world where the zoom lenses have become more compact with excellent optical characteristics out to the edge of the field of view. Consider for a moment the choices that are available to you in designing a zoom lens. You have a variable number of lenses available, each made of different glass and focal lengths; the focal length is the distance you need to hold a magnifying glass away from a page to read the enlarged print. The separations between each lens may be different. We cannot handle all these variations because there are too many choices but the computer does it for us by a process called **optimisation**. Optimisation techniques tell us the most efficient way to travel around a city to deliver goods, to design the box with the largest volume using the least amount of cardboard, or to solve the classic travelling salesman problem—that is, which path should the salesman follow to minimize the distances travelled between the lower continental US State Capitals. Similarly, in astronomy where problems generated in one part of the optical train—main mirror, or objective, **secondary mirror**, plus assorted optics getting the light to the detector—are corrected later, just before the image is recorded. The best example of this is in the original Hubble mirror that had been ground automatically to be optically perfect. Unfortunately, one number had been entered incorrectly during the grinding stage and the images from the telescope were severely degraded. It took a while before the root of the problem was discovered and then a set of optics was developed and installed in the HST on one of the shuttle-service missions that corrected much of the problem. This is not the first time there has been a mammoth failure because of an incorrect number. A probe to Mars burned up in its atmosphere because of a confusion between miles and kilometres!

2.11.2 Enhancing the light throughput in a telescope/instrument

It is not enough to have a huge mirror and a good detector because not all the light falling on a mirror reaches the detector. Not only does the light go through the telescope and its instruments but also through the fancy new devices which enable you to minimize the twinkle or seeing. All these reflections or refractions potentially remove light from the system. As an example, the configuration where the light goes to the Coudè focus can produce light losses amounting to ~55% because each time the light is reflected there are losses that go with the reflection. But it is in this Coudè laboratory where detailed work on the spectra of stars is best accomplished since the spectrum can be easily spread out over 60 cm or two feet! Ironically, such a stretch of spectrum can be handled photographically but not with the modern CCD detectors which are far too small though CCDs are being butted together to remove this limitation. Getting back to the light losses. Mirrors were originally silvered but silver tarnishes and the amount of light they reflect degrades with time. Because of its durability, aluminium replaced silver but in the blue part of the spectrum, where a lot of interesting features are found in stellar spectra, the reflectivity is only 90%. In the Coudè arrangement, at least seven reflections are required to get the light from the telescope to the detector so you end up with (0.90 × 0.90) seven times, or in shorthand 0.90^7, or only 48% of the light in the original beam. This limits the faintness your telescope can go by approximately a magnitude. For this reason, achieving high reflectivity is a top priority in any telescope/instrument construction. In the past, this was accomplished by having two sets of optics optimized for greatest throughput in the blue and the red regions of the spectrum, respectively. But recently, hybrid **high-reflectance coatings,** based on silver, allow more light to be reflected in the blue (95%) which halve the losses. At longer and longer wavelengths, the reflectance increases to nearly 99% removing the problem altogether.

Whenever light is refracted through a lens (goes through glass) there are light losses. Take for example the window of your house. There is light loss off any piece of glass that is not specially coated to allow the maximum amount of light through. Typically, glass allows 96% of the light through the first surface and 96% through the next. In the bright of day, you never notice this. Unconsciously though, you use the reflected light off a window to see behind you, a favourite ploy in the espionage movies. For a terrestrial telescope where the light levels are high, you'd never notice this but for observing stars you need to preserve as much light as you can. Now that lenses are coated with anti-reflection coatings, special material that coats the glass surface to minimize light lost by reflection, these losses are kept to a minimum. Binoculars and zoom lens have many glass elements inside them that necessitate coating which you see as a blue sheen on the lens of your single lens reflex camera or binoculars.

2.12 Beating the atmosphere

2.12.1 Speckle photometry

In the 60s, a method called **speckle photometry** was developed to beat the effects of the atmosphere. Imagine taking a video of a binary star or any star for that matter. An inspection of the individual frames would reveal what the eye sees when it looks at a star image under high magnification. The star viewed in an eyepiece, dances around. If there are two stars there you get a clear view of both for an instant and then it moves, changing its position every tenth of a second. An examination of the frames shows nicely defined images of the stars but displaced from each other. When you take a time exposure these images form a larger blurred image. Now, given a recording of these motions, and choosing one image as being the master, you can stack them all up on top of the master to get a single, nicely defined image of a binary star that might otherwise appear as a blurred blob that might look like two but is very poorly defined. This is speckle photometry, which provides another way of limiting the negative twinkling effects of the Earth's atmosphere. The technique has been around for 50 years now and some amateurs routinely use this technique where image clarity is of overriding importance, such as during recent Mars oppositions—the time when Mars is closest to us. Once upon a time this superposition of the dancing images took place later in a photographic lab but now, because of the power of the computers, CCD images can be processed or stacked in real-time. There are some wonderful images of Jupiter and other solar system objects taken by amateurs using "**apps**" designed to do this.

In some cases where a star is very large such as Antares or Betelgeuse, an astronomer using a 4-metre-class telescope can measure the apparent diameter in **milliarcseconds (mas)** directly. Unfortunately, there are very few stars large and close enough to be amenable to this approach. The main use of speckle is the observation of the orbits of binary stars that appear as two on the sky. So why the emphasis on binary stars? The mass of a star is the primary factor that governs how a star evolves and a star's mass can only be determined reliably by its effect on another star, but more about this in Chapter 6.

2.12.2 Deformable mirrors

Since the time of the debate about the HST, whether the money should be invested in space or on Earth, optical design and technology have really come of age, proving that we ***can*** achieve the same image sizes on Earth as we can in space. On the other hand, above the Earth's atmosphere the whole of the cosmos is available for examination with the fullness of the electromagnetic spectrum. Now it is possible with "rubber", or deformable, mirrors to modify the images "on the fly" to correct for the turbulent effects of the atmosphere. Initial experiments that confirmed the potential for this were conducted by the US military with their "Starfire" program in New Mexico where they shone a laser into the sky and used the returning beam as a reference with which to correct for atmospheric shifts (see Figure 2-7). This has an obvious military application in order to obtain clear images of satellites or spacecraft flying 150 km overhead. A variant of this technique is used in the latest telescopes and retrofitted to older telescopes such as the Palomar 200-inch. Part of an image is fed to a device that sees how the starlight moves around in the plane of the detector, forecasts the next shift, and corrects for this motion. In this way the light mostly falls on the same part of the detector, whereas, in the absence of correction, the light would turn a star into a large, or blurred image. The notes to Figure 2-7 add to my comments here. This is the heart of the argument against expending vast amounts of money on a space telescope when much larger telescopes could be erected on Earth with images just as good but much less costly. In this regard, the two huge Keck telescopes atop Mauna Kea cost about $180 million in total with running cost of about $70,000/night. The Hubble and the necessary backup facilities including shuttle servicing costs tens of billions of dollars until its planned termination in 2010. It is still going! These relative numbers speak for themselves.

Figure 2-7. The smaller telescope beside Yepun is one of four Auxiliary Telescopes that have diameters of 1.8 metres. When combined with Yepun for example, these telescopes make the Very Large Telescope Interferometer (VLTI). Yepun, one of the four **VLT** 8.2-m telescopes, is equipped with the Laser Guide Star Facility that is caught in action in this picture. The laser beams colour is precisely tuned to energise a layer of sodium atoms in the upper atmosphere which creates a small bright spot—an artificial star. This spot can be used as a reference star to correct for atmospheric distortions of the twinkling light from actual stars—a process called adaptive optics. Credit: ESO. The author modified original comments.

The way that deformable mirrors located within the optical train can be controlled to handle the twinkling of stars is one of the most exciting developments in astronomy. This means that telescope mirrors can be ground to the ultimate precision, one limited only by the nature of light. In other words, you can’t make the images obtained by the mirror any sharper.

In the past, aside from the HST, this precision has not been needed but now with a mirror doing a correcting dance throughout the night, we can expect stellar images to be points of light surrounded by small imperfections related to the metal supporting the small (secondary) mirror that reflects the light towards its destination. We can now realistically hope to match the clarity of the images from space. The 200-inch telescope has the intrinsic ability to see two stars separated by only 0.021 arcseconds but in practice the limit is 20 times worse because of the Earth's atmosphere. Now telescopes with this technology can reach their theoretical optical potential. These sharp images produce a huge gain in efficiency because it takes much less time to record a sharp image than a blurred one. I guess it is akin to reading with a spotlight on the page as opposed to the same amount of light being diffused over a larger area.

2.13 Why are telescopes located in weird places?

You might notice that the newspaper and TV astronomical reports come from places such as northern Chile, the Canary Islands, Sutherland in South Africa, northern New South Wales in Australia, in the foothills of the Andes in Argentina, Space, the big island of Hawaii, and so on. The location of the telescopes depends on several things; to be as cloud-free as possible and perhaps the need to see a different part of the sky. Remember the Earth is round and what is visible in the far south is not visible from the north. You can't use the North Star, Polaris, for navigation in the southern oceans, just as you can't see the spectacular Southern Cross or the richness and beauty of the galactic centre from the Northern Hemisphere. Hence, to properly examine our universe, we need observatories in the Northern and Southern Hemispheres. Sir William Herschel's son, Sir John Herschel, surveyed the southern skies near Capetown in the early to mid-1800s to extend his father's work in the north, just as American observatories established southern stations over a hundred years ago in Chile and South Africa to complement as much as possible work going on in the north.

2.13.1 A brief aside. An observer with a different priority

Maintaining an observatory in the south at the turn of the 20-th century was not necessarily straightforward, particularly when you were not doing the observing. Observers always feel that they are the best and don't like to have someone else do it. Perhaps the thought is nurtured because you are the one with the vested interest in getting reliable data. This type of observing would be termed sub-contracting out in modern terms. The following story may be apocryphal but I do recall reading it in the notes, written about 1900 or so, from one of the American southern stations. At that time, spectra were being taken on glass plates, developed, and then shipped back to the States as part of a survey of bright stars. Then, spectrographs were new to the telescopes and little was known of the differing spectra of stars and their velocities. The person in question was selecting stars from observing lists provided by the supervising astronomer in the US. Tired of doing for someone else, and what is particularly grinding drudgery night after night in a dome, often chilled to the bone (remember this is the life of an observer working in the ambient air), and eager to go to the fleshpots in the nearby city, the observer made some changes. It took a long time before the researchers noticed a similarity in the spectra they were receiving and then discovered that observations were being made of the same bright stars night after night such that the data could be acquired in the first few hours leaving the rest of the night free! Scandals related to falsifying data are rare in astronomy but they do occur. A subtle falsification more readily occurs when an astronomer removes data that don't quite fit with the rest.

2.14 Back to the "weird places"

In addition to the location, whether in the north or in the south, there is a need to be as unaffected by clouds as is possible and to get above much of the Earth's atmosphere as is practicable. The first of these reasons is obvious—the reliability of the weather. How many people have heard of an interesting upcoming celestial event such as an intense meteor shower like the Leonids that promised a huge display in mid-2000, or the arrival of comet Halley and found that clouds spoiled the party. Astronomers face this each time they are granted time to do some research project. While I'm a keen photographer, I don't do astrophotography for this very reason. It is no fun sitting around in a lounge at some remote observatory waiting for clouds to clear knowing that you may only have this shot to do what you want to do. Obtaining telescope time is a hard-fought process and we have been known to invoke many Gods in the hope that the sky will miraculously clear!

I've mentioned earlier queue observing which only works on large telescopes, and which is still subject to the vagaries of the weather, but most astronomers do their own observing, particularly on telescopes less than 4 metre in size. Because there is the growing capability of being able to control telescopes remotely, in principal, I can sit in my office half a world away and control a telescope, gathering data in the comfort of normal surroundings just as householders are able to initiate a meal or some other household function using a fancy app and ultrafast broadband. But you need what we describe as a "good site", a place where you have a 75% chance to get the data you need. There are several places that provide astronomers with more than 330 clear nights a year. ESO has located its four 8-metre telescopes at Cerro Paranal in the Atacama Desert in northern Chile. An American presence is found further south at Cerro Tololo and Cerro Las Campanas. Mauna Kea on the big island of Hawaii hosts several observatories: the US Keck twins, the Japanese Subaru telescope, the Canada-France-Hawaii 3.6-metre telescope, the UK **infrared telescope** and the Gemini 8 metre. These telescopes are run by a consortium of many countries. Banding together is common in order to share the enormous costs of building and maintaining observatories in remote or difficult sites. In looking at the countries involved on the big island, I was reminded of the international cooperation involved in the science of astronomy. Our scientific collaborators can come from any country; the only requirement for us is that they share a common interest. Most astronomers will have written many papers in conjunction with others from overseas. The language of the science is English and that simplifies collaboration and the presentation of papers at meetings worldwide.

In addition to the weather at a site, the quality of the star images is a factor. Is the atmosphere very calm or is it turbulent? Not only does a site have to have good weather but also the star images should be as small as possible. Within the Earth's atmosphere the best we can do is about 0.4 arcseconds, a factor of 20 or so worse than the theoretical limit governed by the nature of light. Until the advent of satellite-borne telescopes and deformable mirrors the limitations of the Earth's atmosphere had to be minimized by finding a place where the seeing was good and if possible, enhancing that seeing by going as high as possible where the atmosphere's turbulence is lessened. Initial attempts to limit the effects of the atmosphere were made by the French in establishing a solar observatory in the Pyrenees at an altitude of 2800 metres or 9,350 feet. But most observatories are located at about 1600 metres or 5 to 6000 feet. At that altitude, it takes a few days to become acclimated. Sleeping is often disrupted and walking up slopes becomes a deliberate exercise. But working on Mauna Kea at 4200 metres is another story. Oxygen bottles are at hand and some people can't work because of altitude sickness. Brainpower might also be degraded. Thus, gaining altitude to minimize seeing, may come at a physical price for the astronomers observing on site. In addition, more can be gained by going to higher altitude in that windows in the electromagnetic spectrum that might be closed at low altitude become open. I'm referring here to the detection of infrared radiation or heat from the stars. IR is absorbed by water vapour and in dry climates, such as may be found at high altitude or on the edges of deserts, the effects of water vapour are minimized giving astronomers another ground-based window through which to observe the universe.

In space, all these problems disappear, hence the drive for the HST, though the downside of this is the cost. The technical difficulties are huge, for example, the whole telescope must be controlled remotely and it must be serviced. The propellant that moves the telescope from one object to another (we call this slewing) must be periodically replenished and the instruments must be replaced as new technology arises. The computers must be upgraded. Remember there are many years of lead-time in designing and building a spacecraft. Because of this, most of the detectors and computers are out of date before the launch. Faults must be corrected—we all know about the HST's faulty mirror! This means that service missions were scheduled with the Space Shuttle—I'm not sure what happens now that the shuttles have been retired. Astronauts require training. Telemetry must be sorted out. The challenge was daunting, but the HST has been wildly successful, just as a pioneering space telescope The International Ultraviolet Explorer (IUE) vastly exceeded its "use-by" date a decade earlier. This earlier spacecraft was the first to give us a systematic look at the stars over a long period of time producing spectra of thousands of objects in the UV in a wavelength region between 120 and 330 nm and laying the framework in terms of the science and instrumentation needed, and the procedures required to control any future spacecraft. Think about it. On Earth we observe at night with the only source of bothersome light—the Moon. For a spacecraft orbiting the Earth, there is light from three sources, the Earth, the Sun and the Moon, that needs to be avoided and when going from observation to observation the telescope must move in the shortest—but safest—path in order to conserve the precious propellant that provides the slewing. As the telescope moves, the communication antenna must maintain or pick up new ground-based stations for control and to download the data that will soon be acquired. But, going back to the beginning of the discussion, having a telescope or combination of telescopes in space, while hugely expensive, gives us something unattainable on Earth.

2.15 Uses of computers in astronomy

Computers are ubiquitous in astronomy and are used in every aspect of an astronomer's working life. I've been using computers since 1961 and have been enamoured of them ever since. In the early days you had to write the software to do a specific task, whether it was to work on the data, we call this reducing your data, because generally we condense the data down to as few numbers as possible, or to write some modelling program to help you know what is going on. One of the problems of modelling data was the realisation that computers are the ultimate slaves, they do exactly as you tell them. So, in writing a program to work out the orbit of a star for example, you ***must*** know every nuance of the process. No half-baked knowledge of the method can work because a computer cannot read your mind! Computer programming demands an absolute understanding of the problem. In the early days, there was no "canned software" aside from a very reliable IBM software package which I use to this day—the "ancient" equivalent of an app—and most of the time you had to learn about various numerical procedures before you could begin programming. When I look through my well-thumbed books, most cover the mathematics I need to adapt to do some computing task. I've enjoyed this part of astronomy, as I now have a wider grasp of applied math than when I started and still enjoy learning more, though understanding the derivations has been problematic for me.

Some people take to programming and some don't, but for me the ability to write my own software spells freedom. Using someone else's software is often frustrating because it never quite does what you want. Slowly, over the years, the need for software packages resulted in standardising how we store our data, so that in principle data produced by one telescope can be exported and read by anyone (the astronomical version of Word). This type of cooperation removed a lot of headaches, but even standardised systems have become bastardised and it always helps to be able to modify the software (yet again) to correct for someone else's "improvement"! Nowadays, the large observatory groups in the US and Europe have software experts trying to meet the demands of the astronomical community, often by writing monolithic programs that are supposed to be all things to all people and seldom are.

Astronomy pushes boundaries both in technology and in ever seeking the boundaries of our universe. In technology, the optical and mechanical engineers have mastered the design and construction of large mirrors that cannot support themselves under their own weight and require active control to maintain their shape or focus. Mirror grinding has long been computer controlled and, in part, the success of this process resulted in the failure of the first HST mirror. In the past, the task was laborious with continuous interplay between the grinding process and the testing. How close are we?

And, what do we do next? Obviously, even with the failure of the HST mirror, mirror-grinding is now long past that state, a fact that still amazes me. Still, a quick optical test at the end of the HST grinding would have surely prevented the embarrassment and outcries of disbelief that accompanied the public failure of a billion-dollar enterprise. **Computer Aided Design (CAD)** software packages have revolutionized the design of mechanical parts. I've had the good fortune to watch videos of cars being assembled by robots as well as parts being machined under computer control, that have affected my programming. Though building a telescope is hardly likely to be done by robots because they are generally one-off, computer-controlled machining is routine these days. The process finds its way into software and reducing data. Most of the time when we get our data, we do the same thing to each image. For more than three decades I've been efficiently reducing data by remembered keystrokes that allow me to perform repetitive tasks automatically once the template has been established by doing it once. I got the idea watching a Japanese car production line on TV. They "played it back" to make cars and I did much the same thing to process my data. I can recall the exuberance I experienced the first time I got it going because it meant an end to repetitive work and brought me closer to ***the*** answer! Observing is positively affected also. In the past, our life at the telescope was spent mechanically directing the telescope to the next star or galaxy, finding the object on a TV screen and then observing, while keeping track of the telescope and the dome slit, the opening through which the telescope points. Now technology allows us to control the telescope without having to worry about the dome, which is slaved to the telescope. The only worry is the weather and rain—and its detection.

Part of the ease of operation also comes from the digital detectors in use, for now we are not spending part of our night in a darkroom loading photographic plates to be placed in the focus of the telescope, combined with developing our latest exposures, getting cracked skin from prolonged exposure to the developer and fixer. The process might seem more leisurely, but now freed from the necessity of worrying about the dome and the photographs, our task shifts to the data. How does it look? How can I do better? And, as I mentioned briefly earlier, we have the capacity to reduce our data online, or have a colleague do it remotely as we work. In doing this, deficiencies in our observing technique are revealed. Are your exposures too weak? Are you looking in the right place in the spectrum? Is your instrument working correctly? Sometimes, in the press of getting going, some critical check is insufficiently addressed—a wishy-washy way of saying you screwed up! Remote access to your telescope and the data makes a huge difference. I routinely log on to a computer in Canada to do software development or debug programs "on the fly" while the user frets at the other end of the communication link.

One of the difficulties we have with our data these days, precipitated by the development of CCDs, is the effect of cosmic rays on our images. Cosmic rays, or the products of cosmic rays interacting with our atmosphere, are passing through our bodies all the time, hence the need to screen the detectors that are hunting for the elusive neutrinos by locating them in mines deep in the Earth or deep in the ice in Antarctica. These cosmic ray products leave traces on our CCDs which, if you ignore them, limit the accuracy that can be achieved. The work that I do is affected because it often require long exposures and hence there is more time to record these cosmic ray hits. These "hits" cannot be ignored, so we clean our images pretty-well automatically before we start processing the data, reducing the vast numbers of events to a reasonable few. Given that we have cleaned our images and reduced them to the form we need, then we begin to make measurements, maybe measuring positions, shapes, brightness, and colours. Perhaps we draw maps, it depends on whether one is observing galaxies or stars and so we derive results from the data. Now we need to make sense of it all. Some of the work is routine here, for we may have a model into which we plug our results. Perhaps you aren't the one who makes the measurements, you're the one who has the good fortune of dreaming up some scenario to explain the data but need to prove it. The only way to prove it is to model what you think will provide a plausible framework upon which to hang your data. This is fun. Maybe you don't achieve what you want. Perhaps the model just doesn't do it because the data don't support your bright idea. This isn't fun.

Where do your ideas come from now that you're at the "sharp end" of your research? Research hinges on what you know and how well-versed you are in the science and how imaginative you are. Maybe, it depends on a conversation you had with a colleague during a conference. Maybe, a new means of getting more from your data surfaces in a journal and you mull over how to do it, from structuring your program, being sure that you have the math to do it and the confidence to complete the task. Perhaps it comes to you in the night. Maybe while you're driving, but ideas come. Often it means going out on a limb with very thin resources from the literature. Literature means libraries. Aside from asking about the availability of telescopes and the quality of the available computers an astronomer seeking employment will immediately ask, "How good is the library?", though with library holdings and journals providing an online capacity the need for a great library has lessened. We use libraries. Some information, at least in my line of work, is almost historical so occasionally we need data published sixty or more years ago. This is not available online. There are, in fact, very few observatories where the exotic holdings go back unbroken over a hundred years. If they are not already, such libraries should be regarded as national treasures. I've had the good fortune to walk into one of those in Eastern Europe that survived the war in a miraculous manner. In that library, I held and examined first editions of works by Tycho Brahe, Copernicus, Kepler (1571-1630) and Newton, among others. Now ***that*** was a library! In writing this book, my major resource aside from my experience is the Internet from which I get answers to questions. Is this fact, right? Did I get that explanation right? I didn't know that! The Internet is a marvellous resource, not just in the big scientific websites such as the HST, **JPL**, ESO, Keck and the like, but because of the university lecturers who put their classwork on the Web, or enthusiasts who do their own research and put up the results. I've benefited from all these sources. And lastly, here I am writing the book on a computer, downloading images across the Web, and putting it all together in a word processor. The Internet is also the lifeblood of scientific communications. Over the last 40 or more years email has been a necessary part of our lives and we've learned the lessons of a finger too quick on the "Send" button; As always, it seems we continue to learn the hard way.

2.16 Next steps

I've covered the astronomer's observing world and its tools from a modern viewpoint, and with reference to the past, trying to give a flavour of the excitement and boredom of observing which probably hasn't changed much over the last few millennia. Now we need to follow the astronomical observations that led to our current picture of the Sun. I've chosen to do this in an historical context for ideas develop slowly, just as my comprehension of the subject has developed. I feel comfortable learning this way. Of all the early observations, the greatest challenge has been measuring the distance to the Sun. The measurement of the Earth's diameter was made in 240 BCE, but then it took two millennia to measure the distance to the Sun and hence determine its size, and in the process, enabled Newton's laws of gravitation to be fully realised within the solar system!

But astronomy is not only measuring angles, it is in measuring velocities and stellar temperatures and this requires an introduction to spectroscopy, the splitting of light into its component colours to create spectra, thus allowing us to investigate motion, temperature and the abundance of elements. The subject is continually being advanced using observational techniques that reveal more and more about what at first glance seems to be an unknowable universe. The development of spectroscopy over the last two centuries has had a profound effect on the subject, just as have recent satellites that have probed the very beginnings of our universe using microwaves, the radiation that cooks our meals in ovens!

Now to the Sun.

Chapter 3

Learning about the Sun

3.1 Early days

The unfolding story of our Earth, the solar system and the stars has come to us incrementally over thousands of years. Over that time, ideas were spawned and then rejected or accepted just as they are today. Some were rejected in favour of more reliable theories, such as the Moon eclipsing the Sun rather than some space demon chomping bits from it. Some correct ideas were advanced and later rejected for religious reasons—think of the Earth-centred **cosmology** and Galileo's problems with the church. But on top of these difficulties and retardations the science made progress.

In trying to get to grips with our Sun, the subject of this and the next chapter, I must go back in time to reveal what our predecessors knew. This is not intended to be an historical review, but part of the discussion is necessary to establish how we learned of the facts about the Sun—size, distance, etc—and how the first gleanings of understanding about the stars and what they are began to percolate through the consciousness of astronomers scant centuries ago. In this discussion, the primary emphasis is to present selected results that underpin modern astronomy as it unfolded at the start of the 20th century, when the physics providing the foundation of the science was laid, and more sophisticated telescopes built.

The detectors we use may be different, the math more complex, but the process of discovery and advancement is much the same—make reliable observations, interpret them, and put the results out there for your peers to review and then go from there. The science is also about information and how it flows among its practitioners. My work is built on others, depends on others also. It has always been this way. We can see how it works today with huge libraries that have been (generally) protected over the last 500 years but what about two or three thousand years ago. How was information passed? This question I cannot answer for it is in the realm of history and archaeology but I do know about the great library at Alexandria. I know that scholarship and works of art and imagination were valued enough to be collected and that this library was a great repository of mankind's mental riches. The idea of the value of knowledge has been with us for a long time!

3.2 Ancient book burning: The library at Alexandria

In looking at the ancient historical record, the thing that stands out for me is the dissemination of information. Hipparchus knew that the Earth was not only rotating once every twenty-four hours but its axis rotated too, wobbling like a top, over a 26,000-year cycle! He was able to predict eclipses. How could he determine events like this without access to observations spanning centuries? Obviously, observations of all types were recorded and there were libraries or retrieval systems available. One such library was the Great Library in Alexandria reputed to contain more than 500,000 manuscripts.

Probably the greatest scholastic calamity the world has ever known was its destruction. Part was accidentally lost during a siege by Julius Caesar in about 48 BCE and the remainder, perhaps lost piecemeal, until the remnant was destroyed by the Arabs in 642 CE, though the actual "perps" responsible are still debated. Within the library, along with irreplaceable ancient literature by Greeks and others, were centuries of astronomical data. Now we can only infer what earlier astronomers knew from the work of later writers or from contemporaries whose work survived. I am always amazed that we consider ourselves more civilized than the "ancients" or that somehow, we're smarter than they were. For me, my assertion is exemplified by their exquisite artwork in prehistoric caves: the fascination with the sky, the pyramids, Stonehenge, the resources put into building primitive observatories (count the stone circles in Britain alone!), the astronomical records, and the assembling of an enormous library, shows the same dedication to art and knowledge that we pride ourselves on today. Perhaps even more dedication, since life was surely harder in those distant days, but in thinking about the bloody 20^{th} century I may be wrong.

3.3 Getting started

Prior to trying to unravel the mystery of the Sun's evolution, what are the things we need to know about the solar system before we tackle other stars out there? We'd like to know the size of the Sun. We know how big it appears on the sky—about the size of a full Moon, or half a degree—but that doesn't tell us how ***big*** it is in kilometres. In addition, how massive is it in terms of the Earth, and what is it made of? It is so bright that it burns and endangers our eyes, so how hot is it? They say it has been around for

4.5 billion years. How do they know that, and how long will it go on? They blame power disruptions on sunspots. Is it true? And what about global warming? Everyone talks about how we are messing up the Earth's atmosphere making it hotter than it should be. Could the Sun play a role in this? If the Sun was responsible for at least a little of the mess we're slowly getting into, maybe it could free me from this terrible guilt of not doing enough.

The story starts with the Greeks who developed a clear picture of how our solar system works.

3.4 Measuring the distance to the Sun

Because the Greeks had mastered geometry, they used this knowledge to learn more about the scale of the Earth and the solar system. In about 260 BCE Aristarchus (310-230 BCE) attempted to measure the distance to the Sun in terms of the Moon's distance by observing the angle between Moon and Sun at first or last quarter when the angle between the Earth, Moon and Sun was 90 degree as judged by the Sun's bisecting shadow on the Moon (shown in Figure 3-1). In this way, by making an extraordinarily difficult measurement, he obtained a distance to the Sun 20 times that to the Moon. Remember this was done in 260 BCE! While the number was wrong—the correct answer is 390—at least Aristarchus knew that the Sun was at a very great distance in terms of the Moon's distance. In addition to these

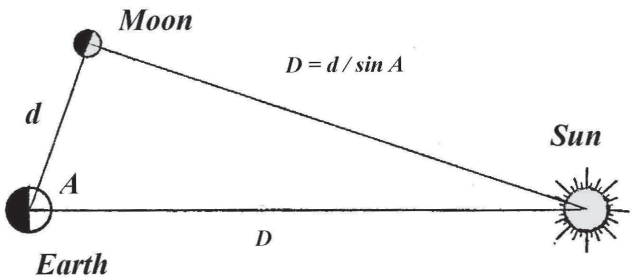

Figure 3-1. At the time when the shadow of the Sun bisects the Moon (exactly First Quarter) we have a right-angled triangle with the right angle at the Moon. Measuring the angle at the Earth between the Earth-Moon and the Earth-Sun (angle *A*) gives a measurement of the Earth-Sun distance (*D*) in terms of the Earth-Moon distance (*d*). Credit: Redrawn from Discovery of the Universe, de Vaucouleurs 1956.

measures, he also suggested that the planets all rotated about the Sun! (For a wake-up call, ask your dinner party guests about what the Greeks knew. You'd be surprised by their answers!)

3.5 The size of the Earth

In about 240 BCE the Greek astronomer Eratosthenes measured the size of the Earth by geometric means (Figure 3-2 lays out the method) and found a circumference of 250,000 stadia, in turn yielding a circumference of 45,500 km to be compared with the modern value of 40,000 km. The chief uncertainty in our interpretation of this determination is the measuring unit, the stadia, a Greek unit of length equal to the size of a stadium laid out as a racecourse—hence our word stadium. Fortunately, there are enough references

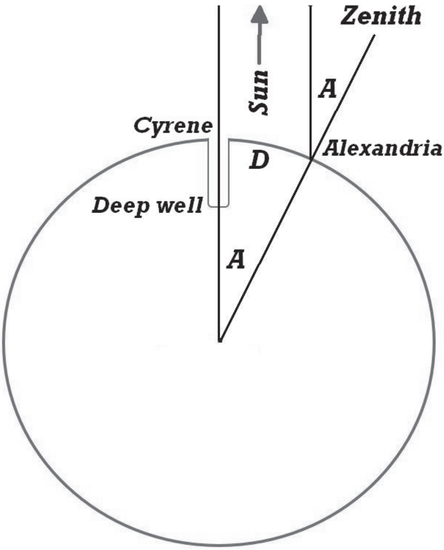

Figure 3-2. Illustrating the basis of Eratosthenes' method for measuring the diameter of the Earth. When the Sun is directly overhead at noon at (Cyrene) it is not directly overhead at a different latitude (Alexandria)—if the Earth were flat then the angle would be the same as measured at both places. The measurement of the angle away from the vertical at Alexandria, A in this figure, combined with the known distance between the two sites (D) gives a measure of the Earth's circumference and hence its diameter = $360 / A \times D$ in the units of distance D. Credit: Redrawn from Discovery of the Universe, de Vaucouleurs 1956. Annotated by the author.

about the sizes of Greek buildings still in existence, that we can obtain a reliable distance for the stadia in terms of a Greek “foot”. In making my calculation I've used a value of 1 stadia = 182 m or 606 feet.

3.6 Aristotle’s views hold things up

The Greeks made a lot of progress. They knew that the distances within the solar system were vast but their instrumentation (or lack thereof) let them down. However, unlike those that followed a millennium and a half later, they knew that the Earth and the planets rotated about the Sun even though this theory (**heliocentric theory**) was challenged on the basis that, because of the Earth’s motion around the Sun, we should see seasonal displacements of the stars, in just the same way that distant mountains appear to change their position with respect to foreground objects when we view them from different places down the freeway. (This part of the discussion is obfuscated by the loss of many of the ancient documents of which only fragmentary parts are available.) These periodic shifts, the star moving one way in the sky and six months later moving the other, is called **parallax** and you can see it by holding your finger up at arm's length and looking rapidly at it with each eye in turn. Your finger jumps from side to side against the distant background. Knowing the distance between your eyes and the angle of shift of your finger against the background yields the distance to your finger. The parallax principle is used in surveying. Every country that has been surveyed started with a known baseline from which all measurements were made. Where did the baseline come from? Historically, a surveyor’s chain was 66 feet in length and a baseline was created from this. After establishing a baseline, we could, for example, measure the distance to a mountain inaccessible to us by taking sightings, measuring angles from each end of a known baseline. Nowadays, the global positioning system (GPS) can measure a position accurate to a few millimetres (mm), thus immensely simplifying the surveying process. And so it is with the stars, only our baseline is the diameter of the Earth’s orbit, a mere 300 million km! ***The distance scale of the universe is rooted in simple trigonometry.***

The Greeks could not detect the changing positions of the stars, and not surprisingly, for the angles involved were far beyond what they could measure with the crude sighting equipment they had. The angles are small, the equivalent of measuring the diameter of a dime seen at about 3.5 km, a measurement not successfully made until the early 19th century. The Greeks could have guessed the reason for the lack of success in detecting the relative shifts in the stellar background because they knew they were dealing with large distances and sizes within the solar system but didn't imagine the sheer scale of the universe they were contemplating. (Maybe they did, but with the loss of that library we will never know.) Thus, as Aristarchus did with his measurement of the Earth-Sun distance, Aristotle (384-322 BCE) underestimated the vast distances to the stars. The measurement of this effect, which Aristotle was correct in predicting, was to prove elusive for more than two millennia! Looking back from the twenty-first century, the Greek's understanding of the heliocentric nature of the solar system still causes me wonderment. However, Aristotle's view prevailed and for more than a thousand years an Earth-centred (**geocentric**) cosmology, as developed by Ptolemy, held sway.

3.7 The Copernicum revolution

The Polish monk Copernicus overturned the geocentric picture just before his death in 1543. Over the centuries, trying to shoe-horn the extensive planetary observations into the Ptolemy's Earth-centred system to predict positions of the planets had clearly failed. Copernicus revised the picture and placed the Sun at the centre with the planets revolving about it and the Moon revolving about the Earth. He also ordered the planets in increasing distances from the Sun and measured the sizes of their orbits in terms of the Earth-Sun distance. A comparison between his results and modern ones is given in Table 3.1. When measured in kilometres this Earth-Sun distance is called the **astronomical unit (AU)**. In terms of Copernicus' model, shifting the Sun to the centre of the solar system not only improved the results but also made the whole picture simpler. The essence of any theory is simplicity. If, to make a theory work in the face of discrepancies, more and more bells and whistles are added that ***still*** leave a little to be desired, then

Table 3.1. A comparison of planet-Sun distances

Planet	Copernicus	Present
Mercury	0.38	0.39
Venus	0.72	0.72
Earth	1.00	1.00
Mars	1.52	1.52
Jupiter	5.22	5.20
Saturn	9.07	9.54

maybe you're on the wrong track. The expression "keep it simple stupid" has its place in science. Much like a lie to explain what you were up to last night when buttressed by more and more improbable lies is often a dead giveaway that the truth is somewhere else.

One prediction that came from his change was that Venus and Mercury, the planets between us and the Sun, should show phases like the phases of the Moon, but that prediction had to wait until Galileo turned his telescope to the sky. Copernicus was able to measure the relative distances of the planets from the Sun surprisingly well. What was missing was the scale in km since everything Copernicus measured was with respect to the Earth's orbit.

3.8 Galileo and the telescope

In 1609, Galileo used a small refracting telescope to verify Copernicus' prediction that Venus and Mercury should show phases (quarter moons, full moons, etc). He also saw the craters and mountain chains on the Moon, the rings of Saturn and discovered the four moons of Jupiter that collectively bear his name. The Galilean moons are Io, Europa, Ganymede and Callisto. Galileo also viewed sunspots (see Figure 1-6), but he could not use a telescope to directly view the Sun because he would be blinded in an instant. He would have viewed the Sun as I view it, in projection; point the telescope at the Sun and put a piece of white paper behind the eyepiece, the place where you would otherwise look. On the paper you will see a small image of the Sun. By moving the paper further away from the eyepiece you get a larger image and if any sunspots are there you will see them. With the telescope's invention, the capacity to make more precise measurements became possible and this increased precision led naturally to the development of better ways to sight and mount telescopes. This is another way of saying that the telescope led to related engineering advances.

As an aside, I point out what has long been known to scholars of antiquity, that lenses were commonplace thousands of years ago. They've been found in Egyptian tombs and in Greek and Roman excavations. It is hard to imagine that two lenses had never been put together to form a telescope long before a Dutch spectacle maker discovered the principle in the early 1600s.

3.9 Kepler

Kepler was a contemporary of Galileo and spent time observing and analysing extensive positional data of Mars, trying to reconcile the positions with circle-based geometry. While the deviations from circular are quite small, he was not satisfied, and began experimenting with ellipses (ovals). We use some of Kepler's observations in freshman astronomy to reproduce his results but it is not easy. With an ellipse, he could match the data much better than he could with circles and from this labour came three laws for which he has been immortalized. These laws govern the behaviour of the planets about the Sun, the moons about the planets and artificial satellites about the planets or hunks of rock revolving around asteroids (see Figure 3-3). They also govern how stars revolve about each other, as well as the Sun moving about the centre of the galaxy or how groups of galaxies rotate about a common centre. The laws could hardly be more universal than that!

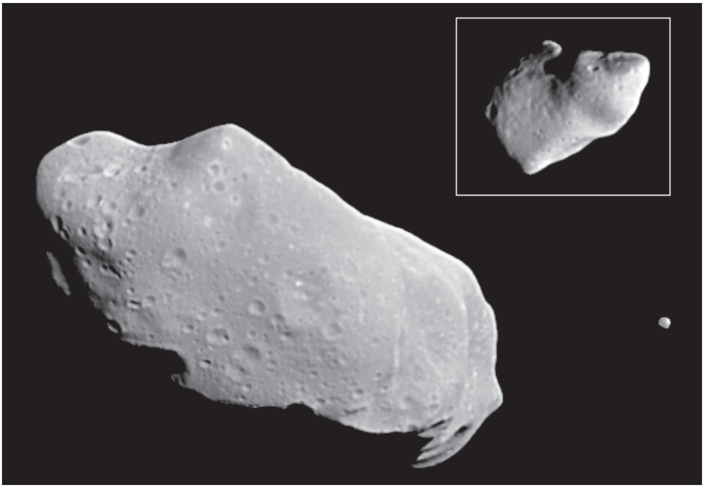

Figure 3-3. The moon Dactyl orbiting the asteroid Ida as seen from NASA's **Galileo spacecraf**t in 1993. Ida is the large object to the left and Dactyl is the small object to the right. This portrait was taken about 14 minutes before Galileo's closest approach to the asteroid from a range of 10,870 km (6,755 miles). Ida is 53 km long and Dactyl, the small image to the right of Ida, is 1.6 km. The insert shows a close-up of Dactyl taken when the spacecraft was almost at its nearest point. Credit: Commentary and image NASA/Galileo.

The first law says that the orbits are not circular but elliptical, while the second law says that when an object orbits close to its companion it moves faster than when it is further away. We see this behaviour in the comets that periodically swim into our ken. They are generally detected well outside the Earth-Mars orbits and, as they slowly approach us, it takes them a long time to brighten. They rapidly gain speed after crossing the Earth's orbit, racing in towards the Sun, swinging around it and then to race back out, slowing as they go. With the third law, Kepler discovered a direct relationship between the period, or time that it takes a planet to revolve around the Sun, and the size of the orbit, such that the further a planet is from the Sun the longer it takes to revolve about the Sun. Similarly, with the planets and ***their*** moons. We call this time, the period of revolution, that is the time to make one cycle around the Sun. While Kepler discovered an empirical (experimental) law and knew it was significant, he could not make sense of it. This awaited Newton.

3.10 Newton

Newton, with his theory of gravitation, gave a framework upon which to hang the data about the planets and their moons. With Newton and his amazing imaginative analytical skills, the measurement of distance promised a lot more, the ability for us to weigh many of the constituent parts of the solar system. With his law of gravitation, which related the force between two objects as depending on their respective masses and the distance between them, he was able to show how Kepler's laws arose. In addition, he did pioneering work in optics, and, along with Leibnitz, developed the **calculus—**the mathematics of change—laying the groundwork for **celestial mechanics**, the study of how stars and planets move with respect to each other. His work provides the basis for the precise way in which our spacecraft are guided. Using Newton's results, we can use the Earth's orbit and period to measure the **mass** of the Sun provided we know the Sun's distance in absolute terms such as kilometres. Furthermore, we can measure the sum of the masses of any stars that are linked together by gravity whose separations and periods of revolution known (in terms of an Earth year). Looking ahead, we can estimate the mass contained within a **black hole** at the centre of a galaxy as well as weigh galaxies themselves by measuring the motions of satellite systems moving within and around them. Knowing that the Sun circles our Milky Way galaxy at a velocity of ~250 km/s and is 25000 LY from our galaxy's centre, allows us to measure the mass of our galaxy interior to the Sun's orbit! Figure 3-3 illustrates that from the largest to the smallest, Newton's laws work. In this image we see an asteroid with an attendant "moon"! But more importantly, in the "real world", Newton and Leibnitz's mathematics, and many others building on their work, provides the foundation for all modern engineering, mathematics, communication technology and science.

Newton's theory and the mathematical tool, the calculus, not only made it possible in principle to predict the positions of the planets with unprecedented accuracy, but it also opened conjecture about other celestial happenings. Prior to Halley (1656-1742), a contemporary of Newton, comets were thought to be objects that came randomly into view, bore pestilence and other evils and left as mysteriously as they came—they may well do if theories of **panspermia**, or the seeding of life from space (comets perhaps), prove correct! In 1705, Halley made his famous prediction based on the analysis of a series of comet sightings over the centuries. He explained some of them on the assumption that many comets were repeat sightings of a single comet with a 76-year period and predicted it to return late in 1758, a prediction borne out long after his death. This comet now bears his name. His work is typical of modern science which success hinges on the ability to formulate a theory, make a significant prediction based on it, and then seek verification. A scientist's work stands and falls on this principle. It was true then and is true now. Without a prediction, a theory is just that—a theory, no matter how appealing. In Halley's case, 53 years had to pass before his prediction could be confirmed.

3.11 How far away is the Sun? The solar parallax

In order to apply Newton's theory of gravitation to the solar system, one last measurement was needed—determining the distance to the Sun in kilometres. This value would establish the distance scale of the solar system, leading to finding the sizes and masses of all the planets and many of their moons. Again, the process used is that of triangulation. All the fundamental distances in astronomy, distance from Earth to the Moon, Earth to the Sun, Earth/Sun to the stars have their basis in trigonometry or surveying if you will. Through the 17th and 18th centuries attempts were made to determine the astronomical unit by observing Mars at sunset and twelve hours later at sunrise and then measuring the amount its position shifted among the background of stars. Over twelve hours the rotation of the Earth displaces your viewpoint by the Earth's diameter, giving you a chance to triangulate Mars. The complication is that the Earth has also moved over the twelve hours and to a lesser extent Mars has also. Applied to Mars, the sunset/sunrise approach yielded an angle of 16.8 arcsec, the angular size of a dime seen at about 220 metres, and a distance to the Sun of 130 million km. That was a good start. Alternatively, one could simultaneously observe a planet from two locations, one in the north and the other in the south. It works for the Moon. By sighting on the same lunar feature, astronomers working in Berlin and Capetown initially measured the lunar distance in

1751-53. The method fails for Venus because, cloud-covered, it is featureless.

Because the Sun is about twice as far away from us as Mars, measuring its distance by sighting say on the same sunspot from well-separated sites is still very difficult. There was another way. You may have heard the words "Transit of Venus" at school, but what is it and why was it important? Halley, a contemporary of Newton, suggested that if the planet Venus was observed crossing the face of the Sun from two well-separated places on Earth, then its distance could be measured by triangulation. The geometry is shown in Figure 3-4. Because Copernicus had already measured the relative distance of Venus from the Sun in terms of the Earth-Sun distance, knowing the distance to Venus in kilometres would yield the Earth-Sun distance in km. Two transits were attempted, one in 1761 and the other by Captain Cook, who observed the transit of Venus in Tahiti on his way to explore New Zealand and Australia in the first of his famous southern voyages. Incidentally, he also observed a transit of Mercury in New Zealand in a bay that now bears the name Mercury Bay, a place where my grandchildren's ancestral sub-tribe welcomed him.

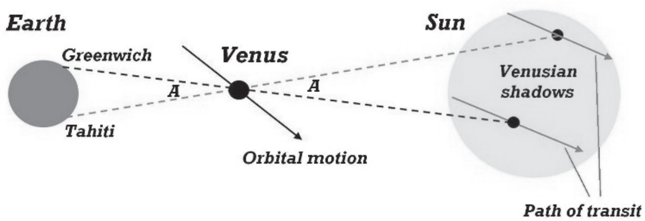

Figure 3-4. The triangulation of Venus after Halley, showing the views of the planet Venus transiting the Sun as seen from Greenwich and Tahiti in 1769. The measurement of the size of the arcs on the Sun (we know the size of the Sun in arcseconds) gives the angular distance to Venus (A) as seen between Greenwich and Tahiti. Knowing the distance in km between these places, then gives the distance to Venus in km, and, therefore, that of the Sun. Credit: Redrawn from Discovery of the Universe, de Vaucouleurs 1956. Annotated by the author.

Prior to 1769, the date that Cook observed Venus transiting the Sun, astronomers already knew roughly the scale of the solar system by triangulating Mars as described above. In the 18th century, finding the size of the solar system was deemed important enough for Cook to be sent to the South Pacific to observe the transit. By comparing the time that it took Venus to transit the face of the Sun in the Northern and Southern

Hemispheres it was possible to measure the angular distance to Venus and hence its distance in km. Knowing the relative distance of Venus from Earth from Copernicus' measures (1-0.72 AU or 0.28 AU) then gives the Sun's distance in km. The results yielded a value of 155 million km to be compared with the current value of 149.6 million km. The complications in the method were mainly caused by Venus' bright atmosphere confusing the timing as to when Venus was at the edge of the Sun or at the **Sun's limb**. An example of the beginnings of two transits, both of Mercury, one in 2006 and the other in 2019, are shown in Figure 3-5. Notice the appearance of the Sun in each picture. The left-hand panel is displayed in "normal light", the benign light we are used to, but the rightmost image reveals the active **chromosphere** displayed in hydrogen light. A movie on the NASA site is available, showing the full transit of Mercury. In viewing it, what struck me dramatically illustrated the size of the Sun, because Mercury was barely visible as a fly speck transiting its face. The right panel in Figure 3-5 also emphasises how small the inner planets are with respect to the Sun. We are small among the stars, as we are small within the confines of the solar system.

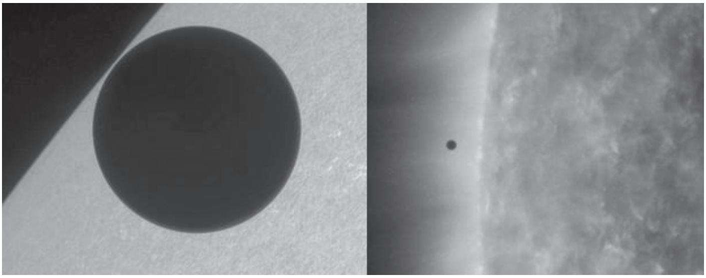

Figure 3-5. See Centrefold. The beginning of two modern transits of Mercury. In the left panel, as imaged by the Japanese Spacecraft **Hinode** in 2006**,** Mercury is seen against the limb of the Sun. The limb looks darker because we are looking at an angle into it and into the cooler upper **solar atmosphere**. The effect is called **limb darkening**. The right panel shows Mercury about to begin its transit in November 2019. The image is from a NASA movie. Credit: Left panel. **JAXA**/NASA. Right panel. NASA.

3.12 The velocity of light

The latest values for the astronomical unit are based on measuring radar reflections from Venus and later from Mercury as well as the Sun itself. Thus, the limiting precision depends on how well we know the velocity of light. Strangely enough, the first determination of the velocity of light in 1676(!) was given in terms of the astronomical unit. Roemer (1644-1710), a contemporary of Newton, discovered that the speed of light was finite and made its first measurement using a technique that is still current today. In this regard, aside from measuring the positions of the planets and moons with respect to the planets, astronomers recorded when moons were eclipsed, that is, the times that they disappeared or reappeared behind the planet or moved in front of the planet. Many of you will have seen Jupiter through a small telescope and noticed a black shadow on its surface. The shadow is from a moon passing between Jupiter and you—have a look at the Galileo spacecraft images on the JPL website. These timings would all have been recorded and used to predict eclipses. We do the same thing with stars that eclipse one another, similarly on Earth with the Moon eclipsing the Sun or the Earth casting its shadow across the Moon in what we call a lunar eclipse. From these various timings we work out what is called an ephemeris for each object. That's how we can say when and where there will be an eclipse of the Sun in place "X" and how long it will last etc. Ephemerides are much like a railway timetable, though more reliable! By studying eclipse timings of Jupiter's moons, Roemer discovered that the predictions were in error and that the errors depended on where the Earth was in its orbit with relation to Jupiter (near or far). He realised that the only explanation for these varied delays was if light had a finite velocity. He estimated that it took light 11 minutes to travel the distance between the Earth and the Sun or 1 AU—the real value is about 8.5 minutes. But even having measured the delay, he could not convert the timing to km/s because the scale of the solar system had not yet been determined. These time delays affect all our measurements, so we correct all our times of observation as if the observation was made at the Sun, thus avoiding the very effect that Roemer discovered. In addition, because the Earth is moving (30 km/sec is its average orbital speed), we must correct for this motion too when we make velocity measurements of the planets and stars and we record the velocities as if they were made at the Sun.

The logic Roemer used in deducing the finite velocity of light has been used extensively since then. Later, when we discuss the results of stellar evolution, or the stellar by-products resulting from stellar evolution, I'll talk more about these timings and how important they are.

3.13 The Sun's size

Given the distance to the Sun it was then possible to measure its size. But how do we make a measurement of how large the Sun appears in the sky when it is so bright it can blind us? Anyone who had witnessed an eclipse knows that the Sun and the Moon are close in size. The ancients would equally have known that, so a measurement of the Moon's size using some sighting equipment that measures angles would also give that of the Sun, at least to a very good first approximation. Alternatively, a pinhole can project the Sun's image onto a flat surface inside a darkened room. The pinhole needs to be about 6 metres (20 feet) away from the screen. By measuring the size of the image and the distance from the pinhole to the projection we could find the size of the Sun in fractions of a degree (about half a degree). The same ratio, image size to projection distance, holds for the Sun's diameter and the Earth-Sun distance so by multiplying our pinhole/projection ratio by the astronomical unit we have determined the diameter of the Sun in km. We know that the diameter of the Sun is about 32 arcminutes (60 arcminutes = 1 degree) or 0.53 degrees. This gives a solar diameter of 1.4 million km compared to 12,700 km for the Earth, and 143,000 km for Jupiter, the largest in the Sun's retinue of planets. From these numbers, the Earth is about a hundredth of the Sun's size and Jupiter a tenth!

Measuring the size of the Sun and Moon is easy but measuring the sizes of the planets becomes very difficult for they are a long way away and the Earth's atmosphere plays havoc with the measurements, particularly the planets and their major moons outside the orbit of Uranus. Neptune, for example, is only 1 arcsecond in diameter at best, so the measurement of its diameter is very difficult and Pluto's diameter was only determined recently with the HST. Looking down a list of the sizes of the moons of these outer planets in a textbook published in 1962, we are presented with a series of question marks as to their diameters. Only with the success of the Voyager probes have we been able to fill in the details of the sizes of many of the moons for the majority are at the limit of measurement with Earth-based telescopes.

3.14 Measuring the Sun's mass

Once the distance to the Sun was known it was then possible to use Newton's theory to "weigh" the Sun and other bodies in the solar system. As noted previously, given the period of revolution and the distance to the Sun, Newtonian mechanics predicts the sum of the masses of two objects revolving about one another. In measuring the Sun's mass this works just fine because we can ignore the mass of the planets as insignificant. For example, the most-massive planet Jupiter is only one thousandth the Sun's mass. Similarly, we can weight Earth, Mars, Jupiter, Saturn, Uranus and Neptune provided we can measure the distances between their moons and the parent planet in km and can determine their period of revolution. It is easy to judge how readily a moon's distance might be measured when we think of the occasions we've looked through a small telescope at Saturn or Jupiter and seen their moons. Uranus is more distant, but aside from the faintness of the object, made more difficult if you are in a city looking out through the city lights, you will still make out its brightest moons. Given that we can see the satellites, how do we measure the sizes of their orbits? In the past, the separations were measured at the telescope by using a specially designed optical instrument called a filar micrometer that measures angles (in degrees) and distances (in millimetres) in the focal plane of a telescope. In this way the angle and distance between a planet and its moon could be measured and converted into seconds of arc. Knowing the time of observation and referring to what is called an almanac, a book that lists the distances of the planets for every day of the year, these separations in arcseconds are converted to km. Before the days of almanacs, the distances had to be derived for eccentric orbits, requiring complicated calculations, both for the Earth and the planet concerned.

But how do you know you have measured the ***maximum*** separation between the planet and its moon? You don't, at least not for a single observation. Only a series of observations will tell you when the moon has reached its maximum separation or distance from the planet. And even then, you need to discover if the orbit is circular or oval shaped and if you've got the right moon. What happens when the weather turns bad? You wait and do it again later. This is the story of most observational astronomer's lives. We are at the mercy of the weather and blithely quoting the sizes and periods of orbits in a textbook hides the massive amount of labour required to determine for example, that Phobos and Deimos, the two moons of Mars—and incidentally not two parked spaceships from some alien expedition—rotate at distances of 9380 and 23500 km from the planet with periods of 0.319 and 1.263 days.

The accurate determination of Mercury and Venus' masses was delayed for 200 years since, lacking satellites, they could only be measured indirectly from their gravitational pull on the Earth and each other. The first opportunity to measure the mass of these planets came in 1974 with the **Mariner 10** flybys which gave us a close-up view of Mercury's battered surface. Their masses were calculated by the effect of each planet's gravitational field on the spacecraft's trajectory. But the ultimate way is to orbit a spacecraft around them. The **Magellan spacecraft** orbited and mapped the Venusian surface through the clouds using radar—check out the reconstructed images on the NASA website. Mercury has been orbited by a NASA probe in 2011 and so its mass has been determined just as the Magellan spacecraft has measured the mass of Venus. The upcoming **MESSENGER probe** will provide the first new up-close data about **Mercury** in 30 years!

3.15 The discovery of Uranus: The power of analysis

Thinking about the effects of the planet on the motion of the spacecraft reminds me of the discovery of the eighth planet, Neptune, in the nineteenth century. With Newton's theory of gravitation, it became possible to consider the gravitational effects of the planets themselves on their neighbours, particularly the effects of Jupiter's mass on Mars and on comets that sometimes pass by it. We all saw a graphic example of Jupiter's effect on the orbit of a comet when comet Shoemaker-Levy was physically disrupted into pieces and ultimately captured by Jupiter, resulting in some spectacular impact and post-impact images of the planet's surface. Back to Uranus and its orbit. By the start of the nineteenth century there were anomalies in the positions of the planets, particularly in the motion of the newly discovered planet Uranus, found by Herschel in 1781, that led two astronomers to independently consider that another planet outside Uranus was responsible for these differences. Two men, La Verrier and Adams, worked independently on the problem of reconciling the observational disparity between what was calculated, or predicted, and what was observed. The orbital differences were small but enough to provide a challenge to these mathematicians. Adam's result, correct to within 2^o and easily within the view of the telescopes of the day, was published in 1845 but not immediately confirmed by observation, whereas Le Verrier's result, reliable to 1^o, was published in 1846 and verified immediately at the telescope. Adam's position should have yielded Neptune's discovery first, though now history records the discovery jointly—and it should! Originally, the credit went to La Verrier because nobody in Britain was prepared to look for the planet. In other words, Adams had trouble getting telescope time! This simply reminds me that there is nothing new under the Sun!

3.16 An instrumental interlude: The spectrograph

In one of Newton's experiments, he passed sunlight through a prism and examined the dispersed coloured light (see Figure 1-7). In that way he discovered that white light, or sunlight, is comprised of many colours. By now we are familiar with the effect that a prism has on light, or a diamond for that matter. These colours form a spectrum, like what we see in a rainbow, where the water droplets act as miniature prisms to produce the arcs of coloured light we see in the sky. Imagine we are in a darkened room with a little pinhole letting in sunlight and we pass the light through a prism. If you put white paper behind the prism then you will see a spectrum laid out with all the colours nicely separated. In doing this, basically you have a pinhole camera, the first sort of cameras ever used. A pinhole camera is a box with unexposed film inside at the back and a small hole covered by a shutter—something that exposes the film to the light coming through the pinhole. Whatever the camera is pointed at is recorded on the film. Now think of what happens if the hole is larger. Intuitively, I think you'll accept that the image will be smeared out a little. For the photographer, the size of the pinhole governs how crisp the recorded image will appear. It is the same with the prism and the size of the hole the light passes through. The pinhole camera was refined by having a lens collect the light which it focused on the film. We can do the same with our prism. If we replace the pinhole with a long slit and put in a couple of lenses, one to gather the light, and the other to focus it onto a detector such as film or a digital device, we have just created what is called a spectrograph, the most important instrument in astronomy (you may detect a bias here). You can put a series of prisms together in a train, each one taking already dispersed, or spread out light, and spread it out further. Each prism gives a more detailed spectrum. Through the early years of the 20th century 3-prism spectrographs represented the pinnacle of design.

There is another way to create a spectrum by using what is called a grating, something which spreads out the light more efficiently than a prism. What is a grating? We've all seen flashes of coloured light coming off a stainless-steel bench top that is scratched. If you haven't, look at the reflections next time the Sun is bright in the kitchen. A grating has many parallel lines ruled on a glass or reflective surface and light reflected off such a surface gets spread out into all its colours, performing the same function as a prism. This is a more efficient system in that less light is lost in reflection compared with that lost in its passage through a train of glass prisms. Modern spectrographs are almost exclusively based on gratings but hybrids are also useful for specialized tasks.

A spectrograph takes sunlight or starlight, spreads it out into its colours, and records the image with a detector. Initially, before the advent of the photographic process, the detector was a human eye that viewed the image but left no permanent record—unless you viewed the Sun and got blinded! The first effective astronomical spectrographs (ones attached to a telescope) were developed in the late 19^{th} century and they have been continually refined to give the maximum amount of spectrum recorded in the shortest possible time. Remember that the (weak) starlight is spread out into its colours, making it appear even fainter to the detector that must record it. This means it is less efficient than taking a picture of the sky. When gauging the size of the universe we rely on two things, how bright a distant galaxy appears in the telescope, and how fast it is travelling. The galaxy's brightness comes from a direct image of the galaxy, a picture if you will, while the second is derived from the galaxy's spectrum. Because our direct images are taken of objects fainter than we can capture with a spectrograph, the limit for us in trying to determine the age, or extent of the universe, is governed by this instrument. For studies of the Sun, there is no problem for it provides all the light we need, feeding huge spectrographs laid out in large rooms, while for the stars we may use similar laboratory-style spectrographs (Coudè spectrograph) for bright stars. But most spectrographs are carried piggyback on a telescope or perhaps placed on the floor with light piped to it through fibre-optic cables from the telescope focus.

The image produced by the early spectrograph was viewed with the eye and later, after the development of the photographic process, captured by a photographic (glass) plate and for special purposes—such as recording the spectra of galaxies—photographic film. As a variant, before the advent of digital detectors, the eye was replaced with a photoelectric cell that produced an electric current proportional to the amount of light that was falling on it. By rotating the grating with an electric motor, the spectrum swept over the detector producing a varying electric output that was then used to feed a chart recorder like those used in a lie-detector test. This configuration was called a scanner, but what astronomy really needed was a detector that would record the whole spectrum at once and give an array of numbers that could be fed into a computer for analysis. Early use of photoelectric photometers necessitated using these chart recorders to record the signal and then you had to measure the height of the signal on the chart with some sort of ruler. This measurement yielded the number that a computer could deal with, though in those days the computers were slow and software non-existent for use in these reductions.

From the foregoing discussion, I hope you, the reader, will become aware of the intense labour involved, both at the telescope and later during the image processing, when the whole aim of the exercise was to generate a number. Or in the case of the scanner, hundreds of numbers all gleaned from tedious measurements on long pieces of paper; themselves taking a daunting, inordinate time. Now that the digital age is upon us, the emphasis is not on getting the numbers, they automatically come with the territory, but upon the problems that come with two-dimensional detectors, for example the effects of cosmic rays on the data and the vagaries of the detectors themselves which if not cooled properly will render observations useless.

Now we have our longed-for digital detectors, but the problems do not disappear. In my experience a photographic plate at its longest may be two times 20 cm in a Coudè spectrograph. The focal plane is curved, the glass plates I've dealt with have never been longer than 20 cm and are butted together in a single plate holder and also bent. I've faced this situation at the Cassegrain focus where breakages were more common. My heart was always in my mouth fearing to hear breaking glass as I unclamped the plateholder to remove the glass and its precious contents—often five exposures taken over hours. A digital detector may only be about 6 cm by 4 cm with a pixel size of say 15 microns (15 × 0.0001 cm) yielding about 10 MPs. For the larger format of a similar size found in some cameras, the pixels are much smaller leading to about 60 MPs. The size of the detector must be matched to what you think you can learn from a given spectrum, or the spectrum dispersed (spread out) to match the detector. In deciding what configuration to use when seeking observing time, a lot of labour is expended in getting this match right. Often the perfect match is impractical because it would take too long to acquire the data. The observer is always compromising. Is the spectrum too compressed and therefore will only lead to poor velocity measures, or is it stretched out giving very good velocity measures? In the former case you may be dealing with galaxies and the velocity requirements are much less stringent because the velocities are very high (thousands of km/s) and quite manageable with what we describe as a low dispersion spectrum that fits nicely on a CCD. When we need to measure velocities of only 10 m/sec (thousands of times more accurate than required for a galaxy) we need to analyse a much longer stretch of spectrum and the situation is quite different—I'll talk about velocities a little later. Unlike the photographic plate that may cover a 100 nm, the CCD is too small by far to get the same spectrum coverage and hence to get the required accuracy. However, it is possible to create a spectrograph which splits up a spectrum into segments and stacks them one above the other on a CCD detector in an arrangement called an echellè (see Figure 3-6). This gives marvellous spectrum coverage but with its own problems that hinders its effectiveness.

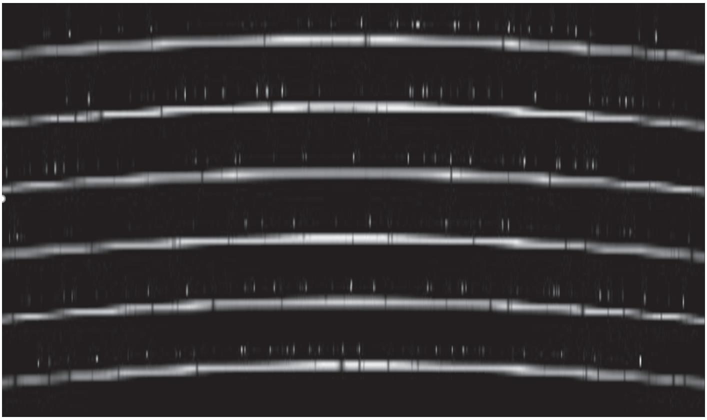

Figure 3-6. The partial echellè spectrogram of a cool star. The star's spectrum is white and the lines of the star appear dark (discussed in next section). The bright white lines beside the stellar spectrum come from the comparison spectrum needed to convert the horizontal scale into wavelengths. Each of the 6 spectra displayed here cover different wavelength ranges which overlap at each end and so they can be assembled into one piece, thus simplifying later analysis. Credit: ESO. Modified by the author.

Summarizing, the modern digital detector provides astronomers with the ability to get high-quality data (little noise) of high accuracy, something totally impossible with a photographic plate. Contrast this with the larger wavelength coverage available photographically but with much lower accuracy compared to the CCD. Beyond this, there is the analysis itself which demands sophisticated software that you most likely did not write and which use is often rife with the user misunderstanding the instructions and forging ahead into new and incorrect territory. Said differently, presently, it is easy to get a number but the emphasis is now on the software-user knowing what the software can and can't do. Impersonal judgement is always paramount. Why impersonal? Well, we work hard to get the numbers. Maybe not in getting them when we're ***at*** the telescope, but in getting the time that allows you to even use the telescope and to make the observation. Time. The numbers of nights approved for you to use the telescope, is assigned by committee and without this time, no matter how well-thought out your project or proposal is, you are dead in the water as an astronomer. Some notable "blowouts" between astronomers and such a committee have been over what has been perceived as bias in approving a project. Perhaps someone felt that another has unfairly scooped their proposal. Ah, we human beings are all flawed, whether an ivory-tower scientist or a politician! There are other pressures. We may hope that the project we have chosen will yield some sort of important result and there is always self-imposed temptation to perhaps bend the results to favour the discovery you so desire. Somehow, the astronomer needs to stand outside their observational results and judge them impersonally. Recognizing this, the astronomical community uses peer reviews to judge and help improve the results you "write-up" and submit to a journal for publication. But not all publications have the same high standards for acceptance and the review may be limited, just like a degree from a lowly State University may not be as appreciated, for example, as one from Harvard or Cambridge.

3.17 Spectral lines in the Sun

Early in the nineteenth century Fraunhofer (1787-1826) investigated the solar spectrum using a spectrograph. Because he began observing the solar spectrum before the photographic process was invented, his work was done laboriously by eye. In 1817 he discovered that the spectrum of the Sun was replete with lines (see Figure 3-7), though unknown to him, lines had already been observed in the Sun a decade earlier.

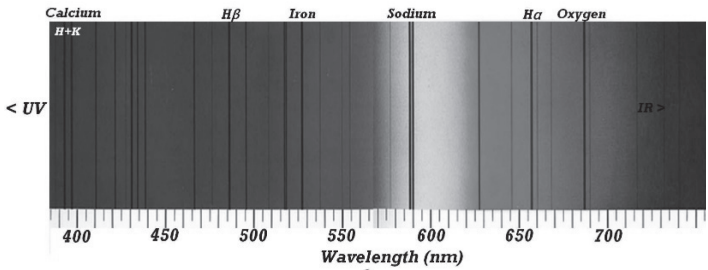

Figure 3-7. See Centrefold. A stylized spectrum of the Sun showing the lines originally recognised by Fraunhofer. The colours represent the radiation caused by it simply being hot—the photosphere. The dark lines (**absorption lines**) result from light being absorbed by specific elements in the Sun's atmosphere. Some are identified along the top (H refers to hydrogen). The lines due to sodium are what gives our streetlamps the orange glow. By studying these lines, the astronomer can tell what elements are in the stars. Credit: Many sources, annotated by the author.

What is a line? The light of the Sun arises because the Sun is hot. The place from which this light arises is called the **photosphere** or sphere of light as its name implies. All bodies above absolute zero temperature produce electromagnetic radiation. Humans radiate electromagnetic radiation in the form of heat just as does every living creature. Further, the hotter the object, the more energetic the overall radiation will be. Cool objects (temperature 2000-3000 K), like those that are condensing out of the interstellar medium to become stars, radiate in the infrared (IR) whereas very hot stars (temperatures greater than 20,000 K) that are much more massive (weigh more) than the Sun will radiate largely in the UV. The solar radiation peaks in the yellow part of the spectrum, hence the Sun would appear yellow to eyes on distant planets, though to us sunlight looks white.

There is an atmosphere overlaying this sphere of radiation and a line results when the atoms within the atmosphere selectively absorb some of the light passing through it. The absorption is peculiar to the atom involved, since each element only absorbs light at specific wavelengths and every atom is different with its own plethora of potential lines, some of which are identified in Figure 3-7. This selective absorption appears as a series of absorption, or spectral, lines that subtract a little light from the photosphere. Iron atoms, absorbing the light passing among them, cause most of the lines we see in the Sun. With Fraunhofer's discovery, came the development of spectroscopy, spreading the light from celestial objects out into their constituent colours that can be analysed. Spectroscopy is the primary means by which we examine and interpret the universe and its importance cannot be overstated.

3.18 Spectra

What is recorded by the spectrograph on a photographic plate or a digital detector is called a spectrum. Some spectra are seen as dark lines against a bright background like those in the Sun, whereas in other objects the lines appear bright against a dark background. These latter lines are called emission lines. Thus, every element that is “burned” (forgive me, but when I started doing spectroscopy, we created an iron spectrum at the telescope by generating a spark between two iron electrodes) but nowadays, the element, in gaseous form, is electrically stimulated to create a characteristic set of emission lines; for example, from neon or argon gas. The orange light we see in a sodium streetlamp is produced by an emission line just as is the blue light in a mercury vapour lamp. Throw salt onto a flame and it will “burn” orange because of the sodium in it. Light passing through sodium atoms in the solar photosphere will reveal the same lines but dark in absorption because they have subtracted light and so they appear black against the overall solar radiation.

After the spectrographs were pointed to the stars, astronomers were faced with interpreting a variety of spectra, some with dark lines and some with bright emission lines. In 1868 Huggins (1824-1910) concluded that the emission lines came from gas between the stars, termed **gaseous nebula**, and the dark-lined spectra were from stars. Remember that this was the exploratory phase of spectroscopy, where everything was new and each observation was unique—the same situation we face with **gravitational waves** today. The word nebula means cloud. Gaseous nebulae glow in different colours and cover extensive volumes of space many light-years across and are the direct result of stars either exploding or shedding layers of their outer atmosphere as part of their evolution. The most accessible of all nebulae to a small telescope is the Orion Nebula located in the "Sword of Orion" which is the central one of three "stars" that point to Orion's Belt. From the Northern Hemisphere, Orion is to the south at New Year. The image and spectrum displayed in Figure 3-8 illustrates the IR spectrum of

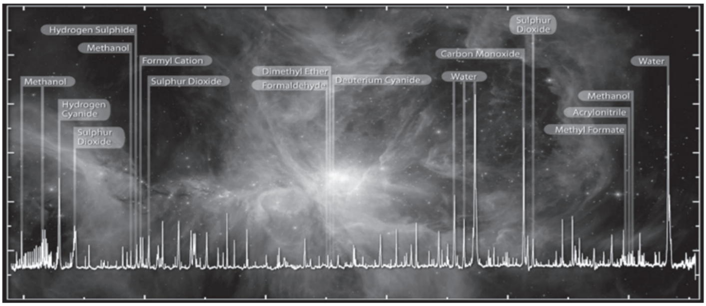

Figure 3-8. Showing the spectrum of water and organics in the Orion Nebula. Each type of molecule emits radiation with well-defined patterns known from laboratory experiments on Earth. So far, some of the elements discovered are water (H_2O), carbon monoxide (CO), formaldehyde (CH_2O), methanol (CH_3OH), dimethyl ether (CH_3OCH_3), hydrogen cyanide (HCN), sulphur oxide (SO) and sulphur dioxide (SO_2). The identification procedure is ongoing. Credit: ESA, **HEXOS**/Bergin (U of Maryland).

molecules detected in this nebula. The image has no wavelength scale because none was offered. I chose to display this complex spectrum rather than one showing the "simple" lines of oxygen, helium, nitrogen, sulphur among others to make the point that "out there" is not simple. Similar complex molecules were detected by radio telescopes years ago. An additional point to make, is that the interstellar medium (the space between the stars) contains molecules which could be the precursors to life. I quote from the commentary associated with Figure 3-8. This commentary in a small way supports the idea of panspermia, the notion that perhaps life could be seeded from space.

> "Molecules like these are precursors to life and must have been present on the early Earth. Seeing these molecules in a star-forming region such as Orion can provide key information as to how they are formed in such environments. This region of Orion will, in many millions of years, contain many stars and each one will probably have a planetary system. Knowing that these complex molecules are already present at this stage could provide clues as to the chances of life eventually emerging."

Gradually, through the 19th century, by a combination of laboratory measurements and a study of the Sun's spectral lines, the chemical content of the Sun's atmosphere became known with about 50 elements identified. Helium, the second most abundant element in the universe, was identified in the Sun before it was discovered on Earth. The solar studies were done in conjunction with studies of emission lines in the laboratory by heating gases, recording their spectra, and measuring the wavelengths of the lines. Remember that the wavelength at which light is absorbed or emitted by a gas is its signature. A single element, say hydrogen, only absorbs light at specific wavelengths. That is, it forms a pattern of lines readily identifiable. By comparing the patterns of individual elements measured in the laboratory, we can identify the elements in the stars. Aside from the development of the telescope no other development changed observational astronomy, and hence our understanding of the universe, more than spectroscopy!

3.19 The Doppler shift

In 1842 Christian Doppler (1803-1853) said the pitch of a note should be affected by the source's motion. We are all familiar with this effect. Think of the times a police car, siren blasting, has swept by you, or a train sounding a warning as it whizzes by at a railway crossing. The pitch of the sound increases as the siren gets close to you and then drops once it passes by. This is the effect Doppler noted, but the principle does not relate to motions across our line of sight—you can't get caught for speeding if you are moving at right angles across a distant radar gun. In the sky, these sideways motions of the stars are called **proper motions**. By measuring the change in the pitch of the sound one can measure the velocity of the source. The laser that the police nail us with when we speed is based on this principle. Doppler commented further that the colour of a star would be changed by the star's velocity. In the stars, the shift in colour produced by this effect is too small to detect. A star moving at 500 km/s for example has the wavelengths of its absorption lines in the visible part of the electromagnetic spectrum shifted by only 0.8 nm, that is 8/10s of a billionth of a metre. But in the galaxies with their enormous velocities of tens of thousands km/s, the wavelength shifts are huge, bearing out Doppler's original assertion (see Figure 3-10 later). The velocities we see in galaxies are velocities of recession, which produce a shift in wavelength towards longer (or redder) wavelength. Hence the name "**redshift**" to describe the motion of galaxies. The shifts are so great that spectral lines originating in the ultraviolet have their wavelengths shifted to the visual part of the spectrum leading to the difficulty of identifying new spectral features, and, on occasion, making the measurement of a velocity dependent on the identification of only ***one*** line. Because the identification of lines in a spectrum depends on patterns imposed on them by the physics of various atoms, with one line there can be no pattern and other information, aside from an act of faith, must be used to buttress the line identification.

In 1848 Fizeau (1819-1896) related Doppler's principle to the practical observation of stars by saying that the absorption lines in stars would be very good fiducial marks in order to measure this very small effect. For Fizeau's contribution, the Doppler principle should be named the **Doppler-Fizeau effect** when we talk about stars. The fractional amount of the shift in wavelength is directly related to the velocity as a fraction of the speed of light and works well for stars and nearby galaxies, but when velocities are a significant fraction of the speed of light—the situation we have in distant receding galaxies—then the formula must be corrected for what are known as relativistic effects. For high velocities then we come into the realm of Einstein and his theory of relativity.

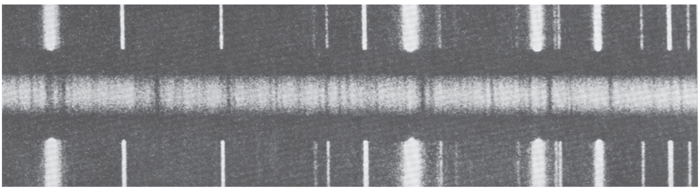

Figure 3-9. Shows how a star's velocity alters a spectrum's wavelength. The white central band represents the spectrum of a star crossed with dark absorption lines, largely due to iron. The bright (white) lines astride the stellar spectrum are due to an iron spark which provides a reference scale. Compare the white and the dark lines which appear to match up except for a slight shift (dark to the right to larger

wavelengths). This shift occurs because the star is moving away from us and the size of this shift determines the velocity of the star. Credit: Unknown.

The shift is measured with respect to a spectrum source operated at the telescope (see Figure 3-9). Nowadays, we use gaseous sources contained in tubes that are excited by electricity—much like neon lights—that we may record before and after any observation to calibrate our CCDs. This gives us our scale which we impress on our spectrum, replacing the pixel number with a wavelength. In earlier times we created a spark between two iron electrodes and used the resulting iron spectrum as a reference source. It always was nerve-wracking burning the iron with its sparks and what-have-you dropping down onto your hand. The wavelength shift is unbelievably small and it's one of the most testing measurement in observational astronomy. Given a wavelength shift, Doppler's formula enables the velocities of the celestial bodies to be measured from their spectra. Initially the errors of measurement were given in terms of tens of km/s but are now down to 1-2 m/s. This latter value is the speed of an easy walk (!!), and a gain of ~10,000 in precision over the 150 years these measurements have been made. For the Sun, where the spectrum is enormously spread out (dispersed), velocities are measured in cm/s! I found it eerie inside a solar observatory because of the heat and shimmering air generated by focussed sunlight. The whole place seemed to be alive with power. Not all velocities need to be measured in microns on some delicate machine, some can almost be measured with a ruler! Check the images in Figure 3-10 where I show a series of galaxy spectra ordered according to the velocity of recession.

The use of the Doppler-Fizeau effect has had a profound effect on astronomy. Without our ability to measure line-of-sight velocities we would know little of the individual masses of the stars, or galaxies, or groups of galaxies! We'd not know that that our galaxy was rotating, nor would we know that the universe was expanding, though we might surmise it. We could not measure the age of the universe or have any hope of determining its and our fate! Moreover, without the ability to weigh the stars, the study of stellar evolution would be stillborn.

Now that we have weighed the Sun and measured its size, we are able to examine it as an example of a star, though we don't know where it fits amid those twinkling objects that abound in the night-time sky.

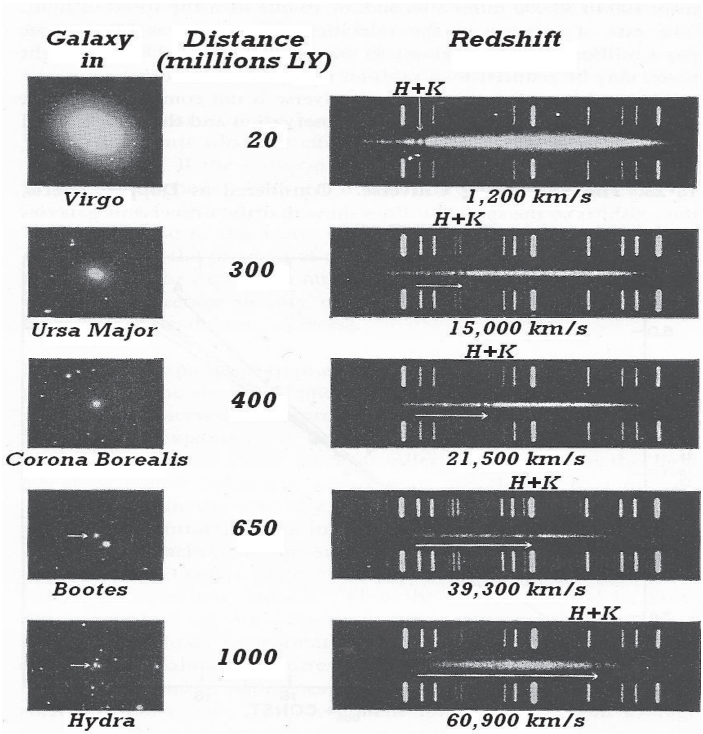

Figure 3-10. A series of spectra of galaxies ordered according to velocity of recession. Check the positions of two close lines called the H and K lines of calcium (wavelengths 393 and 397 nm) also identified in Figure 3-7, seen to the left in the upper panel. This pair of lines shift to longer wavelengths through the lower panels as the velocity of the selected galaxy increases. The distances are from the past and are unreliable. Credit: Unknown source, but derived from Humason, 1936, ApJ, 83, 10. Modified by the author.

CHAPTER 4

OUR FIRST PEEK: THE SUN AS A STAR

4.1 Some solar details

We've learned from the historical record that the Sun is a giant ball of gas about 1,400,000 km across. Its mass is about 2 x 10^{30} kg, 300,000 times the mass of the Earth! If we divide its mass by its volume, we find a density of 1400 kg/m^3, to be compared with that of water 1000 kg/m^3. The Sun, on the average, is like a hot, giant, spherical ball of water. Now, how hot is the Sun at its surface? The Sun is hugely luminous and we know its energy output because we measure how much energy we receive on Earth and then scale it back to the Sun's surface. When we try to measure the Sun's energy output, or the **solar constant** as it is called, the Earth's atmosphere makes life hard for us because it transmits some electromagnetic radiation and blocks others (nothing is ever easy). On the other hand, we are lucky for the atmosphere also blocks lethal UV, X-rays and gamma rays. So somehow, we must account for these missing data in estimating the amount of the solar constant. In pre-satellite days, sounding rockets were used to measure the Sun's output in the unseen part of the solar spectrum. But even when the Sun is directly overhead the atmosphere absorbs some of the light we see and we must also correct for this. Now satellites, unhampered by the Earth's atmosphere, monitor the solar constant (**solar irradiance**) which oscillates between 1365 and 1367 Watts/square metre (W/m^2). Scaling this back to the surface of the Sun this represents an output of 3.85×10^{26} Watts per second (W/s). This is the **solar luminosity**. The Earth's warming is ***not*** caused by variations in the total electromagnetic radiation the Earth receives from the Sun (see Figure 4-1). What is going on ***inside*** the Sun probably causes the periods of variable warming the Earth experiences but ***how*** it works is currently a mystery though radiation in terms of the **solar wind** must play a part since that is the only way we are directly linked to the Sun by matter. The solar luminosity is of critical importance to us for it controls life on Earth and is monitored every day at solar observatories around the

Earth giving us a constant supply of energy we can rely on. Phew! But then there are the ice ages and the frozen mammoths in the Siberian tundra that should remove any sanguinity we might feel.

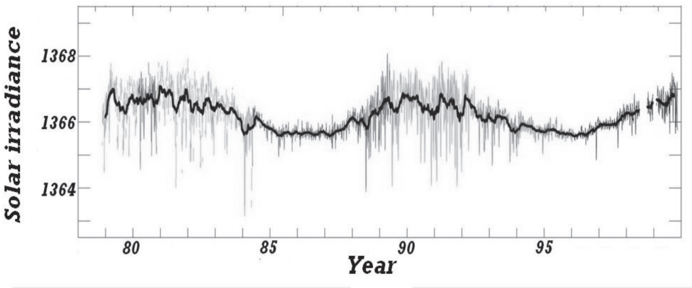

Figure 4-1. The solar constant as measured by various spacecraft (different colours), scaled and assembled to form the image. The black line represents the average. The fluctuations are due to the slight blocking effects of the sunspots and the wave is caused by what is known as the **solar cycle**—the coming and going of sunspots over an eleven-year cycle. The peak of the solar cycle is when the number of sunspots is at a maximum and the Sun is more variable. Credit: NASA/**SOHO**.

Intuitively, we see that the Sun's energy output will depend on its size or total surface area and its temperature. Experiments and theoretical developments dating back to the start of the 20th century relate the total energy output of a heated body to its temperature, a fact that is used to determine the Sun's surface temperature. Knowing the Sun's, distance, size and the solar constant enables us to calculate the Sun's total energy output and hence we find its surface temperature.

When we look out at the night-sky, we see that the stars are of differing colours. The most noticeable examples are the two prominent red stars, Betelgeuse in Orion and Antares in Scorpius. Why is this? Most of the stars look white to our eyes. But think about heating an iron ball in a furnace. Continue heating it until it glows a dull red, then bright red, until it gets white hot. Implicit in this statement is the knowledge that an object changes colour the hotter it gets. Put your hand near the stove as it heats and you'll see my point. In other words, temperature is related to colour. Work by physicists precisely relates an object's temperature to its colour. The Sun looks white to us, but is this its real colour? What colour would it appear if we viewed it across the reaches of interstellar space? From the physicist's theoretical results linking colour and temperature, we find that the Sun's surface temperature is about 5800 K and its colour is yellow! I've read that if you look at the Sun just right, though I can't ***ever*** recommend doing it, whatever "just right" means, that the Sun does indeed look yellow. It's an experiment that doesn't interest me having endured a lifelong phobia about accidentally looking directly at the Sun.

4.2 At the Sun's surface

The Sun has shone brightly down on Earth for about 4.5 billion years and will do so for at least as long again. Over the centuries we have gotten glimpses of its surface despite its blinding light. On very cloudy days when conditions are just right, I can take very, very, brief glances at the Sun, mindful that even though heavily cloud-covered, the blinding unseen UV radiation is still pouring into my eyes. At similar times, our ancestors would have seen sunspots, just as they are revealed on face of a Sun deep into sunset. The eclipses give us a different view, and again I counsel you to avoid looking directly at the eclipsed Sun because the invisible UV is still pouring forth from the bright surrounds. Maybe, when the Sun was totally obscured by the Moon, the ancients saw the red rim of the Sun, called the

Figure 4-2. See Centrefold. The Aurora Australis, the Southern Hemisphere name for aurora, seen from the Space Shuttle Endeavour. The colours of these lights indicate the element that is affected by the incoming solar wind. The bright spots are stars in the constellation Orion, slightly elongated because of the time exposure and the motion of the shuttle. The three stars aligned vertically in the middle represent the belt of Orion. Angling down from the left are three stars forming "Orion's Sword". The large fuzzy central object in the sword is not a star but a gaseous cloud called the Orion Nebula. Credit: NASA.

chromosphere. Perhaps they saw the **corona** or crown as it is called which also blossoms forth in deep eclipses—we call them total eclipses. While the connection between what happens on the Sun's surface and what we see on the Earth would not have been made centuries ago, the **Aurora Borealis** and **Aurora Australis** that shine gloriously in dynamic colour tell us more about the Sun (see Figure 4-2). Apart from the sunlight that beats upon our faces, aurora link us to the Sun in ways we're only beginning to understand. The weather, and long-term climatic effects on Earth, are modulated or altered by solar magnetic activity and the particles (the **solar wind**) that flow towards the Earth from the edges of the sunspots.

Telescopes that study the Sun are never at a loss for light, unlike the puny starlight we try to capture at night. Orbiting, and Earth-based telescopes, keep a watch on the Sun, monitoring it to detect monster storms that affect communication on Earth. With the solar telescopes as they are called, we see only the Sun's surface but what we see there gives hints as to what is happening deep in the core of the Sun. When we look at the Sun, we see its outer layers and from these data we try to unlock its inner secrets. Why is it rotating so slowly now when it had naturally speeded up as it collapsed out of the interstellar cloud that gave it birth? How are the streams of atomic nuclei that impinge on the Earth, and which we call the solar wind, accelerated to high speeds and how do they escape the Sun anyway? How does the **solar dynamo** work that generates the Sun's magnetic field? Do we really know how sunspots are spawned? Is the Sun's energy output variable? Is this the cause of climate change we seem to be experiencing and which the Earth has experienced before? From the chain reaction that creates hydrogen bombs and fuels the Sun at its core we expect to find neutrinos, tiny massless particles, by-products of this nuclear fusion, which continuously traverse the Earth and our flesh. Calculations describing these reactions predict the number of these neutrinos emitted from the Sun's core. Do we see enough of them, and how do we detect these elusive particles?

I'll touch on these questions but first let's see what we're looking at when we talk about the Sun.

4.3 The solar atmosphere

The Sun's atmosphere encompasses three zone, the photosphere, chromosphere and the corona. From the distant past all have been observed though the chromosphere and the corona were only ever observed during total eclipses of the Sun. Considering the warnings we get about looking directly at the eclipsed Sun, I hate to imagine the eye damage done to our forebears when they had a really good look at the rim of fire, the chromosphere, seen peeking out from the edges of the Moon and the corona surrounding it all in a splendid display. I'll look at each of these in turn.

4.3.1 The photosphere

When we quote the Sun's size, we are referring to its size where we cannot see into it any further. We call this the photosphere or sphere of light and this is the surface from which the energy flows which had its origins in the nuclear furnace in the core of the Sun. Though the energy from the core of the Sun is enormous, it must sustain the Sun against the force of gravity that is trying to collapse it. The radiation resulting from this task is emitted from the hot photosphere and passes through an atmosphere only a few hundred km thick. Thus, the central temperature of 15 million or so degrees shows forth in the photosphere as a "modest", by astronomical standards, mean temperature of 5770 K. The photosphere is hot but not quiescent, for at the base of the photosphere is a zone where the energy from the centre of the Sun is carried upwards in giant liquid convective bubbles. **Convection** is the movement of energy by motion. We see it in a pot of similarly bubbling boiling water where overheated water at the base of the pot is forced upward in bubbles. Over the Earth's surface, heat is transmitted upward in giant draughts. This is convection. Those hammer-headed thunderclouds are the result of huge upward convective draughts. In the Sun, convection begins a few hundred thousand km below the surface (remember the **solar radius** is 696,000 km), moving material upward where it cools off at the surface and is then circulated downward. We see this mechanical energy erupting in the form of convective cells or **granulation** (see Figure 4-3). Remember that hot air, water etc., rises while cool air, water etc., falls. Motion pictures reveal that these granules survive for a few minutes and then reform. The centres of the granules are about 300 K hotter than the edges and, as the gases rise and cool off, they spill into the areas between the granules. It is possible to measure the speeds that these granules move and these give a clue as to what is going on in the centre of the Sun, but more of this later.

The photosphere is about 500 km thick and it is here where the cooler gases above the hotter lower layers absorb light to create the lined spectrum or the Fraunhofer's spectrum from which we learn so much. This process involves atoms selectively absorbing light at discrete wavelengths specific to the atoms involved. For example, the lines created by hydrogen gas are quite different in wavelength from those absorbed by iron. Not only do they differ in wavelength but they differ in the numbers of lines they produce. A simple atom such as hydrogen with only one electron produces few lines, but iron

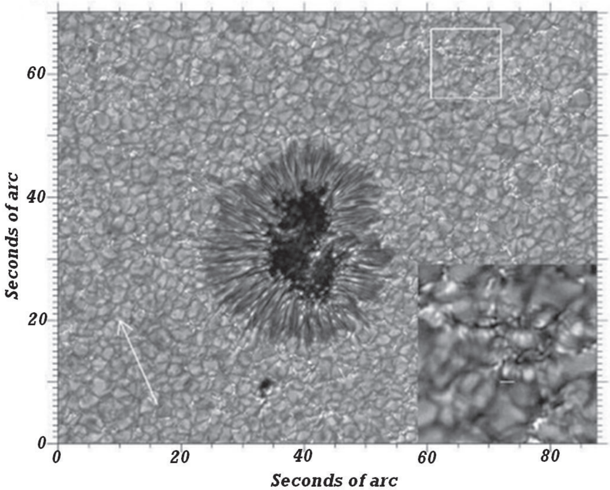

Figure 4-3. An image of the solar photosphere showing the granulation, or convective bubbles near a sunspot. The bright patches are bubbles of hot gas rising from within the Sun. The darker areas among the patches are cooler gases dropping back into the interior. Similarly, the darker areas in the sunspot indicate that they are cooler than the surrounding gas. The black centre of the sunspot is called the **umbra** and the radial parts are called the **penumbra**. The sunspot is about 20,000 km across and the granules about 1500 km. Credit: NASA. Modified by the author.

which has 26 electrons will produce many more. Additionally, these characteristic lines are limited in where they are found. Most of the hydrogen spectrum is found in the visible region of the spectrum but iron is found from the UV into the IR (15 to 2,500 nm). In traversing the solar atmosphere, part of the energy is used up in a mechanical heating of the layers above the photosphere, particularly in the corona where the temperature of the tenuous atmosphere is about a million degrees.

4.3.2 The chromosphere

Immediately above the photosphere is a layer of gas called the chromosphere (sphere of colour) where the temperatures rise and any comparison with what we have on Earth disappears. During a solar eclipse the chromosphere is seen as a reddish-pinkish layer about 2000 km thick (see Figure 1-6, and later, Figure 4-5). Now with satellite-born telescopes, by choosing the wavelength of the light we want to use, we can look directly onto the solar surface where some of the most amazing pictures have been taken. Energy from the solar surface is pumped into this region because the temperature rises to about 50,000 K 2000 km above the solar surface. The situation on the Sun is different from the Earth where our atmosphere gets cooler and less dense the higher you go until it reaches the vacuum of outer space. Not so on the Sun, which is far more complex than Earth. There is all the mechanical energy from convection bubbling to the surface that heats the chromosphere and additionally the Sun has a dynamic magnetic field that it must cope with. Consequently, the chromosphere is heated by the transference of mechanical and magnetic energy into the gas. The chromosphere is in a continual turmoil with flares of light erupting and millions of long arches of gas thousands of km long standing up from the solar surface. The magnetic field bursts out of the surface of the Sun exposed by the hydrogen gas lifted with it (Figure 4-4). The point of these comments is not to give a litany of the Sun's activities but to show that the Sun is a whole lot more than it appears. Consider your friends displaying serene countenances. Do you really know what is going on behind their eyes? A satellite, **TRACE (Transition Region and Coronal Explorer)** was, as its name implies, looking at the transition region where the temperatures range from about 6000 K to millions of degrees in the corona. This satellite, whose mission ended in 2010, has provided us with some remarkable images of the Sun's dynamic, turbulent surface as shown in Figure 4-4. This varied solar activity has the potential to affect us on Earth for these magnetic storms place satellites at risk along with our power supplies. Look at the NASA site for TRACE and SOHO (**Solar and Heliospheric Observatory**). The images are fascinating.

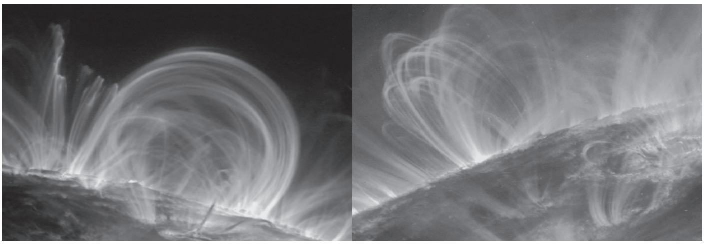

Figure 4-4. These are images taken towards the limb of the Sun by TRACE. The loops represent some of the millions of magnetic lines of force (called field lines) erupting from the Sun's surface. Gases move along these field lines and are heated to millions of degrees as they rise upwards to 500,000 km above the photosphere. Credit: NASA/TRACE.

When the chromosphere was photographed using a spectrograph, many bright lines were seen. The fact that the lines were in emission—were bright—meant that the region was of low density and very hot, with the incoming energy stimulating some atoms to radiate electromagnetic energy in a process analogous to that which produces the orange light from sodium gas lamps used to illuminate many highways and city streets. Whereas, in outdoor lighting, electricity is used to excite the atoms to emit light, in the stars, radiation provides the energy. We see coloured gaseous shells around aging stars that are blowing their outer layers into space on their march to oblivion (check the frontispiece). We call these objects **planetary nebula** because they have size when viewed in a telescope, whereas stars always look like small points of light. In this case, the tenuous gas around the star is excited or stimulated by the UV radiation from the hot central star. So where does the pinkish rim of the Sun come from? This colour comes from the stimulation of hydrogen atoms that emit light at the red wavelength of 655 nm.

4.3.3 The corona

The corona forms the transition region between the chromosphere and the emptiness of space. The name means crown, and the corona was first seen during eclipses where it appeared as a halo around the Sun. It is known to be very hot, with a temperature of a million degrees or more. The size of the corona varies with the variation of the Sun's magnetic field, or solar cycle, and because of this, it is thought that the energy involved in heating a gas to a million or so degrees is related to the Sun's magnetic field (see Figure 4-5).

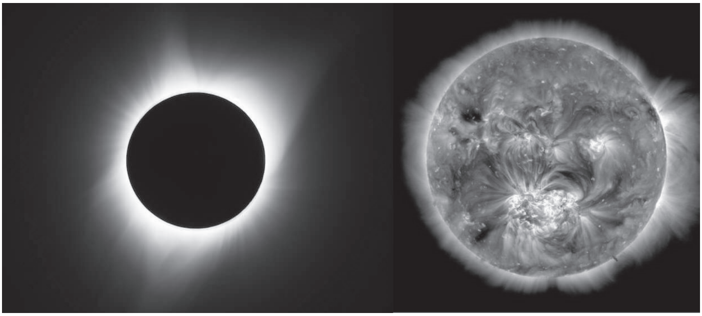

Figure 4-5. Left-hand panel. Image of the solar corona during a total solar eclipse on Monday, August 21, 2017 above Madras, Oregon. Right-hand panel. Image of corona from NASA's Solar Dynamics Observatory showing features created by magnetic fields. Credit: Left panel. NASA/Gemignani. Right panel. NASA.

The corona is not necessarily the crown-like image we see in Figure 4-5. Like the rest of the Sun, it is dynamic. Occasionally the corona bubbles outward at speeds of 500 km/s or 2 million km/hr. These coronal bubbles eject clouds of gas that leave the Sun's surface and spread out through the solar system. At 2 million km/hr it takes about 3 days to cover 150 million km to reach the Earth where the particles in the clouds produce bursts of radio noise. These coronal bubbles are called **coronal mass ejections (CME)** and they are routinely seen on live images from SOHO which studies the corona as well as the photosphere. Because these loops produce intense X-rays, which affect the satellites orbiting the Earth as well as communications on Earth, it is easy to justify the expense of maintaining these satellites and the associated research. From their research, astronomers can now give warnings of intense magnetic events, even those unseen but still detected on the other side of the Sun!

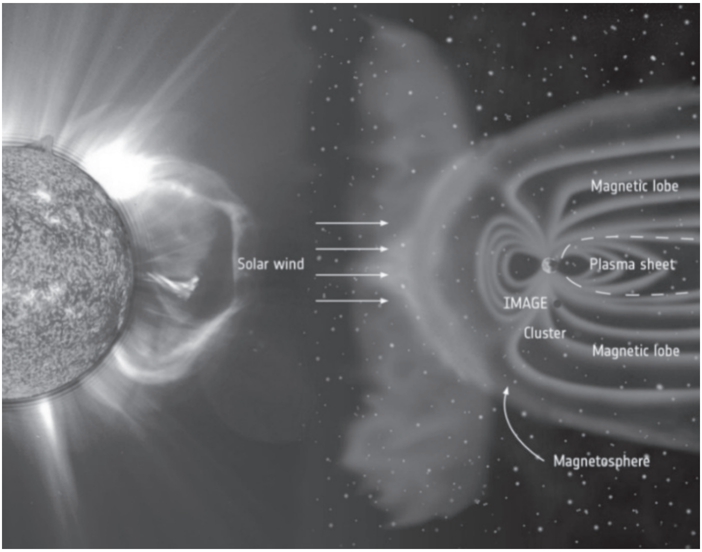

Figure 4-6. A CME interacting with the Earth. Note that the objects are not drawn to scale. Credit: NASA/ESA

The illustration in Figure 4-6 shows a CME erupting from the Sun's surface in the direction of Earth. A few days later this cloud of material starts to interact with the Earth's magnetic field, which, in the absence of the solar wind, would look like the magnetic field surrounding a bar magnet. But now the field is forced to change its shape and the magnetic lines of force are pushed to the far side of the Earth. This cloud may be 50 million km across by the time it reaches the Earth where these atomic nuclei run down the magnetic field lines to interact with our atmosphere at the North and South Poles. We see this interaction in the form of aurora. The CME can disrupt communications and navigational equipment, damage satellites, and even cause blackouts as occurred in Montreal in 1989. Because of this unexpected, and massive disruption, our electricity networks have been "hardened" to avoid a repeat catastrophe.

This description of the Sun's atmosphere, the photosphere through to the corona, seems overly simple to me. Maybe, if we think of the Sun in terms of its outwardly benign appearance, this is true, but when we look at it in a different way it has a totally different appearance and is hugely complex. That's okay, because that is what we see, but I'm thinking ahead about the realism of the models of the solar atmosphere and how we treat it as a "simple" entity in much the same way as atmospheric physicists model the Earth's atmosphere to produce the weather forecasts that get better every year. With my comments here, I'm thinking about the twisted lines of force we see that obviously pass through the solar atmosphere along with the red glow of excited hydrogen gas that permeates the whole. How does this physical reality affect the results when we match modelled atmospheres and the predicted spectra with observation? This modelling business is what enables us to get a handle on how stars evolve and here I am fretting about the approximations, or simplifications, in building an atmosphere in a computer to match what we see in the Sun. If I'm wondering about the Sun, what about the complex models of the stars that we must build for the rest of the universe's stellar content? I can't answer this, but I've brought it all up because the description up to here seems a little like a travelogue—maybe Shangri La—and in getting to the nitty-gritty of a hard-nosed analysis of stellar evolution we must be aware of the warts within the narrative.

4.4 What is the Sun made of?

How do we know what elements are in the Sun and what are their proportions? The question must be answered in two parts, one part observational, and the other theoretical. Remember from the previous chapter how all the atoms produce distinctive patterns of spectral lines at specific wavelengths. Therefore, we attempt to match the wavelengths of all the lines in the Sun's spectrum with what has been measured in the laboratory. In this way we have identified about a hundred elements in the

Sun. Getting their proportions is not as easy and it requires complex theoretical and observational analysis to establish their ratios. For example, gold atoms are four trillionth as abundant as hydrogen atoms. Obviously, this is not an easy measurement. Helium is only 8% as abundant as hydrogen. But how do we really know how much hydrogen is in the Sun to start with? We can only answer this by building computer models of the Sun with varying chemical composition and matching our models with what we see. Hence, the abundance of the elements is derived by a joint analysis of the observed solar spectral features, by modelling the interior of the Sun and by making predictions about the amount of helium and other elements that were created from hydrogen when the universe was formed. From this comment, you can see how much astronomy depends on theory, from trying to find out which elements were created and in what quantities during the Big Bang, and the use of these results in modelling the stars.

4.5 The Sun's magnetic field

Space is permeated by magnetic fields stemming from the very origin of the universe in the Big Bang and therefore they are already imbedded within the giant clouds that collapsed and will collapse to form stars. When the Sun collapsed out of a giant cloud of gas and dust, the magnetic field collapsed with the gas also and has been part of the Sun, as it is with all stars, ever since. How do we know there is a magnetic field on the Sun? Using solar telescopes, we can ***see*** the looping lines of force on the edge, or limb of the Sun (Figure 4-4) and witness the sudden rise of gas thousands of km into space within these arches (Figure 1-5 and Figure 4-6). We see the similar events from the spacecraft TRACE but with clarity unmatched by Earth-based data. Think about the teacher who used a long magnet with a piece of paper on it. When the iron filings were spread on it and the paper tapped, the filings lined up along loops from one end of the magnet to the other. That is, they lined up along the lines of force. The surface of the Sun is complex and undoubtedly this complexity is tied up with the Sun’s magnetic field. Our star is moderately well-behaved, so imagine a star with more intense magnetic activity! The second way we know about magnetic fields is by the effect they have on ***some*** spectral lines because not all lines are sensitive to magnetic fields. Sunspots are known to be associated with magnetic fields because of the appearance of their spectra. We take a spectrum by passing the light through a slit which serves the same role to better define the light as the pinhole in a pinhole camera. When this long slit is lined up over a sunspot and the larger area around it where there is no sunspot, a spectral line is single but when the slit is on the sunspot the line splits into two or more lines (see Figure 4-7). This effect is called the **Zeeman Effect** after its discoverer Zeeman (1865-1943), and the amount of splitting indicates how large the magnetic field is. We've long known about magnetism on the Sun, so the question is, "What effect does it have on the models of the Sun that we build in the computer?" Here, I'm reiterating what I said earlier, but with more brevity. Bear with me. Our only knowledge of the age of stars is by using computer modelling. This leads to the next question. "If the Sun holds its secrets such that we cannot model it correctly because of possible complications derived from its magnetic field how much faith can we have when we model other stars?" Having said that, recently, I noted that some stellar modelling has been done including the effects of magnetism.

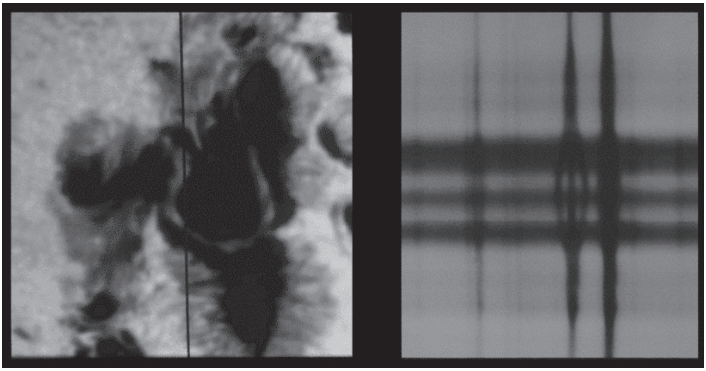

Figure 4-7. The image on the left is a picture of a sunspot. The dark line running through the middle of the picture is a slit which feeds the spectrograph to produce the rightmost image. The three vertical lines are from a single line, due to iron, split into three because of the magnetic field in the sunspot. Outside the sunspot the line is single and is unaffected by the Sun's magnetic field. By measuring the amount of this splitting, we can find out the strength of the magnetic field across the sunspot. Credit**: NOAO**

4.6 The solar cycle

The solar cycle is a cycle defined by the number of sunspots visible on the Sun. Typically, the numbers increase and decrease over a period of 11 years (see Figure 4-1 earlier). The maximum number corresponds with a peak in the overall magnetic activity in the sun. This is the time when the northern lights are at their most magnificent and the times when communications on Earth are affected. As I mentioned earlier, in 1989, an intense magnetic storm on the Sun produced electric currents in the earth that blew a key transformer. This event triggered a widespread failure that collapsed the whole of the northeast Canadian electrical grid. This storm had produced an **electromagnetic pulse (emp**) like what might result from a nuclear explosion and against which we now try to harden our electrical grids and communications. At the maximum of the cycle the northern lights are active because of the link between the solar wind and its interaction with the Earth's magnetic field. Aside from spawning aurora, the solar wind is literally seen in action by its effect on the dust liberated from the frozen gases surrounding a comet. Comets have two tails. The pressure of light on the gases evaporated from the comet as it warms forms one tail, and the second tail forms from dust pushed away from the comet by the solar wind.

Until recently, the source of the solar wind was a mystery. What mechanism could accelerate these nuclei away from the Sun's confining gravity at speeds of about 2-3 million km/hr? When the spacecraft SOHO examined the spaces between the edges of the bubbles or convective cells, scientists discovered that these spaces play a crucial role in generating the solar wind. Each of these cells (granulation) has a magnetic field and streams of particles that become the solar wind pour out around the "cracks" between the rising and falling cells and then surf on magnetic waves wiggling out from the Sun to high velocities. The speed of the particles begins at 30,000 km/hr at the surface and accelerates to 2-3 million km/hr taking about two or three days to reach the Earth where the particles alter the shape and structure of the Earth's magnetic field (Figure 4-6).

You might wonder how we know the speed of these particles. There is a time delay between any large-scale bout of activity on the Sun which we see (ignoring the 8-minute time delay for the information to get from the Sun to our eyes) and then when we detect it on Earth. Perhaps a giant plume of hydrogen will erupt from the surface along one of the magnetic arches that abound over the surface. These are known as **solar flares** that drive large quantities of particles and radiation out into space. A few days later the effects of these explosions are seen when the atomic nuclei are captured by the Earth's magnetic field and then race down the lines of force in the Earth's polar regions reacting with the atoms in the Earth's upper atmosphere that creates the glorious aurora we see. Flares have also been detected emanating from stars cooler than the Sun. But solar flares are not on this large scale and would be undetectable when viewed from other stars. The fact that we can detect flares on other stars is a reminder of how benign the Sun really is.

4.7 Sunspots and the weather

Sunspots have been seen on the Sun for thousands of years, their numbers growing and shrinking over the solar cycle. Sometimes they disappear completely as they did between 1645 and 1715. Sunspots often cluster and large clusters are active in spawning vast storms above them. The spots appear dark because they are about 1500 K cooler than the surrounding photosphere and are places of intense magnetic fields. The fact that they are cool is caused by the local magnetic field which impedes the convective flow, or bubbles, of hot gas to the surface. This observed effect is what makes the model building so difficult. How do we calculate this? Above these areas, great arches of hot hydrogen gas are flung outward. Most of the material falls backward onto the solar surface, though it may remain suspended for days in the looping magnetic fields, but some reach **escape velocity** and are flung into space at speeds of 1000 km/s or about 4 million km/hr.

4.7.1 A brief aside—escape velocity

The escape velocity is the velocity that an object must reach to free itself from the gravitational bonds of its host. A spacecraft leaving the Earth must be accelerated to more than 11 km/s or 40,000 km/hr otherwise it will be pulled back by Earth's gravity. For the Sun, the velocity is 618 km/s! By comparison, the escape velocity on the Moon is only 2.4 km/s—hence the small size of the lunar lander and its propulsion system. The escape velocity has a major bearing on whether a planet or moon has an atmosphere. If a planet is to retain its atmosphere, the escape velocity must be greater than the effects of solar heating which causes the molecules in an atmosphere to speed up. If molecules in an atmosphere move faster than the escape velocity then the atmosphere inevitably evaporates into space. Mercury, the closest planet to the Sun, is small, with a low escape velocity and is savagely heated by the Sun, hence its lack of an atmosphere.

4.8 Back to Sunspots

Recent research has revealed a link between the sunspot cycle and weather patterns on Earth, so we are not free from happenings on the Sun's surface 150 million km away! Indirectly, the solar wind does influence our weather in ways only now being understood. The record of the numbers of sunspots seen in a year date back to 1600. The mini "Ice age" recorded in Europe between 1645 and 1715 is directly correlated to a minimum in sunspot

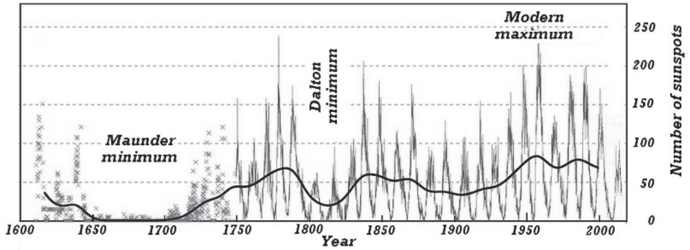

Figure 4-8. The Maunder minimum, a period when the Sun had few sunspots and Europe experienced very cool weather over about 50 years. Credit: Wikimedia Creative Commons/Rohde. Modified by the author.

numbers called the **Maunder minimum** (see Figure 4-8). What is striking, is to see that hardly any sunspots were recorded during the time when the weather in Europe was such that the North Sea froze at times, glaciers developed in the Alps, and the river Thames froze. Earlier, between 900 and 1400 CE, the weather was so mild that the Vikings, settled on the coast of Greenland, grew barley and corn. Grapes were grown in northern England and 500 km further north than they are currently grown in Germany.

There is a correlation between the ocean temperature and the sunspot cycle and we know the Earth had an Ice age about ten thousand years ago. There are these links to the Sun but not caused by any changes in the solar constant, but how it works is unknown. There is now active discussions among the solar physics community that changes like the Maunder minimum and other similar earlier events paralleling the sunspot results, identified by the analysis of the radioactive element **Carbon 14** in tree ring growth, that may be related to some form of solar variability making the connection for global warming and greenhouse emission less clear.

The issue of solar variability is complex, for we have only been able to make reliable measures of the Sun's energy output since the early 20th century and latterly using purpose-built satellites (see Figure 4-1 shown earlier). To go back even earlier, we must make a model of what we think the Sun is currently doing, extrapolate (or extend) the prediction backwards and then find corroborating evidence that would give a researcher faith that the model was realistic. We know two things that will change the solar energy output. The first is the Sun's evolution and the second, from the lead-up discussion, is the solar magnetic field. Evolution takes place over billions of years so we can forget this effect, though Earthlings won't always have that choice. What about the Sun's magnetic field, might it be changing on top of the solar cycle? The Sun has been modelled to make a link between its luminosity or brightness and its base magnetic field, which is the magnetic field that remains even when there are no sunspots. This model projects back about 150 years making a prediction about the solar energy output. Remarkably, this prediction correlates very well with northern hemisphere temperatures averaged over the solar cycle. Results for the later part of the 20th century indicate that the temperature is anomalously high relative to the model and it is likely that here we are seeing the “smoking gun” which shows what we are all feeling, the effect of greenhouse emissions on our climate.

Sunspots have been seen on stars. In looking at double stars which eclipse one another, astronomers have been able to infer the presence of sunspots. On some class of stars, the sunspots take up about 10% of the surface area and produce marked variations in a star’s brightness as it rotates about its companion, presenting differing faces to us, just as we see similar changes in a single, rotating, spotted star. We are fortunate on Earth that the sunspots are small for life here seems tenuous at best and a variation of 10% in the Sun's energy, coupled with the intense magnetic storms the sunspots would create, would have affected the evolution of the species on Earth.

4.9 Solar seismology

Because the Sun is a giant ball of gas with an average density a little more than water, it can carry sound waves or vibrations within it, just like the Earth’s interior transmits sound-like waves, and, when recorded at the Earth’s surface, we call them earthquakes. Sound travels in water, for in the sea we hear whale cries and other sounds of the deep. What is sound? Sound is a vibration that our eardrums react to. Bounce a laser beam off a window to detect vibrations caused by speech in a room under surveillance, record the vibrations detected by the laser, and play them back in a reverse process to retrieve what was said. We listen to the sounds of the Sun by detecting the variations in the vibrations of light from the solar surface. But what are the variations in the vibrations of light? They are simply velocities. Why should the Sun make sound? Turbulence makes a sound. Think of waves crashing to shore on a beach. In the same way, we might expect these hot cells of gas that bubble to the solar surface to make a roar, but at a frequency far below anything we could hear. Put in context, the lowest frequency our ears response can hear is about 20 cycles/sec or 20 **Hertz (Hz)**, whereas the Sun vibrates over frequencies thousands of times lower. Not that we could literally hear these deep vibrations here on Earth for sound does not travel in a vacuum, we'd have to dip our heads into the Sun to hope to hear the noise. Those explosions and screams we hear in a Star War's movie are silent in space.

If we can't hear sound in a vacuum, so how do we know the Sun makes a roar? The development of **solar seismology (helioseismology)** took place when astronomers started to measure the velocities of these rising and falling convective cells and since then this branch of solar research has never looked back. The speeds at which these bubbles rise may be as much as a few 100 m/s or as low as tens of cm/s. Remember that sprinters run the 100 metres in about 10 seconds or at a speed of 10 m/s. Since then, other rhythmic velocity variations were detected related to circulation, that is the process of material being transported from the equator and moving it to the poles, and with this discovery helioseismology was born, promising much in terms of unlocking the secrets of the Sun. It has delivered on these promises. If we measure the velocities over time and in different regions of the Sun then we can detect the Sun's "rhythm of speech". We can measure the granulation velocities near the equator and look at polar regions to check for differences. Because we have a large object to look at, and not a point source of light like a star, we have the potential to make a thorough analysis of the Sun through its surface velocity characteristics. Typically, a million points distributed over the solar surface are regularly sampled, so we have no shortage of data. As someone who has dealt lifelong with large amounts of data, the thought of processing and digesting such a vast amount of information is daunting and gives me a headache just thinking about it!

The Sun vibrates in many ways and scientists have developed extensive models of the Sun's interior to try and fit—or what we typically say—satisfy the velocity data. The technique is similar to what geologists use on Earth when they examine earthquake results from around the world or when they set off explosions to examine more localized areas in greater detail. The only difference is that they deal with vibrations they can record and solar astronomers deal with velocities. Again, they can't see what is in the Earth, but they can infer it from the results, provided they have a model of the sub-Earth strata or layers which is realistic. The Sun vibrates, roughly with a five-minute period, and like any sound wave it spreads outward. In this way the Sun acts like a bell. Where there is no atmosphere, like at the surface, the wave cannot be propagated but may be reflected at the Sun's photosphere. Those waves that move back into the interior may, in areas of high density, be reflected back towards the surface where they interact with other sound waves. In this interaction sometimes they'll cancel each other out and sometimes they will be amplified (**resonate**). To get an idea about resonance think of how you really get going on a swing. You kick your legs, or get a push, just at the right time and you swing upward. Pump your legs at the wrong time and your motion is severely hampered. Getting it right is called resonance. These interacting oscillations set the Sun oscillating in millions of patterns called modes of vibration. By examining them, scientists have been able to see how the interior of the Sun rotates and find that the Sun's inner core rotates like a solid ball with a period of near 6-7 days. Inside the convective zone we get what we call **differential rotation** where the fluid in equatorial regions rotate at different speeds than those at the pole. These differing interior happenings we see ultimately on the surface where the Sun rotates with a period of 25 days at the equator and 33 days near the pole, at latitude 75^{o}. Because of this differential movement inside the Sun, there is a lot of shearing between layers that will produce more turbulent motion. The effects of shearing elsewhere in the solar system are dramatically revealed in the NASA movies displaying the rotation of the atmospheric bands of Jupiter around the **Great Red Spot**. In thinking about the shearing between two layers I immediately thought of the junction between the Pacific Ocean and the Tasman Sea to help make my point. This beautiful and illustrative comment comes from Māori lore:

> "Cape Reinga marks the separation of the Tasman Sea from the Pacific Ocean. For Māori, these turbulent waters are where the male sea Te Moana Tapokopoko a Tawhaki meets the female sea Te Tai o Whitireia. The whirlpools where the currents clash are like those that dance in the wake of a waka (canoe). They represent the coming together of male and female—and the creation of life."

When the model fails, someone comes up with a modification. Maybe it is a temporary patch or perhaps the next suggestion really works well. Perhaps you're on totally the wrong track and you try again. Certainly, in the Sun, the effects of magnetism, its generation and growth will affect the Sun's structure so the interior modelling will become quite difficult. But out of this work has come some fascinating results because now we can "look" inside the Sun in a way we'd never thought possible a few decades ago. Because of the promise that helioseismology holds, an Earth-based network of observatories **Global Oscillation Network Group (GONG)** has been established to look carefully and continuously at the velocities over the Sun's surface. The spacecraft SOHO combined with GONG provide continuous velocity studies of the Sun.

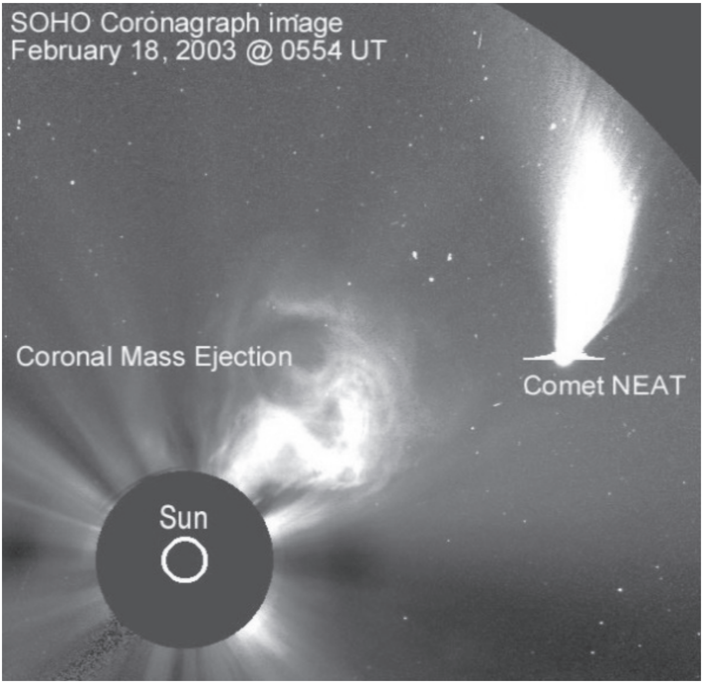

Figure 4-9. The panel shows Comet Neat and a large CME. The small white circle to the lower left represents the Sun which is blocked from view by a disk in the telescope. The white spots are stars. Check in at the SOHO website and maybe download a screensaver showing the Sun in real-time, which will do nothing to allay any insecurities you may have about the world "out there". Credit: ESA/NASA/SOHO.

SOHO also takes direct images of the Sun and its immediate environs. These images unexpectedly reveal comets either surviving an encounter with it and whizzing back into space or being consumed. Surprisingly, SOHO has discovered more comets (3700 plus) than any other single source. In Figure 4-9, Comet Neat is shown in its passage around the Sun. A coronal mass event (CME) is in the frame and looking at the movies of solar activity on the SOHO website shows that the Sun is active but—fortunately—not to our eyes. There's little I can do here but give you a wee flavour of the current research. Part of the solar study is to unlock the secrets of the solar dynamo that creates the magnetic field, because understanding this is fundamental to understanding the 11-year solar cycle. I mentioned earlier about the magnetic field in the Sun being hugely compressed because of the collapse of the original gas cloud that gave it birth. The magnetic field is made up of many lines of force. Remember my early example of the bar magnet experiment. The end-product is a paper on which the iron filings line up along the lines of force joining the poles of the magnet. Imagine these lines of force running north south inside the Sun and then getting twisted up in loops because the Sun does not rotate evenly—recall that the polar regions of the Sun rotate slower than the equatorial region. The outcome of this rotation is that the lines of force get wound up in tighter and tighter loops. Eruptions on the Sun can be pictured like a rubber band that you twist and twist with the little loops popping out over the surface (see earlier Figure 4-4) until finally it breaks, releasing stress. On the Sun we see these loops as magnetic eruptions. The solar cycle is thought to result from the slow build-up of magnetic forces close to where the dynamo is produced. The forces increase until they reach a pitch where the magnetic field bursts through the solar surface and, with it, we get the amazing storms imaged by SOHO and TRACE (Figures 1-6, 4-6 and 4-9). Some of these storms show vast loops of hydrogen extending out more than five or so solar diameters from the surface, that is to a distance of at least 5 million km or about four percent of the distance to the Earth. (Looking at Figure 4-9 we see the solar prominence there extending well past 5 solar radii.) We see the effects of these events in records of the solar constant, the amount of radiation arriving at the Earth, which may change by 0.2%—fortunately not enough to bother us! After the peak of the solar cycle it is as if the Sun shakes itself and the magnetic lines of force go back to their original simple form and then the cycle of twisting and entanglement begins again.

By a combination of observation and modelling, solar physicists can see right through the Sun to witness magnetic events on the other side and thus give us ample warning of approaching magnetic storms on Earth. When people ask me to justify in terms of the usefulness spending money on the study of stars I can't, for stars have no interaction with us, but the Sun is another matter. But if we aren't interested in the larger world, of what use are we?

We are learning a lot about our Sun, information that will prove invaluable when we start trying to interpret what we see in the stars. But historically, there is the mystery of the source of solar energy and the measured abundance of the elements. From where do the elements arise? In coming to grips with these questions we need a flashback to the formation of our universe and look at the progress of 20th century physics and mathematical developments that enable us to "build the Sun" in a computer. Given this information we will be able to go further afield to see and interpret what's out there.

CHAPTER 5

THE SOLAR INTERIOR

5.1 Origins

In the beginning, just after the Big Bang started, the universe was pure energy contained in a volume of diameter about 2 x 10^{-33} cm (2 divided by 1 followed by 33 zeros)—just think of the whole universe being contained in zero volume! It looks like a hole opened and our universe poured through, expanding the opening as it did so. On its expansion, in the process that formed space in which we live, the universe cooled from hundreds of trillions of trillions of degrees to a value of 2.7 K today—which is 2.7 degrees above absolute zero! At that time—which we may call creation—it is thought that there was but one force at work in conditions outside the bounds of what we know as physics and so the quoted temperature has no meaning. None of it has any meaning really: the distances are unimaginably small, the times unreally short and the temperatures high beyond comprehension. But it seems it started from nothing and grew, which, in itself, is a mouthful. In the course of this expansion, the four forces we are familiar with, thought to have been part of the one (currently unknown) unifying force, separated out when the universe was less than the size of a pinhead (much, much less!) and only (!) 10^{-43} seconds old (1 part in 1 followed by 43 zeros of a second!!). This process, which we are still trying to understand, left its legacy in the four known forces of nature. The first is the force of gravity which we are all familiar with. The next is comprised of a combination of electric and magnetic forces termed the electromagnetic force. (Our world runs on electromagnetism for we see it at work generating electricity in turbines—or the inverse, producing motion in electric motors.) The third is the strong nuclear force that binds the constituent parts of the atom together (protons and neutrons, themselves made up of elementary particles called quarks, which are made up of…). Without this binding force, complex atoms could not form and the universe would be one of pure hydrogen and residual radiation and we'd not be around to view it. The fourth force, the weak nuclear force, is that which lightly binds radioactive elements together and when released generates heat, such as in the fission bombs used against Hiroshima and Nagasaki. The centre of the Earth is molten because of heat released by radioactivity in the core.

5.1.1 The fourth force and the age of the Earth

As a brief aside, it is this latter force and its radioactive nature that allows us to measure the age of the Earth, and hence the age of the solar system. I've talked about 4.5 billion years often enough so it might be useful for you to gauge how we know this. Radioactivity exists naturally, and those elements that decay (notably uranium and plutonium among a long list) shed part of themselves (protons and neutrons), over known timespans, slowly transmute into elements which are less massive. As an example. an **isotope** of uranium, (the same number of protons and electrons as uranium but with extra neutrons) will decay over billions of years to become lead. Its half-life, the time taken to turn half of the original uranium to lead is 4.46 billion years. We know the rate of decay, and therefore, if we find the proportion of uranium to lead in sample rocks, we can measure the time of decay and hence the age of the Earth. The problem is, we don't know the amount of lead in the original sample before the radioactive process started. A refinement of the method has been to use meteorites containing lead and no uranium to provide the natural abundance of lead. This value can then be used to give a more reliable measure of the age derived from a meteorite containing both lead and uranium. In going to the Moon, it was hoped to find lead and uranium rocks that could be used to corroborate the Earth-based results. Results reported in 1976 involving radiometry (measures of radioactivity) of isotopes of potassium and argon, yielded two ages, one for the lowlands—the large, smooth appearing areas known as the Maria—of 3.2 billion years and the highlands of 4.4 billion years. Recently, a reanalysis of uranium found in the Moon rocks containing zircon, seems to have provided a definitive value of 4.51 billion years for the age of the Moon.

5.2 Hubble's law and the fifth force of Nature?

The fifth force is rooted in the discovery that the universe is not only expanding but that its expansion is accelerating, and there is no known force that can act like that. How do we know this? To answer, we must go back to the observations that gave us the notion of an expanding universe in the first place. Here, I'm referring to the work of Hubble who presented the diagram that now bears his name, the **Hubble diagram** seen in Figure 5-1.

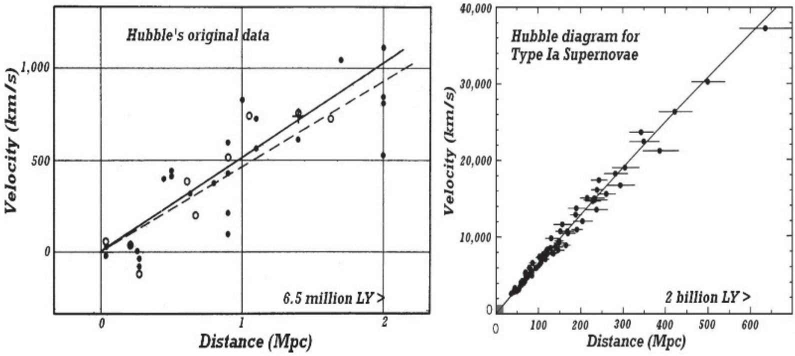

Figure 5-1. Plots of Hubble's Law showing the relation between galaxies recessional velocities and distances, illustrating the expansion of the universe. The left panel is contained within the black square to the bottom left in the right panel! Note that 1 Mpc = 3,260,000 LY, where LY is the distance light travels in one year**.** Credit: Left panel. Hubble, 1929, PNAS, 5, 168. Right panel. Kirshner, 2004, PNAS, 101, 8. Modified by the author.

This diagram shows that a galaxy's distance measured in megaparsecs (millions of **parsecs**) from us is related to its velocity. I'll discuss this distance measure in Section 6.2. Why does this fact reflect an expansion of the universe? Follow this argument with these analogies because an expansion is not obvious from these diagrams. Imagine that our universe is contained on the surface of a balloon that is expanding with time. Put some dots over the partially inflated balloon to represent galaxies. Now blow it up to twice its size. Now, all the dots will have doubled their distances in the time interval you spent blowing it up, the close ones and the far ones. In terms of speed or velocity, it means that the furthest ones have, in that time, travelled over greater distances which means that the most distant galaxies are travelling faster. This is what Hubble found, and what these diagrams show. But importantly, no matter where you sit on the balloon, you will see the same expansion so there is no centre, no place that can be pinpointed as being the origin of this expansion. This origin is in another dimension that may exist mathematically, but we have no concept of it because our world is one of three dimensions.

Now to another analogy for the Hubble expansion concept. You have a loaf of bread with raisins in it. As it rises the raisins get further apart. When it doubles in size. the distance between all the raisins will double, and, just like the balloon, the more distant raisins will appear to have moved faster than the ones close to each other. This is the expansion of the universe implied by the Hubble law shown in Figure 5-1. What has this to do with the age of the universe? Look at the coordinates at the top right in Figure 5-1. A galaxy is moving at 40,000 km/s and is at ~650 Megaparsecs (650 million parsecs); now divide the distance by the velocity and you have the age of the universe which, according to these crude numbers is 14.7 billion years. Note that one parsec is 3.26 light-years (LY), but I will discuss this later in the next Chapter. For the moment, just think of a parsec as some arcane measurement of distance.

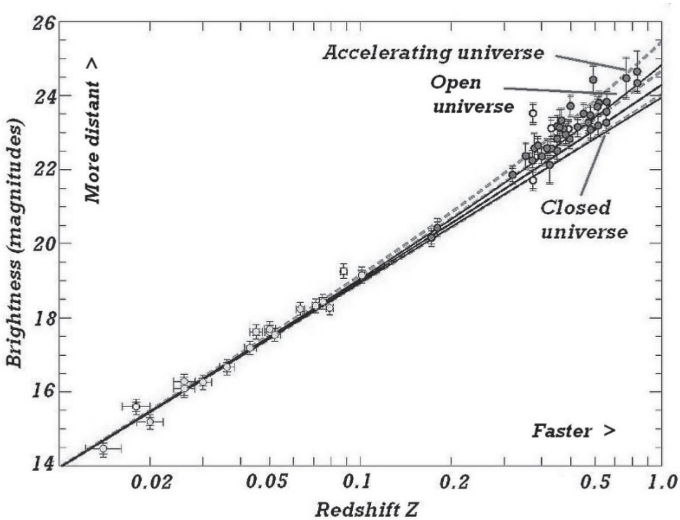

Figure 5-2. Here is shown a more recent Hubble Diagram where the redshift Z is related to the velocity of recession of Type Ia supernovae and the absolute magnitudes of these objects. The upper dashed lines show the cosmology of an expanding universe and the lower line that of a closed universe. A closed universe will ultimately collapse, like a rocket whose escape velocity is not enough to overcome the Earth's gravity. Credit: Hamuy et al., 1996, AJ, 109, 1, and data from the Supernovae Cosmology Project, Perlmutter et al., 1999, ApJ, 517, 565. Modified by the author.

But recent observations, as displayed in Figure 5-2, tell a different story. This graph is confusing because the axes are reversed from the previous figure and the velocities are replaced by a redshift (z), itself a measure of velocity. Also, the distances are replaced by magnitudes, themselves a measure of distance. Nevertheless, this figure boils down to the same thing as Figure 5-1 and shows an expanding universe where the fastest moving galaxies are the most distant. The figure shows a series of straight lines, each representing a model of the universe, whose slope dictates whether the universe goes on forever (an open universe) or whether it ultimately collapses on itself (a closed universe). In the former situation the universe dissipates into infinity and cools off, while the latter, ultimately squishes up under gravity—and then what? But the figure also shows a divergence from these linear relations shown in the upper right corner. A divergence that indicates the velocity of recession is accelerating! The nice linear relation is no more. Currently, there is no known mechanism that could or should accelerate the universe after its expansion (unless mass is still pouring through the original Big Bang plughole at a greater rate than when it started). What's with the acceleration of the universe? Imagine tossing a ball into the air. It comes back to Earth under the force of gravity. But given enough impetus the ball or object would escape the bonds of Earth but it will not accelerate unless some other force comes into play (one of Newton's laws). The same is true of our universe. If it turns out that these results, based on using exploding stars called supernovae as distance markers, survive the scrutiny of time, then we'll indeed have a fifth force to incorporate into what is called a **Grand Unifying Theory**, with the unlikely acronym GUT, relating the four/five forces of Nature. Coming up with a theory that unifies these forces is the Holy Grail of cosmology. What ***is*** out there beyond our concept of space and time, beyond the bounds of the known universe? Back to the story.

One second into the expansion, electrons, protons and neutrons, the commonly known building blocks of our world, started forming out of the radiation when photons collided—remember Einstein postulated that matter and energy are interchangeable (recall the famous equation $E = mc^2$ where E is the energy, m is the mass, and c the velocity of light) and there are many physics experiments that show the formation of fundamental particles out of pure radiation. At this time helium and nuclei close in mass to it, were formed out of the fusion of protons and neutrons in a process called **nucleosynthesis**, but more of this process later. As a result of expansion, the universe cooled, allowing the nuclei to begin capturing the electrons to form stable atoms. At this point the universe began to shift from being radiation dominated—remember matter was forming out of radiation—to matter dominated. Another way of imagining this is to consider oncoming blinding headlights slowly fading to reveal the car. About 380,000 years into the expansion, the universe became transparent, or it became matter dominated—the car was now in clear view. At that time, the temperature of the universe was about 3000 K, about as hot as our hottest furnaces. This is a significant number because we see the remnants of this radiation today!

Over the intervening 14 or so billion years, space has expanded and with it the wavelength of this radiation, its peak slowly shifting to longer and longer wavelengths. Remember the earlier discussion about heated iron bars where the temperature of an object is related to its colour. In this case, with the expansion of the universe and the increasing distance scale, the colour shifted from blinding blue white to red and beyond. Now what once peaked in the IR region of the electromagnetic spectrum now peaks in the microwave region corresponding to a temperature of 2.7 K. The detection of this radiation, called the **cosmic background radiation (CBR**) or the **cosmic microwave background (CMB)**, is one of the greatest observational feats of modern astronomy and its continued study provides us with another tool with which to learn more about why the universe is the way it is. The first satellite that investigated this remnant of the Big Bang was the **Cosmic Background Explorer (COBE)**, superseded by the **Wilkinson Microwave Anisotropy Probe (WMAP)**, a similar satellite, but with much increased resolution and hence with the ability to see more detail than COBE,

Over the next one or two billion years the galaxies condensed out of clumpy distributions of hydrogen and helium. The question of why the universe should be clumpy provides a continual challenge to cosmologists along with the fact that the universe looks very uniform on a large scale wherever we look. WMAP has made some extraordinary discoveries starting with determining the age of the universe to be 13.7 billion years give or take a few hundred thousand years. The value sounds precise but it is model-dependent, that is, it depends on whether the early model of the universe is correct. If the model is seriously questioned then so is this value. Though WMAP could not see the stars, from the data, astronomers inferred that stars formed 200 million years after the Big Bang when filamentary structures crisscrossed pre-galaxy space like a cobweb. The nodes of the web were condensations brought about by gravity which caused the simple gases to slowly compact together. From this material the galaxies formed and in forming so did the stars. We see these wispy filaments in current 3-D maps of the universe based on observations of a million galaxies. As the clumps that ultimately became the galaxies formed, they rotated and flattened into the giant spiral systems we see today. Our Milky Way is such a spiral. The clumps themselves formed larger hierarchies linked by the ubiquitous force of gravity. We see these remnants today as clusters of galaxies—thousands of galaxies bound together and rotating about some common centre at speeds too slow for us to measure. Without this rotation, gravity would have drawn all the clumps together to form one gigantic super-galaxy. When we look around the sky, we see many of these groups. The Milky Way forms a group with the Large and Small Magellanic Clouds (LMC and SMC) seen in the Southern Hemisphere as fuzzy patches in the night sky (remember Figure 1-2). Another member of what is called "**The Local Group**" of galaxies is the Andromeda galaxy (M31)—the most photographed of all the spiral galaxies—and a more difficult object to see in the Northern Hemisphere than the Magellanic Clouds in the southern skies.

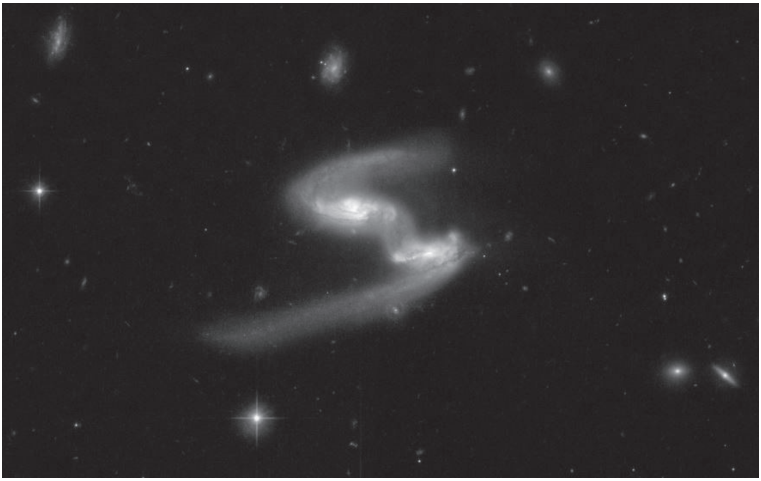

Figure 5-3. Two colliding galaxies. Notice the bridge of newly formed stars linking the two galaxies. Credit: NASA/HST

But when we look at galaxies, we also see ones that are spherical or egg-shaped. These galaxies are called elliptical galaxies and their formation posed many difficult questions until the idea arose that maybe they formed by "mergers" of spiral galaxies. There are magnificent Hubble images showing what can be interpreted as collisions between galaxies (see Figure 5-3). Anyway, if two spirals collide is it possible to form these elliptical galaxies? Can we ever know this? We don't know it by some abstruse deduction but by looking at the possibilities. The fact that galaxies are so much closer together relative to their size than the stars makes collisions much more likely, particularly when they are clustered together in large groups. The probability of two galaxies colliding in a cluster of galaxies is finite whereas it is negligible between stars. Astronomers examine this possibility by simulating a couple of spiral galaxies in a computer, making them collide and then look at the results. Obviously, this really stretches the capacity of any computer because of the large number of simulated stars required. While the simulation is approximate, the results are sufficiently encouraging for us to accept the proposition that mergers of spiral galaxies result in elliptical galaxies. But when we look at a spiral galaxy, we see it is rich in gas but an elliptical has little or none. Where does the gas go? The clue is with the oldest objects in our Milky Way, the globular clusters, which orbit up and down like yo-yos through the galactic plane—the disk where most of the stars and gas reside. These ancient objects, more than 10 billion years old, have no gas in them because they've been swept clean of it through the interaction of their gases with those of the Milky Way. Swept clean of it in the sense that, in their early periodic passages through the gaseous and dusty precincts of the galaxy, the colliding gas triggered "clumpiness" and the inevitable formation of stars. The same story is true when spirals collide. The stellar orbits are all churned up to provide the overall elliptical shape but the gas interacts to form more stars.

5.3 Birth of the Sun

The current age of the universe is about 13-14 billion years. (Having written this, I see a paper, based on measuring the velocities of **microlensed galaxies**, that suggests the universe is 2 billion years younger than what I've just quoted.) Please forgive me for this interpolation but jump forward to the discussion around Figure 7-16 if you need more of a context. In that time, innumerable stars have gone through their life cycles. Some are out in space as dead embers of the process of evolution, while others have exploded, producing different sorts of embers. All these stars have seeded space with gas to provide the raw material from which other stars formed. We'll talk about this now in the context of the Sun's birth.

Our solar system was formed billions of years ago out of a vast cloud of gas, light-years across, containing hydrogen, helium and other elements created when stars exploded (supernovae explosions) or when stars shed their atmospheres (planetary nebulae). As it collapsed, it began to spin since the collapse was not symmetric and any asymmetry results in a rotation. A collapse can only be symmetric if the clouds are perfectly evenly placed about the centre of collapse and this is highly unlikely (think about how easily a rugby scrum starts to rotate). In looking through HST images of gaseous clouds they are anything but spherical. Thus, rotation is a necessary consequence of every collapse. The core of the Sun formed first while the material falling into the Sun was spun outward to form a disk. As it contracted, the central part of the collapsed cloud spun faster and faster for the same reason that a skater spins faster when they move their arms to their side utilizing what is called the conservation of momentum. Therefore, an initial cloud, light-years across, then collapses to form a huge spinning disk only light days across with the Sun at its core. The disk gave the Sun its retinue of planets, their moons and the comets. The same process formed spiral galaxies, only on a gigantic scale.

The story sounds plausible but it still has the same flaw that I read about in Fred Hoyle's book “Frontiers of Astronomy” in the 50s. We see the Sun now spinning at a leisurely rate of 2 km/s when, after a collapse, it should be spinning at 1000 km/s! Somehow the Sun's rotation was braked or slowed down, most likely by the magnetic field now associated with the Sun and some sort of braking of the Sun by the planets themselves. I’m not going any further on this. In looking through the papers on the Sun’s interior I became aware of how huge its study is. Enter “solar rotation” on your web browser and look over the material that is presented. I’m shaking my head in wonderment that we can learn so much about places we’ll never see.

While we have theorised about how the solar system formed, astronomers are now able to get telescope snapshots of the birthing process! The **Atacama Large Millimetre/submillimetre Array (ALMA)** is now resolving—literally seeing—disks around nearby stars validating our view of how the solar system formed (Figure 5-4).

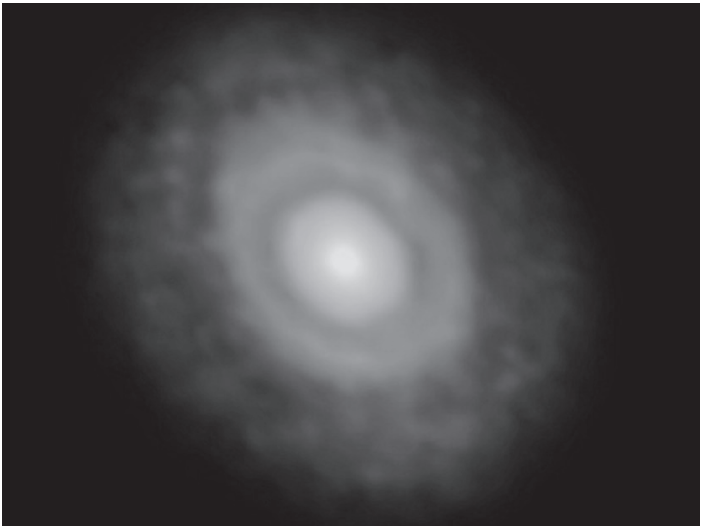

Figure 5-4. Showing the protoplanetary disc surrounding the young star HL Tauri. These new ALMA observations reveal substructures within the disc that have never been seen before and even show the possible positions of planets forming in the dark patches within the system. Credit: ALMA (ESO/**NAOJ/NRAO**).

The large solid bodies in our solar system were originally subject to an unbelievable barrage of impacting space debris. Over the eons, in their march around the Sun, most of the material has been swept up. Look closely at all the moons and asteroids—the band of rocks between Mars and Jupiter—and you get a clue as to where the remnants of our birthing placenta have disappeared. Whether we look at the surface of our Moon, or the planet Mercury or the asteroids—Eros is typical with dimension 33 × 13 × 13 km—you see impact craters. Alternatively, look at Figure 3-3 where the asteroid Ida shows impact craters. The sweeping up continues. We saw a graphic example of that when the planet Jupiter gobbled up Comet Shoemaker-Levy in 1994. Now we are concerned about a potential comet strike on Earth that could snuff out human existence just as the dinosaurs were wiped out. Because of this concern, and the ready availability of excellent digital detectors, many searches are taking place for what are called **Earth-crossing asteroids**. Out of this work has come the detection of two large objects almost as massive as Pluto, leading again to the debate as to whether Pluto, which has a rather strange orbit anyway, should ***ever*** have been classified as a planet.

5.4 Sources of solar energy generation

The source of the Sun's power is a consequence of gravity squishing and compacting matter in the solar interior. In the 1840s, initial ideas of the source of the Sun's heat involved infalling comets and other debris left after the formation of the solar system. While this theory might seem bizarre today, it is no less strange than what the New Physics is hypothesising about the nature of our physical world. Talk of "dark energy" bubbling into space that provides the force driving the expansion of the universe even faster. Brane theory, describing a universe of 10 or more dimensions of which our three-dimensional world is but a part. Black holes are routinely accepted as existing in the central cores of galaxies. The strong anthropic principle (SAP) that says the universe is here because if it were different there would be nobody here to observe it. Barrow and Tipler give their version of Brandan Carter's SAP assertion:

> "The Universe (and hence the fundamental parameters on which it depends) must have those properties which allow life to develop within it at some stage of its history."

Barrow and Tipler then state that that the SAP implies, "The constants and laws of Nature must be such that life can exist." This is fascinating stuff—read their book, "The Anthropic Cosmological Principle". And so, the ideas about the universe go on… Parallel universes and our lives being made up of an infinity of choices to move from one universe to another are no more bizarre than fuelling the Sun by cometary accumulation.

In 1854 Helmholtz (1821-1894) proposed the mechanism that operates in every star; that the energy source could be caused by compressive heating of the Sun as it slowly shrank under the relentless force of gravity. In terms of physics, what is happening is that the potential energy of a large cloud is converted into kinetic energy. This is the identical situation that arises when we sit stationary at the top of a hill on our bike and then, as we go down the hill, we gain speed. We are converting the potential energy due to our original position into motion. Motion, as pertaining to the material inside the gas cloud, is heat. Remember, heat is motion. Because of this, the cloud that collapses gains heat because the potential energy can't be lost but is transformed into another form. Helmholtz's work built on that of Laplace (1749-1827) who in 1796 suggested that the Sun and its retinue of planets were originally formed from a gigantic cloud of gas that collapsed under its own gravity. Seems like he got it right. Compressive heating is what we experience when we pump up a bicycle tire. After a while, the pump gets hot at the bottom where you hold it. Though, in the Sun's case, the compression is produced by gravity and not by muscle-power! This is gas responding in a way we are familiar with. You heat the gas and the increased pressure expands it. Increase the pressure and the gas heats. Cool it and the pressure reduces. Most of the time this process works in the stars but there are exceptions and the exceptions are what will happen to our Sun one day when it takes on a bizarre form of matter (more of this later). The theory of compressive heating is jointly named after the English physicist Lord Kelvin (1824-1907), the man who gave us the temperature scale with respect to absolute zero.

Kelvin's contribution was to put a time scale on the duration of compressive energy generated in the Sun in this way. His calculations yielded an age for the Sun of about 20 million years, in conflict with the age of the Earth determined from the geologic record based on the measurement of radioactive decay in rocks which, at the time, indicated ages of about 2 billion years, numbers not even close to the derived collapse times. Obviously, another (unknown) source of energy was involved. This created a huge problem because physics at the time—circa 1900—had no answer. But while these men did not discover the source of energy powering the Sun, they got much of it right for the role of collapse, compression and heating is fundamental to the evolution of stars. Without compressive heating we will not have the range of evolution we see in the stars, for gravity is the source of energy that a star needs to evolve as it transmutes the elements within. Without this fundamental way of generating energy we do not exist.

The situation regarding the age of the Sun then, was much the same as a recent determination of the expansion age of the universe being younger than the ages of the stars within it! And, as I commented earlier, the universe could be 2 billion years younger than currently thought. Maybe this problem could arise again. These delicious contradictory moments are what makes a science really grow! You might wonder how such a ridiculous situation could arise. In the advancement of science, a lot of important research is often not done, or deemed relevant or "sexy" enough, and occasionally the omissions come back to bite you. But to be fair, knowledge is expanding exponentially and a finite number of astronomers and physicists vying for limited jobs and funding cannot keep pace. Those seeking the jobs need a CV showing that they are at the forefront, or "cutting edge" of their discipline, which inevitably leads to imbalances in our knowledge. Choices must be made, and one's economic well-being is an obvious consideration and results at times as shortfalls in our science.

Returning to the Sun. It was clear that the stars had to be powered by some unknown energy source. Einstein and the associated rich growth of the then new physics was still on the horizon. At this time, circa 1900, radioactivity had been discovered and scientists were aware of the energy released by what we now call the weak nuclear force. They also suspected that perhaps some unknown subatomic energy source might be involved. The main choices were a radioactive process involving the breaking ***down*** of heavy elements such as uranium, or the building ***up*** of the elements in some unknown way. The former was favoured because radioactivity was known and the other hypothesis was simply a wild speculation. But often what is wild for one generation is normal for the next. Calculations were made of how much uranium was needed inside the Sun to produce the energy we feel and see as heat and light. Eddington, Britain's leading astrophysicist at the time, and incidentally, the person who undertook to verify Einstein's prediction that space would be deformed in the presence of the Sun, made the comment that if the Sun was totally comprised of uranium, the heat released by its decay would only produce half of the Sun's observed energy output. Therefore, the scientists were forced to look at a subatomic process that could involve energy release.

In 1905, Einstein developed the special theory of relativity. One of the implications of his theory was that matter and energy are interchangeable (remember $E = mc^2$). Because c is huge (300,000 km/s), a small amount of mass can beget huge energies. Soon astronomers realised that this conversion might be energising the Sun, and that the energy could result from building atomic species from simple to complex and not tearing them down via the process of radioactivity. The suggestion that the stars could be powered in this way was made in 1920 when it was theorized that the creation of helium from hydrogen just might be the process. ***How*** it could happen was another question! A hydrogen atom is made up of a single proton and a single orbiting electron, while a helium atom is made up of a nucleus containing two protons, two neutrons and two orbiting electrons. The atoms are made of combinations of protons, the positively charged nucleus of the hydrogen atom, neutrons, particles neutral in charge but similar in mass to the proton, and electrons, negatively charged particles about 1840 times less massive than a proton. It was hypothesized that four protons might go through a process that creates a helium nucleus with a little mass left over. Calculations showed that the mass differential (four protons minus two protons and two neutrons) produces enough energy to power the Sun at the rate observed. This was great, the numbers were right, though the process unknown. Eddington said that even though the method of forming helium from hydrogen was unknown, the fact that helium had been discovered in the Sun favoured the hypothesis. I see his point. Trying to explain a new source of energy production where the product—helium—had not been detected would have been a hard sell.

But guessing the energy source is not the same as knowing it for sure and there was still a long way to go to verify the suggestion, even though the numbers worked out. "Working out" the numbers are often done by what we term "back-of-the-envelope-calculations"—another way of saying approximate calculations. The process is straightforward. Get the idea, make it as simple as possible by a few "reasonable" assumptions and do some calculations. If the idea hangs together then you can embark on a fuller line of inquiry. I've seen my colleagues, sitting in a pub, justify an idea for an observing project based on a piece of paper, a pencil, a jug of beer and a pizza!

To verify the transmutation hypothesis, the following conditions needed to be met. The temperature had to be hot enough and the pressure sufficient to force the protons past the resistance of the positive charge that formed the barrier to transmutation (the third force of nature). Try pushing the positive ends of two bar magnets together. Finally, there would need to be enough fuel in the form of hydrogen to sustain the Sun over the billions of years indicated by the geologic record. Once these conditions were met, then the

Sun could be modelled so that temperatures, densities, and pressures in the Sun's core could be found and energy output calculated. The most important question to answer was, "How extreme ***are*** the temperatures in the solar interior?" In the time since Eddington modelled the Sun and other more massive stars, several clever methods have been derived to yield approximate estimates of the solar central temperature and pressure. They are very crude methods but, surprisingly, they all give values reasonably close to what more sophisticated modelling produces. I will outline one method here involving the notion of heat in its fundamental form and the escape velocity. Heat is motion, the faster the particles move the hotter the object is. Consider a pot of water that is heated. As the water is heated, the molecules of water move faster and faster until some move so fast until they escape from the water. We see these molecules as steam. Think of us here on Earth. We jump up in the air but the force of gravity pulls us back. Now we know that if we could jump fast enough, we would be freed from the bonds of Earth. Rockets going to the Moon or taking payloads to Mars must get free of the Earth's gravitational field. So, there ***is*** a velocity that will provide an escape. Intuitively you will recognize that the escape velocity depends on two things, how massive is the Earth and how far from the centre of the Earth you are. Given the formulas that describe motion in terms of temperature, and escape velocity as a function of distance and mass, we can equate these two things and do the calculation for the Sun. We equate the Sun's internal heat to the velocity of escape and see what temperature that yields. Using values for the Sun's mass and radius and assuming that the Sun is only made of hydrogen, we find a central temperature of 15 million degrees! Eddington's value of about 10 million degrees, while low by modern calculations, was sufficiently high to support the notion that the Sun's internal energy ***was*** fuelled by fusion.

It was not until 1938 that two physicists, Bethe in the USA. and Weizsacker in Germany, discovered a series of nuclear reactions dependent on temperature and pressure that turned hydrogen into helium. Given that reaction, and the energy resulting from it, model building could begin—not that there were computers around to do it! The Sun gains its energy by converting hydrogen to helium at the rate of four million tonnes (4×10^6 kg) of hydrogen/second. In case the magnitude of this number gets you nervous, remember that the Sun's mass is 2×10^{30} kg! Considering the present age of the Sun, it contains enough matter to burn like this for about another 5 billion years! Remember, it is already 4.5 billion years old! Looking at it differently, if 1 kg of hydrogen makes helium then there is 0.007 kg left over. Converting this mass to energy via $E = mc^2$ generates an energy equivalent to burning 30,000 tonnes of anthracite coal per second! With this sort of energy release, you can see why fusion research is important because the ultimate payoff is an unlimited supply of fuel with ample energy to serve mankind forever, or until an evolving Sun gobbles up our beloved Earth.

Once this nuclear reaction, termed the **Carbon-Nitrogen-Oxygen (CNO) cycle**, was discovered, then the study of astrophysics took a huge leap forward. Ironically, it was not this reaction that powers the Sun for the CNO cycle only works efficiently at temperatures higher than are found in the Sun's core (see Figure 5-5). Later a process called the **proton-proton chain**

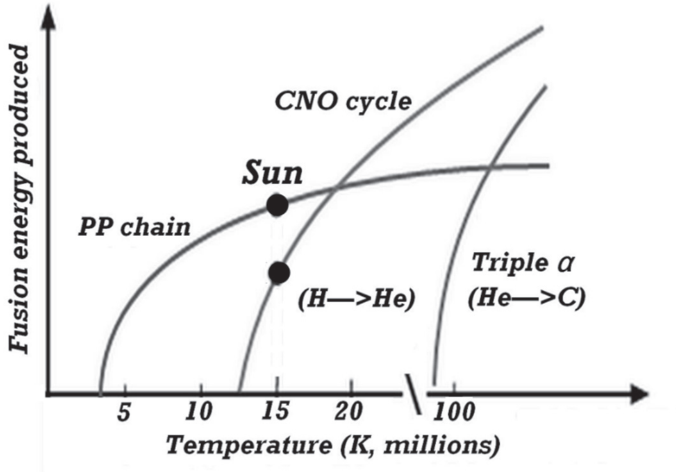

Figure 5-5. This graph shows the relative energy output for the proton-proton (PP), the carbon-nitrogen-oxygen (CNO) and triple-α fusion processes at different temperatures. At the Sun's core temperature (15 million K), the PP process is more efficient. Credit: Wikimedia Creative Commons/Xenoforme. Modified by the author.

was found which is the principal power source in the Sun. With the mechanism known, it was then possible to begin to understand how stars might evolve by building up the nuclear species found in the **periodic table**. The periodic table is a two-way tabulation of all the atoms according to ascending mass and arranged so atoms of similar chemical properties are in the same column (just accept this!). Given the possibility that the elements we see on Earth, iron, lead, gold, calcium, sodium, chlorine, etc. might be produced in the stars. Are they? Even after all this progress, the question remained as to whether the elements were built up during the Big Bang or whether they were subsequently built up in the stars—or some combination of the two. Now it is accepted that the elements produced by the Big Bang are almost solely hydrogen and helium by mass in the percentages 75 to 25, with traces of deuterium (heavy hydrogen) and lithium. Given the initial mix of hydrogen and helium from the Big Bang or Calvin's **Horrendous Space Kablooie**, it turns out that almost all the remaining elements are built up in the stars, In fact, the whole theory of the Big Bang hinges on the percentage of helium found in the stars. If a star is found with less helium than the above percentage, the Big Bang theory has a major, perhaps fatal, problem!

5.5 The need for mathematical modelling: Modelling the Sun

Where do we go from here? We've weighted and measured the size of the Sun and have an initial idea of the processes we find within it. We know it is very old but have no idea how its planetary system was created. In terms of the Sun's interior we know—or guess—that the core is very hot, hot enough we think to transmute hydrogen into helium but we have no idea how to calculate the rate because we don't know how the process works—and won't until 1939. But we're inching towards getting started. The Sun is remote from us and we cannot make experiments involving it. All we can do is try to represent it in some mathematical way. We need to model the Sun. That is what Helmholtz and Kelvin did when they tried to estimate the age of the Sun by assuming it generated its internal energy by squishing up under gravity. Now, with the suggestion that the (unknown) process of converting helium from hydrogen could power the Sun over billions of years, another step was taken in its understanding; this part of the puzzle should be incorporated into the mathematical calculations. Eddington came a long way in building models of the Sun and other stars but they were based on inadequate physics, There was an hiatus it seemed, from what was started in the 20s by Eddington, to the what was begun in the fifties by the Princeton astronomer Martin Schwarzschild (1912-1997). To this point, little was known about building a model of the Sun that might represent what was observed in terms of total brightness and size. Schwarzschild's book, "The structure and evolution of the stars", published in 1958, changed all that; it became our bible. So how does this model building work?

To generate a model star—in our case the Sum—there are four equations that need to be solved. These equations describe how mass varies throughout the star, how pressure and luminosity vary and the temperature gradient. Associated with these basic parameters are the databases or formulae that enable us to calculate the energy produced in the core by the transmutation process and how energy is transported and hindered in its flow throughout the model. The interlinking of these equations is required to create a model star that is in equilibrium, i.e. not collapsing, with a resulting luminosity (or radius) and a surface temperature. If we can match these values against those observed for the Sun then we can say we've been successful. We start the calculations only knowing the abundance of the elements in the Sun and its observed mass (M), temperature ($\mathbf{T_e}$) and luminosity (L) and make the calculations. There are a few approximations at the solar surface to get us going. After that we won't know how successful we are until we have finished the model building process. The calculations proceed with the aid of auxiliary tabulated values of quantities dependent on those variables needed in the calculations; e.g. the way that photons or energy moves through the stellar interior (**opacity**), the rate of energy production through nuclear fusion and the transmutation rates that turn hydrogen to helium, helium carbon and so on. We used logarithmic tables for multiplication and division, maybe a slide rule—mine is in my desk, a venerable 70 years old—and interpolated or calculated the values of opacity, etc. between the values taken from published tables of opacity and nuclear energy generation given as a function of temperature and density. It was laborious, and, like much of astronomy, the effort to get a result is huge. The fact that what Schwarzchild (and many grad students like me) did was labour intensive didn't change much when computers were introduced to replace the hand calculation process. The labour involved, has simply been moved to a different place. Now, you spend more time in improving the physics, or graphic output to make more sense of the results. It's like getting twice the disk storage on your computer, you simply fill it up. Or getting an increase in salary, it evaporates as fast as it did before. Starting with a guess as to temperature of the outside of the star and its luminosity in solar values (for the Sun it would be a temperature of 5770 K and a luminosity of one), this assumption kicks off the whole modelling process. Given these values we start by solving these equations. I'm not going to delve into the fussy nuances that get it started. Then we start stepping in towards the centre of the star making fractional changes to the radius using the equations to get new values of density, mass etc. at each point until we reach the centre of the star. Now, with this process, we're like the navigator that overshoots or undershoots their target. If we reach the centre with mass left over or the radius has a way to go before reaching zero, then we have failed, but we have the luxury of changing our starting values (T_e or L) and doing it again.

Not that we are thrilled in repeating the awful labour. Finally, when the star runs out of mass and radius to some small limit near the centre of the model then the process has been successful. In the end, the calculations predict T_e and *L*. Do they agree with the solar values? If yes, then the process has been successful, but life is not like that. But back to this later. What we did by hand illustrates the way that models are generated and, when later transferred to a computer, initiated the whole study of stellar evolution.

There are a lot of questions about these calculations and ones to come involving evolving our models. What about the passage of energy through the star? How readily does this energy flow? And what about the surface? We know that the Sun's surface is quite complex—photosphere, chromosphere, and corona. How do we approximate these parts of the atmosphere, or do we ignore the latter two—and we do—for distant stars whose surfaces we'll never see? How do you know when convection is relevant? What physics needs to go into the modelling process that will allow us to evolve a star? What are the effects of rotation on the evolution of a star? What happens in binary systems? Even if we can make the calculations, how can we test the results? And how do we do these calculations? What math do we use? Can you use the physics mathematically in a way that is digestible to the software? Said differently, do you know ***how*** to model the stellar interior? If the data are given in tabular form can you adequately find intermediate values you'll need in the calculation? This is called **interpolation**. (My software only came to life for me when I adapted a wonderful interpolation program from the US Airforce Research Laboratory.) Are you familiar with all the numerical techniques required to solve the equations involved? It is all quite a job!

Energy may be transported from the centre to the surface in three ways, conduction, radiation and convection. We're familiar with all three processes. Touch an iron as it is heating up and you detect heat by conduction. Hold your hand close to it and you feel radiation in the form of heat, or alternatively, put your hand close to a block of ice and feel the cold. Watch water boil in a pot and you witness convection. Conduction is only effective in solids where the atoms are packed together and motion (or heat) is easily transmitted between the atoms. In a normal gas the atoms are too far apart for this process to be effective, though in the centre of stars where the matter is packed extremely tightly—many times the density of gold—conduction is a very effective way to transmit heat. Convection plays a huge role in stars, both in transporting energy from the centre of hot stars outward and in the atmosphere of cool stars. We see convection at work in the Sun's atmosphere where convective cells are rising and falling (Figure 4-3) so we know that convection must constrain our model Sun and, as we build it, the outer parts must show up as a convective region. There are no definitive workable theories for convection in the interior of stars—I may be wrong here—a situation that renders all models suspect because, no matter how incomplete a model might be, it is generally possible to fudge the convective model you have adopted to fit the data, i.e. the observables T_e or L. Radiation flows outward in regions where convection is not a factor. Here the high-energy photons interact with each other, losing energy through absorption where an atom "captures" an electron and scattering where an atom absorbs a photon and immediately re-emits it, or in its passage near an electron, a photon changes direction. Scattering is a common phenomenon in our normal experience. You are travelling at night on a dusty road into the lights of an oncoming car. The lights don't look like point sources; they produce a bloom of light. This is scattering. The sky is blue because UV and blue light are scattered by the atoms and molecules in our atmosphere more than yellow or red light. You may run into trouble at the beach getting burned by UV light even if you are under an umbrella since the blue sky is radiating UV light that you can't see. This interaction, the hindering of radiation flow, is called opacity that I mentioned briefly earlier. For us it would be like walking down a crowed street being jostled and continually trying to avoid people but slowly reaching your goal. In a less crowded street you make faster progress. Starting at the Sun's core, a photon may only move a centimetre before interacting with matter and may take hundreds of thousands of years to reach the surface from the core.

Now, the stars are formed of elements created during the formation of the universe and added to by "enriched" products stemming from the life and death of innumerable stars since that beginning. Remember that the universe is old enough for myriads of stars to have lived and died, and in their dying they've cast their parts into the vastness of space. Some stars live for barely a million years—they are the profligates—and others for 10-15 billion years. It is from these stellar remnants that new stars and accompanying planetary systems are formed, as well as our flesh and bone. As outlined above, for a given mass and chemical composition, we can model a star that predicts a given luminosity (or radius) and surface temperature. For different values of chemical composition, the model will produce different values of luminosity and surface temperature, some of which we hope will match the solar values. The variations involved in making these calculations appear to be never-ending, and the literature is replete with yet another set of stellar models with differing physics, abundances, and convective theories hard on the heels of an earlier version.

In our Sun, the inner core is where the nuclear transmutation takes place and this energy is carried outward by radiation. At a boundary above the radiative region lies the convective zone where energy is transported upwards in bubbles because the matter is overwhelmed by the heat rising from below—the bottom of our saucepan is really hot! We view this convection when we look at the surface of the Sun and see the bubbles rising and falling back into the Sun's interior and measure their velocities of ascent and descent. But not all stars have "bubbly" surfaces. In the outer parts of hot stars, >10,000 K (> means greater) energy is moved by radiation and in contrast to the Sun, it is in the core of these stars in which convection takes place. Under these conditions, the CNO cycle is so vigorous in producing energy that it cannot be transported by radiation alone but needs the physical movement of gas bubbling outward. As the effectiveness of convection wanes then radiation takes over. This energy flows outward through cooler and cooler layers of the star until it reaches the surface and escapes into space. Just enough energy is released to support the material pressing inward. The whole structure is in equilibrium, like a bridge on its foundations. Jumping ahead a bit, the reason stars explode (and thankfully they do otherwise we wouldn't be here!) is that the interior sources of energy are suddenly exhausted, resulting in a catastrophic collapse and reactive explosion that annihilates the star, seeding interstellar space with the newly created heavy elements upon which our existence depends.

As an example of what might results from a modelled Sun look at the graphic in Table 5.1. Here, we see how the temperature, density and pressure vary from the centre of the Sun to the atmosphere whose temperature we think we know. When you have determined this, then the model predicts a central temperature that we can never directly observe and a size, luminosity and temperature that ***can*** be compared with what we observe. When the theoretical results don't gibe with the observations, then you must think about the physics underlying the model. And if the results do gibe, then chances are you don't look further into the problem because you might have just gotten lucky! For example, we look at the surface of the Sun and see the convective cells about 1500 km in diameter. Does our model predict the size of these convective cells or do we ignore any differences in favour of the larger picture? Trying to physically model the process of convection as envisaged in the stars has been a seventy-year project. Because of the uncertainty in modelling convection, we find that trying to match the size of our closest stellar neighbour to our model Sun is not a simple task. One can "fiddle this" and "fiddle that" to get a match but there still might be another effect that needs to be considered. In trying to get to the heart of the matter to do it correctly, we must continually look at every possibility even though we think we have come up with the answer.

Table 5.1. The run of temperature, density, and mass as a function of radius in the solar interior

Radius	Mass (Fractional)	Temperature (K)	Density (water =1)
1.0	1	5,800	0.0
0.9	0.998	600,000	0.0
0.8	0.99	1,400,000	0.1
0.7	0.97	2,300,000	0.2
0.6	0.94	3,100,000	0.6
0.5	0.89	4,000,000	1.3
0.4	0.79	5,100,000	3.9
0.3	0.61	6,800,000	12.0
0.2	0.33	9,400,000	35.0
0.1	0.08	13,100,000	87.0
0.0	0.00	15,700,000	154.0

We cannot see into the Sun, but we can get a peek, just like the geologists get a peek into the Earth by monitoring earthquakes or even nuclear explosions that cause vibrations to permeate the Earth's interior. The information detected by the many seismic stations can then be integrated into what we think is the structure within the Earth. This is not a whole lot different than trying to fathom what is going on in a person's mind when all you have is their facial expressions and a few well-chosen words to go on. We need somehow to see inside this beautiful orb, but before these solar observations can be successfully incorporated into a model, they must be understood and a robust physical theory applied to the model. Inevitably, observations stretch the theoreticians who are continually challenged to treat these complications.

Now that we’ve had a look close to home it is time to go further out into the cosmos to look at other stars and see what knowledge we might glean about them. First, we need to measure their distances and sizes and weigh them according to some variant of Newton’s laws. Given these data, we want to transfer what we know about the Sun to the larger stellar family in the hope of learning more about their evolution. The transition is not easy for our Sun is hugely bright and the stars are only seen at night as dim points of light. Measuring the distance to the Sun proved difficult and stars are at almost unimaginable distances from us so we cannot expect an easy ride. What we have learned about these objects over the last 200 years has come slowly, but now, with the advent of very efficient detectors, fast and numerous computers, giant telescopes and adaptive optics we are learning more than my generation might ever have dreamed possible. It is an exciting time for stellar astronomers with the HST orbiting above—though always under a budgetary death sentence—just as it is for those who are using giant Earth-based telescopes to uncover secrets unattainable and unimaginable but a few short years ago.

Chapter 6

What's out there? First glimmerings

6.1 Double or binary stars

In the late 1700s, one of the greatest of all observational astronomers, William Herschel (1738-1822) and his sister Caroline (1750-1848), started observing stars that are close together in the sky, with the object of measuring the star's distance or parallax. Their thinking was straightforward recognising that if one star was in the foreground and another in the background, they could measure a parallax by measuring the small angular shifts between the stars as the Earth swung around the Sun. The effect was too small to detect with their telescope, but just as importantly they discovered the positions between these close pairs of stars were changing, but not as you'd expect if the motion was related to a reflex of the Earth's orbital motion. In some cases, one star moved away from the other across the sky in a linear fashion, but not by large amounts. They'd discovered what we call proper motion, the angular motion of stars across the sky. The second thing they discovered is ***central*** to the advancement of the science. The stars were moving in arcs indicating that they were revolving ***around*** each other (see Figure 6-1). This observation meant that the stars ***had*** to be gravitationally bound to each other as the Moon is to the Earth and the Earth to the Sun. Herschel and his sister had discovered binary stars or **visual double stars**. With this discovery, astronomers had the opportunity to weigh the stars in the same way that the Sun could be weighed by the passage of the planets around it, provided, ironically, the distances (or parallaxes)—the very thing they were trying to measure—to these double stars could be measured. As an aside I'll comment on the fact that Herschel's results were based on the observations made by brother and sister and I wonder if more credit should be given to Caroline as her observations were of critical importance to her brother's conclusions regarding the nature of these stellar motions.

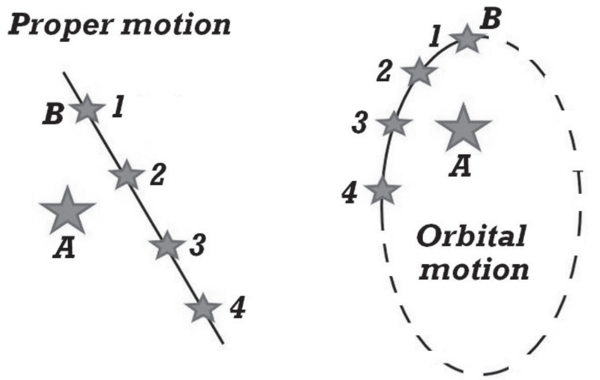

Figure 6-1. The images demonstrate the two sets of motion that Herschel discovered when he and his sister attempted to detect stellar parallax. On the left, a star marked B changes position in a linear fashion (1 to 2… etc) in what we call proper motion. On the right, the star B exhibits orbital motion, that is, star B is orbiting star A just as A is orbiting B. The dashed part indicates its possible orbit over a much longer period. Credit: Redrawn from Discovery of the Universe. de Vaucouleurs, 1956.

With the discovery that stars revolved around each other, and that it was possible to observe their orbits, nineteenth century astronomy took a huge leap forward. Beautifully made refracting telescopes were erected at many universities and the domes containing them can be seen today on many Midwestern campuses. I had my first teaching experience with one of these beautiful telescopes at the U of Minnesota, literally days after arriving in Minneapolis fresh off the boat from New Zealand. I'd been tossed into the deep end. It was a real challenge as I'd never seen a large refracting telescope. On top of that, I was looking at a sky I didn't know, and what I could recognise was upside-down! The refractors played a huge role in providing precious orbital data on many double stars, later put to good use by Eddington. A good example of how quickly double star observing started after the startling results of the Herschel's, is by looking ahead at Figure 6-3. There you see in the left panel a few times of observation that extend back to about 1830. But more than that, the availability of such unanticipated data for many binary stars made the experts in celestial mechanics (how Newton's laws govern stellar and planetary motions) look at Newton's work and apply it in order to derive the masses of the component stars in well-observed systems. This exercise is non-trivial as I discovered in Minnesota as a rookie grad student. Not only were the equations complex but there was the necessity to "massage" the data so the noisy observations conformed to

Kepler's laws. Only then could you "solve" the equations and go forward to determine the individual masses and the binary's orbital inclination. (This is all coming back to me.) The observations of visual binaries became the dominant 1800s observing programs. Each telescope was equipped with a small instrument (called a filar micrometer) with which to measure the positions (angles and distances) of double stars with respect to each other. The changes in position were small and the orbital periods, the time to complete one revolution, were mostly measured in decades. Thus, the astronomer who worked in cold and solitude to make a measurement of the angle and separation between two stars, only ever seen dancing around under high magnification in the eyepiece of the instrument, would generally never live to see the fruits of their labour. Those of you who have looked through a telescope at a binary star will immediately recognize the difficulty of making such a measurement. But despite the difficulties, many orbits were completed and, after wading through the extensive mathematics of the reductions and the delicate treatment of the noisy data, the first determinations of the masses of stars were made. Check Figure 6-3 later, to get a good idea of the quality of these visual data. These masses then allowed astronomers to get a feel about how the Sun fitted into the larger universe seen then like a blurry picture.

6.2 Measuring the distance to the stars: The elusive parallax

In 1838 Bessell (1784-1846), using the Earth's orbit as the baseline, successfully triangulated the distance to a star called 61 Cygni A (Figure 6-2 shows the principle). Almost simultaneously, two other astronomers measured distances to Vega, a bright star in the northern summer sky that has long been the subject of my own research, and Alpha Centauri, the brightest star in the pointer to the Southern Cross. A faint companion to Alpha Centauri called Proxima Centauri is our closest stellar neighbour, excluding the Sun of course, with a parallax of 0.772 arcsec. This success followed on the triangulation of the Moon from Berlin and Capetown in 1753, and of Venus, and hence the Sun, in 1769. In this way the first steps towards determining the distance scale of the universe were taken.

But let's revisit an arcsecond. How can one picture it? As usual with astronomical numbers they are either too large or too small to comprehend. This is my best shot. Imagine having a metre or yard rule with an infinitely stretchable rubber band attached at each end. Now pull the rubber band further and further away until you are at ~206,000 metres (actually 206265 m) away or 206 km. The angle between the two strands of rubber is one

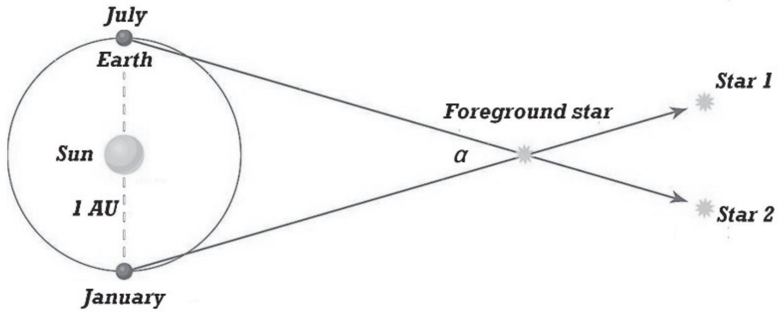

Figure 6-2. Showing how the Earth's motion produces a change in a nearby star's position with respect to a distant background of stars. The motion of a star against the background is called the parallax (angle α/2 arcseconds). Check the position of the Sun and the foreground star from the Earth. In January the Sun will be rising as the star is observed and in July the Sun will be setting, therefore astronomers engaged in parallax work are very active just as the Sun goes down and at sunrise when eyes are bleary and a bed looks very comforting. In interpreting the figure, we are looking down on the solar system and the Earth is rotating and revolving around the Sun anti-clockwise. Credit: By the author.

arcsecond, larger than the angle Bessell first measured. Prior to the space telescope, Gaia, the best accuracy attained for an angular measure was about 1 **milliarcseconds (mas)** or 0.001 **arcseconds**. But now, ESA's Gaia spacecraft. can measure angles down to 7 microarcseconds (0.000007 arcseconds!). This is a ***very*** small number, equivalent to the diameter of a human hair in Chicago as measured in NYC. With such accuracies, the distances measured by Gaia extend as far as the centre of the Milky Way!

Because of the incredibly small angles involved (remember the dime seen at ~3.5 km) we measure stellar distances in terms of the distance a star would have if its parallax were 1 arcsecond, just as we measure relative stellar diameters and masses in terms of the Sun, or we measure an aircraft's speed in terms of the speed of sound, Mach 1, Mach 2 etc. A star with a parallax of 1 arcsecond would be at 206265 AU or 3×10^{13} km, or a **parsec (pc)**, and a star with a parallax of 0.5 arcsecond is at 2 pc (distance = 1/parallax pc or 1/0.5 pc) twice that distance. Proxima Centauri, with a parallax of 0.772 arcsec is at a distance $3 \times 10^{13}/0.772$ km or 4×10^{13} km.

Because the numbers are so huge, with the use of parsecs, we have abandoned using kms to describe stellar distances. Our basic unit of distance is a parsec, the distance to a star when its parallax is one arcsecond. All distances are measured in terms of the parsec though in presenting our results to the public we use the light-year (LY)—the distance light travels in one year—because it has an obvious meaning. "Well, how far ***does*** light travel in one year?" If you do the arithmetic, knowing that light travels at 300,000 km/s, you'll find that a light-year corresponds to about 10 trillion km, or 3.26 pcs, and the nearest star, Proxima Centauri, is at 4.25 LY! As a contrast, the Sun is 8.3 light minutes away. Think about distances some more. The current best estimate of the age of the universe is 13.7 billion years and therefore a distance of 13.7 billion LYs, corresponding to a hundred and thirty billion trillion km (1.3×10^{23} km!!).

In looking at these numbers, we immediately get an emphatic notion of how isolated we are in the universe, even though we look up at the night sky from a place in the country and see the Milky Way as a band of stars seeming so close together that they appear as a white glow. The distances between those stars are like those around us. Space is empty. The distances to the stars are vast in terms of the speeds we need to get to them and begin exploration. Even if we could travel at the speed of light, which we can't, the nearest stars will take tens of light-years travel time. Exploring the reaches of space is daunting, but one day the peoples of Earth will take a one-way trek into the vastness of space to avoid the inevitable fate brought on by a maturing Sun (read Arthur C. Clarke). The distances, vast as they are, ***will*** have to be traversed.

Soon after Bessell determined the first parallax, the first astronomical photograph, a daguerreotype of the solar disc, was taken in 1850. Then, when the dry gelatine plate was invented in 1870, astronomers had a wonderful tool with which to explore the universe since they had a means of keeping a permanent record of what the telescope could see. Programs of measuring parallaxes and proper motion from photographic plates were begun late in the nineteenth century and continue to this day though digital detectors have largely supplanted the photograph.

6.3 A sidebar: The development of mathematical analysis

Behind all these discussions is the mathematics. Only with the development of increasingly clever ways to make the theories more tractable could we have ever come to the point where we could determine the parallaxes of stars from the measurements. Perhaps an example from the past, including my own I may add, will suffice. To measure a parallax, we take a series of photographs over the course of a few years in the hope of detecting the wobble of the star and its general movement across the sky we call proper motion. There are many effects we must consider. We take our photographs at different times, sometimes at sunset and others at sunrise six months apart. Maybe the temperatures are different—undoubtedly, they are—which means the focal length of the telescope is different each time. Think of your camera and the need to focus it anew each time you use it. Because of the change of focal length, the images of the background stars don't exactly match. You've cut the glass plate in the dark with a diamond cutter so each plate fits differently in the **plate holder**. Because of this, each plate is a little bit different also. Maybe the camera has been taken off the telescope and is not back in the original position so when you take an image it is slightly cocked with respect to the others. Right now, you must deal with four complications: the parallax, the proper motion, the change of focal length (the plate scale), and the various rotations of the photographs, but to find the motion of the star the images must ***exactly*** overlap each other. To get the scale and rotation many stars in common must be measured along with the star you are interested in and you want the results to be as accurate as you can make them. Now you must create a process that will enable you to correct for the photographic complications before you can find the parallax and proper motion. The analysis requires the use of trigonometry with its sine and cosines—numbers involving angles. You don't have a computer because they haven't been invented yet. You have sets of logarithm tables which allow you to do multiplication and division by addition and subtraction—don't ask any more—and trigonometric tables of sines and cosines that people have laboriously worked out over the years. Logarithm tables are often not good enough because they don't carry enough numbers, or enough significant figures. How accurate could we specify someone's age if we limited our description to decades? "He's in his twenties, she's in her sixties." Maybe you must do the multiplications longhand, and woe is me, divisions, and there are hundreds of them! People engaged in this work in the 1920s developed ways, in the form of extensive tables, to deal with these immense parallax calculations. It wasn't until the rise of computers in the 60s that astronomers could savour the results without being exhausted by the labour of getting the proper motion and the parallax. I recall all this very well, because my master's thesis was to measure the parallax of a white dwarf! Working through the numbers that you need to determine a parallax and proper motion is called a reduction. In essence, you are reducing a mountain of calculations to the few you really need. Like an election, where all the votes are reduced to win or lose. What I've described here is what many of you do when you work with some software package to tidy up your camera's digital images. You perform the rotations I've just talked about, and you scale your images, perhaps to morph a head on another's torso, doing it over and over until it looks right—but the calculations are done for you!

Back to astronomy. Once the numbers were available, then the task was to use them to determine the orbit, the parallax, the proper motion etc. The people who did a lot of this work were women, called computers. They made the measurements and did the long calculations to produce the results that the astronomers then used. (Willem Luyten did logarithms in his head for these calculations!) They also measured the positions and sizes of stars on photographic plates to get a crude measure of the relative stellar brightness for that plate. I filled one of these roles as a graduate student, along with female computers, measuring, reducing the plates, and analysing the results without the use of a calculator—I guess I was learning the trade. I also learned the shortcuts that enabled the most complicated of calculations to be rendered manageable. But shortcut or not, the level of hand-calculation was huge, no wonder I learned to program as soon as computers came available in graduate school! Nowadays, we do the calculations in full without any shortcuts, either by using someone else's software, or by writing our own.

Given the required data, calculating the orbits of visual binaries by hand was a real challenge, again because of the difficult calculations. But doing it and producing an orbit which you then plotted by hand, also gave me a kick—perhaps because the pain was finally over! Every aspect of astronomy pre-1960s was difficult from an analysis point of view, but the theories were all there along with shortcuts that worked, so that a competent programmer could (relatively) easily produce the results that were so hard to come by in the past. Now it is a world of computers. In the past you either wrote your own software or used an obliging friends'. Nowadays, there are many canned programs out there but it is surprising how often the available program just doesn't ***quite*** do it for you, and because of this I've kept my dependence on others to a minimum by writing the software myself. But while computers have advanced, so have the methods of mathematical analysis. Always new mathematical methods are coming forward that promise to make more of our observations than we could before. In this I am reminded of my own work where measurements made the old way produced a result that was good for its time. In later years, I revisited many of the spectra and extracted much more from them just because of a different mathematical approach. One closes one's mind to the hours of early, ineffective toil "wasted" this way because it causes depression. The science moves forward on a wave of improved telescopes, instrumentation, computers and mathematics and puts our earlier labour-intensive efforts aside. One of the reasons I'm writing this book is to give the reader a sense of the past and to show how things are today. Once upon a time we walked to where we were going, today we drive, but our days are just as full.

6.4 Stellar photometry: Measuring brightness and variability

Obviously the first measures of stellar variability or brightness changes, were made visually, maybe a star caught someone's eye over a series of nights and they monitored the changes with reference to nearby stars in the sky. Stars were noted before the rise of telescopes as brightening out of nowhere giving rise to the name **nova,** or new star, and then often fading back into obscurity. The most famous of all these new stars is the exploding star associated with the **Crab Nebula**, a supernova, literally a super new star, that was recorded by the Chinese in 1054. The later identification of the remnant with the star that had suddenly appeared provided an important link into the evolution of stars by raising the question, "Why do stars explode and what, if anything, is left after the explosion?" Over the years many amateurs have made huge contributions to the study of variability by making visual or eyeball observations of **variable stars** with a coverage unable to be matched by the professionals who perhaps had limited access to a telescope or whose teaching duties hampered observing work. Remember that astronomers generally must travel to use a telescope, only the lucky ones have a superbly equipped telescope close at hand, but then its use is generally severely limited by the weather. Of value are the amateur's observations of giant red stars called **Mira variables**, that were found to vary over months and years. Without the work of amateurs who discovered these variables, the professional astronomers would not have had ready "finding lists": lists of stars, their positions, charts of the sky, the type of variability, basically the shape of the light curve, their periods—the time taken for the star to brighten, get fainter and brighten again. The observations of any variable star are made with reference to a star nearby, preferably brighter so that the measuring errors are less than the variable of interest. This technique is used whether one is making visual, photographic, photoelectric or CCD observations. For maximum precision, the best process is a comparative one.

With the rise of photography, it was possible to measure the brightness of stars by their appearance on a photograph plate. The correlation was simple, the brighter the star, the larger the image it created on the plate. I mention plate here because astronomers use photographic emulsion on glass like portrait photographers. You can imagine that a faint star will have but a small effect on the photographic emulsion but a bright star will have a large effect and an overexposed star will blot out a much larger area of the plate. Therefore, by measuring the diameter of the image, one might hope to derive an accurate magnitude. This expectation was never completely borne out for a number of reasons: the variations in the emulsions from one production batch to another, the variations in how the emulsion responded to light across a plate, and the differing chemical mixes used to develop and fix the emulsion from night to night. When developing a plate, and I’ve literally developed thousands of them (though mine were spectra), the temperature varies from night to night, sometimes you leave it in the developer too long—remember the astronomer is both running the telescope and attending to the darkroom. In addition, the star sizes depend on seeing which differs from night to night depending on the weather, so results in terms of the diameters for one night might bear little relation to other nights. It would be akin to measuring the heights of various groups of people with a tape whose length varied from one measuring session to another. Also, the blackening of the plate is not easily related to the amount of light falling on the emulsion. Even given ideal conditions one still needed some reproducible way to standardize each night’s work. Prior to the 1950s, the best precision we could hope to get on the observation of the brightness of a star was about 10%. On a digitized photographic plate where the whole image is matched by some mathematical function this value of 10% is improved—enough said, as the variations on this theme are endless.

The exploratory work through the 19th century identified many types of variable stars though how these stars fitted into the general scheme of things was totally unknown. The variables were classified according to the shape of their light curves (observations assembled over many cycles onto one) and their positions complete with finding charts, generally published by individual observatories. Nowadays these types of results, along with welcome data from amateurs, find a home in a central clearing house where researchers can recover the data and look for other interesting objects to observe.

6.5 Stellar positions and motions

Because the Sun is moving around the centre of the Milky Way at about 250 km/s or 900,000 km/hr, nearby stars appear to move against the distant stellar background, much as nearby people appear to move faster as you observe a crowd. This motion, which Herschel discovered, is generally caused by the reflex of the Sun's motion but there are also other motions at work. The most distant stars hardly move at all and these can be used as reference points for measuring the positions of the closer ones. But everything in the Milky Way is moving and you might wonder if there is a way to anchor the whole system to non-moving reference points, much like bridge foundations which cannot be left to "float" but must rest on bedrock. Quasars, or quasi-stellar objects—galaxies that look like stars—are among the most distant objects we can see in the universe. Because these galaxies appear as sharp points of light their positions can be reliably measured to provide a fixed frame of reference with which to make what we term absolute measures—positional observations of objects so far away that they may be considered stationary. But galaxies aren't visible in every region of the sky. For example, in the plane or the disk of our galaxy where the dust and gas obscures distant stars and the even more distant galaxies. Because of this, the hope that **quasars** might provide a reliable set of anchor points upon which to hang an absolute positional system was not fully realised for an early spacecraft **Hipparcos** that used an inertial positional system (the gyroscopic system that keeps our plane on course). In fact, in reading about this as I was editing this book, this idea of an absolute inertial system involving quasars is a rat's nest of effects involving microlensing and measuring subtleties within Gaia—my eyes glazed over—that limit the method to accuracies of about a microarcsec/year (0.000001 arcsec/year). But the boffins are working it out, having in hand the total dataset of quasar data for Hipparcos that is self-consistent (like a building that is stable and true) and an equally self-consistent burgeoning dataset for Gaia.

Prior to the development of the photographic plate, measurements of position, essentially getting a GPS shot on the stars, was done at the telescope one star at a time while the observer was literally trying to do many things at once, the first of which might be keeping warm at -10°C! Measuring live is an art, complicated by the physical discomfort of standing on a ladder behind the telescope twiddling knobs while gazing through an eyepiece at a star image that dances around a set of crosshairs, while simultaneously making sure that the telescope properly tracks the star. And all this done in the dark! And when you make the tracking correction it is always the wrong way! A comment de Vaucouleurs made to me when I first started observing for him as a grad student.

A brief diversion. Describing this observational technique takes me back to recount the experience of what are called night assistants, technicians who are responsible for the large telescopes at all the major observatories. The telescope in question was the 2.1-m telescope (84 inch) on Kitt Peak. On this night, one of the masters of this type of measurement got observing time to make double star observations at the Cassegrain focus with a filar micrometer. Recall how you'd have to be on a ladder of some sort, even with a rising floor, to observe at the back end of a telescope that can point anywhere within 60° of the vertical. At ninety or so years of age it must have been one of his last observing sessions. He'd have known that it was likely his observing swansong and I know exactly how he felt. I was observing there at the time and the next day, the night assistant, a good friend of mine, said that the night was the hardest one he had ever had. He'd observed incompetence often enough but this was in the area of danger to life and limb, something he'd never experienced before. The astronomer lacked balance—one of the things that age wants to take from you—and it was necessary to hold the astronomer in place as the observations were being made. My friend did not want an accident on his shift to one of astronomy's revered double star observers who, despite unsteadiness, worked steadily through the night. This was more than the swansong for this man's observing career, but also for this way of observing. Speckle photometry was being concurrently developed on the same mountaintop and its measuring accuracy far outweighed the difficult live measuring process required to achieve results. The advent of the digital detector soon matured the technique, making it fast and reliable.

Remember that the Earth is rotating and without the ability to track the stars they quickly scoot out of the field of view. Now you're wondering how you can make a telescope move when there was no electricity. Telescopes of that era—the 1800s and into the 1900s—all came with gravity drives, basically a weight that was regulated by a spinning weighting system (termed a governor) in its gradual fall under gravity which you adjusted so that it moved the telescope exactly to compensate for the Earth's rotation—we call it a drive system. When it hit the bottom, the observer would wind up the weight but in the early 20th century, electricity played a welcome role. I'm sure people of the time craved a recording device that would enable them to examine the sky at their leisure without having to deal with the pressures of controlling a telescope while simultaneously making measurements.

The photographic plate changed all that by providing us with a permanent record of the observations that could be examined later. Along with the photographic plate, came the development of what we call measuring engines. They're not engines at all but opto-mechanical devices that allow precise measurements to be made of a star's position or size in fractions of millimetres (mm) on a photographic plate by moving the plate on two screws at right angles to each other and looking at the star image under a high-powered eyepiece. The key to these measuring engines was the accuracy of the screw, just as was the accuracy of the large gears that controlled the motion of the telescope and its setting precision, which was obviously hugely important. Because of this, machining came to play a big part in astronomy, but also the optics, not just in the telescope, but in the optics of the measuring devices that enabled the images to be magnified and to then be measured. But, while the machining and optical requirements are as demanding today as they were yesterday, the measurement of a star's position on a photographic plate is a demanding task. Some people make very good measurements. Most don't. It seems to be an art. Measuring the plates themselves often sent me into a reverie. Many of the plates I measured dated back to the late 1800s and it gave me a real sense of history when measuring something old from a telescope in a far-off land and a far-off time. Even now, I still recall the wonderment about using historical material, some taken on the day I was born and some in May of 1940. No wonder I felt sick when I saw the Mt Stromlo Observatory destroyed by a devastating forest fire.

Given these positions, what do we do with them? By comparing the measured positions, we convert them to motions in the sky. Some motions are caused by stars revolving around each other (orbital motion), others are stars simply moving across the sky—albeit slowly (proper motion)—and others are moving with the reflex motion of the Earth as it orbits the Sun (parallax). For a few stars, what we see in the sky is often a combination of all these motions. Sirius, the Dog Star, is the best case in point (see Figure 6-3). It is moving across the sky at a rate of 1.3 arcsec/year. and at the same time, it oscillates because of parallax, a yearly amount of 0.4 arcseconds (the size of a star viewed in a large telescope may be at best 0.4 arcseconds!). In addition, Sirius has a companion about which it orbits every 50 years and the amount of this wobble is 7 times larger than the parallax. In analysing Sirius three effects must be taken into consideration. The right-hand image in the shows the progressive improvement of the orbit from measurements made at the telescope while standing on a ladder, twiddling knobs, to photographs and, ultimately, from space with the HST.

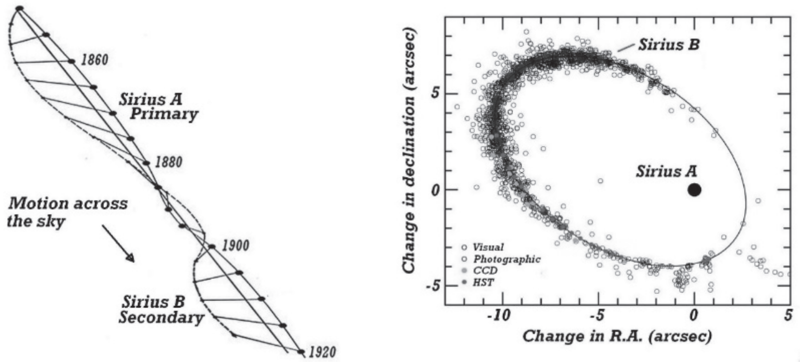

Figure 6-3. Left panel. The combined wavy motion of Sirius A (large dots) and its faint companion (Sirius B) as they move across the sky. Because the white dwarf is less massive than its bright component, its path is wavier. Think of the relative positions of a parent and a child on a teeter-totter or a seesaw. The right panel shows the motion of the faint white dwarf around Sirius A. The haze of open circles represents the observations made at the telescope. Credit: Left panel. A common diagram on the Web. Right panel. Unknown source. Images annotated by the author.

There are other motions astronomers are interested in. The continuous search for "killer asteroids", hunks of rock orbiting the Sun that have the potential to devastate our civilization if we are unlucky enough to get in their way. The last killer asteroid that landed near the Yucatan Peninsula wiped out the dinosaurs 65 million years ago! Every night there are professional and amateur astronomers monitoring the sky with telescopes large and small, equipped with CCD cameras, making repeat observations and then comparing one image with another to find anything that has moved from night to night. Now there are no laborious measurements that needs to be made because it is all automated and at the end of an evening a list of targets and their positions may be automatically sent off to an international databank. This is observing at its finest and is a far cry from the labours of the past.

Whether it is in the construction of larger and larger telescopes or in the instruments we hang on them, mechanical and optical technology always will be critical to the development of the science. It has always been this way. Astronomy demands accurate measurement for, in the extreme, the effects we seek to measure in any sort of study are all very small.

6.6 Brightness and colour

The first thing we notice about the stars is their range in brightness as they form bright and fainter patterns across the sky and which patterns the ancients wove into stories. The stars appear different in brightness for two reasons. First, they are at vastly differing distances and second, they are intrinsically quite different from each other in brightness. That is, if you viewed all the stars at the same distance there would be bright ones and faint ones. In this context the Sun is a very ordinary star.

How do we compare the true brightness of stars and not how they appear on the sky? We need to place them at a specific distance and then compare their brightness in order to see what we have. After all, we couldn't judge the range of people's heights if we looked at them spread out over a football field for example. We'd need to line them up at the same distance from us and then judge their relative heights. It is the same with the stars. Once we have measured their distances, we place all the stars as if their distance from us is 32.6 LYs or at a distance corresponding to a parallax of 0.1 arcsec or 10 pc and recalculate their brightness. The Sun, whose apparent brightness on our weird magnitude scale is -26.7, when shifted to 32.6 LY, would have a magnitude of about 4.8. This magnitude is called an **absolute magnitude** **(M_V)**. When we compare the brightness of stars, we are comparing their absolute magnitudes and not the observed or apparent brightness (**visual magnitude**) they appear to have in the sky.

The second thing we notice about the stars is their colour. Most people who have looked towards the equator in December will recognize the constellation Orion, sometimes called “the Pot”, with its belt of three stars and the group pointing to it is known as Orion’s sword. Within the bright quartet of stars surrounding the “belt and the sword” is a noticeably red star, Betelgeuse; a star so large that if it replaced the Sun in our solar system, the Earth would be swallowed up inside it! A similar red star, Antares, is in the tail of the constellation Scorpius, as it peeks above the southern horizon as seen in a Northern Hemisphere summer. Most of the other stars appear white to our eyes, including the Sun. But stars with similar temperatures to the Sun appear yellow as would the Sun if we viewed it from a nearby star. The stars not only differ in brightness, they vary in colour. In addition, observations reveal that there are many more red stars in the solar neighbourhood than blue or white stars.

And what does colour tell us? Imagine you have left an iron pot on a gas stove by accident. After a while the iron gives off heat but it still looks black, then it begins to glow, first a deep red and later the colour changes to a bright red. With an increasingly hot flame, the colour would change to orange, yellow, white, blue, and ultimately deep violet. We recognize that the iron—long melted—had been getting hotter and hotter. So, we see that colour is a direct indicator of temperature, and by their apparent colours, in principle, we can measure the temperatures of the stars.

A by-product of these data showed that very red stars were cooler than the blue stars and that there were many more cooler stars than hot stars. This has implications for stellar evolution.

Chapter 7

Stars are not just points of light

7.1 The growth of spectroscopy

The start of the twentieth century saw a melding of astronomy and physics triggered by the amazing development of physics, which was driven by a remarkable number of exceptional physicists slowly uncovering the world hidden to our eyes and which, in its manifestation, yields the world we see. Coupled with the development of a telescope-mounted spectrograph and a new class of 1.8-metre telescopes, astronomy was ready to blossom. These spectrographs yielded spectra of stars that opened a whole new field of study and with it, added a new, exciting complexion to astronomy. Astrophysics was born—the study of physical processes in the stars. The notion of stellar evolution was still decades into the future and from my own point of view, its unfolding coincided with my own experience in astronomy. As I write these words, I'm taken back to my first exposure to spectroscopy and away from my initial experience that had been limited to measuring stellar positions on glass plates using large screw machines, and stellar magnitudes and colours using photoelectric photometers. After this introduction I had a happy home for thirty years with both a 1.2-m telescope and a 1.8-m telescope and their quite different spectrographs and feel comfortable as I write about spectroscopy.

7.2 The appearance of spectra: Absorption lines

Once the spectrograph had been taken from the laboratory and put at the Cassegrain focus of a telescope, it was possible to study stellar spectra. Of all the branches of astronomy, spectroscopy, or the study of spectra, whether of galaxies, interstellar gas (the gas between the stars) or stars, promises and delivers the most in terms of our understanding of the universe. But it is hugely demanding in terms of observation and analysis. Spectroscopy tells us what the stars are made of: perhaps it tells us if extrasolar planetary companions are present, it weighs stars, or reveals the expansion of the universe. For those who got the first glimpse of a stellar spectrum, either "live" on the end of the telescope, or recorded by photography, the variety of images must have been confusing. Some stars had a few absorption lines while some had a lot. Remember an absorption line is formed by the passage of radiation, light if you will, through a cool atmosphere above a star's photosphere, or starlight through a vast, cold, gas cloud in interstellar space. Atoms of elements in the atmosphere selectively remove energy at specific wavelengths. The absorptions take place over a narrow range of wavelength making them appear as lines. An example of a stellar spectrum like the Sun is shown in Figure 7-1. In stars hotter than the Sun, lines due to hydrogen are easily recognizable because they are broad by comparison though they are not shown in this figure. The wavelengths form patterns according to the element involved in the absorption. By comparing patterns with what was observed in the laboratory, the elements present in the stars were identified. An example that demonstrates this is shown in Figure 7-2. A direct comparison is also afforded in Figure 7-1 where the iron lines in the arc are also seen in the star. The study of elements and the wavelength of electromagnetic radiation they absorb or emit is by no means complete, particularly in the UV where many lines have yet to be identified. Not all the lines we see in a stellar spectrum are from the star, some are formed by the absorption of starlight by interstellar clouds of gas. The most common interstellar line results from gaseous calcium (λ393.3 nm—λ is a symbol for wavelength) and it was a 1930 study of the velocities found from this element in distant, hot stars that revealed the rotation of our galaxy. Studies of quasars at the limit of the observable universe reveal absorptions due to numerous intervening clouds of hydrogen gas and their study allows us to probe the regions between the galaxies.

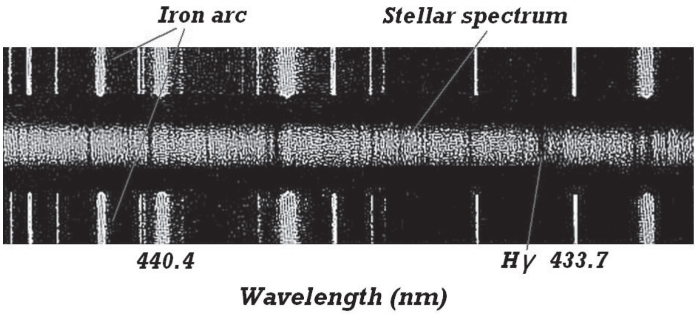

Figure 7-1. A spectrum of a star like the Sun. The graininess of the three spectra comes from the silver halide crystals intrinsic to the photographic process. The outer spectra come from the telescope where an iron arc has been produced and provides a wavelength scale with which to calibrate the stellar spectrum seen in the centre. Also note that the stellar lines are shifted to longer wavelengths when compared to the arc. This indicates that the star is moving away from us. Credit: A spectrum from the **Dominion Astrophysical Observatory (DAO)**. Annotated by the author.

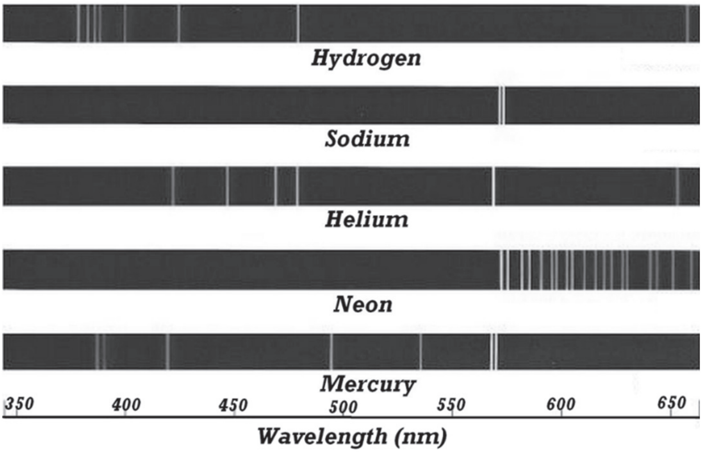

Figure 7-2. See Centrefold. Emission lines characteristic of some elements. The sodium lights, which are familiar to us, radiate in the yellow-orange region of the spectrum. The now outmoded mercury lights shine in the blue from the lines to the left in this figure. Note that these are emission lines whereas in the stars it is the atoms of these elements that absorb light flowing outwards from the hot photosphere. Credit: Source unknown. Adapted by the Author.

7.3 Stellar classifications

Once obtained, astronomers set about classifying the spectra trying to make sense of them in the same way that the botanists of the time organized the new material that was coming to them from places such as Africa and Latin America. Harvard Observatory began a massive spectroscopic survey of the sky in 1885, initially in the Northern Hemisphere, and latterly in the south. Down to magnitude 9, these catalogues contained about 360,000 entries. The observers were getting the data at a phenomenal rate because the telescopes had a prism over the lens at the upper end which projected many spectra directly onto a photographic plate. Dozens of spectra could be classified from one plate. I found an image from what is called an **objective prism** to give the reader an idea of what was accomplished (Figure 7-3). As an aside, I point out that handling these large plates of glass gets you very nervous as they are heavy, they have a history, and represents some poor souls cold, long night at the telescope. But more. To get the photograph you are handling, requires the exposed plate to be removed from the telescope and then processed in a darkroom to develop and fix the plate for posterity. The modern version of the prism is to place a transmission grating, remember a grating, which also creates a spectrum, which can operate in both reflection and transmission modes. The latter mode is where the light goes through the grating, gets dispersed, and ultimately falls on a digital detecting device.

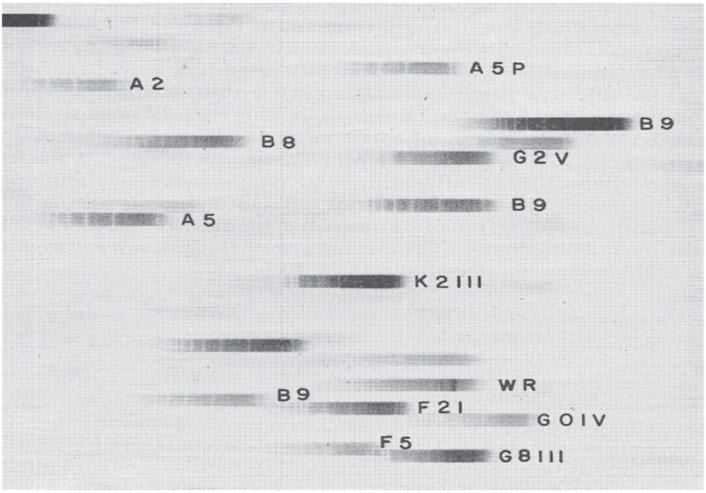

Figure 7-3. Example of an objective prism or getting more bang for your bucks. With an objective prism there is no more getting one spectrum at a time! In this way it was possible to examine the whole sky to below about a factor of 10 what we could see with the naked eye and multiplexed to boot. Credit: Unknown.

The original classification scheme developed by Miss Maury (1866-1952) in the late 19th century grouped stars according to how their spectra looked, and each spectrum was assigned to boxes, each given a letter (A, B, C…) which were called **spectral classes**. The initial problem was one of interpretation—what made ***this*** spectrum different from ***that*** one? It was not until the mid-20s, when Cecelia Payne (1900-1979) made the connection that the variously classified spectra could be logically ordered into a temperature sequence, that modern stellar spectroscopy was born. I suppose the notion of profiling in law enforcement would be similar, or the classification of fingerprints into broad categories. By 1918, the first catalogues of stellar classification were available, A monumental work, in its entirety, the **Henry Draper Catalogue**, named after the sponsor supporting the research, contained about 360,000 entries with most of the classifications made by Miss Maury and Annie J. Cannon (1863-1941) at Harvard College Observatory. The catalogue was a bible for many of us and provided the basis for many research projects. A similar, but more precise, classification project of the southern skies, was begun about 60 years later by another woman, Nancy Houck. The system of classification was refined to a high art, for it is an art, in the middle of the 20th century at the University of Chicago.

Table 7.1. A coarse summary of spectral classes

Spectral Class	Temperature range (K)	Element visible
O	> 30,000	Helium (He), silicon (Si), oxygen (O), hydrogen (H), carbon C
B	10,000 to 30,000	Helium, hydrogen
A	7,500 to 10,000	Hydrogen, calcium (Ca)
F	6,000 to 7,500	Hydrogen, iron (Fe), calcium
G	5,200 to 6,000	Iron, calcium, titanium (Ti), chromium (Cr)
K	3,700 to 5,200	Iron, titanium, growth of molecules
M	2,400 to 3,700	Strong molecules such as titanium oxide (TiO).

Once the temperature dependence was understood (see Table 7.1) some of the letters were dropped and the order changed. Stars classified as O stars were recognized as very hot and those classified as M stars were cool. The scheme itself "OBAFGKM" is generally remembered by men as, "Oh Be A Fine Girl Kiss Me", or by women as, "Only, Bright, Articulate Females Generate Killer Mnemonics!" Take your pick! Within these broad categories, or bins, a number system was included to handle the gradations between the classes, e.g. B0, B1… B9. Some numbers were dropped, just like the original letters were dropped. The careful investigation of many stars yielded a sequence of spectra running from hot to cool. The table shows the spectral classes, the approximate temperature associated with each, and the elements you'd expect to see in a spectrum. Representative spectra are shown in Figure 7-4. The hot stars show prominent lines of hydrogen while cooler stars reveal the increasing presence of lines due to iron and other metals. At the coolest end, molecular lines are readily identifiable by the

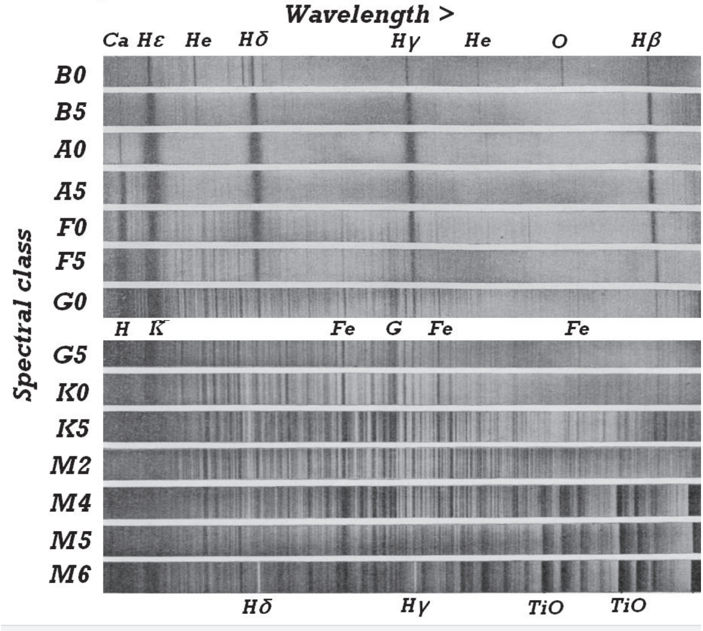

Figure 7-4. Representative stellar spectra. The spectra here show the differences between the hot stars (B0) with temperatures about 30,000 K and cool stars with temperatures near 2,500 K. In hot stars, hydrogen lines predominate but below 10,000 K iron lines become more and more prevalent. For even cooler stars like Betelgeuse near M6, iron is replaced by lines due to carbon-based molecules and titanium oxide. Credit: Assembled from various source and annotated by the author.

confluence of many lines called **band heads** of the absorption which provide an unmistakable sharp, low wavelength edge—we call it a blue edge—to a group of molecular absorption lines. To show how it works, the Sun is classified as a G2 star and looking at the table of temperatures we'd expect the Sun to have a temperature around 5500 K and have a spectrum laden with iron lines. This early work culminated in the 30s, where a new breed of classifiers using better spectrograms (the image of a spectrum is called a spectrogram), began to refine the system and twenty years further on other fractional numbers were included. Thus, a very hot star might be classified B0.5 or even B0.2. Once established, the classification system is defined by a series of stars (classification standards) deemed to be representative of a specific **spectral type** or spectral class. By comparing a spectrum against these stars one can, in principle, make a respectable classification.

It gets more complicated. The spectra of the stars not only differed in their absorption line patterns but similar patterns (presuming similar temperatures) differed from one another. Specifically, some stars with similar patterns had strong lines compared to another's weak lines. Under these circumstances it looked like the temperatures of two stars could be the same but that something else was going on. When examined in more and more detail, there always seems to be "something else going on" in the spectra of stars. This difference heralds one of the most major developments of the early twenties and is still an integral part of modern astronomy and studies of stellar evolution. Bear with me about the complications relating to the analysis of stellar spectra because what follows leads directly to the resolution of this "complication". This is one of those stories within astronomy where two people come up with an identical discovery which then demands others to adjudicate the issue. Other examples that immediately come to mind is the discovery of Neptune by Adams and La Verrier mentioned earlier and long before that, the development of the calculus by Newton and Leibnitz.

7.4 The Hertzsprung-Russell diagram

After the turn of the 20^{th} century, as the distances to more and more stars were known, a Danish astronomer Hertzsprung (1873-1967) noticed that among red stars, classified K and M, there was a huge range in luminosity. That is, their absolute magnitudes varied widely even though they were of similar spectral type. The luminous red stars he described as giants and the fainter ones, dwarfs. The reference to giants and dwarfs reflects the fact that if two stars have the same temperature but one is magnitudes brighter than the other, then the difference is in their size. Later, an American, Russell (1877-1957), devised a diagram that demonstrated Hertzsprung's observation. Known as the **Hertzsprung-Russell** or **H-R diagram,** it honoured both men and succinctly summarized both astronomers' observations. In this diagram, the original published by Russell (Figure 7-5), the vertical axis gives the intrinsic brightness of the stars and the horizontal axis the spectral type or temperature. The diagram holds a critical place in this unfolding story of stellar evolution. Most of the stars fall on a diagonal line going from the upper left corner to the lower right. This major grouping of stars is called the **main sequence**. Off to the sides away from the main sequence are a lot of interesting stars for it is into these regions where stars evolve. In the lower left are found stars called white dwarfs, the endpoint of the Sun's evolution where a teaspoon full of material weighs a tonne! The stars spend a long time in those parts of the H-R diagram where we find them grouped. The

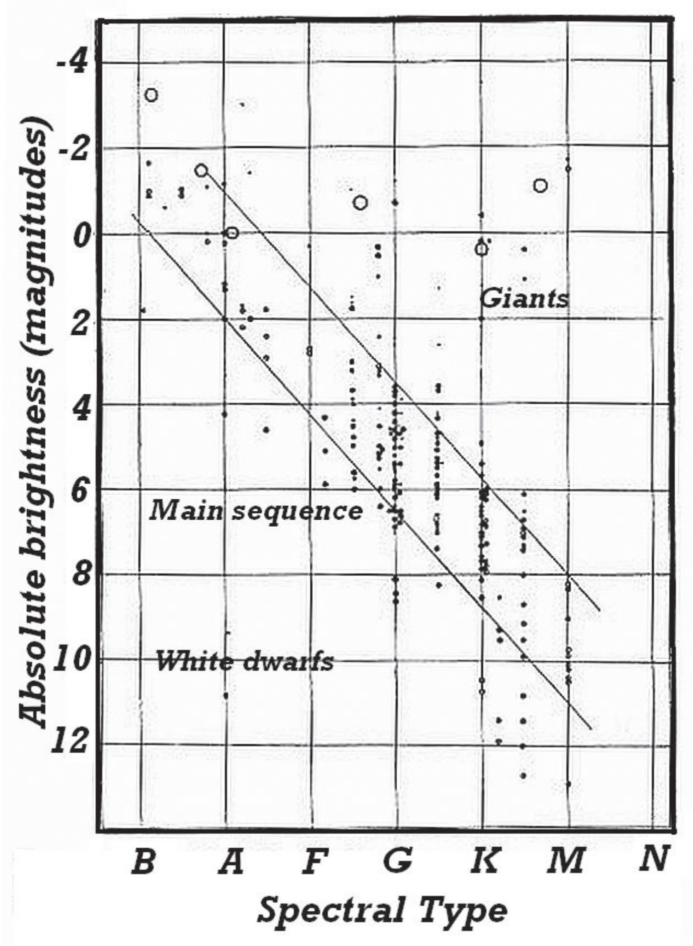

Figure 7-5. The Hertzsprung-Russell diagram (H-R diagram) as Russell first presented it. The main band of stars is called the main sequence. Upwards and to the right are the **red giants** and **red supergiants**. In contrast in the lower left we have the white dwarfs. Note the difference in magnitude between the white dwarfs and their main-sequence spectral counterparts above them and the crude classification scheme available at the time. The main sequence is well-populated because stellar evolution is very slow there. Credit: Russell, 1914, Nature, 93, 252. Modified by the author.

gaps are regions through which stars evolve rapidly. It turns out that this diagram is a snapshot of a mixture of stars that are very young with ages in the millions of years and very old with ages in billions of years. Our snapshot covers knowledge gained over a few decades at the start of the 20th century but the stars live for millions and billions of years. We just don't see the evolution through the gaps, which may be slow in the stars but hugely long for us. The interpretation of this diagram was a mystery until stellar masses started to be measured and the source of the energy powering them was discovered. We'll learn about later how the H-R diagram raises a lot of questions about the evolution of stars and only in the last decades have we begun to more fully understand this remarkable diagram. Familiarise yourself with this diagram because throughout the book it will be continually referenced.

Anticipating a later discussion, the notable thing about the H-R diagram is that it works so well. When we begin evolutionary calculations, we monitor the progress of stars within its confines, mapping and comparing the evolving star's location against key observations. But what, in addition to giving an indication of timescales where stars mostly spend their lives, does the diagram initially indicate?

7.5 The effects of gravity seen in spectra

The H-R diagram raises a lot of questions about the evolution of stars. A question that might spring to mind is, "Do we have to know a star's distance and measure its temperature to know that it is a **giant** or **supergiant** star or a lowly main sequence object?" ***No*** is the answer. The spectra of stars identified as giants or supergiants in the H-R diagram are different in appearance to those of dwarfs or main sequence objects, in the sense that the spectral lines in **dwarf stars** are much stronger than those in giants and supergiants. Annotated spectra displaying these differences are shown in Figure 7-6 predating the nomenclature later adopted to classify stars. Recalling what I said when discussing spectra, that two stars can have the same patterns of lines, in one case appearing strong or well-defined and in the other appearing weak (maybe sharp is a better word). Once distinctions were made between main-sequence stars, giants and supergiants it was found that there was a correlation in the H-R diagram such that giant stars had weaker lines than their main sequence counterparts and the supergiants weaker yet. Therefore, the spectrum not only relates to the temperature of the star but also indicates how luminous or bright a star is and hence how large it is. Therefore, our system of classification can be expanded to be more than a temperature sequence, we can add a category related to brightness or size, since for the same temperature, the larger star will be

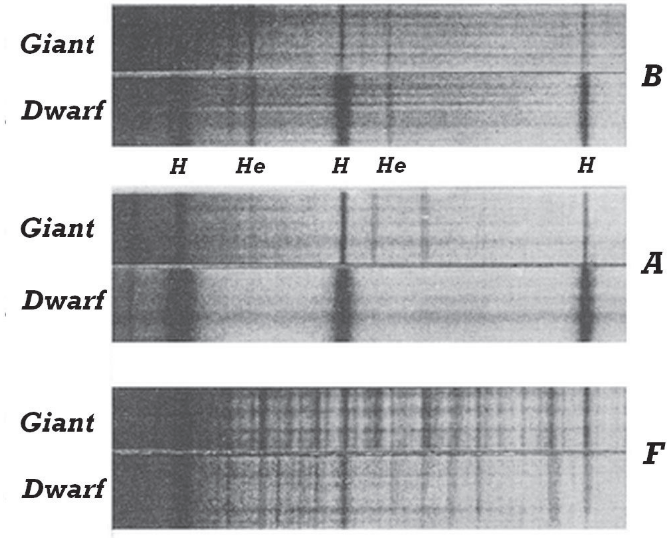

Figure 7-6. A series of spectra showing the change in appearance of spectral lines depending on temperature and luminosity. Here, main-sequence stars (dwarfs) are compared with giants, while the letter to the right indicates a broad spectral type. The giant designation reflects the star's gravity. The main-sequence stars have larger gravities than the giants. The three prominent lines in the upper images are due to hydrogen and those lines in giant stars are sharper than in dwarfs. Credit: Morgan. Yerkes Observatory. Modified by the author.

brighter. In summary, lines are sharper in the distended, giant and supergiant atmospheres compared to the main sequence. The classification scheme handles this by adding an additional category called a **luminosity class**. It is quoted in terms of Roman numerals such that main sequence is designated, "V", giants "III" and supergiants "I" appended to the spectral type classification. Thus, the brightest stars we see at a specific spectral type are the class I objects or supergiants, with giants (III) less bright, followed by main-sequence objects (V). Our Sun falls in the main sequence band in the H-R diagram and has a classification of G2V. As the astronomers became more adept at classifying stars, they were able to define it better, with other categories such as IV, III-II, II, Ia and Ib, but these broad classes give you the idea. The increased distension of a star produces lower and lower gravity on the star's surface and with it, lower atmospheric densities. Think of the Earth. If we increased the size of the Earth by a factor of 2, we'd be that much further away from the Earth's centre where most of the mass is and it would have less of an effect on us. Because gravity was less, we could jump higher and run faster. Therefore, in stars of similar mass or temperature, the larger a star is, the less its surface gravity. Under reduced gravity, the processes in the star's atmosphere are altered and the spectrum is quite different. As mentioned earlier, we model a star’s atmosphere in much the same way that atmospheric physicists model the Earth’s atmosphere, relating pressure, temperature, etc to height. Astrophysicists compute similar atmospheres for a star with a given temperature, gravity, and abundance of the elements.

In summary, the appearance of various spectral lines enables the stars to be classified in a temperature sequence as well as identifying them as main sequence or giants or supergiants. After a brief glance at a stellar spectrum the astronomer knows roughly what sort of star it is and may even be able to judge its temperature to within a within a thousand K for what we term late-type stars (AFGKM) and to 2000-5000K for early-type stars (OB). All the elements are found in the atmospheres of these stars though we don’t necessarily see them. Some show up in the UV, others in the IR, and because these atoms depend on the star's temperature, they are missing or weak along the spectral sequence. For example, we don’t see lines due to iron in a hot star, at least in the visible region of the spectrum, nor do we see lines due to say silicon in cool stars. Whether lines are seen or not depends on how sensitive the atoms are to temperature and gravity, but we won’t delve into the physics of stellar atmospheres any more than I already have.

In addition to determining a star’s temperature and brightness, astronomers have the capacity to determine how fast it is rotating (Figure 7-7), whether it is a giant or a dwarf and its chemical composition.

7.6 More binary stars

7.6.1 Spectroscopic binaries

With the development of a spectrograph carried at the base of the telescope tube behind the main mirror—the Cassegrain focus—surveys were begun of the bright stars in order to classify their spectra and to measure their **radial velocities** (or line-of-sight velocities) by the Doppler-Fizeau method. We describe the process of obtaining spectra as taking spectra. In 1887, Pickering (1846-1919), as part of the observing program on the Henry Draper Catalogue at the Harvard College Observatory, discovered two sets of spectra in the star Mizar in the Big Dipper. He took more spectra and saw that the lines became single and later split again (see Figure 7-8) and he recognized that these spectra were from two stars orbiting one another, even

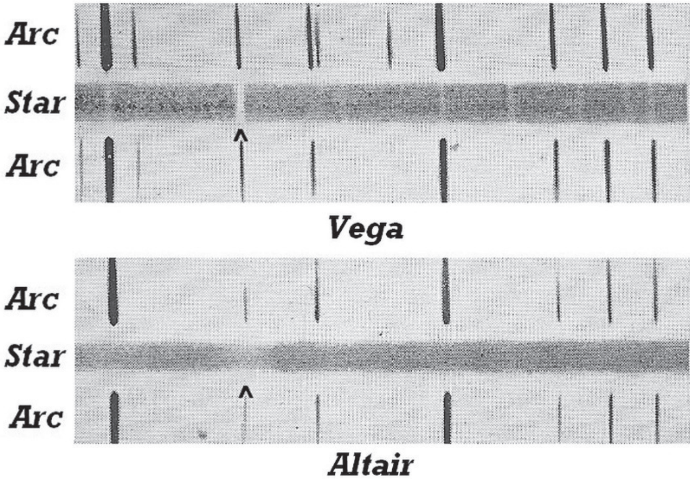

Figure 7-7. The two spectra above, aligned against their star names, show the effects of rotation. Vega appears to be rotating very slowly (20 km/s) and Altair is rotating at 240 km/s. Sorry about this, but research shows that Vega is rotating at almost the same velocity as Altair but we're looking down on it! Credit: From Yerkes Observatory Photographs. Modified by the author.

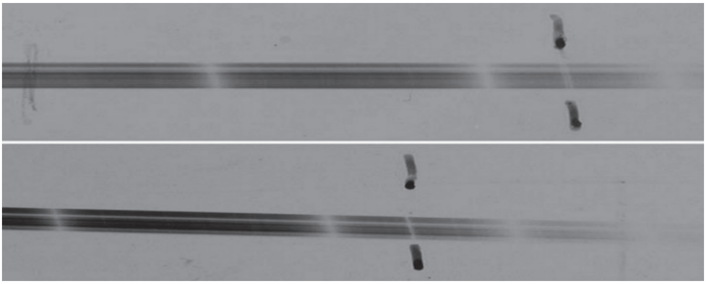

Figure 7-8. Two objective-prism spectra of Mizar, showing a double set of lines as marked on upper panel and a single set in the bottom panel. The broad lines are due to hydrogen and the double lines are due to calcium at λ393.3 nm. The hydrogen lines are too broad to show the splitting. Pickering saw these double lines while observing on the Henry Draper Catalogue program—he had discovered the first spectroscopic binary. Credit: Pickering, 1887, Harvard College Observatory.

though the star's image was only seen as a single point of light in the telescope. He had discovered **spectroscopic binaries**. This discovery initiated the rise of binary star research, and though they knew it not, provided one of the keys needed to unlock the secret of stellar evolution.

You can imagine that if a double star is a long distance away then you won't see two separate stars on the sky but only one, like the distant, merged, headlights of a car seen at thirty kilometres across a West Texas landscape. If you look at a spectrum of a binary system then chances are, you'd see two sets of lines with their positions changing as the two stars revolve around each other. Consider one star. As it orbits the other star, sometimes it's coming towards you and sometimes going away. The same is true with the other stellar component except it goes in the opposite way (see Figure 7-9).

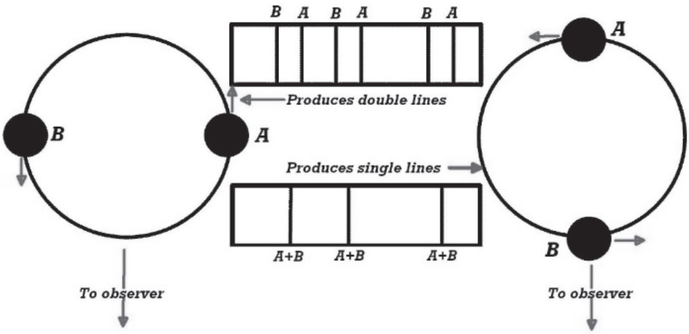

Figure 7-9. A schematic diagram showing how spectrum lines are displaced in a spectroscopic binary. The upper spectrum refers to the picture on the left where one star is moving towards us creating the left-hand (violet) set of spectrum lines. The star going away from us creates the right-hand lines or redward lines. In the right-hand image the stars are moving at right angles to our line of sight so both sets of lines coincide. Credit: R. Baker, Astronomy, 1930. Redrawn by the author.

By measuring the velocity shifts in both stars, we can measure two orbits and derive the relative masses of the two component stars. But the stars don't orbit each other; they both orbit about a point between them called the centre of mass. The best analogy to describe this motion is that of a teeter-totter where balance can be achieved between an adult and a child by moving the adult closer to the rotation point or fulcrum. It is the same with the stars. The centre of mass is always closer to the more massive object whether a star or a planet. For example, the Earth and the Moon revolve around a point that is about 1.2% of the Moon's distance from Earth, which is the approximate ratio of the masses of the Moon to the Earth. In addition, the less massive star moves faster than the more massive component, and we use these velocities to weigh each star, just like we can use the Earth's velocity to weigh the Sun. The problem is that we can't see the system as two stars like a visual double star so we can't find out the angle the orbit is to us. We call this the angle of **inclination**. The stars can be orbiting each other at any angle to us. Think of looking at a saucer and liken it to a star's orbit. If we look down on it, it looks round. At an angle it looks oval and from the side it appears flat. When we view spectroscopic binaries, we don't know the angle at which we are viewing them and because of this, we cannot find the masses of the stars in the system but we ***can*** measure the ***ratio*** of their masses. To find the inclination we need more information. If by chance, the orbits of some spectroscopic binaries are oriented almost side on to us, one star will block, or partially block, the light from the other as it swings by between the eclipsed star and us. It's like the transit of Venus with Venus the size of a star. These stars are called **eclipsing binaries** and we detect them by light changes as they orbit each other. I'll talk more about them later but this configuration gives us the opportunity to measure the orientation of the orbit and so measure the individual masses of the spectroscopic binary components.

I've talked about velocity shifts and getting orbits. What is involved in getting an orbit anyway?

7.6.2 A chat about measuring spectra for radial velocity

For direct images of stars—photographs of the sky—we put the photographic plate on a screw measuring machine with magnifying optics to look at the round star and then rotate the knobs to move a crosshair over the star to bisect it in **two** directions and then record the measurement. This was how I was taught as a grad student in Minnesota measuring direct stellar images on glass plates that were 70 years old even then. In the sixties, the approach was no different from that used in the past. Turn now to a spectrogram as displayed in Figures 7-1 and 7-7 where the spectra of arc and star are recorded on a glass plate that is long and narrow. It is long to record the spectra, and narrow because it must be bent in the plateholder to match the focus of the telescope. When I started measuring velocities from spectrograms at the DAO it was the same process except it was in one dimension. Measuring stellar lines this way is relatively easy for the late-type stars where the lines are sharp, but with hotter stars the lines are broad and difficult to bisect (imagine measuring Altair in Figure 7-7). But it wasn't just a task of measuring the positions of the stellar lines, the whole set of measures had to be calibrated for wavelength and that is where the iron arc burned at the telescope came into play. The iron-arc spectrum straddles the stellar spectrum and must be measured too (see Figure 7-1, or Figure 7-7). Knowing the wavelengths of the arc enables any measurement of the stellar spectrum to be converted into wavelengths. In Smart's book "Some Famous Stars" I never made the connection between the arc and spectra displayed and the calibration process—sorry for being so thick! With the coming of the computer, digital scanners, and then digital detectors, everything changed. What was once an act of faith during the measuring process was placed on a solid footing where two people could measure the same spectrogram and come up with the same answer. Doing it the "old-fashioned way" could never guarantee this level of reliability—even if ***you*** repeated the measurements with your own bias.

The first of the advances were in hitching a screw machine to an oscilloscope that produced a profile of individual spectral lines along with a reverse image that could be matched up for the measurement. The method worked fine for single stars but the interesting results are for binaries where there is a hope of at least measuring a reliable mass ratio—or more, the masses of both stars. Another technique was developed that could reduce all the various line measurements to one. The reason I'm going through the details is because, in its digital form, this the way that we measure velocities of single stars. What I describe here is the method in analogue form I originally used to measure spectra at the DAO. The machine was unique and required looking at two spectrograms at once through some optical arrangement, after first making sure that the arcs of each spectrogram exactly coincided before shining a light through the combined spectra. For the arcs you looked for a minimum of light on an oscilloscope screen—think of the blackened arcs obscuring the light when the two spectra matched. Now for the stellar measurement. By sliding the spectra with along each other there was a peak on the oscilloscope screen when the less exposed central parts of each spectrum were aligned. Check the arc and stellar spectra in Figure 7-7 to see how the method could work. The difference between the stellar minimum and the arc peak gave the star's velocity, in this case in millimetres which needed to be converted to km/s. When used with digital spectra, it is impossible to accomplish what was so easily accomplished in this analogue way without some help from the distant past. Here, I'm referring to the work of Fourier (1768-1830), a wonderful French mathematician whose mathematics is at the heart of much modern astronomy and communication technology. This sliding technique is embodied in face recognition software used by law enforcement agencies. The best sliding fit in analogue or digital form creates a peak which yields the desired velocity and, if dealing with a binary system, the other star is detectable there will also be a match though less pronounced at another velocity. If the image of the variable star is compared with a spectrum more attuned to the second star then the match will be better. This latter technique took the measuring process a long way, and still works wonderfully well for single stars. Binary stars are always a challenge.

Now comes the linking of the sciences. The next step is to recognise techniques from other disciplines that might be applied to your needs. Now it is possible to unravel, or separate out, each spectrum by using techniques pioneered in the medical profession to build 3D images of parts of the human body—or to uncover hidden recesses inside the Great Pyramid. Again, I note that often astronomical advances result from adaptations from other fields, e.g. medical (**tomography**) or the military (detectors, optical, and in my case the basis for a wonderful interpolation program). This was how the difficult measurement in the left panel Figure 7-10 was made by

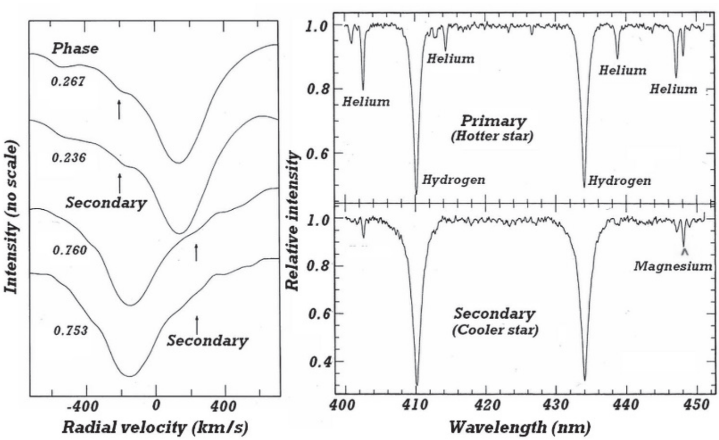

Figure 7-10. Left panel. An example of a blended line in the eclipsing binary V1425 Cygni. Compare the shape of this profile to what was shown, albeit in a different way, in Figure 7-8. This is the sort of demoralising image that started me writing software that freed me from pencil and paper and totally inadequate measurements. It might appear a hopeless task to derive reliable velocities from profiles as badly blended as these but the separated spectra in the right panel show what is currently achievable with the combination of new mathematics operating on the ***total*** sample of digital spectra. Right panel. Tomographically reconstructed spectra of the **primary and secondary components** of V1425 Cygni. Credit: Hill and Khalesseh, 1993, A&A, 276, 57. Annotated by the author.

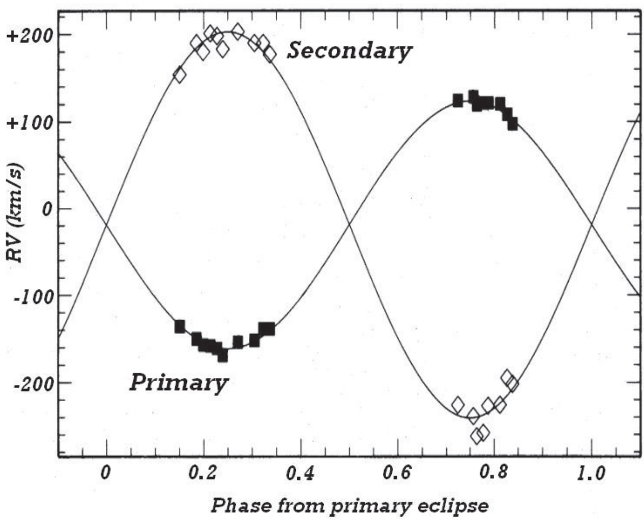

Figure 7-11. The velocity curves derived from tomographic reconstruction. Solid squares represent observations of the primary or the most-massive component. It's hard to imagine the data displayed in Figure 7-10 yielding such a successful result. Credit: As in previous figure. Annotated by the author.

using medical-based software to separate out the two spectra forming the images in the right panel of this figure and using them as masks to measure the original blended binary spectra yielding the velocity curves for the two stars in Figure 7-11. Tomography has been replaced by using the redundant information contained in any series of spectra taken throughout an orbit, which enables the spectra to be **disentangled**. This process employs another of those arcane mathematical procedures (called sparse matrices) that the blue skies mathematics researchers would never have envisaged as being "useful". The point of this wee diversion is to show that techniques like this are needed if we are ever to measure masses better than 5% so that they are useful in checking stellar evolution theory. Aside from the analysis, there must be a great deal of care taken in obtaining "well-exposed" observations to enable you to make reliable measurements of the spectrum and combining these results using some canned program that will give you the final few numbers you've laboured hard to get. If your spectra are poorly exposed then what you'll be reduced to is a guess about whether to accept your data or not, but there should be no room for guesswork in making a measurement. I always go back to the measurements when refereeing a paper or examining what I've done. Some people throw away data that looks wrong, leading to a bias in their results. A common enough happening with respect to facts of an issue in the larger world I may add. I've adopted the philosophy of deciding ahead of time whether a measurement it is worth making. If I then make the measurement, I am stuck with the result and often, despite my best intentions it is difficult to be ***that*** objective. The real problem is, we are always pushing the boundaries. The telescopes are never quite large enough to give well-exposed spectra, which means the spectra maybe very noisy or maybe the spectrum is not spread out (dispersed enough) to allow the best measurement. You want to measure the distance to a nearby galaxy using humble eclipsing binaries, so you push the boundaries to demonstrate the potential of this observation. Then you work with what you've got! Because of this pushing, we also interpret our data a little too much, but for the best reasons—to advance the science, knowing that tomorrow someone using a larger telescope, a more sensitive detector or improved software will do a better job.

7.6.3 Eclipsing binaries

Picture the two stars gravitationally connected but with an orbit that is edge on to us. Then what do we see? We will see eclipses like the eclipses we experience on Earth when the Moon in its orbit passes between the Sun and us. For stars in an edge-on orbit, at one stage one star will get between us and the other creating an eclipse, or dip in brightness, and if the orbit is circular, half an orbit later the other star will also experience an eclipse though not necessarily the same dip in brightness. This is an eclipsing binary system where the eclipses cause light changes. If the orbit is oval-shaped then the timing of the eclipses is not every half orbit, giving us the opportunity to measure how oval it is. What might we see? Well, it all depends on the relative sizes of the stars: their temperatures, how close they are together and the actual angle, or inclination, of the orbit. This circumstance gives rise to a class of variable stars where there are two stars gravitationally bound and the light varies because of the geometry of the situation and not by any intrinsic changes in the star's brightness! There are multitudes of stars like this! Fifty percent of all the stars are binaries so we would expect to find many eclipsing systems among them—and we do.

The most famous of the eclipsing binaries is called Algol, with a name derived from Arabic sources. The Arabs named most of the bright stars because they, aside from the Chinese, were the only ones studying the heavens in a systematic way during what we termed the dark ages of western civilization. In 1782 an Englishman Goodricke (1764-1786) discovered that

Algol varied in light in just under 3 days (see Figure 7-12 for a schematic of the light changes). To be more precise, the light variations were repeated over this time. This is called the period of the star. The times in between are termed phases and are quoted in fractional terms of the period from the deepest eclipse (**primary eclipse**). Goodricke, who, unfortunately for astronomy, died young, came up with an inspired explanation for the cyclic light variations, suggesting that a star moving in front of another was the cause of the periodic variations he observed. He got it right, but it wasn't until 1912 that astronomers could even work out the geometry of such changes. So began the art—it's supposed to be a science—of "solving" light curves, that is, given a light curve, what are the relative dimensions of the stars and the orbit's orientation to us that produces the observed changes? In 1912 this was not easy, and they had to work with spherical stars (and the

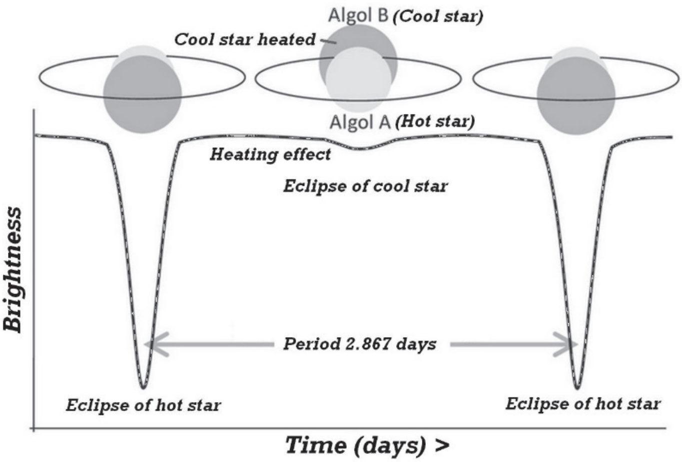

Figure 7-12. This schematic picture shows the effects on the light we see from two stars undergoing successive eclipses. The deepest eclipse occurs when the cooler, darker companion eclipses its hotter companion. When the cool star is eclipsed its heated face is towards the observer. Credit: An obscure newspaper article. No attribute. Annotated by the author.

awful sines and cosines) and simplify all the observational complications seen in such a system in order to get results. There are difficult complications they somehow had to correct for. You might imagine that a cool star might be heated by the other star. This complication shows up in Figure 7-12, where the brightness increases as the heated side of the cooler star becomes visible. This is termed the reflection effect though reflection is ***not*** the process. The hotter star heats the atmosphere of the cooler star which re-radiates at a greater brightness than it would if the hot star was not there and, in addition, the cooler star is not spherical in shape (see Figure 14-1).

The brightness we record is called a light curve, and it is these data that astronomers try to decipher when they analyse a light curve to measure the relative sizes of the components in terms of the orbit as well as its inclination to us. In any light curve, the deepest eclipse is called the primary eclipse and the other the **secondary eclipse**. You can imagine the varied light curves that would occur if the sizes of the stars were different or the orbit was viewed at a slightly different angle. Because these light curves are sensitive to the relative sizes of the stars and their inclination, we can turn the problem around and determine this information. If the light curves weren't sensitive in this way, we could not solve them. By necessity, the observations giving rise to these light curves are pieced together over different nights, since these variations take place over days and not hours. At best, we can observe a star for about eight hours a night. Couple this with weather causing interruptions, means we must combine the data from many nights to get a complete light curve. Assuming that the light curve is unchanged over the various phases, one may then average the data obtained at the same part of the orbit, or the same phase. Then you're ready to begin the solving process.

In 1912, two men, Russell and Shapley, established techniques that were used over 60 years to solve light curves under simplifying conditions, namely the stars were spheres. While they aren't spheres, their assumptions still took astronomy a long way. Their work was summarized in volumes of tables which were the bibles for researchers in the field for over fifty years. Since the 60s these early and very approximate methods have been superseded using computer-generated models. For my part I never did figure out the proper use of these tables which led a colleague and me to model the situation and then have the computer do the work. Now we make guesses as to the approximate values of the parameters and compute a light curve, which we then compare to the observations. If the computed light curve looks something like the observations, we update the parameter values and calculate a new light curve. If we are on the right track the two curves, observational and theoretical, get closer and closer together until changing the values by small amounts make no change to the generated light curve. In these circumstances we have solved the light curve. An example of such a fit is given in Figure 7-13 where the light curve is entirely different from that shown in Figure 7-12. This light curve results from observations

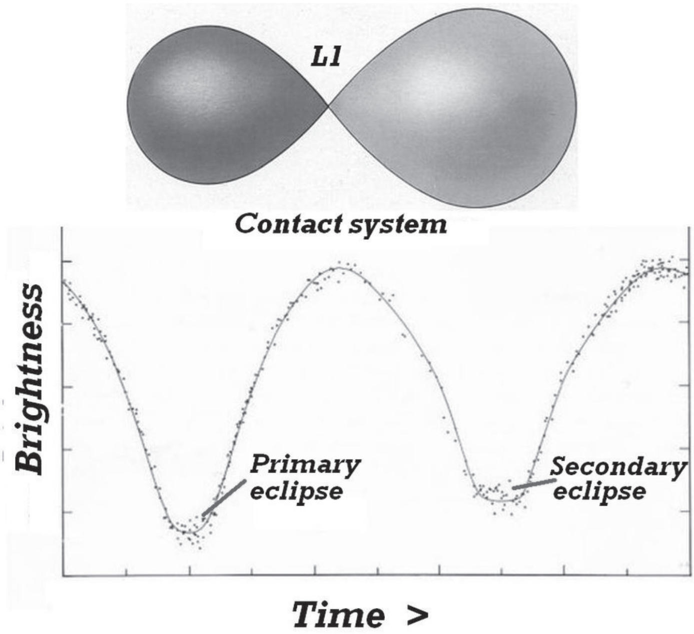

Figure 7-13. A contrasting light curve resulting from two stars in contact undergoing eclipses. These are called **W UMa** (W Ursa Majoris) variables with distinctive light curves. Stars in these systems revolve in less than a day and are therefore easy to use as a fill-in observing program while you do other things. Credit: Hill, 1979, PDAO, 15, 297. Annotated by the author.

of two stars physically in contact forming a dumbbell, yet the model represents the data beautifully. In solving these light curves, often the initial guesses are way off and it takes a while to get on the right track. Once properly underway, the whole process runs automatically. It all sounds rather easy but… I'll return to this in Chapter 14 when I discuss the evolution of binary stars.

7.7 An aside: The detection of extrasolar planets

7.7.1 From a star's velocity changes

We read about extrasolar planets being detected. It's worth talking about it here because their discovery encapsulates much of what I've talked about to this point. Now, how is this accomplished, surely a planet cannot wobble a star enough to be measured? Thinking of the Sun and the most massive of the planets, Jupiter, we find the Sun and Jupiter revolve about a point about 50,000 km above the Sun's surface continuously in line with Jupiter 800 million km away. Under favourable geometric conditions, an external observer looking at our solar system from the nearest star would discover that the Sun's velocity was changing cyclically over 12 years (Jupiter's orbital period) with a total amplitude of 26 m/s, or that the Sun was moving at a velocity of 13 m/s about its centre of gravity with Jupiter. Thus, these observations would show that the Sun has a 12-year period and a velocity that changes by ±13 m/s. This velocity variation is measurable. It is this effect, the wobble of stars caused by accompanying planets, that initiated the extrasolar planetary searches reported in the media. Now this technique has been augmented by detecting planets as they cross in front of their parent stars and eclipse them (see next section).

If the outside observer was looking down on the solar system the Sun's motion could not reveal the presence of Jupiter. This means that even though we find no evidence for planets in the motion of a star it does not remove the possibility that planets are there—the Earth barely causes the Sun to twitch. Look again at this number for Jupiter, 13 metres per second. For once there is a number in astronomy we can comprehend! Sprinters run a hundred metres in 10 seconds, a speed just a little less than the Sun's motion. Under these circumstances, measuring the Doppler-Fizeau shifts is a thousand-fold more difficult than measuring stars orbiting each another. When stars orbit one another, the velocity of both stars might vary by over ±200 km/s, amounting to an easily measurable shift of ±0.3 nm. Now specialists who are looking for extrasolar planets routinely measure wavelength shifts of about 2 millionth of a nanometre (2×10^{-6} nm) corresponding to motions of 1-2 m/s! The speed of an easy walk! These advances in observing and measuring techniques have been achieved over the last 30 years and to date have yielded 100s of extrasolar planets. From these figures, even with today's technology, Jupiter would be detectable from a nearby star, and, in principle, from a nearby galaxy with a large enough telescope and a superb spectrograph! Examples of typical velocity curves revealing the discovery of three exoplanets revolving about a star are shown in Figure 7-14.

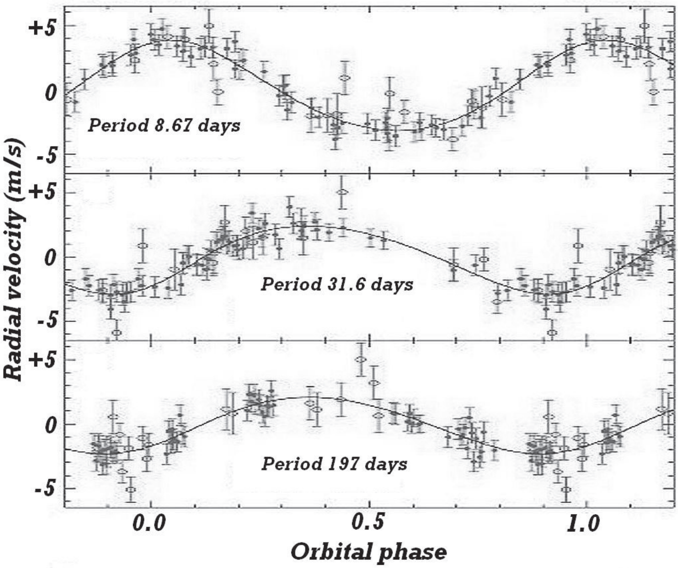

Figure 7-14. Illustrating the detection of three exoplanets from radial velocity measures. Notice the radial velocity scale given in metres/sec, the equivalent of running 100 metres in 20 seconds! Credit: Source unknown. Modified by the author.

7.7.2 Detecting eclipses in nearby stars

If a planet moves across the face of a star we will see, if the eclipsing, or occulting, planet is large enough and data are good enough, a slight dip in the overall light level. A cycle later it will be repeated. When the planet goes around the back of the star no change in overall brightness occurs because the planet is so faint compared to the parent star. Since 2010, the spacecraft **KEPLER** and its reincarnation **K2** have observed many stars looking for these small dips. The dips are at best only 1% of the stars brightness and very difficult to detect. So, it is no accident that these observations are being made from space considering, as I've noted earlier, the many factors that affect ground-based observations. To date more than 3000 exoplanets have been discovered with more than 30 in the Goldilocks zone. K2, now replacing KEPLER, has detected an additional 320+ exoplanets. Unfortunately, after I wrote these words, the spacecraft, housing both Kepler and K2, ran out of the propellant needed to move the telescope from object to object so it is lost. Just enter "KEPLER spacecraft" into Google to get pointed to more information.

Despite my earlier comments about Earth-based telescopes having a hard time measuring light curves to better than 1%, a group at La Silla in Chile made the initial discovery of three exoplanets around a system with a very long name but termed **TRAPPIST-1** after the spacecraft used for the discovery. Later, four other planets were discovered by a space-based telescope, the **SST**! The eclipses seen in this system are quite clear-cut as you can see in Figure 7-15. The transit times depend on two things, the distance of the planet from the host star and where the planet crosses the star's face. The reason that the planets are not all crossing at the same place is because, like our solar system, the planets all orbit at slightly different angles from each other; residual effects going back to their original formation and rotation about the host star. In addition, the relative sizes of

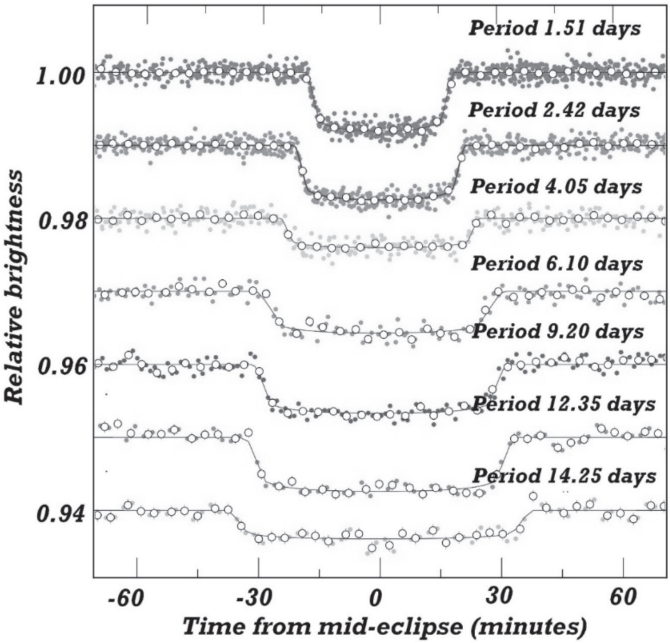

Figure 7-15. Illustrating the detection of seven exoplanets in the TRAPPIST-1 star system from eclipse observation made with KEPLER and the **Spitzer Space Telescope (SST).** The eclipses are clear-cut; the depths show the relative sizes of the planets and the lengths of the flat bottoms indicate the planet's orbital velocity and where they are transiting across the face of the star. Credit: ESA/NASA/TRAPPIST/Spitzer Space Telescope.

the planets are indicated by the depths of each eclipse. As someone who has worked forever "in the business" these are a spectacular series of observations. Disentangling the observed dips to determine these various orbits was no mean feat either.

But the numbers of stars in the universe, coupled by the number of extrasolar planets detected so far, under very special geometric circumstances, places the number of stars with retinues of planets in the billions, perhaps trillions. For me, the conclusion is irrefutable, we are not alone, itself a scary notion.

7.7.3 From gravitational microlensing

Years ago, it was proposed that if a planetary system moved in front of a distant star (occulted it) then the light from the background star would be bent by the gravitational field of the foreground star, resulting in a focussing and hence a brightening of the more distant star and a much smaller light increase from a suitably placed planet orbiting the foreground star. This is called lensing. An example is shown in Figure 7-16 where the lensing object is the cluster of galaxies in the centre of the image.

Quite a few planets have found in this way, but these events are always "one-offs" and not really useful—but exciting—nonetheless. Lensing has come into its own in the study of distant galaxies when foreground galaxies focus the light of ones at vaster distances. If these lensed objects can have their spectra recorded and velocity measured. Thus, based on the velocity, one can leapfrog back in time, for time is distance in the extragalactic world. It was a program based on this type of observation that has led to an uncertainty in the age of the universe mentioned in the Caption to Figure 7-16. Just as important is the fact that unseen matter within say a cluster of galaxies may also lens more distant objects leading credibility to the notion that much of the universe is hidden from us in the form of "dark matter", but in this case, not hidden from gravity. But there is more to lensing than what I've mentioned. A program called **OGLE (Optical Gravitational Lensing Experiment)** begun by a Polish group aimed at detecting unseen matter through microlensing has transformed stellar astronomy, but more of this later in Chapters 13 and 15.

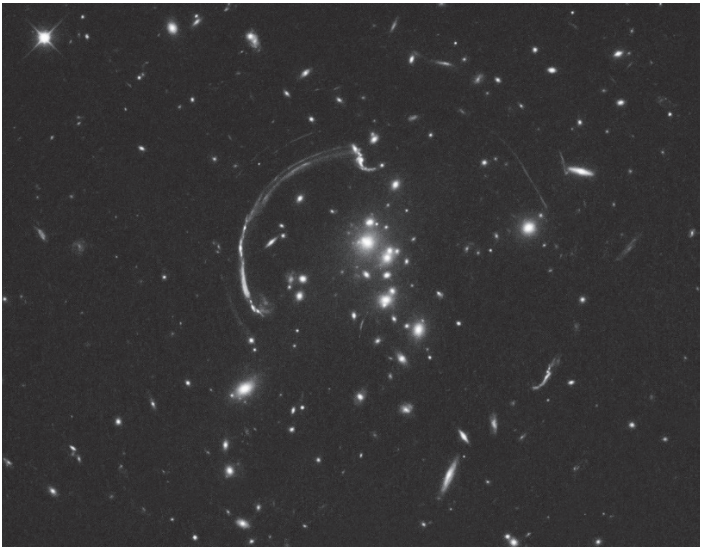

Figure 7-16. This is one of the most striking examples of gravitational lensing, where the gravitational field of a foreground galaxy bends and amplifies the light of a more distant background galaxy. In this image, the light from a distant galaxy nearly 10 billion light-years away, has been warped into a nearly 90-degree arc of light by the galaxy cluster RCS2 032727-132623 which lies 5 billion light-years away. A spectrum taken from this arc would allow us to look back 10 billion years. Credit: NASA, ESA/Rigby (NASA GSFC)/Sharon (Kavli Institute for Cosmological Physics, University of Chicago)/Gladders and Wuyts (University of Chicago).

CHAPTER 8

ASSEMBLING OUR INGREDIENTS

8.1 Preamble

At this point in the story we have the ingredients with which to feed into the stew that will allow us to get a taste of where we are heading. “How do stars birth, live and die?” It is pointless to look at the stars and measure their masses, sizes and temperatures and yet not know their inter-relationships. It would be like going into a new family and ***not*** trying to work out what was what. So far, we know we can measure a star’s intrinsic brightness, though its measurement is limited by the range of its parallax. We know temperatures can be measured using the physics (circa 1920) and through observations of visual binaries (those stars with curving motions on the sky) and so we can accumulate knowledge of stellar masses. Add to that, the masses that can be derived from spectroscopic observations of binary stars which are also eclipsing systems, and we have enough data to reflect upon. Eddington was at this point in the early 1920s, and, along with Einstein and his famous equation, opened the subject of evolution to be discussed in the next chapter. But back to the stars. Let’s see what we have.

8.2 The mass-luminosity relation

Through continued observations of visual binaries and the combined analysis of spectroscopic and eclipsing binary stars, we gained a fair knowledge of stellar masses. Eddington, using these initial data, discovered a significant relationship between mass and luminosity called the **mass-luminosity relation** (Figure 8-1). The relationship had an enormous bearing on ideas of stellar evolution because it immediately yielded information about stellar lifetimes. Just as Hubble’s diagram a decade later opened cosmology, so did Eddington’s mass-luminosity connection open the study of stellar evolution—though he may not have been the first to draw attention to it. He found that the brightness of stars was related their mass but not in a simple manner where, for example, doubling a star’s mass did ***not*** produce twice the luminosity or brightness but an increase of ~16 ($2 \times 2 \times 2 \times 2$). He found the intrinsic brightness of a star (L) is related to its mass (M) such that

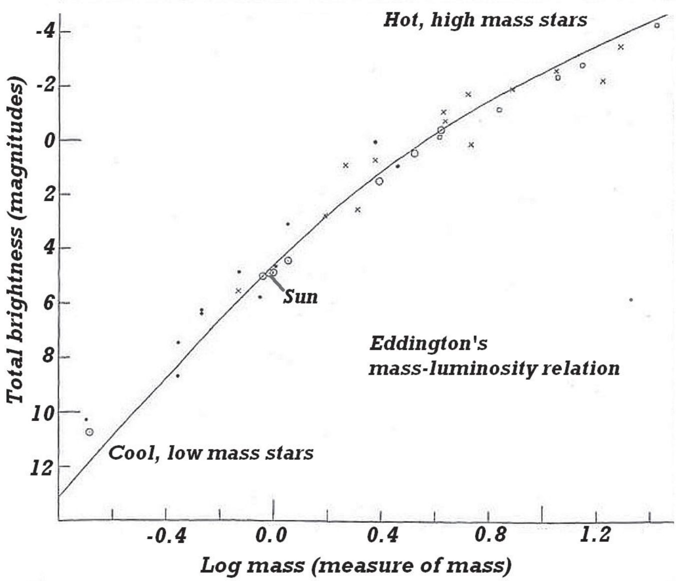

Figure 8-1. Eddington's original mass-luminosity relation based on masses derived from astrometric orbits (orbits seen on the sky) and eclipsing variables. When Eddington discovered this relationship, he knew immediately it said a lot about how stars evolve, and thus seeded more productive studies of stellar evolution. Credit: Eddington, 1926, The Internal Constitution of the Stars. Modified by the author.

$L \sim M^4$ or $L \sim M \times M \times M \times M$. The squiggle (~) means approximate. In a more extreme example, a star ten times the **solar mass** produces 10 × 10 × 10 × 10 (10,000 or 10^4) more energy than the Sun! The relationship worked for stars ranging in mass from 0.6 of the Sun's mass to stars twenty times the solar mass. This relation had huge ramifications in terms of coming to grips with how stars evolve, since the more massive stars were so profligate in their expenditure of energy, they ***had*** to have shorter lives. Once the mass-luminosity relation was established, it was soon discovered that the massive stars were the blue stars and these had to be much younger than the rest because they were expending their energy enormously faster than the stars like the Sun (see next few sections). Without knowing much about the energy source within the stars, the mass-luminosity relation indicated that a 10 solar mass star would live for about half a million years (divide the Sun's age by the relative energy output of the star or 4.5 billion years divided by 10,000), give or take a factor of 2! The number is rough because a larger star has more fuel to burn, so perhaps the result needs to be multiplied by the mass again. In this case a ten solar mass star would live for about 5 million years, a number in the right ballpark.

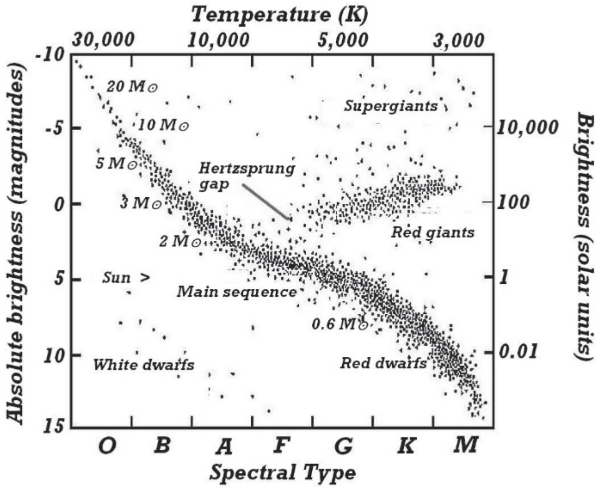

Figure 8-2. A Hertzsprung-Russell diagram showing the masses along the main sequence in terms of the Sun. The spectral types are shown as broad bands along with the temperatures. The diagram already gives clues as to the evolution of stars. The Hertzsprung gap is almost devoid of stars so whatever happens there happens quickly. Where there are lots of stars, as along the main sequence, evolution must proceed slowly, but slightly faster in the red giant region. Credit: NASA/Chandra. Modified by the author.

Given the mass-luminosity relation, when we look at the H-R diagram in Figure 8-2, we find the more massive stars occupy places in the upper left-hand side of the diagram and the least-massive objects to the lower right. This is an application of Eddington's mass-luminosity relation. To the lower left what few masses we have are about those of the Sun. The scale is best related to the Sun, which we use as the benchmark for quoting stellar brightness, size and mass, a practice that brings a context to the numbers. Given a star's mass is 20×10^{30} kg—a number that is hard to picture—but at least I have a rough understanding when the mass is referred to as ten times a solar mass. Similarly, saying a star is 10,000 times as bright as the Sun or 1000 times larger is easier than dealing with the numbers in kgs, watts/s or kms. The scale of masses is such that they range roughly from a tenth of a solar mass for cool stars, to 40 or so solar masses at the hot end, though stars as massive as 120 solar masses are quoted in the literature without any observations to back them up. Other parts of the diagram populated with stars are less straightforward to understand but we will look at this in detail later when we study the evolution of stars.

8.3 Measuring stellar temperatures

8.3.1 The use of colour

The theoretical relation between colour and temperature came about at the start of the 20th century during the amazing explosion of physics that ultimately gave rise to Einstein and the leaders of the unfolding **quantum mechanics**. At this time, it was discovered that heated objects gave off a spectrum of radiation, called an energy distribution (brightness as a function of wavelength), which depended on the temperature of the source. The result showed itself as a shifting of this peak of radiation with changing temperature (see Figure 1-11 earlier). I've talked about heat being detected in the IR. This means that if the peak of this energy distribution is mainly in the IR you are dealing with a cool star just as the peak of a very hot star is found in the UV. Think of a barely heated pot feeling hot to your hand (IR) and looking at a pot melting in a furnace which is not only hard on the eye but will sear your skin with the heat. In principle, if we can measure the location of this peak, we can measure the temperature. But to measure a peak means that the whole energy distribution would have to be examined to see where the peak is located, a possibility that only became a reality in the 70s when the first of the observatories in space were launched. But if your aim is to measure stellar temperatures, gathering these data still takes time and every astronomer wanting to use a telescope in space (or on Earth) must run a gauntlet of assessment before observing time is granted and that is always less than what you requested! Somehow you want to mass-produce your results, leading ultimately to the question: "If the energy distribution is sampled at two wavelengths, will ***these*** results give a measure of the peak wavelength and then the temperature?" In principle, a qualified, ***Yes***. Imagine taking photographs of a star-field through blue and yellow coloured glass. What might be revealed? You will rightly think that a blue star will look brighter through the blue glass than the red star, and the red star will look brighter through the red glass. Given these observations, in principle, by taking the ratio of the two measures and converting them to magnitudes, we should be able to measure the colours on some arbitrary scale. Provided we can calibrate our observations somehow, relating colour to peak wavelength, we should get a measure of a star's temperature. Because of the limitations of the photographic plate, the only detector available at the time, this method yielded poor results. What was needed was a detector that responded to light the same way every time. That had to await Einstein's Nobel Prize winning work on the photoelectric effect—remember when light falls on some special sort of charged material called a photocathode it expels electrons related to the amount of light falling on it. (Strangely enough, Einstein received no Nobel award for the theory of relativity.) In the fifties, with the use of photomultipliers and stable electronics, the method was used to great effect providing reliable colour and brightness measurements of thousands of stars with a precision of about 1 or 2 percent. Nowadays, while observations are made through various combinations of filters, both on Earth and on orbiting satellites, the principle is the same, sample the energy distribution at a number of wavelengths to create what are called **colour indices**, calibrate these indices against temperature, and use this information to obtain temperatures from subsequent observations. In fact, those on Earth who deal with furnaces, may measure temperatures with an IR pyrometer, a device that measures the intensity of the radiation at a series of wavelengths, and calculates the temperature from these measures—this is physics in action.

8.3.2 Yet another aside

I'm sorry about all these asides, but since I was on the receiving end of all the difficulties related to being an observational astronomer, I want to mention them, much like a traveller in a previously unexplored land coming back to recount the exploration, warts and all, in some detail. Above, I mentioned stable electronics. What's that got to do with anything? We switch on our TV and it sits there for years giving us images that look the same whether the room is cool or hot or if the TV has been switched off for months and you are looking at it anew. But it wasn't always that way for those of us having to endure the noisy TVs in the 50s! The amount of light falling on a photomultiplier is small and produces a current measured in milliamps (thousandth of an amp) which is too small to measure unless it is amplified by some means. The developers of the photomultiplier thought to take the electrons or current from the photocathode and direct them to something called a dynode that also responds to electrons falling on it. The dynode produces even more electrons. Add more and more dynodes and the signal may be amplified perhaps a million times, yielding an electric current which can be easily measured. Unfortunately, at every stage, the process is affected by noise which is also amplified. If you can limit the effects of the noise by either only observing bright stars, or by cooling the detector, then you can get a reliable measure of brightness, but you don't want the electronics to create the noise. Think of turning up the volume of a radio station loaded with static. Increasing the volume doesn't help but tuning the radio to maximize what you hear will do the trick. Cooling the detector reduces the noise and this has always been a ritual feature of my experience, whether by using dry ice or some other cooling procedure. Cooling is necessary because, at low temperatures, the photocathodes don't produce as many random electrons (noise) as they would at room temperature. The electronics that control the amplification by stabilizing the voltages between these dynode things also produce noise into the system. Only when these difficulties were met, were observers able to get reliable results night after night—remember your lovely stable TV.

All those years ago, the initial measurements were recorded on paper which we measured by rulers or calibrated paper. Early in the 60s these measurements were replaced by IBM cards with the measurements punched onto them as you observed. You've heard of punched cards and computers the size of rooms! After an extensive observing run at the Kitt Peak National Observatory (KPNO) observatory in southern Arizona I had accumulated a suitcase full of IBM cards—replace the cards with books to get an idea of the weight. This was in the days before baggage was weighed on commercial aircraft, so imagine the shock when the baggage handler lifted it onto the conveyor belt. Those were my irreplaceable thesis data!

8.3.3 Calibrating colours against temperature

The calibration of colour indices against temperature is not simple and to this day has some flaws (see an extensive discussion later in Chapter 13). The method is based on what we experience in relating the intensity of a heated surface to the temperature where a moderate increase in temperature produces a huge increase in heat or energy. It turns out that energy output is related to temperature to the fourth power, thus if temperature is doubled the energy produced is sixteen times (2 × 2 × 2 × 2) the original! Don't get your wood-burner really hot! There is an additional effect that we recognize by experience, that more heat comes from a large freestanding iron stove than from a small one! That is, the greater the surface area, the greater the amount of radiation emitted. Combining both effects means that the total radiation coming from any source above absolute zero is related to its temperature and the size of the emitting area. Thus, the total energy emitted by a star is related to its temperature ***and*** its radius. If we could measure the radius of a star and also measure its total energy then we'd be able to calculate its temperature. That's precisely what we do to derive the Sun's temperature when we measure the solar constant or the amount of energy measured over a square metre at the Earth's surface (see discussion in Chapter 4). The problem is the difficulty in directly measuring a star's radius or diameter in arcseconds because stars are only seen as points of light. Remember, the discussion in Chapter 2 on speckle photometry and in using telescopes in combination? Under these conditions it ***is*** possible to measure the diameters of stars directly in arcseconds (discussion follows later). Given this information, coupled with observations of the energy distribution, it is possible in principle to calculate the surface temperature of the star in question. You may think that the distance comes in somewhere but it doesn't because in manipulating the equations involving radius and brightness both involve the distance so that in the calibration the dependence on the distance drops out. This is the calibration that ultimately provides the relation between colour and temperature. A problem resides in the hot young stars because there are very few of them compared to the cooler stars. There is a distribution of stellar masses that peaks somewhere below one solar mass, and most of the hot stars by chance are at huge distances, facts that put some uncertainty into the calibration at the hot end.

There are other complications related to calibrating temperature and colour. The actual formation of the spectrum in the atmosphere above the star's photosphere alters the ***shape*** of the energy distribution from which we obtain the temperature. Because of the lines formed in a star's atmosphere, we can learn a lot about the star but these lines alter and mask the peak of the radiation so that it doesn't look like what we see in Figure 1-11. This masking occurs because the absorption of radiation modifies the way the light escapes from the star and in doing so alters the shape of the energy distribution one might associate with a given temperature. Secondly, stars hotter than about 20,000 K peak in brightness in the UV beyond the reach of Earth-based observatories, and because of this, the Earth-based colour of the star becomes an inconclusive measure of a star's temperature. But even if data are obtained in the far UV from a spacecraft, these data are useless because of the plethora of lines that are found there. A similar situation occurs at the cool end where stars below temperatures of 3000 K peak in the IR, which we can't see with visible light. One characteristic of stellar spectra is that the number of absorption lines due to atoms and molecules increases as we look at cooler stars again masking the overall shape of the energy distribution that we are trying to use as a measure of the stellar temperature.

Regardless of the complications caused by the masking of an underlying spectrum by absorption lines, the data really need to be taken above the

Earth's atmosphere with a satellite dedicated to the task. This is currently underway with the recent successful launch and deployment of the ESA satellite called Gaia, something I'll talk about in the last chapter. Gaia is a game-changer involving the measurement of many stellar parameters for a ***billion*** stars! Measuring diameters of cool stars should be a far easier task since there are many cool stars close by for us to study. On the other hand, they are much smaller, making a direct observation of their size more difficult.

8.3.4 Use of spectra to determine temperature

We might be able to classify a star but how do we assign a temperature to it? Strangely enough, even today, the link between a star's colour and its spectral type still is uncertain, such that a temperature scale based on a star's luminosity, size and temperature may differ from that based on the spectrum of a star (I'll return to this in Chapter 13). In this latter case, given a spectrum, one attempts to match the observation with one generated in a computer using model stellar atmospheres in a manner similar to how atmospheric physicists create model atmospheres and match their results against data involving pressures and temperatures over the Earth's surface, and so make weather forecasts. At least where I live, the meteorologists do a fine job of predicting the weather. In the astronomical world, astrophysicists have been wrestling with the difficulties of writing realistic software that can predict an observed spectrum. The task is hugely difficult because any modelled spectrum can only be based on lines for which the physics is known and there are millions of them. In my own experience in analysing Vega, in any part of the spectrum I might be interested in, there are unknown lines or lines that appear abnormal in terms of expected strength. Hence, we know that the fundamental data embedded in the software are incomplete. When I first got UV data from the International Ultraviolet Explorer (IUE) that was launched in the 70s I found about half of the lines I "saw" were unidentified. The situation is much better now, a fact that makes a spectrum produced in a computer much more realistic. There have been problems in matching temperatures found in this way to those found in the methods outlined above. The whole process of reconciliation was not helped when the star originally chosen as being the pillar of the astronomical community, Vega (α Lyrae, the brightest star in the constellation Lyra), turned out to be a very unusual star and anything but normal. I've devoted years to its study and, with colleagues, have found it to be a distended, highly rotating star and we are looking down onto its pole. In Figure 7-1 it was selected as an example of a slowly rotating star.

Appearances can be deceiving! So much for a nicely behaved spherical star we'd assumed to be normal in every way! In this context it is Murphy's Law in full flower!

Talking about Vega, my connection with this star goes back to the first time I saw a spectrum reeling out on paper from an actual direct observation made at the McDonald Observatory located in the mountains above Fort Davis in West Texas. In this case, the spectrum showed up at the back end of a spectrograph which used a slowly rotating grating to project the spectrum sequentially onto a photoelectric detector and thence to a roll of chart paper. Acquiring data in this way is called **spectrophotometry** and what was almost impossibly time-consuming then, is routine these days with digital detectors. Each night this star was observed by Bob Tull—a master instrument/detector designer at the U of T (Austin)—for use as a basic calibration star for the night's observing. In this case we could see the spectrum and measure it with a ruler. But pause now to picture it. A spectrum two metres long—or longer—scrolling out on paper with an undefined wavelength scale showing lots of lovely details (lines) and no practical way to render the data suitable for a computer—even if we had the software to process it further. If it had been possible, and the data published, my labours in recent years with Vega would have been far easier because I needed (still do) those data that I'd watched decades earlier every night we observed. In those data, the hydrogen lines rolled out beautiful and wide—succulent even—whereas, in recent years, I've been forced to piece together the spectrum using three segments from an echellè spectrum to cover the 10 nm width of Hγ, a hydrogen Balmer line at 434 nm. Balmer was the scientist who discovered the hydrogen sequence displayed in Figure 7-2 and 7-4. As I write these words 55 or more years later, I see a completed circle in my astronomical studies.

In addition, the way the various elements come and go along the spectral sequence has never been definitively defined. Broadly speaking, the lines we see come and go because the various elements are a product of the temperature. Figure 8-3 shows schematically these variations. It is worth noting the lines due to hydrogen (H in the figure) that peak at about 10,000 K. The line is weak at the hot end (O5) because the lone electrons orbiting hydrogen nuclei have largely been stripped from the atoms so that transitions (remember the analogy of a ball falling down stairs producing a line at each step) within the atoms cannot form a line. At the other end, the temperature is too low to initially "excite" or lift the orbiting electrons to states where they can form a hydrogen spectrum. For the A stars at 10,000 K, everything is just right to produce the strongest hydrogen spectrum.

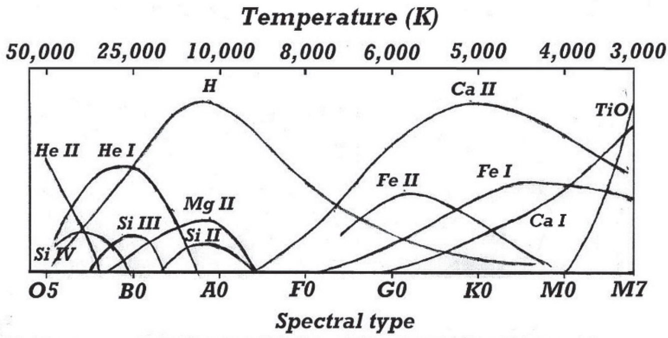

Figure 8-3. A schematic diagram showing how the elements come and go as a function of temperature. If you look at the helium (He), iron (Fe) and calcium (Ca) spectra you'll see how the more energetic atoms are excited (He II, Fe II, Ca II). They peak at some temperature and decline just as the low energy parts of each spectra (He I, Fe I, Ca I) grow and peak and decline as the electrons that form the spectra are not excited because of the cooler temperatures (see text). Credit: Redrawn from Carroll and Ostlie, 1996, Modern Astrophysics. Modified by the author.

Let's look at the spectrum of helium (He). But first, what's with He I and He II? Helium has two electrons orbiting its nucleus with which to form a spectrum and the same arguments I've used to explain how He I lines are formed are relevant for the other elements. In this diagram it looks like He I is strong at 25,000 K but the temperature is insufficient to excite the second electron that "orbits" lower within the atom so He II does not appear. Once the temperature increases (near O5) the electron in the outermost level has been lost so the atoms cannot form a He I spectrum but the electron in the lower level gets excited and so forms what we call a He II spectrum. At the cool end (lower than spectral class or spectral type G) the lines of iron (Fe I and Fe II) predominate, but the pattern is the same. Similarly, with calcium (Ca I and Ca II).

Much of the difficulty has been in the sheer labour of measuring the "strength" of a given line in a spectrum. Here the word strength refers to how black a line appears in a spectrum. It's non-scientific, but if you get my meaning that's just fine. The difficulties in calibrating photographic emulsions, that is converting the densities on the emulsion into intensity, made analysing spectra in any sort of quantitative way extraordinarily time-consuming, though at the DAO the operation was as slick and as accurate as it could be. Now we can avoid all this difficult measuring by obtaining a digital spectrum and directly match it with what a computer model predicts and go from there. But then there are huge limitations on what the models can predict for, while there is a wealth of fundamental atomic data out there, some of it is of insufficient quality to make a reliable comparison between theory and observation. The "buts" seem endless… If I dwell too much on what is still unknown in the realm of stellar astrophysics, I get indigestion.

With the use of CCDs, it has been argued that the issue about the difficulties of photography is irrelevant, just get a new digital spectrum of the pesky star observed photographically. Most of the time this statement is true, but not always. Masses of archival photographic material residing in vaults (plate storage places) are still available for processing and re-processing and can be replaced by simply taking another picture or spectrum, but what if the star is variable, or there are two stars whose orbits change with time and you've just got to have those data? Then the historical record becomes important, just as it is important to compare the image of a star that blew up eighty years ago with a current image to see if the filaments of glowing expanding gas have, over that time, expanded or not. The digital detector has removed many difficulties—and created a few of its own I may add—but now, the main emphasis is away from stellar astronomy to the intriguing world of our expanding universe and a potential new accelerating force leaving the study of stars to a few stalwart souls.

It is worth commenting here that, for me, the transition to digital data was not without its difficulty. For example, contrast the appearance of a spectrum presented as it is in Figure 7-10 against the two-dimensional display in Figure 7-8. In the case of a digital spectrum you get a line shown as a tracing such as in Figure 7-10 whereas I find it easier to see a spectrum as shown in Figures 7-7 and 7-8. It was quite different and for me it was much easier recognising the presence of another spectrum in a spectrogram (a photographic spectrum) than displayed in a CCD presentation. For me, the digital image is more difficult to work with and I rely on mathematical techniques to detect the other component when it is not blatantly obvious.

This comment takes me back to the evening when, staying up late, I'd spread out a tracing of a spectrum of a double-lined binary star on the kitchen table. The dips caused by the presence of two blended spectra were obvious but I could not measure them. In that moment I decided to work only with digital data and my research took a massive U-turn leading me to develop my own digitally-based software aimed at directly dealing with what had earlier frustrated me, giving rise, years later, to the analysis shown in Figure 7-10.

8.4 Stellar size

8.4.1 Direct methods: Interferometry. Two eyes well-separated!

Is there a way we can measure the size of a star directly? The answer to this is, ***Yes***. Even though the stars are only ever seen as points of light, it is possible to measure the diameters of some of the nearest stars in thousandths of an arcsecond (mas). In addition, if we can measure the distances to these stars then we can get their size in km. Earlier in the previous century Michelson(1852-1931), of Michelson-Morley fame, the physicists who made the first “modern” measurements of the speed of light in 1881 (recall that Roemer had an excellent stab at it in 1676!), measured the diameters of a few giant red stars by fitting an interferometer on the Mt Wilson 100-inch, located north of Los Angeles. This is the telescope that Hubble used in his superb investigations of galaxies, leading to his discovery of an expanding universe. I’ve talked about interferometers earlier for they are very important as they give us a view of the universe we cannot get from a single telescope. You may recall their advantage is in increasing our ability to see detail. The interferometer Michelson put on the end of the 100-inch effectively made the telescope a 20-foot (6 m) telescope, or a larger telescope than the famous Palomar 200-inch (5 m) though without its light-gathering power. This configuration enabled him to measure the sizes of a few stars in fractions of an arcsecond. Because measurement of the distance to these stars were available, the measured diameters yielded the size of the stars. Among the sample, they found that two stars I’ve mentioned before, Betelgeuse, the bright red star in Orion, and Antares, its equivalent in the tail of the Scorpion, were gigantic. Their sizes were so huge that if either star were placed within the solar system, they would extend outward past the asteroid belt! Strangely, it is easier to measure their diameters directly, than their distances because they are so far away—though Gaia is changing all that. But their diameters vastly exceeded that of the Sun, thus confirming what had been known since 1914 when Hertzsprung and Russell had divided the stars into two types (dwarfs and giants) based on the observation that some stars of equal temperature had vastly differing absolute magnitudes and hence vastly different sizes.

The Very Large Telescope Interferometer (VLTI) at Cerro Paranal in northern Chile has imaged many stars including an image of Antares as the “sister” of Betelgeuse in the constellation Scorpio (Figure 8-4). The Figure Caption says it all!

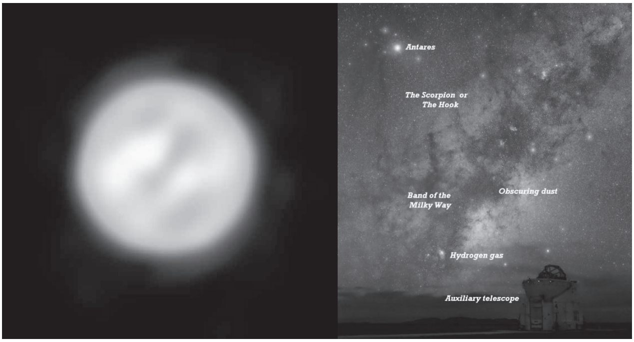

Figure 8-4. See Centrefold. Left panel. Using ESO's Very Large Telescope Interferometer, astronomers have constructed this remarkable image of the red supergiant star Antares to match previous observations of the other giant star Betelgeuse in Orion. Right panel. Antares place in Scorpius and the Milky Way. Note that Antares looks white in this image. Credit: Left panel. ESO/Ohnaka. Right panel. ESO/Tafreshi. Annotated by the author.

8.4.2 Lunar occultations

If the Moon passes in front of a star, we have another way to measure stellar diameters. Under these circumstances the Moon cuts across the light from a distant star in about 70-80 milliseconds producing what is called a **diffraction pattern** as the edge of the Moon interferes with the light waves from the star. This technique is called a **lunar occultation** (examples are shown in Figure 8-5). Diffraction is the reason we can hear sound around the side of a building or see waves spreading around the end of a jetty and into an otherwise protected harbour. To measure a star's diameter, we compare the observations with what we'd expect if the star was a point source. The amount of the difference from what was expected of a point source gives a measure of the size of the star in fractions of an arcsecond. There are complications in that the edges of a star are not as bright as the centre. This is the limb darkening effect I've mentioned in the discussion of the Sun and which can be seen in the early picture of the transit of Mercury (Figure 3-5), but the effects are secondary. Also, the edge of the Moon is not smooth—think of the mountain chains we see there.

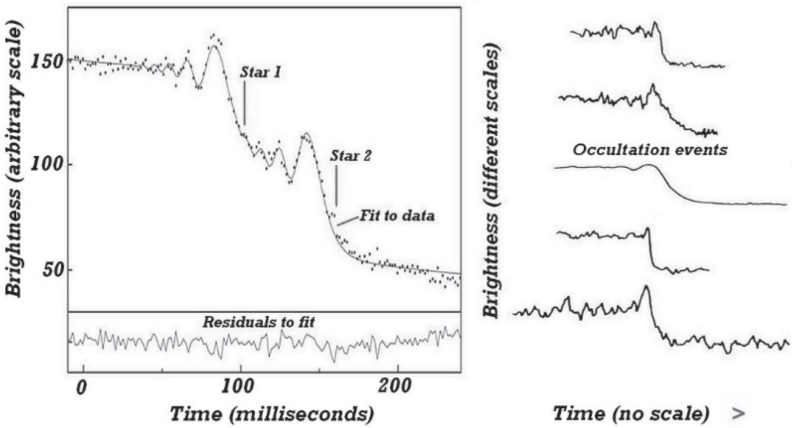

Figure 8-5. The left-hand panel shows the occultation light curve (dots) and best fit (solid line) for HD 160257, at the time, a newly detected binary. The times of geometrical occultation of the two components are marked. The right-hand panel shows a series of occultation results where no other star is detected. The wiggles are caused by the Moon crossing over the diffraction patterns inherent in the occulted star. Credit: Left panel. Richichi, et al., 2013, AJ, 146, 59. Right panel. Morbey and Hutchings, 1971, PASP, 83, 156.

In addition, if the Moon occults a binary star, then there is a potential to measure the separation and sizes of the component stars. In this situation each star produces a diffraction pattern but at different times depending on the orbital positions of the stars with respect to the Moon's limb (see Figure 8-5, left panel). (A diffraction pattern is what we see when we look at a distant light. It appears to have a series of rings around it.) If we later determine the orbit of the binary, we can say what the actual separation of the two stars was at the time of the occultation which then gives the separation of the two stars in km. These events, while rare, are much anticipated because, in addition to the stars, they allow diameters of planets to be measured. In pre-Voyager days (spacecrafts Voyager 1 and 2) this was important, because the planets are at vast distances from us and their diameters are always in need of revision. When the Voyager 2 spacecraft flew to Uranus the astronomers already knew that the planet had rings, not because they'd been seen directly, but because of an occultation event involving a star. When it was forecasted that Uranus would pass in front of a star, astronomers then monitored the light from the star as Uranus got closer, knowing that the timing of the disappearance and re-emergence of the star at Uranus' limbs would give a measure of Uranus' diameter provided the precise location of the passage of the planet across the distant star was known. Remember the planet does not necessarily pass exactly over the star's equator. Similarly, with the Moon. But with Uranus, a series of dips were seen just before the starlight was blocked out and then again shortly after the star reappeared. These dips indicated that the planet had rings and the timings of the various dips gave the ring's diameters.

8.4.3 Indirect methods

I've talked about how the stellar brightness is dependent on a star's size and temperature. We know that the relation which relates the total luminosity (L) of a star to its radius (R) squared (R^2 or $R \times R$) and temperature (T_e) to the fourth power T_e^4 (or $T_e \times T_e \times T_e \times T_e$) is $L = R^2 T_e^4$. So, knowing a star's distance from its parallax, we can calculate its true brightness (L above), and then if we can get the star's temperature via its spectrum, we can derive its radius. As noted earlier, Michelson made the first direct measurements of stellar sizes in the 20s, his numbers verifying earlier calculations that indicated that some stars were enormous, hundreds of times the size of the Sun. At the other extreme, among the white dwarfs, the sizes are like those of the Earth! For the **red giants** and supergiants the sizes are so great compared to the Sun that they really need to be described in terms of the Earth-Sun distance! In contrast, ***along*** the main sequence, the stars range in size from about 10 times that of the Sun to about a tenth that of the Sun. A star's position in this diagram uniquely defines its radius. The situation is best summed up in Figure 8-6 seen here where a series of lines of equal radius are drawn across the H-R diagram. Note here that the H-R diagram gives intrinsic or true luminosities and through the spectral types, and hence the temperatures, the radii can be determined.

In summary then, the sizes of the stars measured by these various methods reveal a cosmos where the stars range from objects the size of the Earth to near the size of Jupiter's orbit! A factor of a hundred thousand! As stars evolve, they get bigger, some explode, and others shed their outer parts until we see an object the size of the Earth yet with a mass that of the Sun. We need to find the links between these stars.

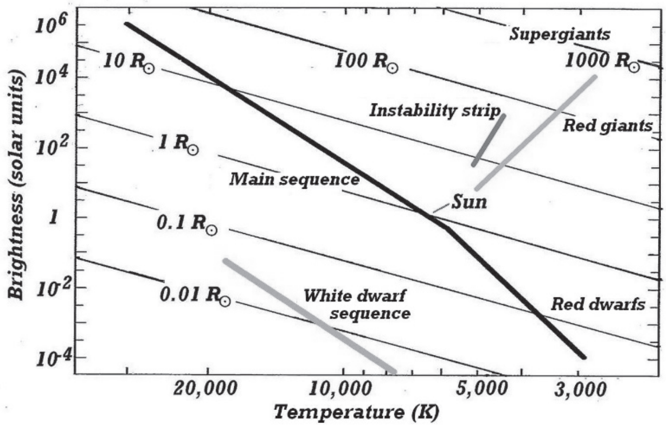

Figure 8-6. Shows how the radii of the stars vary throughout the H-R diagram. The **Cepheids** and **RR Lyrae** variables stars (see Section 8.6) fall within the **instability strip.** Note, along the main sequence the star's radii vary by about a hundred in size, whereas off the main sequence the range is more like 100,000. Credit: Drawn by the author.

8.5 Stellar densities

Now we have some knowledge of masses and radii we can consider the densities in the H-R diagram. Almost everything we imagine about the universe is extreme: the distances are unimaginable, the unbelievable numbers of stars in a galaxy and similar numbers of galaxies. The **stellar densities** are no different. To get an idea of the scale of things have a look at Table 8.1 below. The first two entries, the density of the universe and that of intergalactic space, must be considered to be in the realm of speculation.

For completeness I've anticipated later results for neutron stars and black holes. When the Sun becomes a white dwarf with a radius the size of the Earth its density will be about a million times that of water. In contrast, the Sun, when it evolves to a red supergiant with a radius extending to the Earth's orbit, would have an average density of a few ten-thousandths that of water! Thus, the range in densities the Sun will experience through its lifetime is a staggering 200 million—give or take a few digits. One might imagine that the processes that formed these objects were quite extreme, yet pulsars, the remnants of supernovae explosions, are denser yet by a factor of another 10 million! My mind reels at these numbers, maybe that's why I keep just a little removed from the picture. I can only stay boggle-eyed for a while before my personal operating system closes down!

Table 8.1. Some comparative mean densities

Source	Density (kg/m^3)	Density (Water=1)
The universe	$\sim 10^{-26}$!	$\sim 10^{-29}$
Interstellar space	$\sim 10^{-20}$*	$\sim 10^{-23}$
Red supergiant	~0.02	~0.00002
Red giant	~0.2	~0.0002
Water	10^3	1
Sun	1400	1.4
White dwarf	$\sim 10^9$	1 million
Neutron star	$\sim 4 \times 10^{17}$	~0.4 quadrillion
Atom nucleus	$\sim 2 \times 10^{20}$	~200 quadrillion
Black hole	$\sim 4 \times 10^{20}$	~400 quadrillion

~ Means an approximate value
! Highly speculative
* We don't know how much dark matter is in interstellar or intergalactic space

8.6 Variable stars

Over the years, variable stars have been linked to specific parts of the H-R diagram. For example, the Cepheids, stars that vary over periods of weeks and months, are only found in one part of the diagram. Similarly, with RR Lyrae variables, stars which vary over hours to a day, are only found in another part of the H-R diagram. However, the RR Lyrae stars and the Cepheids all lie in an area of the H-R diagram called the instability strip which is approximately noted in Figure 8-6. This instability strip encompasses a diverse range of stars from white dwarfs to giant Cepheid stars though the white dwarf extension is not shown in Figure 8-6. All pulsate. To the right of the strip indicated in Figure 8-6 are stars in red. These are giant red stars called Mira variables mentioned earlier that vary over 100s of days and are the stars that amateurs often measure and professionals are happy for this because they provide a service likely unattainable by the professionals because their observing depends on getting access to telescopes. In contrast, the amateurs can go outside to their observatory, and with equipment often as good as ours, do the job. The diagram is useful in that it shows the relative sizes of the variables. Cepheids and Mira variables are giants about 100 solar radii whereas the RR Lyrae stars are less than 10 solar radii. These observational facts obviously tell us something about stellar evolution, that in their passage in the H-R diagram, most stars share a common experience leading them to becoming a particular type of variable. Ultimately, we'd expect a study of these stars, both observationally and theoretically, to be crucial to verifying whatever theories we come up with.

8.7 Abundances: What are stars made of?

8.7.1 The origin of the elements

As we have seen, stars are primarily made of hydrogen, the fundamental building block of the universe. Next comes helium. Why helium? The temperature of the initial universe was a million trillion trillion degrees ($\sim 10^{36}$ K), give or take a few zillions—if the notion of temperature has any meaning at all—and then cooled rapidly to a temperature of 10 billion K when hydrogen could easily fuse, and with that fusion other elements more massive than helium should form. Helium is created from hydrogen. The problem is that to make helium, tritium is required. Tritium (a hydrogen atom plus two neutrons) had not only to form but be stable long enough to join with deuterium (hydrogen plus one neutron) to form a helium nucleus. Then helium would have to interact with other helium atoms to form heavier elements. But the scene was so hot that tritium did not last long enough before being broken up by the intense sea of highly energetic gamma rays—another way of saying electromagnetic radiation. Therefore, no helium formed. Because of this, the universe had to cool to temperatures near a billion K when stable fusion reactions began and helium was readily formed. Hydrogen, deuterium (of heavy water fame during World War 2), and helium were created, along with some other lighter elements, lithium and beryllium. Conditions were such that the hydrogen was converted to produce 25% by mass of helium. Thus, the building blocks of the later universe of stars and galaxies were hydrogen and helium, with a few lighter elements produced during the creation of helium. These elements formed in a very small window of time between about ten and a thousand seconds after the Big Bang happened (it all sounds ridiculous doesn't it?).

Why didn't the other elements form, the temperature was plenty hot enough? The problem is that all the elements are built up from the least massive to the most massive, and the temperature progression for this to occur is from cooler to hotter. The earlier universe did not go from cooler to hotter—it was red hot at the start! More complex nuclei making up the rest of the periodic table such as uranium and lead require more and more extreme conditions for their creation but the universe was ***cooling***, leaving the extreme conditions behind. It is like trying to build a house starting with the roof with no supporting walls. It can't be done. This was the debate in the 50s when nuclear physicists were trying to make the elements in the early universe and against that, in the stars, in a process called nucleosynthesis, fighting it out to see who was right.

So out of the fireball that was the beginning, came hydrogen and helium along with traces of other light elements. Anticipating the later discussion on evolution, some elements are produced in the stars in a normal course of evolution while elements heavier than iron are created during a supernova explosion and dispersed into the interstellar medium by an explosive event that immolates the star. From this enriched material new stars formed. If you look at very old stars ("born" when the universe was young) called **Population II stars** (you may well ask why not **Population I stars**?), you might expect them to show rather simple spectra because they are made of material that might have been hardly processed in the stars at all. On the other hand, thinking about the Sun which is "only" 4.5 billion years old, within a universe 14 billion years old, there has been plenty of time for the Sun to have formed out of material that was once inside other stars. Yes, the very flesh of us comes from elements made inside stars. The question is, "How are the elements created in the stars and then released to the interstellar medium?"

8.7.2 Measuring abundances in the stars

In attempting to make abundance measurements astronomers face difficult tasks. Techniques have been developed over the years which sort of work but to really know what elements are in a star you must model a star's spectrum with very complex software. For example, look at the representative spectra shown earlier (Figure 7-4). The B0-B5 stars show no trace of the iron that is so prevalent in stars like the Sun, but this does not mean that iron is absent. It means that the star is so hot that the iron atoms do not have the configuration of electrons zipping around them to show the lines in the visual region. But if you look in the UV you might see many lines due to iron. It works the other way also. Look at the Sun, where is little evidence for helium (though it was found in the Sun before it was discovered on Earth) which is plentiful in the universe. You ***can*** see it but it doesn't look anywhere near as abundant as it should. The issue here is simply the physics of the atmosphere and the fact that at high temperatures some electrons, the ones responsible for a spectral line, are stripped from the nucleus and hence produce no lines. At cooler temperatures, the temperature is insufficient for the atom to absorb energy (photons) so that it ***can*** result in a line. Going back to the analogy of lines forming as a ball falls down a set of stairs, for hot stars most balls miss the stairs and only a few land on them to bounce down, whereas for the cool stars, the balls only get a little way up the stairs, if at all. In addition, at the computational end, there are deficiencies in values of the fundamental parameters, related to what is going on in an atom, that are needed to really do a bang-up analysis. These data must come from measurements in laboratories or from demanding calculations. Computational difficulties are extreme and too few people are engaged in this type of research though those that are, are very well organized—they have to be.

8.8 A summary: Our bits and pieces

From the foregoing discussion we've got an overview of the universe of stars. We find that the stars are of all sizes ranging from that of the Earth (and smaller but more of this later) to that of the Earth's orbit and larger. While their sizes differ dramatically, their masses are confined to a more restrictive range defined by a lower limit at which a star can be considered a star rather than a planet, and at the upper end where stars cannot form because the radiation pouring forth from an embryo star overwhelms the force of gravity trying to create it. These limits range from about 0.1 times to 100 times the mass of the Sun (not that we've directly measured a star more massive than 40 solar masses—I think). Establishing the reality of the upper end is very difficult because of the paucity of massive stars, and therefore binary stars, making it difficult to extend the mass-luminosity relation into that domain. The third parameter, the temperature, ranges from about 3000 K to somewhere about 40,000 K and in this case I'm at a loss to give an imaginative example. For a given temperature near that of the Sun at 5800 K we find stars of similar temperature but 100s of times larger. Among the stars in the larger stellar neighbourhood we find stars like the Sun that are termed dwarfs and the larger ones described as giants and supergiants. In contrast, there is one nearby star (the companion to Sirius) as massive as the Sun but only the size of the Earth. It's all a bit weird.

"But hold, there's more!" to quote a common infomercial. Stars come equally in pairs and in triplets as well as larger conglomerates such as young groups of stars called galactic clusters containing hundreds of stars and very old groups called globular clusters containing hundreds of thousands of stars (see examples in Figure 9-1). These groups of stars hold the key to uncovering the evolution of the stars and provide a partial proof of our theories. But the clincher is in binary stars within these clusters which give us the hope that we can measure the masses of stars and thus tie down the reality of any evolutionary theory we may come up with. Given masses for cluster stars (or Cepheids), astronomers have values to compare against those predicted by theoretical modelling.

We don't see evolutionary changes in real time, the exception being a supernova which turns out to be the ultimate endpoint of one path of evolution—there is another exception that I'll talk about later. The timescales and processes are only revealed by extensive computation. I hesitate to mention that the results come from a computer, as that implies that there is some omnipotent computer out there that produces these results. What a computer spits out is as good as what is put into it. This depends on the programmer who codes the theoretical equations the astrophysicist has derived, while the data feeding the program come from the variety of sources I've touched on up to here. The data needed for the comparisons involving, mass, luminosity (brightness), temperature and radius are hard to come by. Given them, we are now at the point to see what paths various stars may take in the future using theoretical models for predictions and observations for their confirmation.

Frontispiece. The Spirograph Nebula. Credit: NASA and The Hubble Heritage Team/(STScI/AURA)

Figure 1-1. Left panel. The star cluster, 30 Doradus, an **open or galactic cluster** made up of young, hot blue stars with an age in the millions of years. The right panel shows a star-forming region with the unlikely name Mystic Mountain. Credit: Left panel. NASA, ESA/Sabbi (ESA/STScI). Right panel. NASA, ESA/Livio, and the Hubble 20th Anniversary Team (STScI).

Figure 1-2. A view of the Milky Way from Cerro Paranal, Chile. The Magellanic clouds, the smaller (**SMC**) and larger (**LMC**), are our nearest galaxy neighbours, identified by Magellan on his circumnavigation of the globe in the early 1500s, are to the right of the dome. The galactic centre is down to the left of the dome. Credit: ESO/Tafreshi.

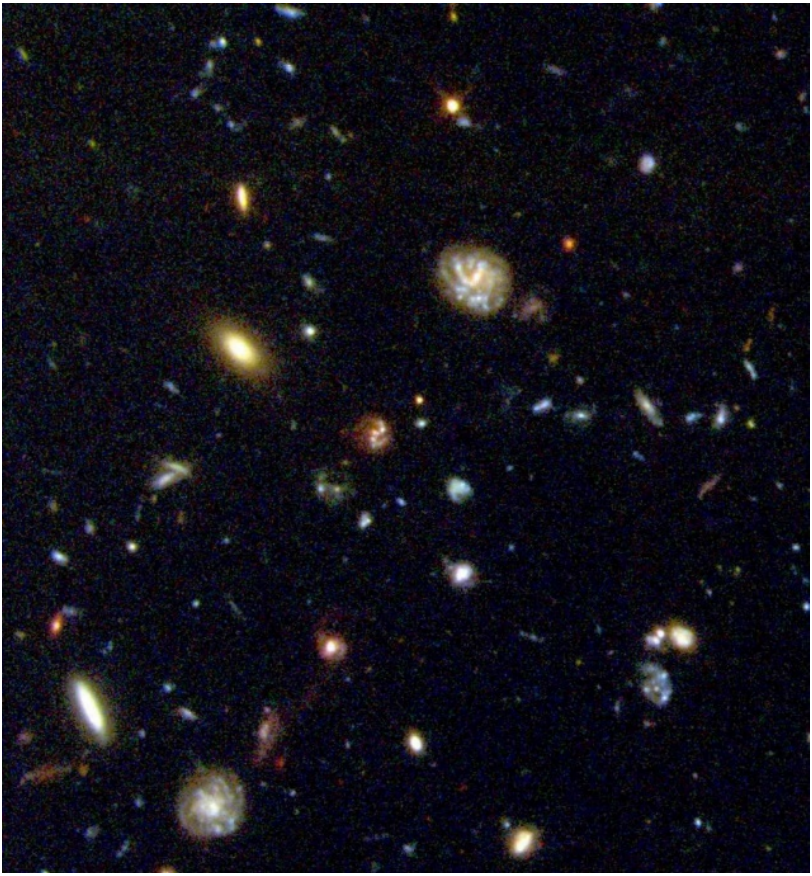

Figure 1-5. A scene 13 billion years ago, less than a billion years after the Big Bang. This exposure, taken piecemeal over 11 days by the HST, reveals galaxies soon after matter “condensed” out of energy at the dawn of galaxy formation. There is no “empty space”. The images of galaxies displayed here are undefined or long, like toothpicks, just as we are undefined in the womb in the early months of our mother’s pregnancy. Credit: NASA/HST

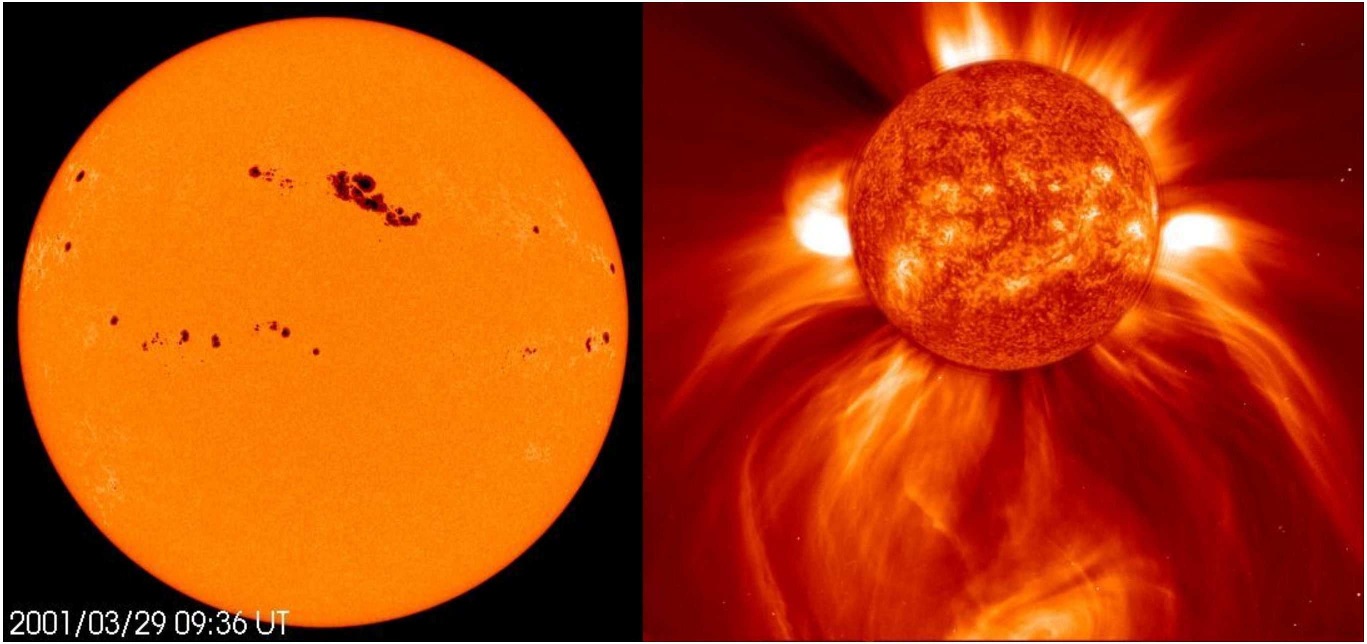

Figure 1-6. Two images illustrating how our benign-appearing Sun seen through a piece of yellow glass (left panel) is different when we look at it through hydrogen light (right panel). Notice the vast plume of hydrogen, termed a **solar prominence**, erupting from the edge of the Sun while the left-hand panel reveals a Sun spotted with **sunspots.** Credit: NASA/HST.

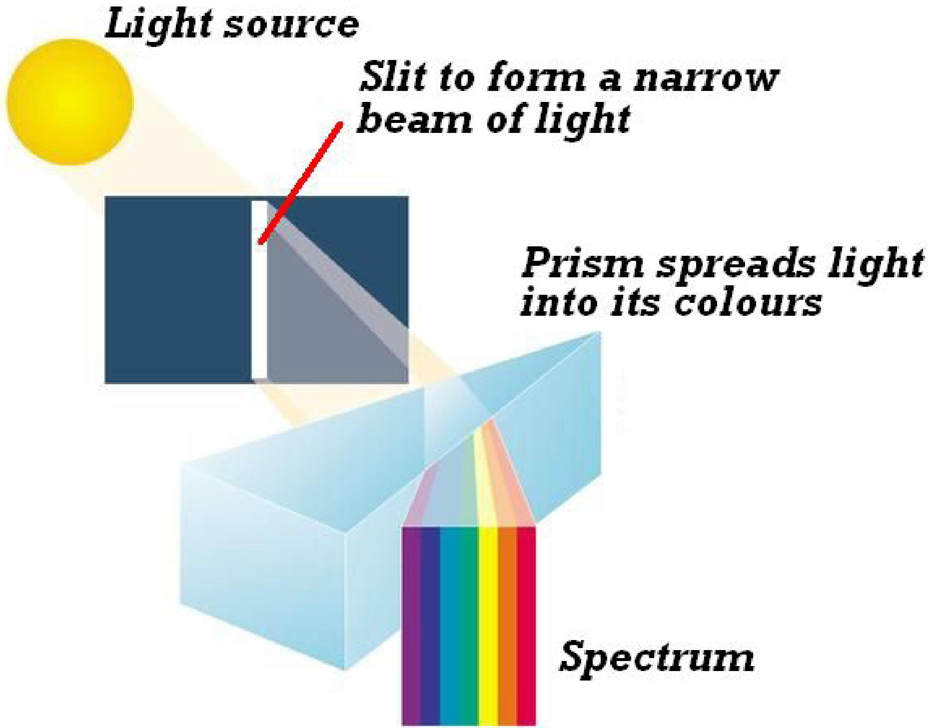

Figure 1-7. An example of a spectrograph using a **prism** to spread the light out into its colours. Credit: ESO. Modified by the author.

Figure 1-8. The Milky Way forms an arc high above the radio antennas of the **Atacama Large Millimetre/submillimetre Array (ALMA)**. This arc is caused by the panoramic view of the camera. Credit: ESO/Duro.

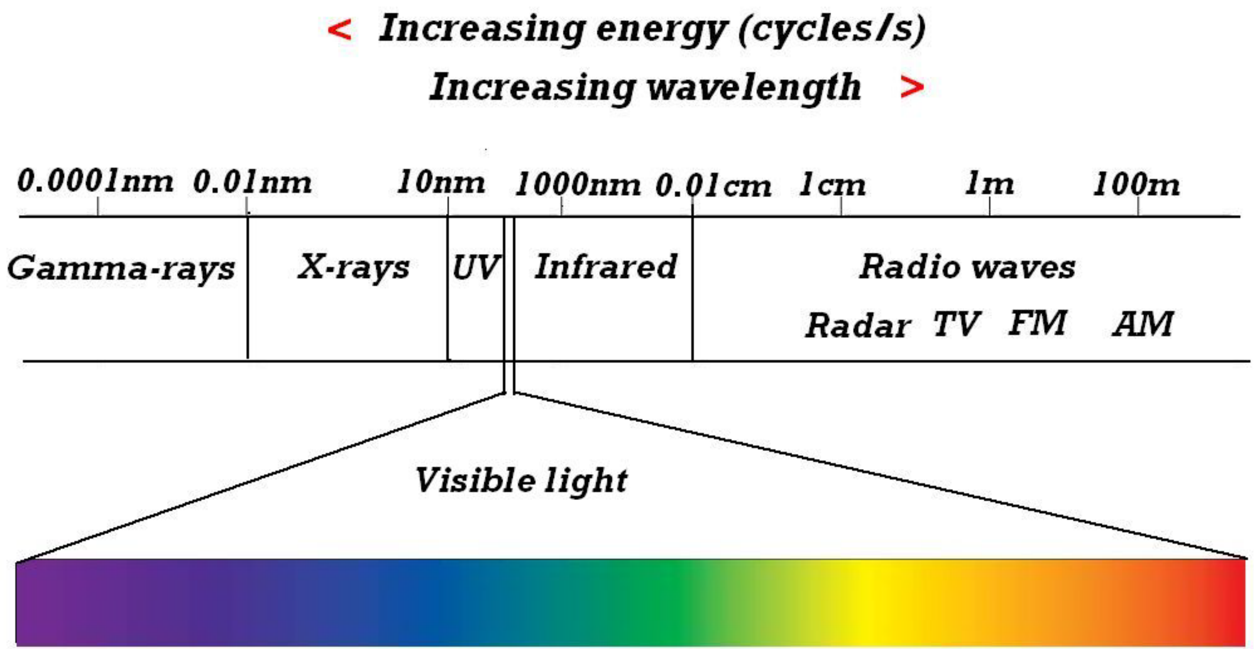

Figure 1-9. The electromagnetic spectrum. Note the narrow band of wavelengths that we traditionally view the universe. Now observations with new detectors launched on satellites allow us to observe the whole of the displayed spectral range (see Figure 1-10 also). Note that the wavelength scale is displayed in **nanometres** (**nm** or 10^{-9} m) rather than astronomers traditional Angstroms (10 A is 1 nm). Credit: Image from the Web. Redrawn and modified by the author.

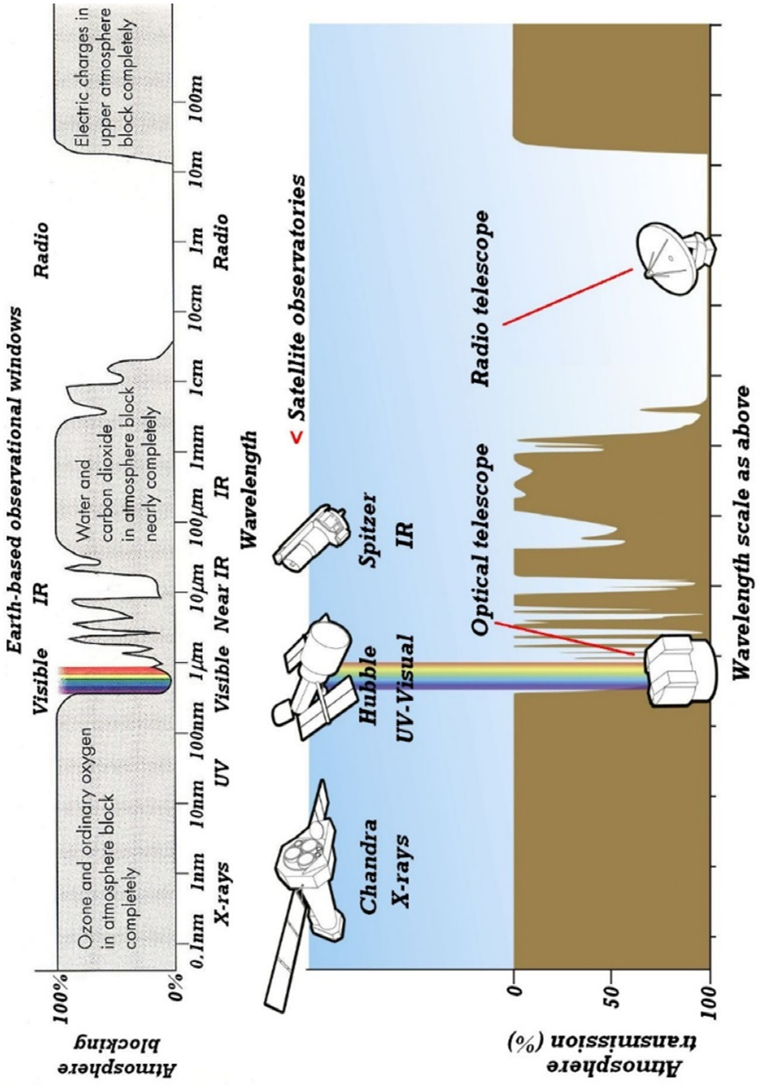

Figure 1-10. The electromagnetic spectrum and the Earth's blocking atmosphere. The upper panel shows the blocking effect of the Earth's atmosphere on the electromagnetic spectrum. A glance at the lower panel reveals that our view of the universe, if limited to the visible and radio regions, leaves out most of the electromagnetic spectrum. Airborne observatories fly at high altitudes to reach part of the IR. Radio telescopes "see" right through the Earth's atmosphere. It is not surprising that since space-borne telescopes have opened the whole of the spectrum, a picture of the universe is forming that contains many surprises. Credit: NASA/ESA Modified by the author.

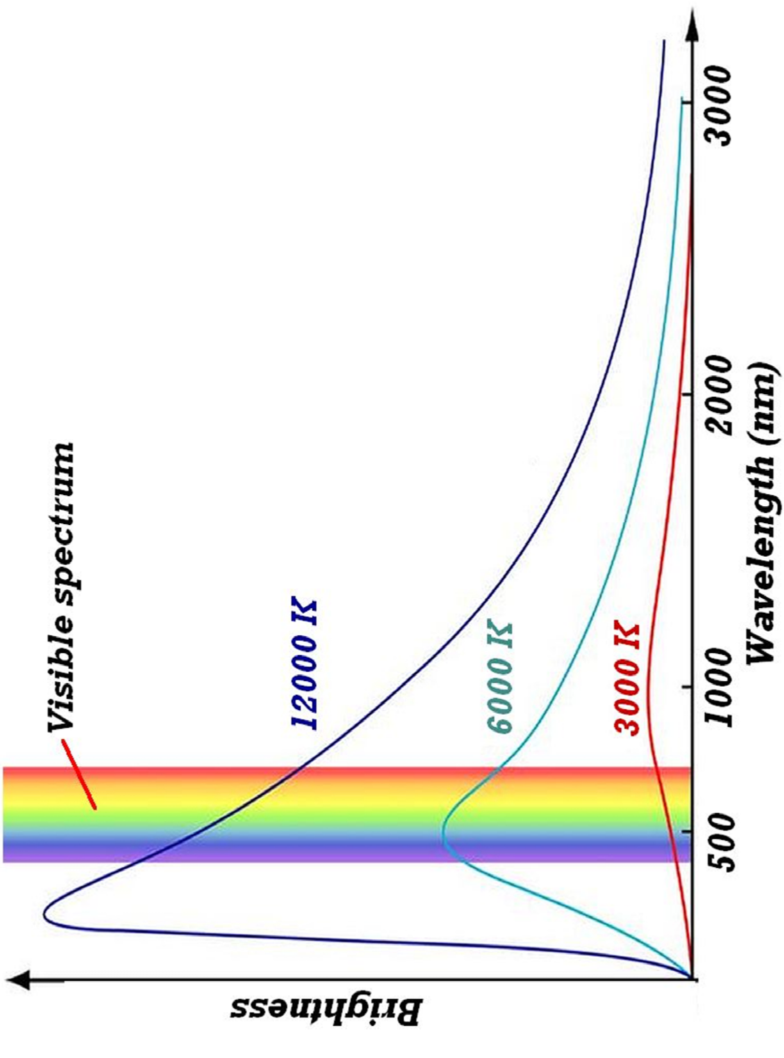

Figure 1-11. The distribution of energy within a heated body is shown for three temperatures. As the temperature increases, the peak of the energy moves to shorter and shorter wavelengths, or to higher frequencies. Our eyes are attuned to the region of the spectrum peaking at approximately 6000 K, which is the approximate temperature of the Sun's surface. The wavelength scale is given in units of a billionth of a metre. Credit: Unknown source. Modified from the Web by the author.

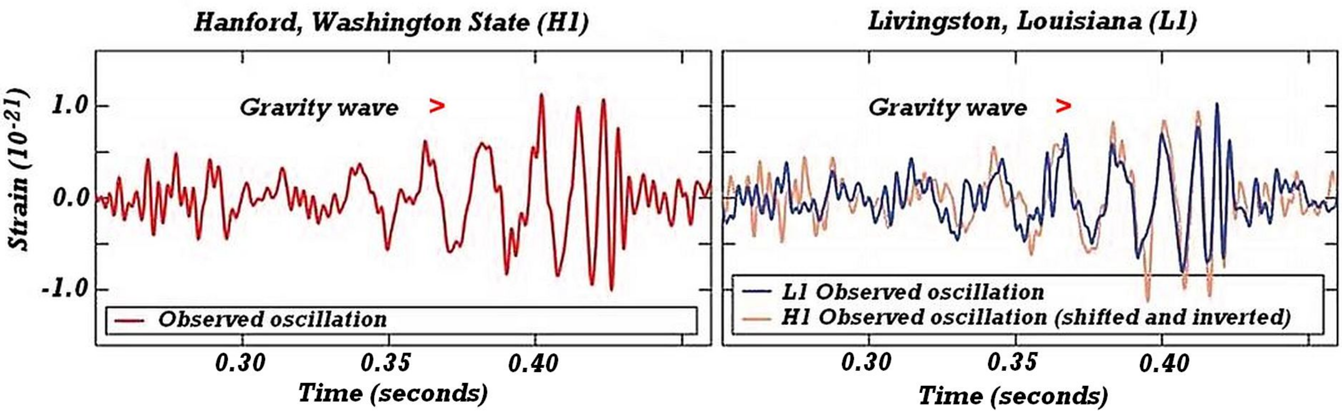

Figure 1-13. The original wobbles of gravity that confirmed the existence of gravity waves. The two sites, one in an old nuclear facility in Washington State and another in Louisiana, recorded the same signal with a 7 millisecond delay in Washington State. Gravity travels at the speed of light so we'd expect a perfect coincidence in time as well as the "wobbles" to be in perfect tune (excuse the pun!). I can't describe the vertical axis called "strain", it's akin to what we feel when we pull against something, but whatever it is it is unbelievably small! The final few vibrations are called "chirps". Credit: Abbott et al., 2016, PRL 116, 061102-1. Modified by the author.

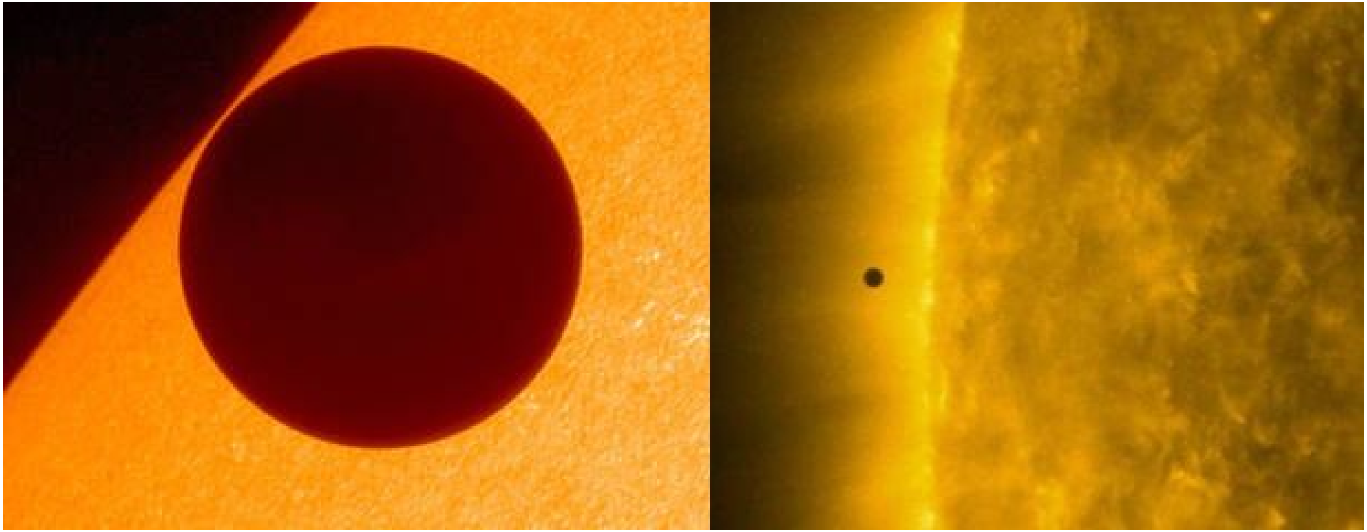

Figure 3-5. The beginning of two modern transits of Mercury. In the left panel, as imaged by the Japanese Spacecraft **Hinode** in 2006, Mercury is seen against the limb of the Sun. The limb looks darker because we are looking at an angle into it and into the cooler upper **solar atmosphere**. The effect is called **limb darkening**. The right panel shows Mercury about to begin its transit in November 2019. The image is from a NASA movie. Credit: Left panel. **JAXA**/NASA. Right panel. NASA.

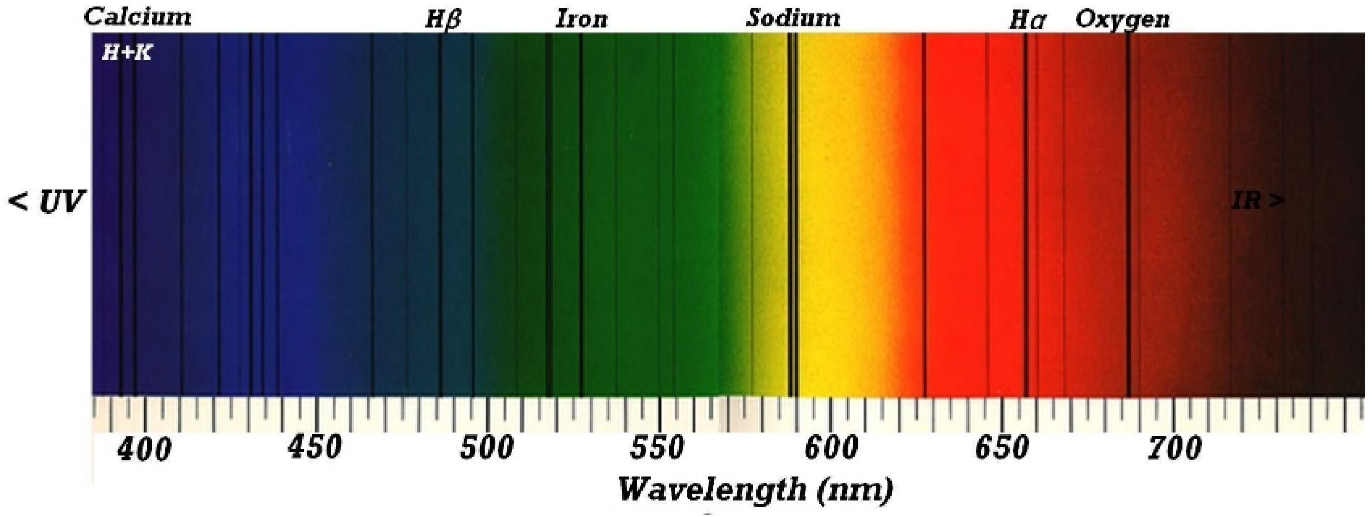

Figure 3-7. A stylized spectrum of the Sun showing the lines originally recognised by Fraunhofer. The colours represent the radiation caused by it simply being hot—the photosphere. The dark lines (**absorption lines**) result from light being absorbed by specific elements in the Sun's atmosphere. Some are identified along the top (H refers to hydrogen). The lines due to sodium are what gives our streetlamps the orange glow. By studying these lines, the astronomer can tell what elements are in the stars. Credit: Many sources, annotated by the author.

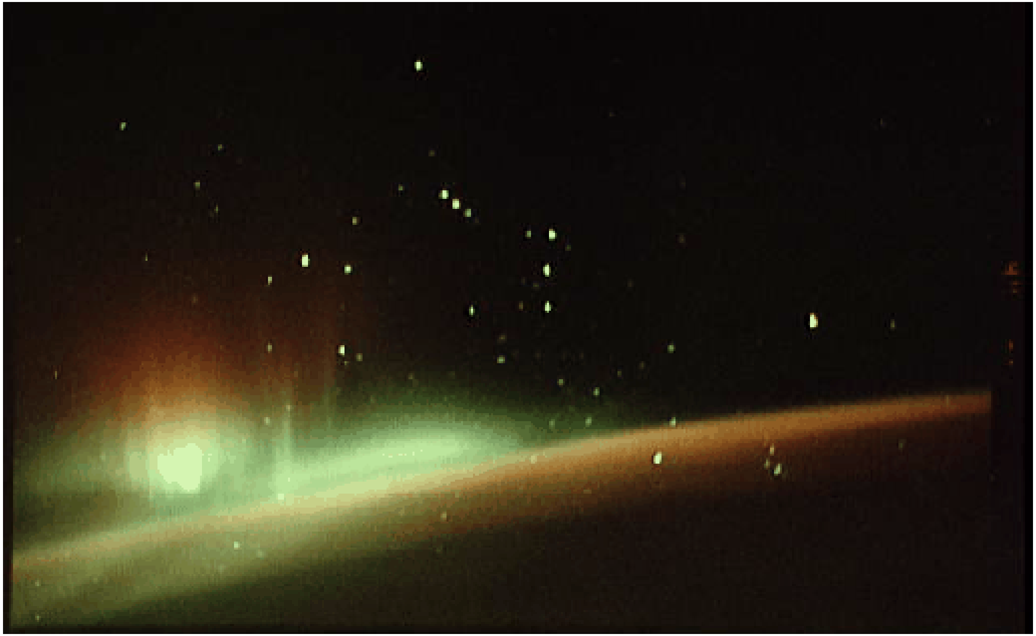

Figure 4-2. The Aurora Australis, the Southern Hemisphere name for aurora, seen from the Space Shuttle Endeavour. The colours of these lights indicate the element that is affected by the incoming solar wind. The bright spots are stars in the constellation Orion, slightly elongated because of the time exposure and the motion of the shuttle. The three stars aligned vertically in the middle represent the belt of Orion. Angling down from the left are three stars forming “Orion’s Sword”. The large fuzzy central object in the sword is not a star but a gaseous cloud called the Orion Nebula. Credit: NASA

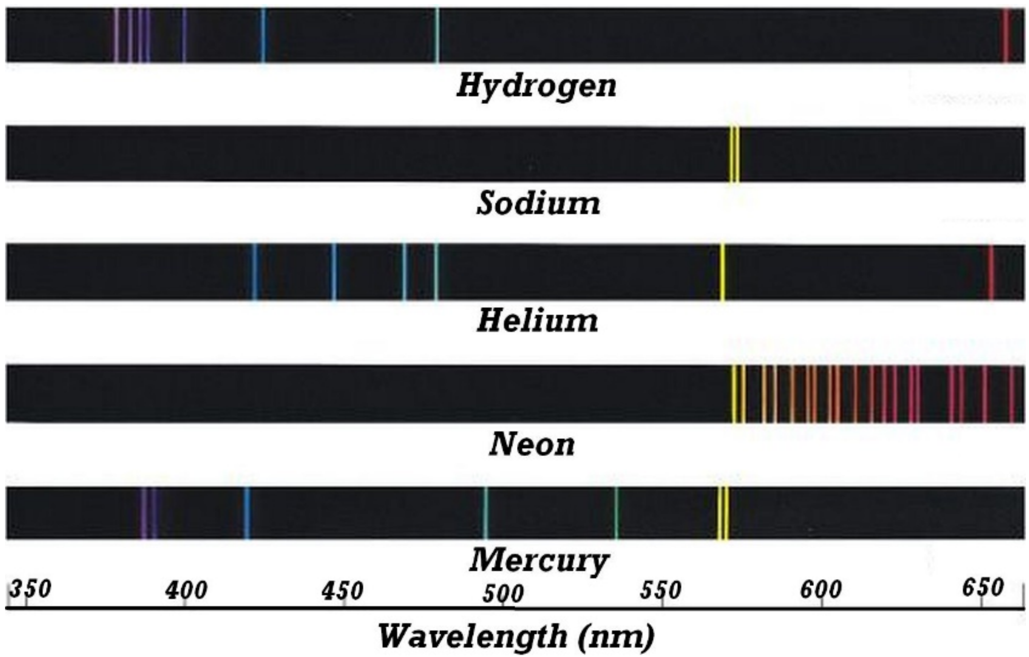

Figure 7-2. Emission lines characteristic of some elements. The sodium lights, which are familiar to us, radiate in the yellow-orange region of the spectrum. The now outmoded mercury lights shine in the blue from the lines to the left in this figure. Note that these are emission lines whereas in the stars it is the atoms of these elements that absorb light flowing outwards from the hot photosphere. Credit: Source unknown. Adapted by the Author.

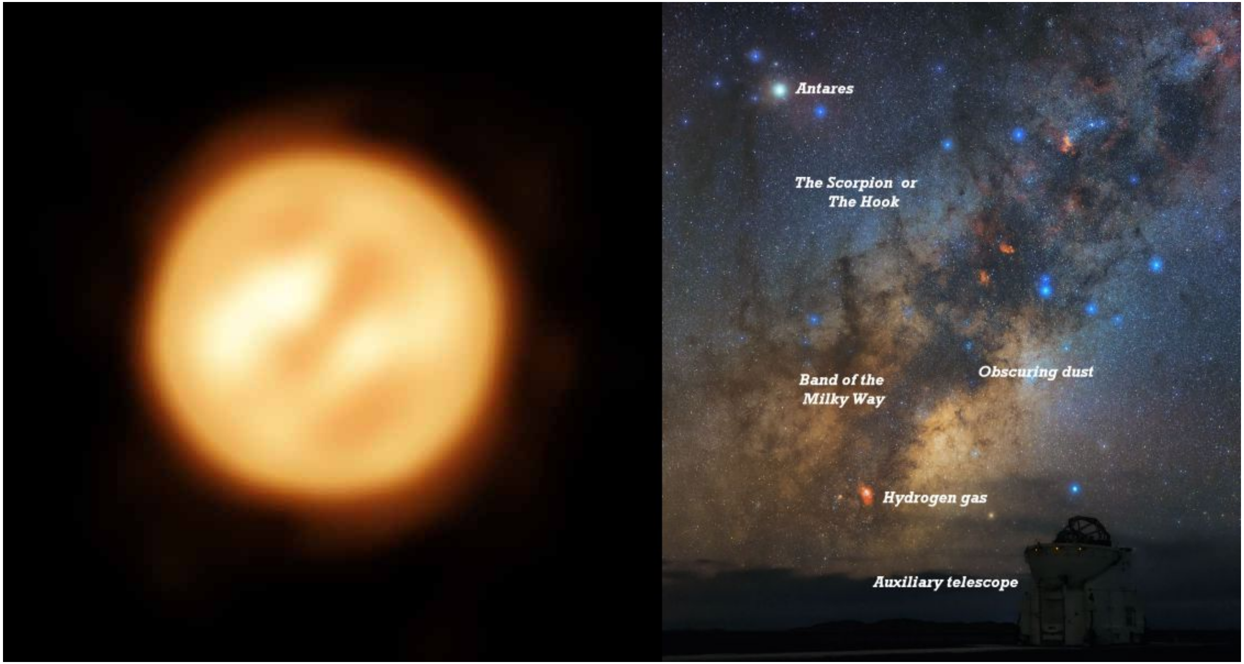

Figure 8-4. Left panel. Using ESO's Very Large Telescope Interferometer, astronomers have constructed this remarkable image of the red supergiant star Antares to match previous observations of the other giant star Betelgeuse in Orion. Right panel. Antares place in Scorpius and the Milky Way. Note that Antares looks white in this image. Credit: Left panel. ESO/Ohnaka. Right panel. ESO/Tafreshi. Annotated by the author.

Figure 9-1. A fine example of an open or galactic cluster Messier 7 (leftmost image) and the star-rich globular cluster Messier 4 (rightmost image). M7 is a very young cluster because of the obvious presence of hot blue stars. M4 is a very old cluster containing evolved red giant stars. Credit: ESO.

Figure 9-3. Two interacting spiral galaxies where the gas gravitationally drawn out from each of them spawns star formation. The blue threads linking the two galaxies come from the light of young, hot stars birthed from the interaction and resultant clumping of the gas under the effects of gravity. The radiation from the stars forces the gas away leading to other collisions and more star formation. Credit: ESO/Muñoz.

Figure 9-8. The effects of reddening on starlight are beautifully revealed in these pictures of two obscuring dust cloud. Around the edges of the clouds you can see the stars appear red, just as distant headlights appear red in a heavy dust storm. The unreddened stars are between us and these clouds. By observing the stars in three colours UV, blue and yellow we can largely correct the observed colours for reddening as it is called. Credit: ESA/Hubble, ESO.

Figure 10-1. This image, called "The pillars of creation" must be regarded as one of the iconic pictures of the 20th century. It shows a mass of stars forming within interstellar material that is the home to future glowing bodies we know as stars. It is thought that all stars formed like this within cocoons of gas and dust. Credits: ESA/Hubble.

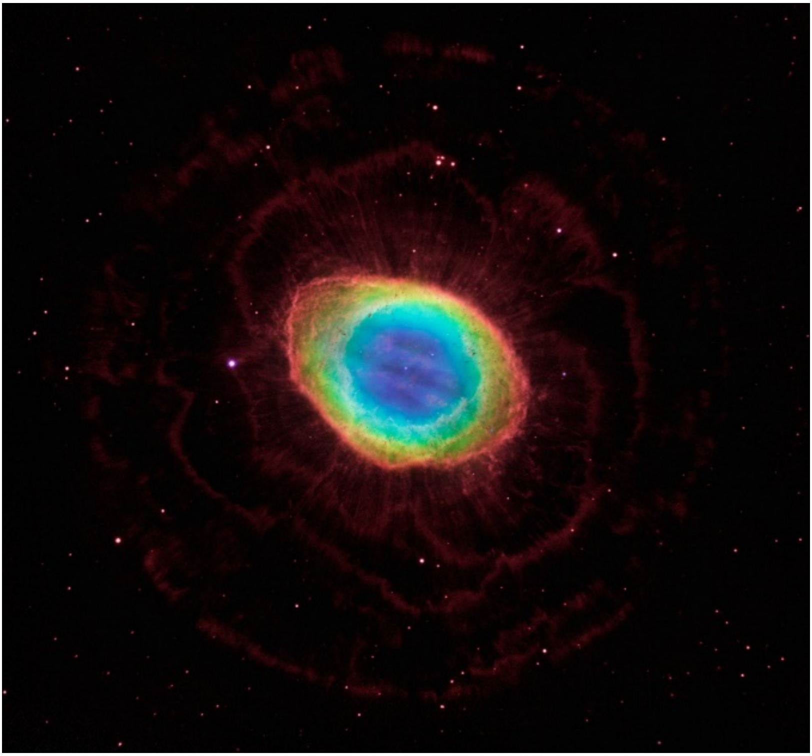

Figure 10-6. The Ring Nebula in Lyrae. Look carefully outside the main image to see remnants of other explosions dissipating into space. Credit: ESA/Hubble.

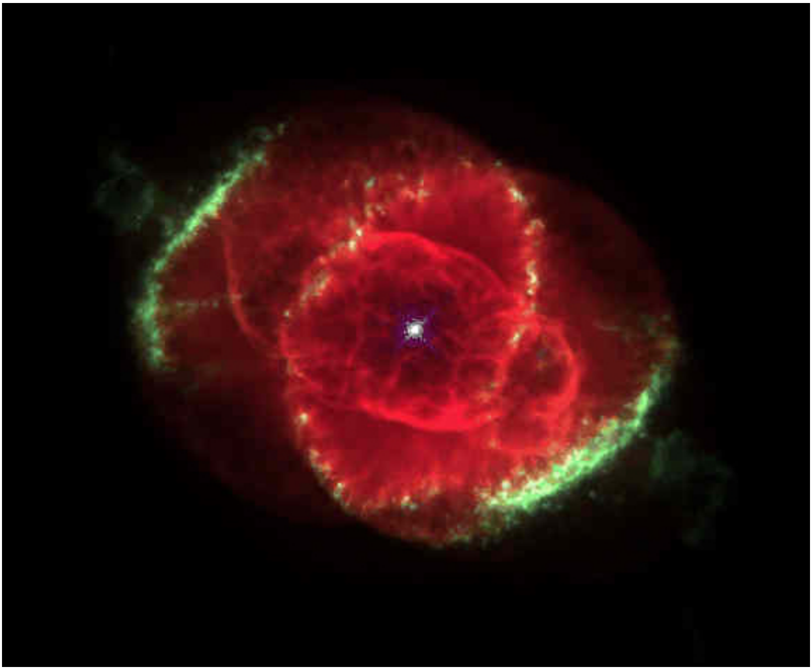

Figure 10-7. This image of the Cat's Eye Nebula shows a blue-white star in the middle of rings of glowing gas. This is the exposed core of the star whose surface temperature could be 100,000 K. At this temperature, the photons, the packets of energy produced at the surface of the star, not only blow away the star's atmosphere but also excite the atoms in the surrounding rings of gas causing them to glow. The colours are specific to each of the excited elements comprising the gas—red is hydrogen gas and green is oxygen. The varying sizes of the rings show that the atmosphere has been expelled at different times over intervals of hundreds of thousands of years. Credit: ESA/Hubble.

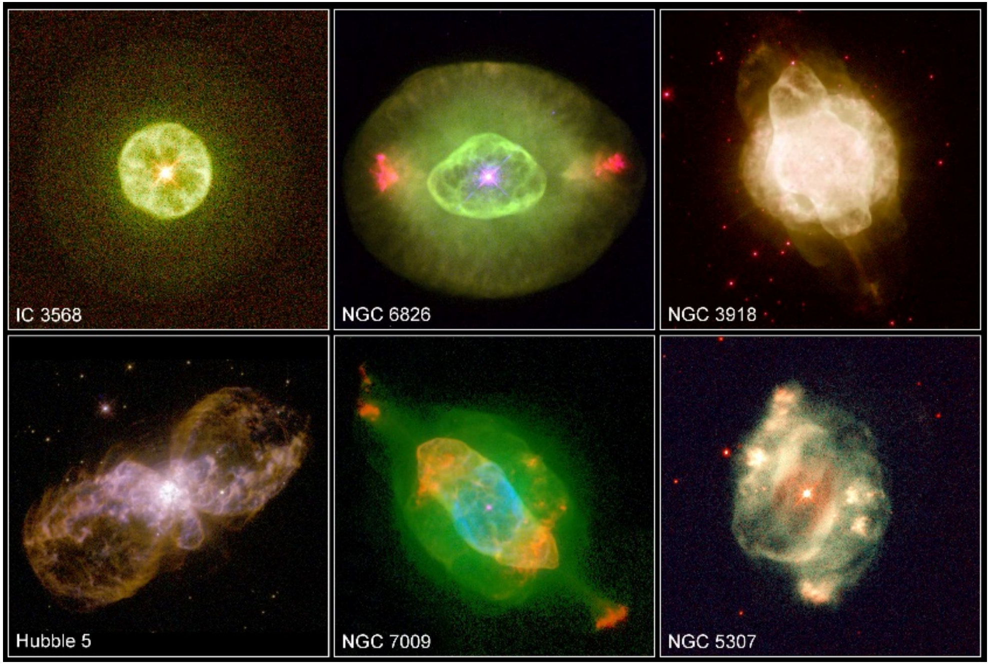

Figure 10-8. A gallery of planetary nebulae showing the varied structure they present. On some of the images you can see rings of differing size illustrating that the atmospheres were ejected from the star in separate incidents. The dramatically differing shapes are thought to result from systems in which two stars are present. There is no general analysis that can be used for these quite different nebulae and each must be investigated individually. Credit: ESA/Hubble/Bond and Balick.

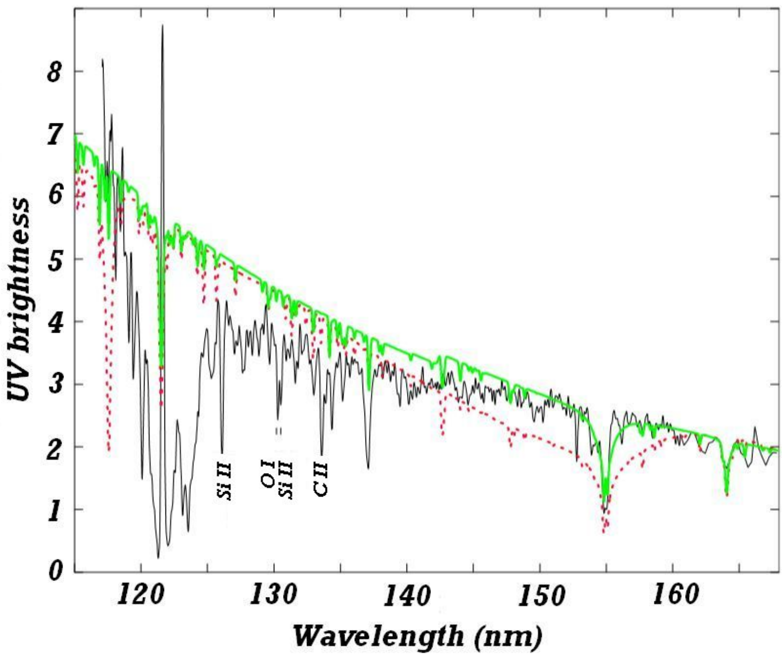

Figure 10-9. This is a spectrum of a planetary nebula's central star. The green line is an attempt to match theory with these observations for a star of 70,000 K—the red data is a failed fitting attempt at 50,000 K. Note that the green line is rising at the shorter wavelengths and if this star is "only" 70,000 K it would peak at about 43 nm, way off to the left, thus there is no way to conclusively judge this star's temperature by this fit (which looks pretty good) except we know that it is very hot. Credit: NASA/ESA/Jacoby et al., 2017 ApJ, 836. 93. Annotated by the author.

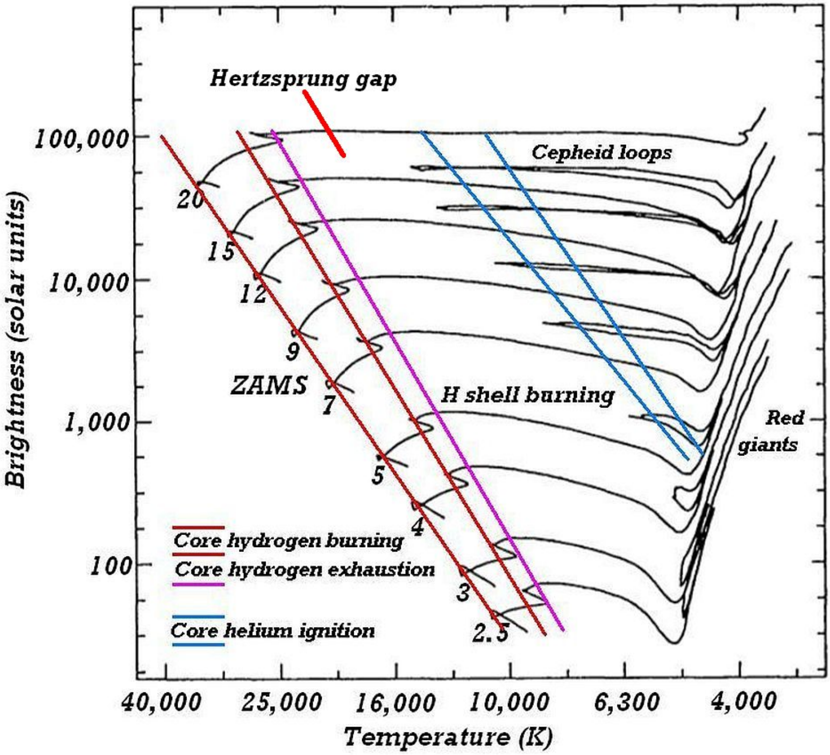

Figure 11-1. Displays a theoretical H-R diagram showing the evolutionary paths of massive stars. The colour-bounded areas delimit hydrogen burning in the core, core **hydrogen exhaustion** and contraction and helium ignition in the core. Credit: Schaller et al., 1992, A&AS, 96, 269. Modified by the author.

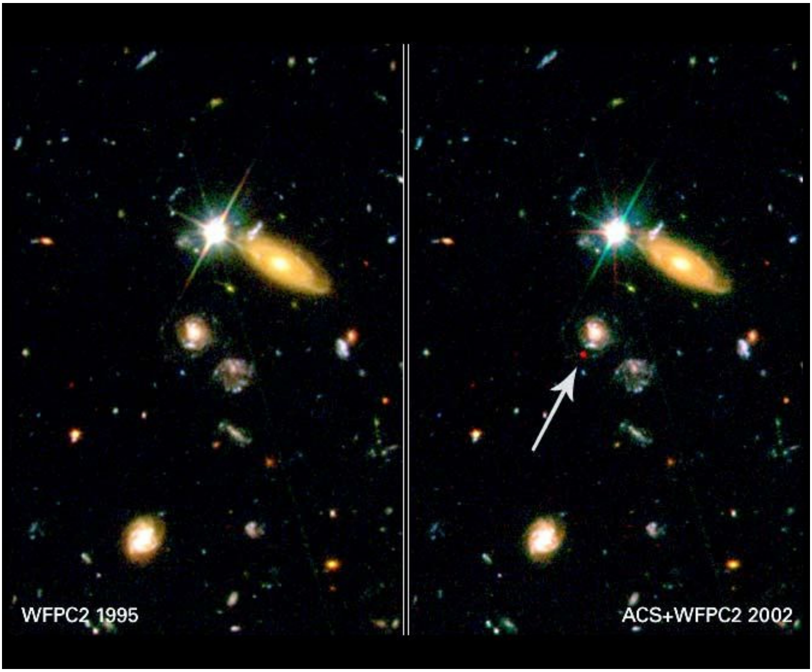

Figure 11-6. A supernova in a distant galaxy. The left panel shows a galaxy with the supernova missing and the right panel shows the supernova as a red object. The bright image towards the top is a star in the Milky Way. Almost every object visible in these frames is a galaxy! If you want to garner an idea of infinity think about this statement. Credit: NASA/HST.

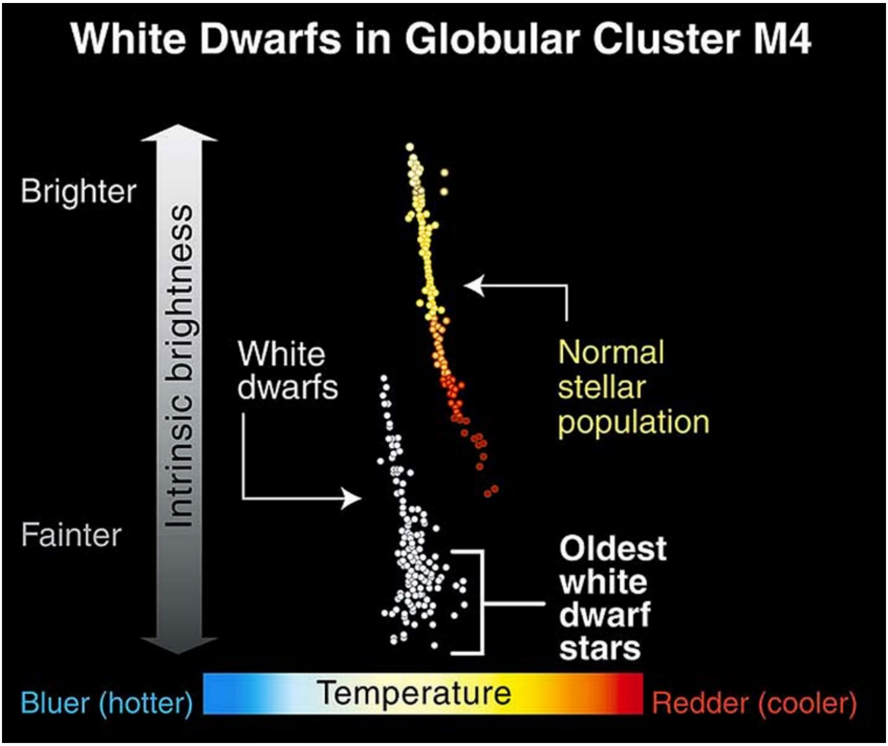

Figure 12-1. Shows the relation between the white dwarf sequence in M4 and the globular cluster's main sequence.It is the lowest part—and superficially—the least interesting part of this diagram but it holds the key to determining the age of the universe! NASA/ESA/Field.

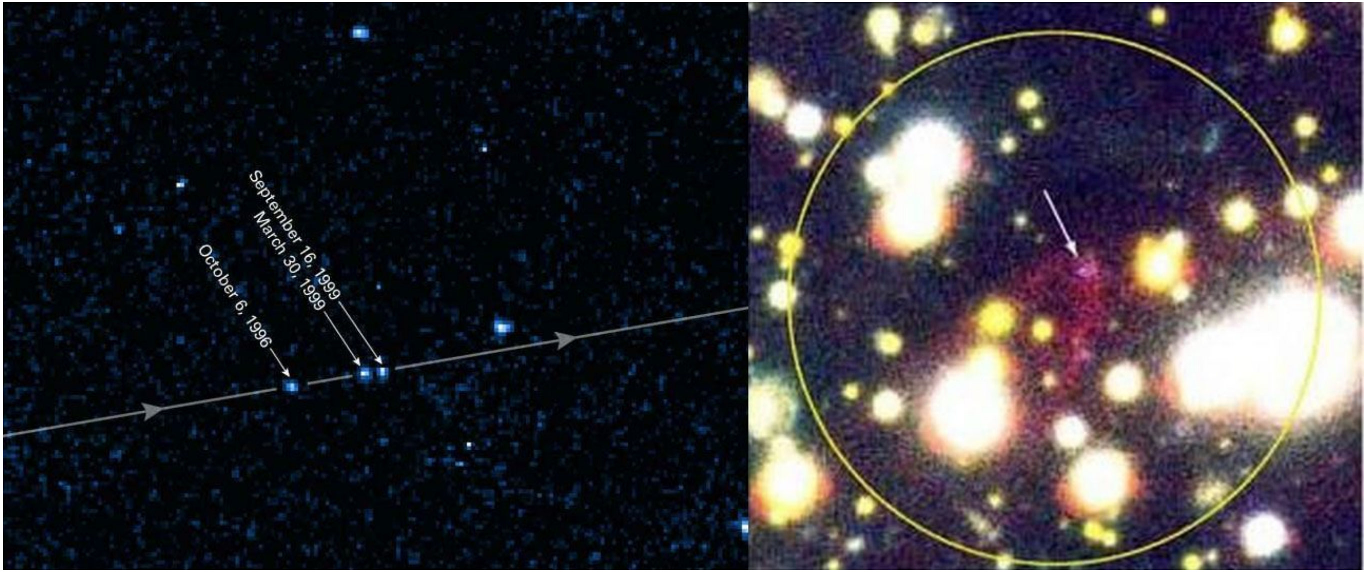

Figure 12-5. Lefthand panel: The rapidly moving neutron star RX J185635-3735 captured by the HST. Righthand panel. The same object, imaged by the VLT, showing the bow wave in red resulting from a neutron star interacting with the interstellar medium. Credits: Left panel. NASA and Walker (SUNY). Right panel. van Kerkwijk (Institute of Astronomy, Utrecht), S. Kulkarni (Caltech), VLT Kueyen (one of the 8.2 m telescopes), ESO.

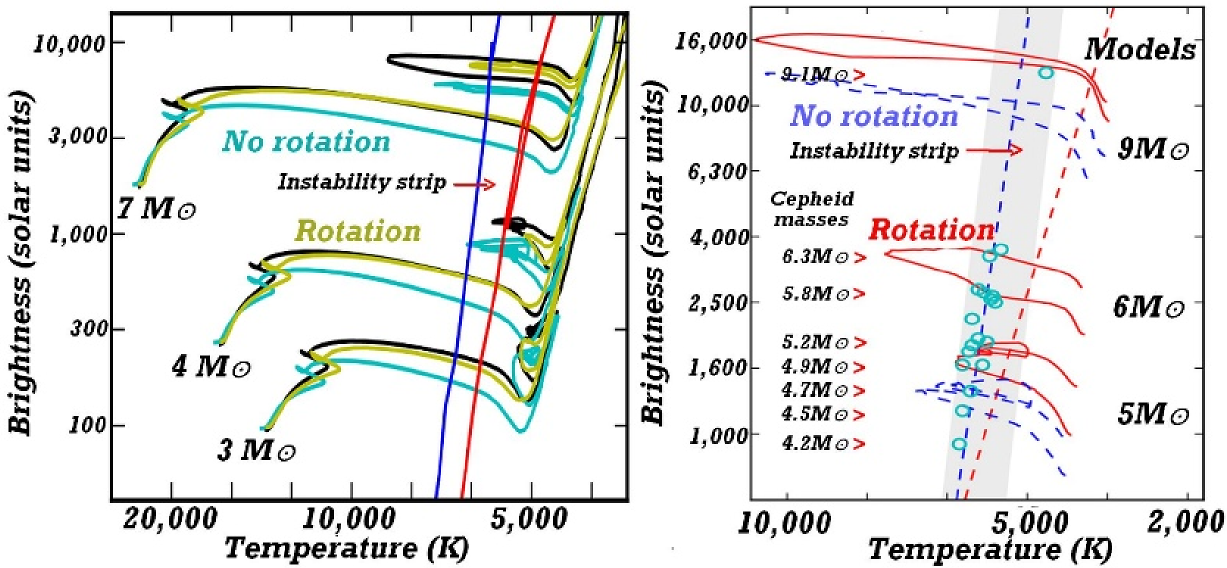

Figure 13-10. Left panel shows the effects of rotation on evolution through the Cepheid loops. Notice how the rotational tracks (yellow-black lines) sits above the non rotating results (green line). Right panel. Cepheids with measured masses plotted as cyan open circles onto the blue loop portions of evolutionary tracks. Tracks corresponding to models rotating at about 200 km/s are shown in red to the right. Non-rotating tracks are shown in blue. The stars and the instability strip (shaded area) are nicely encompassed by the loops. Because the full evolutionary tracks are not shown it is difficult to tell just how closely the two sets of masses agree but it is very close. Credit: Left panel. Anderson et al., 2017, Proceedings of the 22nd Los Alamos Stellar Pulsation Conference "Wide-field variability surveys: a 21st-century perspective". Right panel. Anderson et al., 2014, A&A, 564, 100.

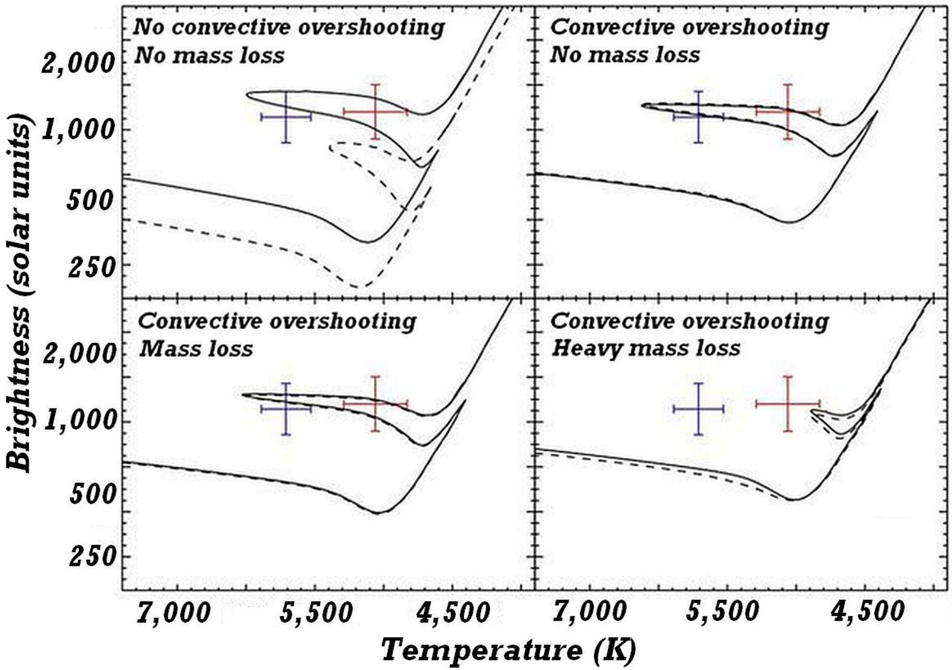

Figure 13-13. Evolutionary results for OGLE-LMC-CEP-0227 plotted in the “loop region” of Cepheid evolution. The Cepheid is plotted in blue and the red giant, which is not pulsating, is in red. Clearly, the loop with maximum mass loss produces a loop that does not encompass the data. All other models are possibilities. Credit: Moroni et al., 2012, ApJ, 749, 108.

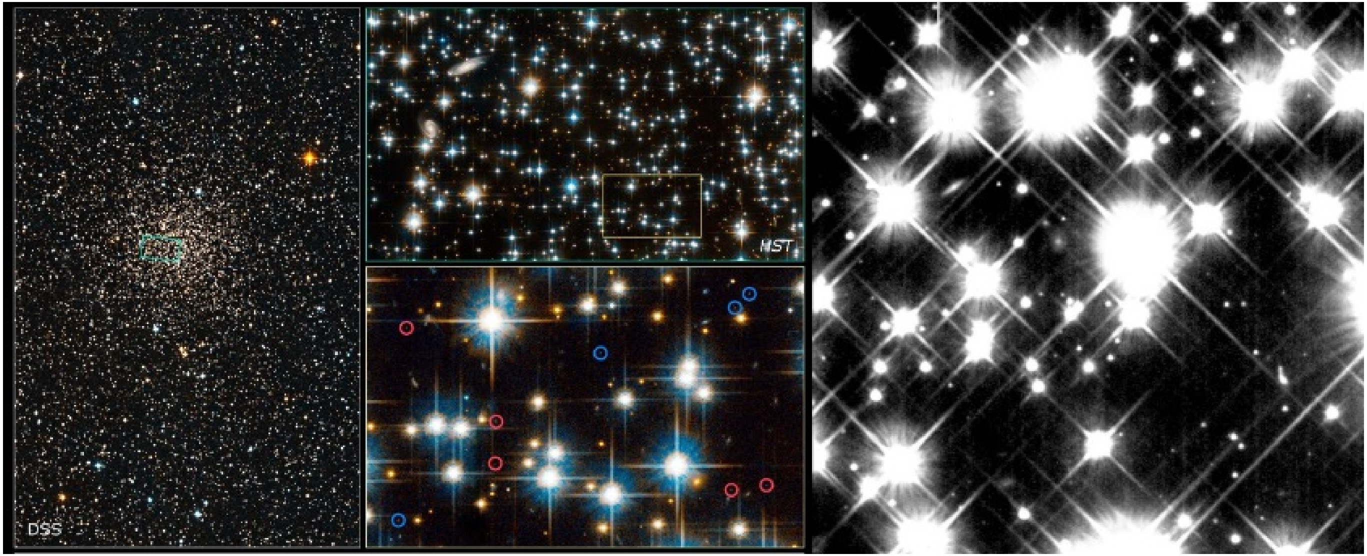

Figure 13-18. The left panel shows the galactic cluster NGC 6791 with the green oblong expanded in the top centre image. The colours of the stars are not particularly noticeable but in the centre panel they are obvious. Without plotting a colour-magnitude diagram it looks like we have a lot of bright blue stars forming the hot end of the main sequence with even brighter red stars that have evolved away from the ZAMS. In the lower centre panel white dwarfs are identified within the red circles. The right panel shows white dwarfs in the Milky Way showing as small dots as in the previous figure. Credit: NASA/HST/Richer (UBC).

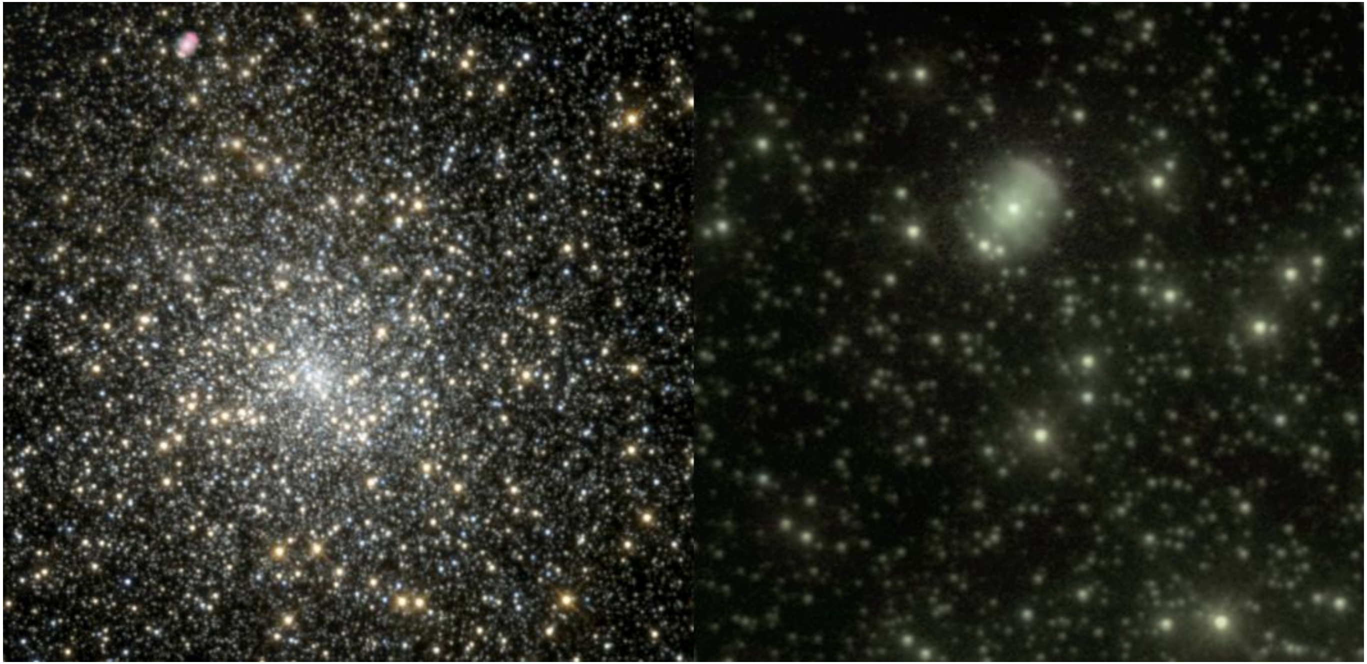

Figure 13-21. An HST image of the globular cluster M 15 is shown in the left panel. Notice the fuzzy orange tinted object in the upper left. This is the planetary nebula discovered by Pease in 1929 and shown in the right panel. The colour has been altered to show the image as it would appear to the naked eye. Credit: NASA/HST.

Figure 13-25. An artist's impression of Cygnus X-1 comprising a bloated star that is losing mass through L1 to a black hole as it evolves. We are familiar with this scene, as most stars grow as they evolve, at least in the early stages. It you look carefully you will see a beam coming from the black hole. Credit: NASA/ESA illustration. Notation by the author.

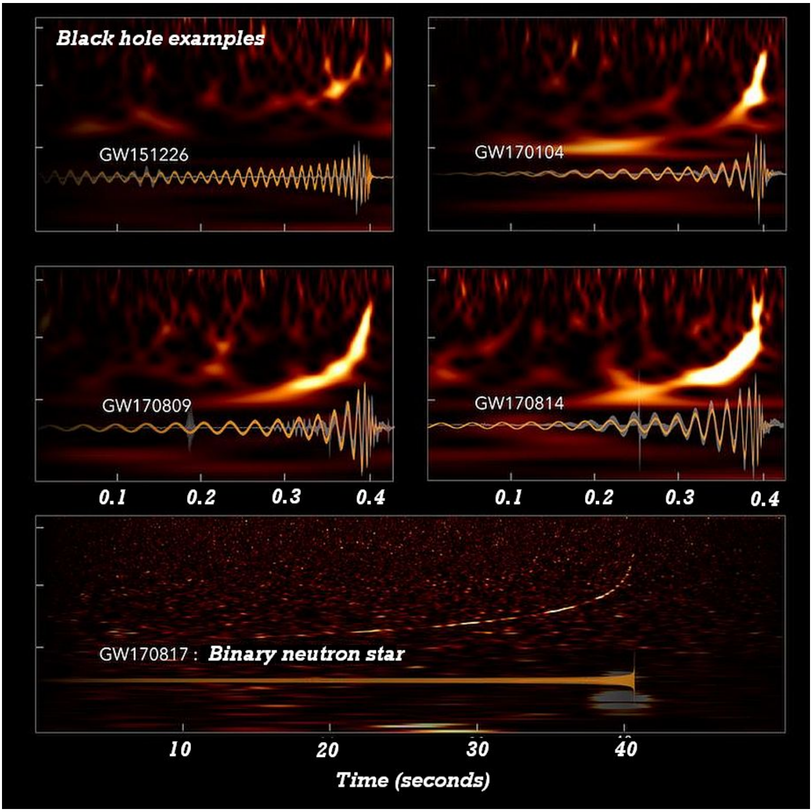

Figure 14-8. See Centrefold. Shows a series of gravitational wave detections interpreted and modelled in the context of mergers within black hole and neutron star binaries. The difference between the two types of mergers is dramatic where we see a long leadup to neutron stars merging, in contrast to the merging of two black holes. Among the black hole traces—the wiggly line—we see marked differences undoubtedly providing necessary data for theoreticians to determine individual masses for the merging objects. Credit: Wikimedia Creative Commons. LIGO Scientific Collaboration and Virgo Collaboration/Ghonge and Jani (Georgia Tech.). Modified by the author.

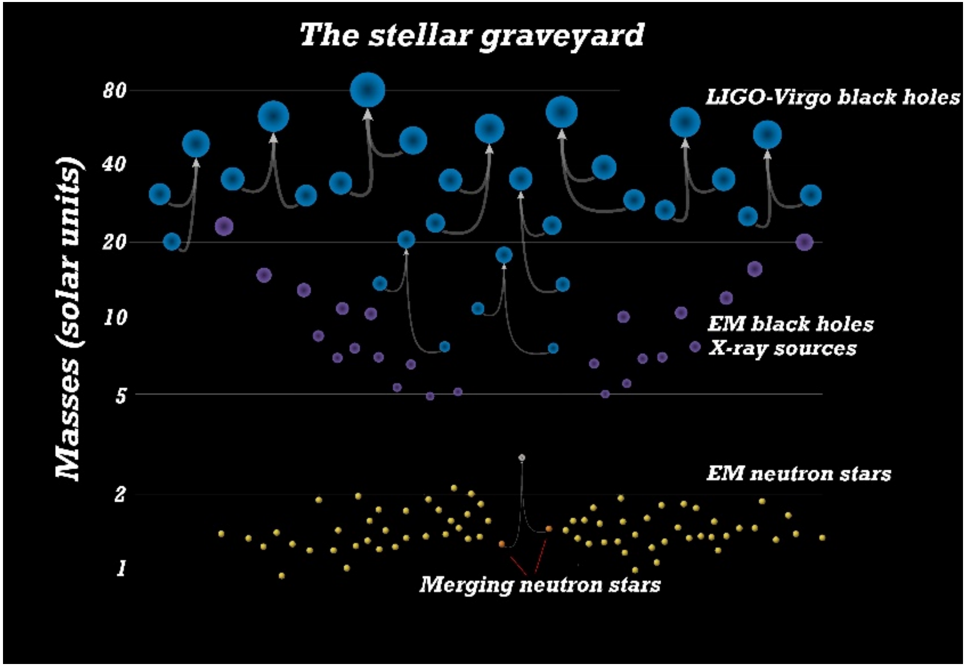

Figure 14-9. The commentary comes from the LIGO/Virgo website. “This graphic shows the masses for black holes detected through electromagnetic observations (purple); the black holes measured by gravitational-wave observations from LIGO and Virgo (blue); neutron stars measured with electromagnetic observations (yellow); and the masses of the neutron stars that merged in an event called GW170817, which were detected in gravitational waves (orange).” Credits: LIGO/Virgo/Elavsky (Northwestern University).

CHAPTER 9

SNAPSHOTS OF EVOLUTION

9.1 A first look at evolution: Early days

It's time to have a look at the H-R diagram shown in Figure 8-2, because, without a clear view of what we're facing in its interpretation, we'll be at a loss to understand what follows. This was the case through the first half of the twentieth century, before the massive observational programs of the 50s provided theoreticians with solid evidence to hang their models on. The H-R diagram is disjointed, with a notable run of stars from the upper left to the lower right which is termed the main sequence. To the lower left there is also a sequence of some sort containing the white dwarfs. The red giants are an obvious problem as they stick out of the middle of the main sequence, whereas the areas above and below them are empty. Like the main sequence, the **red giant branch (RGB)** is well-populated, leading to the conclusion that stars live a long time in each of these locations or evolutionary states. Somehow, the stars had to evolve to the right, and all end up on the same sequence which must therefore contain a mixture of stars of various masses. The H-R diagram is very elegant and astronomers must make sense of it.

I've called it a snapshot and that really causes a problem because there is no movement there—even this statement is not true. Early notions of evolution promoted the idea that a star progressed up the main sequence, but with Eddington's discovery of the mass-luminosity relation, how could that be, because the stars to the upper left were more massive than those near the Sun? A star could hardly gain mass as it progressed up the main sequence, but in contrast, we now know that **mass loss** is a factor in, for example, the evolution of the Sun. At this moment we have a static picture that obviously holds the key to stellar evolution but there is no way to make progress or so it seems. To understand evolution, we need to isolate groups of stars of similar age and look at ***their*** H-R diagrams. Any differences should reveal evolutionary changes. When we look at the sky, we do find groups of stars we call star clusters. Some are loosely grouped and generally contain hundreds of stars, and some are tight, spherical groups of stars containing hundreds of thousands of stars (Figure 9-1). Less than a decade before I started on my astronomical studies photoelectric observations of numerous clusters of stars, obviously moving together around the galactic centre, began to shed light on the true process of stellar evolution. Let's have a look at these clusters and see what they reveal.

9.2 Clusters of stars

The scene is now set to begin to understand the story of stellar evolution as it unfolded through the twentieth century. The ingredients of the story are the stars with their varied distributions of temperature, mass and diverse size, but the real key to a star's evolution is its mass, which governs its destiny. I'm ignoring its mate if it is a binary star because "mates" well and truly alter the star's history—as humans, they alter ours! However, to make progress with this story, we need to extend our distance measures outward from the limited types of stars we find in the solar neighbourhood because the stellar content of our galaxy is more diverse than this. It turns out that the objects we use to extend the distance scale are groups, or clusters, of stars thousands of LYs distant, each group being simultaneously born out of vast volumes of interstellar material and generally too far away for our surveying method to work. For these stars, we need to know their absolute magnitudes, their temperatures and hence their sizes, and, where possible, the masses of eclipsing binaries within their environs. Just as important though, is the fact that a cluster of stars will all have been born together and are at the same age, and the differences we see among them can be directly attributable to their evolution. In looking at the various clusters, we see a series of snapshots of groups of stars of varying ages. But without knowledge of star's masses we cannot verify what we find by theoretical means.

The clusters come in two sorts of groups inside the Milky Way. There are loose groupings of tens or hundreds of stars we call **open or galactic clusters**. In contrast, there are also tight spherical conglomerations of stars numbering in the hundreds of thousands we call **globular clusters**. The two types of clusters displayed in Figure 9-1 are distinguished by their quite differing appearances. Globular clusters are rich in stars with hundreds of thousands of members while galactic clusters are sparse by comparison. There are other distinctions but more of these later.

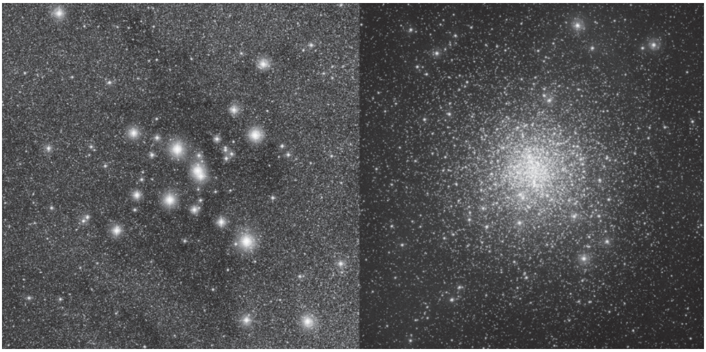

Figure 9-1. See Centrefold. A fine example of an open or galactic cluster Messier 7 (leftmost image) and the star-rich globular cluster Messier 4 (rightmost image). M7 is a young cluster because of the obvious presence of hot blue stars. M4 is an old cluster containing evolved red giant stars. Credit: ESO.

9.2.1 Galactic clusters

Let's start by looking at a galactic cluster, the Pleiades, known also as the Seven Sisters—seen prominently in the spring in the Northern Hemisphere—or as Matariki (its first appearance in the southern fall heralds the start of the Māori New Year in New Zealand). When we plot the colours of individual stars against their apparent brightness, we get another form of the H-R diagram called a **colour-magnitude diagram**—see Figure 9-2 for two representative examples. Here the **colour index** indicates the temperature and the apparent brightness only differs from the absolute brightness by the factor—its distance—needed to shift the cluster to the standard distance of 32.6 LY or 10 pcs. Thus, to all intents and purposes, we have an H-R diagram of a group of stars that formed about the same time out of a single interstellar cloud. That is, they are all at the same age and an assumed homogeneous abundance and only experience one period of star formation. Thus, any changes we can identify will be due to stellar evolution. Consider now the left panel. Of interest, is the narrow line of stars forming the main sequence like the main sequence in an H-R diagram. Notice how the brighter stars curl away from the main sequence. Why? These stars are more massive than the cooler stars which evolve more slowly. How do we know this? Because the mass-luminosity relation that says the bluer and therefore the hotter a star is along the main sequence, the more massive it is. Therefore, we can conclude that the shape of the main sequence is somehow related to the evolution. Now, I'm not saying whether stars evolve upwards along the curl or whether the line of stars is the locus of stars at the same age that have evolved away from a main sequence that is no longer there, but we'll soon get there. The row of stars standing just a tad above the length of the main sequence are binary stars that are brighter than the single stars because there are two of them, though we only see, and, therefore, measure them as one.

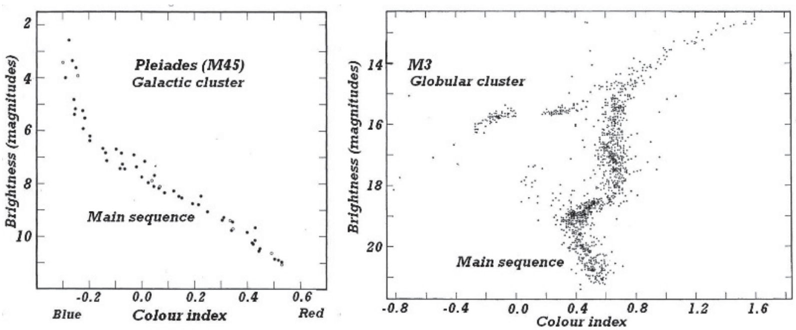

Figure 9-2. Contrasting colour-magnitude diagrams of typical galactic and globular clusters. The scale on the bottom represents a colour measured by taking brightness readings through blue and yellow pieces of glass in succession. Negative numbers indicate that a star is blue and hot. The magnitude scales on the left are a measure of how bright the stars appear to us. The smaller numbers indicate brighter objects. Credit: Left panel. Johnson and Morgan, 1951, ApJ, 114, 522. Right panel. Johnson and Sandage, 1956, ApJ, 124, 379. Modified by the author.

It was not until astronomers realised that the sequence we are seeing here, when put together with the mass-luminosity relation, represents a locus of points of equal age, and not a pathway that a star progressed along as it aged, that the idea of evolution clicked. Evolution moves the positions of stars from left to right in this picture and we only see positions frozen in time. We are looking at a locus, where stars end up if we freeze evolution at a moment in time. But because of the mass-luminosity relation we know that stars in the upper left of the diagram are more massive than those at the lower right end, and, therefore, will evolve faster. Massive stars, stars twenty times or more than the Sun, go through their evolution far more quickly than less massive stars, so the life cycle of massive stars is very short. These massive stars "live" for tens of millions of years, whereas stars like the Sun are billions of years old. In sharp contrast, the H-R diagrams of globular clusters could not differ more than what is displayed for an open cluster like the Pleiades. In addition, the orbits of galactic clusters are notably different from the globular clusters as their motion around the distant galactic centre is limited to the galactic plane. Recall the illustration of the Milky Way in Figure 1-14 that shows the flattened pinwheel nature of our galaxy.

9.2.2 Globular clusters

Globular clusters are spectacular objects (Figure 9-1), approximately spherical groupings of hundreds of thousands of stars, but without any obvious gas present, unlike the galactic clusters which are often embedded in gas and dust—another factor that indicates how young they are. These clusters, like every object in our galaxy, are in some sort of orbit about the Milky Way—but with a difference. The Sun, like most of the stars in the Milky Way, goes around in the disk, or the plane of the galaxy, like a car around a racetrack, but globular clusters are located outside of the plane, orbiting up and down through it over millions of years as they too orbit the galactic centre. They move through the plane and out the other side like a yo-yo dancing up and down. Even though there are hundreds of thousands of stars they hardly interact with the stars as they pass through, but they do interact with the gas. Under these conditions the interactions cause more stars to form and, in the end, after many passages through the galactic plane, they are swept clean of gas. While we have no images of globular clusters interacting with the gas ***in*** the galactic plane, we can still get an excellent view of what happens when gas collides. As an example, there are galaxies, the so-called **starbursting galaxies**, where enormous numbers of stars are born at once, triggered by the collision of galaxies. The image in Figure 9-3 shows the results of one such collision between two spiral galaxies.

Because the globular clusters are the oldest entities in our galaxy with ages of 10 plus billion years, we might not be surprised to see that their colour-magnitude diagrams are quite different from that of a galactic cluster, which we see in Figure 9-2. The tight, almost linear arrangement of stars along the main sequence seen in the left panel of Figure 9-2 for the Pleiades has long gone. The only main sequence is seen to the lower right in the right panel of Figure 9-2 and the rest of the diagram appears complicated. Let's look at the main sequence of M3 located in the lower right corner to see if there is any commonality with the Pleiades. Calculations show that stars get brighter and cooler as they evolve and more massive stars evolve faster than less massive objects and show a hook or a bend away from the main sequence. To the lower right in this diagram we see the same signs of a **turnoff** (or **turnoff point**) that we see in the Pleiades as the stars peel away from the main sequence but that is where any resemblance to the Pleiades ends. The diagram is very complex and because of this we expect the explanation of its nuances to be complex too. And it is.

Figure 9-3. See Centrefold. Two interacting spiral galaxies where the gas, gravitationally drawn out from each of them, spawns star formation. The blue threads linking the two galaxies come from the light of young, hot stars birthed from the interaction and resultant clumping of the gas under the effects of gravity. The radiation from the stars forces the gas away leading to other collisions and more star formation. Credit: ESO/Muñoz.

We can only use these data in conjunction with what a computer produces when we model the stars and set them evolving. A model will ultimately give us absolute magnitudes and colours for a range of masses and ages that we can directly compare with the data presented in Figures 9-2, but in order to use these colour-magnitude diagrams we need distances. The vertical scales of apparent, or observed, brightness for dozens of other clusters need to be converted to absolute magnitudes. So far, we have discussed the measurement of parallaxes, but to use these many clusters for evolutionary purposes we need to extend the distance scale in some way.

9.3 The concept of zero age

Look at the Pleiades colour-magnitude diagram in Figure 9-2. We know that the masses go from small to large up the sequence and more massive stars evolve faster than the less massive stars, and, because they burn more energy than the cooler cluster members, they evolve faster. I guess the human analogy is found in those people profligate in their energy who live incandescent lives and die young (I'm sure the reader can name any number of these human examples). The hook away from the main sequence at the upper left therefore represents evolution and the stars below the hook have experienced little evolution, just as the Sun has experienced little evolution despite its age. We can consider the unevolved part as being of zero-age.

Looking at other similar galactic clusters we see the same effect, a hook away from the main sequence and the main sequence itself that appears unaffected by evolution. Thus, clusters generally exhibit a sequence of zero-age stars. Now look at the colour-magnitude diagram for Messier 3 in Figure 9-2. Again, we see a hook though the diagram is far more complex. Using the same argument, we can consider the short piece of main-sequence stars towards the lower right as being of zero-age despite the eons that have passed since the cluster was formed. These stars are not very massive and so the nuclear processes inside them are not particularly active or maybe not active at all.

9.4 Extending the distance scale

9.4.1 Preamble

The interesting stars are the most massive ones for they are the most luminous, in principle making them excellent for use as distance markers in our own galaxy or in others. Stars that are bright in the sky are generally more luminous anyway but they are too far away for us to measure their distance by trigonometric means. We must find another way to extend our distance measures if we are to measure the distances to clusters in our own galaxy and to those in nearby galaxies and ultimately to determine the distance scale of the universe. In the larger picture, the questions are: "How big is the universe? How old is the universe? Will it expand forever or will it collapse on itself?" The answer to these hinges on the distance scale astronomers established through the 20th century.

While I'm not going in to all the details of measuring stellar distances it is of interest to get the flavour of the exercise. Basically, we've had to pull ourselves up by our bootstraps to extend the distance scale past the place where parallaxes are so small as to become unreliable. Every country that has been triangulated started with a fixed baseline and the survey extended out from this base. What has been discussed to date is the astronomical equivalent, but we cannot go any further with triangulation. Clusters of stars have provided the means for us to begin to extend the scale since a cluster's members are all at the same distance from us, just like the crowd on the horizon watching a football match we can consider to be at the same distance. Once we can get the distance to the first cluster then there is a way of piggybacking clusters on top of one another to get us to the place we want to be. But I'm jumping ahead of myself. We need to start with the closest cluster, the Hyades, the one that is near enough so we ***can*** measure the distances of its stars using parallaxes. Since everything rides on us confidently knowing the distance to this cluster, it would be useful to have another check. The next section describes the check.

9.4.2 Moving clusters or disappearing railway tracks

Fortunately, the Hyades cluster, in the constellation Taurus, is close enough to have its distance measured by parallaxes. For the moment I'm ignoring the results of the satellite Hipparcos which extended the basic distance scale by a factor of five but which initially produced some contradictory parallaxes because of occasional systematic errors in its gyroscopic alignment. I'll be interested to see what results come from Hipparcos' replacement satellite Gaia put up by the European Space Agency (ESA) – this is another story discussed in the last chapter of this book. Unfortunately, the Hyades' parallaxes are at the limit of reliability so to be sure we are on the right track we need another method of verifying the parallax results. Remarkably, by examining the direction and amount of the proper motions of the stars (the direction and amount the stars move in a year) in this cluster, we see perspective effects in the cluster's motion seen against the distant stellar background. The motions of the cluster stars all point towards one

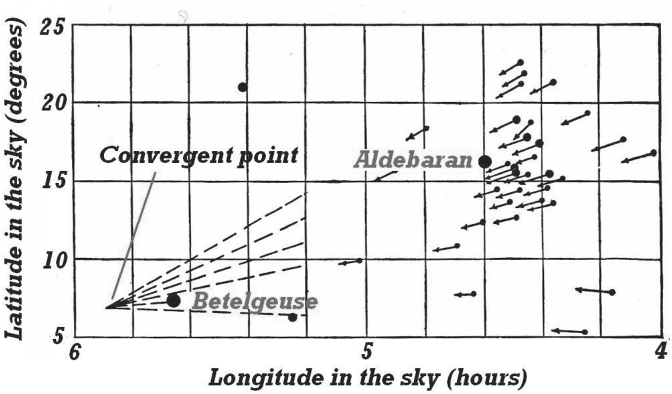

Figure 9-4. The Hyades cluster projected onto the sky showing the proper motions of the cluster stars. These proper motions are all directed to one point, the convergent point. Because all the cluster stars are moving in the same direction, when we measure their motion across the sky, perspective makes it appear that these motions are converging at one point. In this case it is close to the red, supergiant star Betelgeuse in Orion. The geometry of the situation is the key to being able to measure the distance without the need of parallax. Credit: R. Baker, Astronomy, 1930. Adapted from a diagram by Lewis Boss. Annotated by the author.

place in the sky. The motions look like the stars are all converging at one point, called the convergent point (see Figure 9-4), just like railway tracks converge at a single point in the distance. This happy circumstance means that we have a geometric means of measuring the distance to the cluster and getting intrinsic or absolute magnitudes for all of the member stars. Thus, we can extend the types of stars for which we can determine intrinsic luminosities from the faint M stars to the brighter A stars (remember OBAFGKM). Now it remains for us to determine the luminosities of the brightest stars, the B and O stars since, because of their brightness, they will be the most useful distance markers in external galaxies.

9.4.3 Cluster Main Sequence Fitting

In Figure 9-5 (left panel) is plotted a colour-magnitude diagram for the Hyades which anchors our distance measures as we move away from the realm of parallaxes, though the satellite Gaia will change everything I'm mentioning here because Gaia will yield parallaxes of a million stars with accuracies a thousandfold better than what I'm describing, along with a billion more positions and motions! I'll talk about this later in Chapter 15. What say we find another cluster, for example, the Pleiades, also included in Figure 9-5, which is a bit bluer (check the scale on the bottom of the figure, the more negative the number the bluer the star), for these stars will be intrinsically brighter. There'll be an overlap where the main sequence of the new cluster can be slid over the unevolved part of the Hyades. If we line up the colour scale so the colours of the overlapping stars of the Pleiades match the Hyades then we could extend the sequence to bluer and more luminous stars. We could pick another cluster and do the same. This process was followed in the 50s yielding a sequence of unevolved stars called the **zero-age main sequence (ZAMS)** shown in the right panel in Figure 9-5. Here the apparent magnitudes are replaced by the absolute magnitudes we are trying to determine. This whole exercise requires that all the cluster stars must be corrected for the reddening caused by the dust and gas between us and them before being slid upon one another. In it you see sequences of clusters where the stars at the upper left curl away from the others. The pattern seen in the Hyades is true for all clusters. Also, the composite diagram in the right panel in Figure 9-5, is starting to show the characteristics of the colour-magnitude diagram shown in the right-hand panel of Figure 9-2. But even though Gaia's values will replace distances currently accepted, the method will work beyond Gaia's reach.

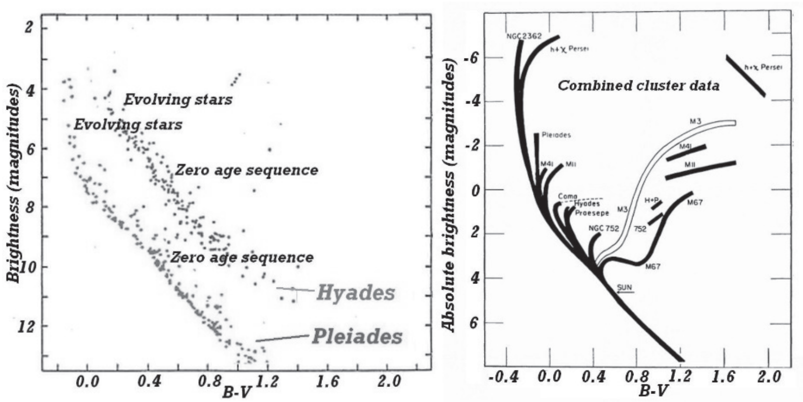

Figure 9-5. Left panel. The colour-magnitude diagrams of the Hyades and Pleiades. The curled parts of the diagram represent stars that have evolved. The little rows of points just above each main sequence are binary stars which are brighter because there are two of them. The main sequences are defined to be unevolved, or of zero age. These unevolved sequences are the key to extending the distance scale to the most luminous stars in our galaxy. If we slide the Pleiades upward to piggyback onto the unevolved part of the Hyades then what is termed the zero-age main sequence (ZAMS) can be extended to hotter temperatures. Right panel. The results of the piggybacking process where various clusters have been assembled to show how the ZAMS was formed. Thus, given a new cluster, we can slide its main sequence onto the one derived from here and so derive its distance. Credit: Left panel. ESO Projects. Right panel. Sandage, 1958, RA, 5, 41. Both figures modified by the author.

There are other fields of study that use this type of method. Consider dendrochronology, the study of chronology, from tree-ring data. This science combines tree rings from remnant bristlecone pines, stacking rings from one dead tree by matching the overlapping rings on another, in much the same way that we've stacked clusters upon clusters to cover a time sequence stretching back billions of years. In the case of trees, we go back 9000 plus years and use it to calibrate carbon-14 dating, an added tool by which we can improve the chronology of ancient Egypt and beyond. In reading about this on the Internet, I got lost in the ramifications of the study with respect to ancient history in the Middle East and tying the volcanic eruptions and solar eclipses to this chronology. Check it out.

In Figure 9-5 this super-positioning is shown for many clusters both galactic and globular. The turnoff points in this figure, the places where the data for a cluster turn away to the right, indicate the relative ages of the clusters ranging from the very young at the top left to older ones as you go further down the main sequence. Our stellar evolution predictions must be able to reproduce the ZAMS for us to have any faith in the theory. Think about it. Aside from the Sun, the ZAMS is the simplest problem we've got when trying to model a sequence of stars because there is no evolution involved, and it is easy to do once you have a starting model, though it wasn't easy in the 50s. Given a model for the Sun, we simply alter the mass a little and, using the previous model as a start, generate the next model star and so we can work up the ZAMS. In principle, the resultant sequence should match the observed one shown in Figure 9-5.

Generating the theoretically modelled sequence is straightforward but… the models are computed in terms of temperatures, and luminosities—I'm using the word brightness interchangeably with luminosity throughout the book—spanning the whole of the electromagnetic spectrum whereas the observations are in absolute magnitudes (crudely stated, stars observed through a piece of yellow glass which hardly covers the whole of the electromagnetic spectrum) and colours also measured through glass filters of some sort. More about this later. (I'm sorry about this "more of this later" stuff but the whole subject is totally interconnected. As you can see, the overall discussion is not a linear progression!) Given that we can match the theoretical data to the observation, there remain two more difficulties, challenges if you wish, notably, how sensitive is our sequence to abundance (***very***) and do the masses that we know for every model in the sequence jibe with masses of ZAMS cluster stars? But here, we must deal with the fact that there may be only a few stars with known masses along the ZAMS, making the discovery of eclipsing binaries in clusters very important.

9.4.4 A wee reality check

The process sounds good but translating the results from the theoretical world of the modellers to the real world of observation is, even today, fraught with uncertainty and difficulty. But before we can place theoretical results on an H-R diagram to see how well we are doing, we must relate the colours to the temperature, which I mentioned earlier, and then relate the measured brightness through a particular piece of yellow glass (called the *V* filter) to the ***total*** energy output of a star across the ***whole*** of the electromagnetic spectrum. The relation between colour and temperature requires a variety of measurements because the spectra we measure rarely peak within the visible spectrum. The hot stars radiate mostly in the UV and the cooler stars radiate in the IR both of which we can't see. For both these extremes we must make a correction to the observed brightness through this yellow filter and it is this correction that is most difficult to determine. Another complication is the abundance, but I'll get back to this later.

In writing these words I'm conscious of a twinge of negativity but think of it as objectivity. I know the feeling when a prediction works out and the joy I felt at the time and, in recall, still do to a degree. I'd like every researcher to feel the joy of success and often surprise.

9.4.5 Creating standard candles

By using a dozen or so clusters and overlapping their main sequences we can determine the absolute, or intrinsic, luminosities of all the spectral types from O to K. We can even establish the luminosity of evolved stars, the giants and supergiants. Thus, for the stars within the clusters, we can create tables that say, given a spectral type and luminosity class of so-and-so, we have an absolute magnitude. It is not sure-fire and there are uncertainties at the bright or hot end because of the reddening commented on above. (In this regard Gaia may remove all these uncertainties because this satellite will extend our parallax scale or geometric measure a thousandfold out across the galaxy.) As a consequence of obtaining all these absolute magnitudes, we can associate an absolute magnitude with each spectral classification. We would know then that if we classified a star as B2III we could read off its absolute magnitude from a table and then derive its distance. We all do this instinctively when we look at the distant headlights of a car at night. By their brightness we judge whether the car is close or far. I've always enjoyed seeing the lights of a car 30 km away across a West Texas landscape and slowly see them gaining in brightness as they approach. In that situation I guess seeing them forms some sort of link between people across an empty, lonely landscape in the blackness of a desert night. Maybe I'm crazy. I had a similar experience with a police car when travelling at high speed across the desert fastness of southern Arizona and New Mexico and feeling a measure of relief when his lights went on behind me. At least someone was aware of me (he just gave me a warning).

This method works well, but we need a spectrum to classify a star and then read off its absolute magnitude. While we classify a star with some surety, it still leaves a problem in that the classification grid is coarse and absolute magnitudes derived from it could be off by 20-60% depending where you were in the table. But it is better than nothing. In a distant galaxy, getting a spectrum is itself a problem since we're dealing with faint light to start with and spreading it out into its spectrum makes it even fainter. This is a real challenge. We can always do photometry to fainter limits than spectroscopy.

In Chapter 15 I'll return to this comment. It would be nice to have another, more reliable, method to measure the distances to our extragalactic neighbours. Happily, Cepheid variables provide this.

9.5 Cepheid variables: Stars that pulsate

Cepheids are very luminous variable stars found throughout the plane of the Milky Way and in young open clusters. The reason that we have a distance scale which extends to the galaxies at all is because of these stars. These giant stars literally pulsate, getting larger and then smaller over weeks or months. When compressing they heat up and when expanding they cool down, producing a light curve that is instantly recognizable (see Figure 9-6). These stars are very luminous, about 10,000 times brighter than the Sun.

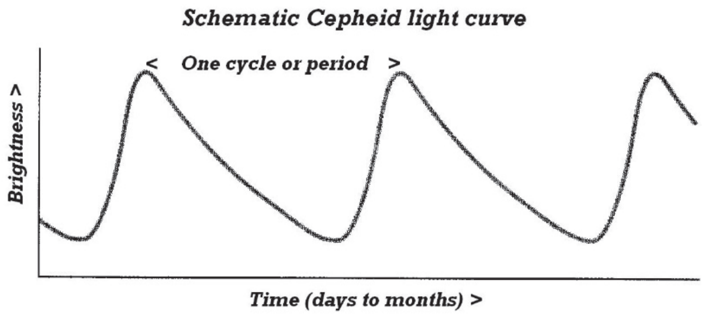

Figure 9-6. A schematic light curve of a classical Cepheid. Because the light curves of these stars are easily recognised in distant galaxies, and there is a relationship between their periods of oscillation and absolute luminosity, they are invaluable in extending the distance scale outward to the galaxies. Adapted by the author.

For this reason, and because their variability is readily detected, they can be seen at large distances, though not as far away as supernovae which are hugely bright. This is very important, but even more useful is the fact that their variation draws attention to them so they can be readily identified. In other words, we can find them, and there are many of them in distant galaxies. It was their study that gave us the first reliable expansion age of the Universe at about 13.6 **Gyr** or 13.6 billion years. It turns out that the brightest stars pulsate over the longer timescales (periods) and the less-luminous stars pulsate over shorter periods. This happy circumstance is amplified, because their intrinsic brightness is uniquely related to their pulsation time. If we can calibrate the relation between the period and the intrinsic brightness (**period-luminosity relation or PLR**) then we can get the intrinsic brightness of any Cepheid by knowing its period alone! The point of mentioning them here is that evolution naturally creates these variables and we find them in the general field and in galactic clusters among massive stars. They occupy a specific place in the H-R diagram termed the instability strip seen earlier in Figure 8-6. We can measure the distance to clusters using "**standard candles"** (stars whose absolute magnitudes we know) provided we classify stars, e.g. B0V, B2Ia etc, in the cluster, or, more reliably, by fitting the cluster main-sequence to the zero-age main sequence. In this way we get a distance and an absolute magnitude that we can use in turn to calibrate the period-luminosity relation. The relation between brightness and period was discovered by Henrietta Leavitt (see Figure 9-7, left panel) a hundred years ago when she was looking variable stars in the smaller of the Magellanic Clouds (SMC) seen outside the band of the Milky Way in the Southern Hemisphere (remember Figure 1-2). It sounds simple, but the amount of labour involved in Leavitt's result

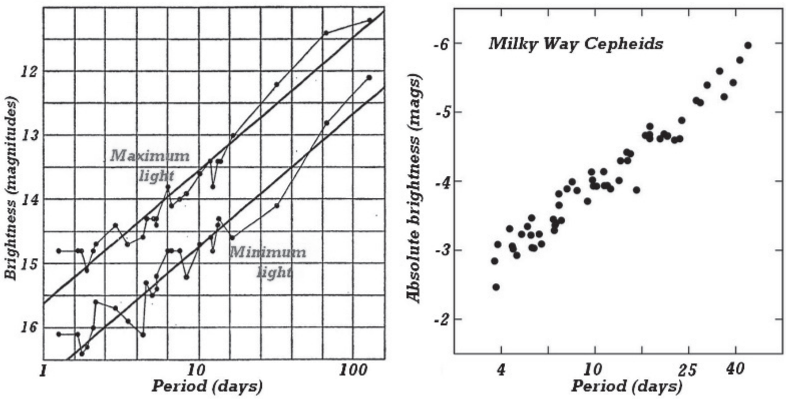

Figure 9-7. Left panel. The relation between the periods of the Cepheids and their apparent magnitudes in the SMC. There are two lines, the upper one is the star at its brightest and the lower line is the star at its faintest. The right panel shows the period-luminosity relation (PLR) as derived in 2007. The funny scale on the bottom of both graphs is a logarithmic scale. This relation is fundamental to establishing the scale of the universe and was a monumental discovery not fully utilized until the 50s. Credit: Left panel. Leavitt, et al., 1912. Harvard Circulars. Right panel. Fouqué et al., 2007, A&A, 476, 73. Both figures are modified by the author.

was enormous. She proceeded initially, by what is called blinking plates, that is having two plates of the same part of the galaxy side-by-side on a special machine and optically switching between the plates—photographic images—looking for two things, a change of position or a change of brightness, or both. This all presupposed you have changed the scale on one plate to match the other and made sure small rotational differences between the plates have been corrected—you don't want to morph a head on your image that was at a wrong angle! I'm not sure how different the relative image sizes would be as they would depend on the focus of the telescope: the consistency of the emulsion coating the glass plate and the seeing during the observing. All I know is that it ***is*** a task. I did some of this in Minnesota while working for my mentor Willem Luyten and have an excellent idea of its difficulty and the labour Leavitt endured. Luyten spent his life doing it! It was a horrible job! The relationship shown in Figure 9-7 promises some very good distances.

It was one thing to have this lovely relationship, but it took a half a century before it could be calibrated and thus be useful in determining the distance to our galaxy neighbours—and beyond. Now this calibration has been used to find the distances to far-flung galaxies and in turn measure the **Hubble constant** or the velocity of recession of distant galaxies, which in turn gives what is called the expansion age of the universe. There are complications and I mention them to illustrate that simple words on a page hide a mountain of work.

The measurement of the magnitudes of Cepheids in distant galaxies is not straightforward because of the myriad of stars within each field of view. Separating out a Cepheid magnitude from the stellar "contamination" of its surrounds needs mathematical modelling of the various encroaching shapes. Measuring the period is simple because even a series of contaminated magnitudes will give you this. There is another complication—that predicted by Doppler—the wavelength of the spectrum will be shifted in colour because of a star's (or galaxy's) velocity. As noted earlier, this factor is inconsequential when dealing with stellar velocities of ±500 km/s as found in a binary system. But velocities of recession of say 15,000 km/s (see Figure 3-10) will shift a galaxy's peak wavelength about 20 nm redward and move the V magnitude off the standard calibrated system, leading to an error in the distance. There is another effect that I have not discussed directly in this book because I don't want to get bogged down the details of the research—this is metallicity I've mentioned. The distant galaxies are of differing ages—remember the distance reflects a galaxy's age—and age is reflected in the metals produced through supernovae enriching the interstellar medium. In addition, the period-luminosity relation is also dependent on metallicity which complicates the distance measurement. Thus, there is a fair bit of "overhead" in using Cepheids as distant markers in redshifted galaxies.

I note that extending the distance scale even further to the edges of the universe depends on using the brightness of supernovae since they all seem to go “boom” to the same level of brightness. A happy circumstance I’ll review in Chapter 14.

9.6 RR Lyrae variables: Other stars that pulsate

As with the Cepheids, the RR Lyrae stars are pulsating variables though their periods are less than a day, in contrast to the Cepheids that vary over weeks to months. The contrast does not end there because, while the Cepheids are young stars (we call them Population I or metal-rich stars), the RR Lyrae variables are very old (Population II stars—the first ones “born”). There is a weak relation between period and brightness and is the subject of much research because these stars are found in a small part of the H-R diagram and, like the Cepheids, are therefore useful as distance markers. Because RR Lyrae stars are found in globular clusters, they must be old, and therefore their chemical composition is different from their Cepheid cousins that were born out of gas enriched by the countless remnants of stars that had gone before. Originally, getting their distances to calibrate the PLR relation was not easy but with the extensive ongoing globular cluster studies there are plenty of data with which to complete the calibration. The star RR Lyrae had had its parallax measured with the HST and Hipparcos so that was a start, albeit for one star. Globular clusters, whose distances have been measured by either main sequence fitting or by matching the cluster colour-magnitude diagram using evolutionary modelling (to be discussed later), yield absolute magnitudes. RR Lyrae stars are present in the general field of the SMC and LMC whose distances are known from studies of constituent Cepheids or galactic clusters. Given these absolute magnitudes, we can calibrate the period-luminosity relation—weak as it is—and use it in turn to measure distances to other objects. Because of their brightness, globular clusters show up very well in distant galaxies and these variable stars are readily detected and observed enabling the galaxy’s distance to be measured.

There are complications. The results, whether measuring distances to the globular clusters or using the PL-relation are all sensitive to the metal abundance in these objects. But in principle, and to a large extent, the system works.

9.7 A complication: interstellar reddening or dust

We know there are always details that we'd like to sweep under the carpet but this complication can't be ignored. Distant stars appear redder than they are. I think of a car's headlights across my favourite desert landscape seen in a dust storm. The headlights look red because of the presence of dust. Dust exists in space, so almost wherever we look we are observing reddened stars and galaxies. Therefore, lining up the cluster so the reddening-free colour indices coincide, as mentioned in the previous discussion of the colour-magnitude diagrams, is not necessarily straightforward. Fortunately, by observing stars through three different pieces of glass, yellow, blue and UV, the last one only transmitting part of the UV, we can get an excellent measure of the amount of reddening a star is experiencing. What this means is that we can correct the observed colours and so place all the clusters on the same colour and hence temperature scale. I'll talk about these pieces of glass later (see Chapter 13). Because of the expedient way the whole photometric system was set up in the earlier 50s, it has produced a world of hurt even though it led to the most wonderful period of accurate cluster observations in the 50s to the 70s and pointed the way to all future studies.

But how do we know that dust is not affecting all the stars, that there is no such thing as an unreddened star? Are there places that are dust free where the colours of the stars are the intrinsic ones? For sure, there are two places that are largely free from intervening dust and that is away from the galactic plane towards what we refer to as the galactic poles (**North and South Galactic Poles, NGP and SGP**). It is trickier when we look outward into the galactic plane (remember the galaxy is disc shaped about 2000 LY thick) because we are looking into the mass of the galaxy. However, dust-free regions have been found, so the basis of the whole structure built on stellar colours unaffected by dust, or able to be corrected for its presence, is sound. If we can get the intrinsic colours for some stars, what about the young ones that always seem to be embedded in dust and gas, the lingering remnants of their own creation? This is another curly question that was largely worked through fifty-five years ago so we have confidence that the intrinsic colours are free from the effects of reddening—but don't look at the fine print. The basis for this comment is found in the appearance of HST images of star clusters that appear to be swathed in gas and dust. Sometimes too much good information is bad for simplistic analyses. But we've come a long way with these analyses before the HST so let's not get side-tracked by pessimism.

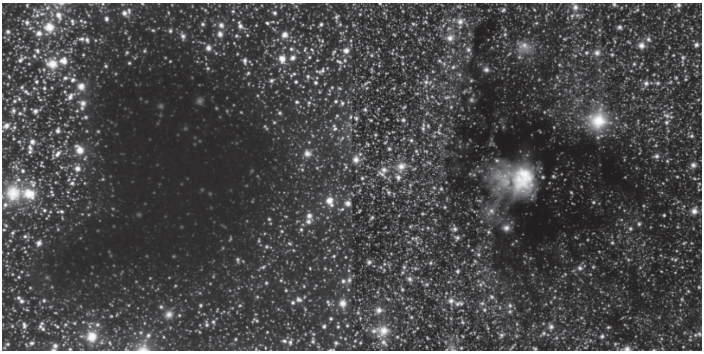

Figure 9-8. See Centrefold. The effects of reddening on starlight are beautifully revealed in these pictures of two obscuring dust cloud. Around the edges of the clouds you can see the stars appear red, just as distant headlights appear red in a heavy dust storm. The unreddened stars are between us and these clouds. By observing the stars in three colours UV, blue and yellow we can largely correct the observed colours for reddening as it is called. Credit: ESA/Hubble, ESO.

Those of you who have experienced driving in a dust storm will have noticed that the lights of oncoming cars are both dimmed ***and*** reddened. The same effect is seen in stars and galaxies. The dust clouds shown in Figure 9-8 amply demonstrates this observation, the larger the colour change, the greater the amount of dust. This means, aside from the colour correction, we must also correct for the dimming, provided we can find the relationship between the two. This is beautifully illustrated in the images displayed in Figure 9-8 which shows reddened stars within dark, dust clouds. Within these images you may convince yourself as have I, that the dimmer the star the deeper red it is, so validating my comment above. Again, in the 50s, a great deal of labour went to isolating similar stars that were both unreddened and reddened in order to define the relationship. It works well. This sounds good, but again there are complications in that space is not uniform, in some regions the relation between the reddening and the amount of dimming is not the same. The most likely cause is that the small grains that make up the dust differ from place to place. A quick check of images in the HST databanks shows the way the dust varies throughout our interstellar environs. And where do these grains come from? Aside from the primordial hydrogen and helium produced in the Big Bang, everything in interstellar space is processed in the stars. The grains come from giant red stars, the Mira variable I've mentioned before, that pulsate, swelling and shrinking over hundreds of days, forming molecules of carbon in their cool, extended atmospheres. These grains are expelled from the star by the pressure of light, the same pressure that forms the long tails on the comets orbiting the Sun.

How does the dimming of light affect our view of galaxies? Generally, galaxies are observed away from the plane of the galaxy where there is little or no dust. Why? The Milky Way is a huge flattened spinning disk, like a giant pinwheel ~100,000 LY across but less than a 2,000 LY thick with most of the dust and gas confined to the disk thus obscuring the galaxies. We avoid the dust by observing away from the disk or plane of the Milky Way. On Earth it would be akin to observing towards the North and South Poles and avoiding observing stars on the equator. In terms of the Milky Way, we observe galaxies at the North and South Galactic Poles where there is little or no dust to redden the stars.

9.8 The spacecraft Hipparcos

In addition to the traditional Earth-based technique for measuring stellar parallaxes, the spacecraft Hipparcos (1989-1993), named after Hipparchus, carried out an historic survey of nearby stars and revolutionized stellar distance measurements. It is worth commenting on this achievement because it also has a bearing on current happenings in space. Until recently, whether one measured stellar positions by photography or with a CCD, against a background of stars, the method had remained essentially unchanged for more than 180 years. The spacecraft Hipparcos changed everything by utilizing the principle of a gyroscope coupled with the present ability to determine its Earth orbit with unprecedented accuracy—another way of saying that stellar positions are not measured by comparative methods but by dead reckoning. Hipparcos was launched in 1989 after a long delay, and even then, into the wrong orbit, with the aim of measuring reliable parallaxes for 40,000 stars and less reliable parallaxes for a million more. At that same time, it measured the parallaxes with 10 times the accuracy and a speed surpassing what had come before. Whereas before, our reliable distance limit was about 40 light-years, these measures extended the range by a factor of 10! As mentioned earlier, the Gaia space program will increase the precision by another factor of a 500 and extend the sample to more than a billion stars—currently it has measured a million distances. However, the principle of trigonometric measurement remains the same, observe the star on opposite sides of the Earth's orbit and measure the displacement against the stellar background, though in the case of Hipparcos the background was defined by a fixed position given by the satellite's gyroscope and orbit. A gyroscope is nothing new to us. The Earth is a gyroscope, just as the Hipparcos satellite is a gyroscope pointing accurately in one direction and spinning about this axis at a fixed rate. This movement, like that occurring on Earth, is called precession, or the shifting zero point of our celestial-based longitude system—the equivalent of a moving Greenwich in the sky. Superimposed upon the precessional wobble is a much smaller wobble with an amplitude of about 9 m or 30 feet over a period of one year and not precession's 26,000 years. Now, getting back to the satellite. Knowing how the satellite is oriented in space and the rate of rotation allows the astronomers to measure the position of the stars with a precision far surpassing the best Earth-based measures…but. There is always a "but".

Hipparcos data affirmed the Hyades distance and also enabled other clusters to have their distances measured directly using parallaxes, thus providing a check on what had gone before. The prime candidate for this study was the Pleiades cluster but, and you can almost anticipate my next words, there was a distance discrepancy of 10% between the Pleiades distance measured ***directly*** by Hipparcos and that from the cluster main sequence fitting method. Technical issues regarding the spacecraft and the inertial system, gyroscope if you will, caused the discrepancy which was resolved in favour of the traditional method, and again, years later, with verification of the cluster-fitting method by the VLTI and Gaia. While the discrepancy caused a whole lot of angst and recalculation, the problem served to remind space engineers to be mindful of similar glitches. Gaia data may also be susceptible to similar errors, particularly in that the tolerances are a thousandfold tighter, but only time will tell. Hipparcos also measured, as will Gaia, the brightness and colours of the stars. A good night's work on Earth might yield data for 80 stars a night. In measuring brightness and colour alone, over a year (and nobody observes for a year and the weather may only be 50% clear at best) an observer might make 14,000 observations. Over three years that is about 40,000 observations whereas Hipparcos measured a hundred thousand stars, acquiring about a 100 observations per star over an equivalent time! The output is about 200 times greater without even considering the positional data that give rise to the parallaxes, or, in its concurrent program **Tycho**, where a million stars with less reliable results were obtained. On Earth, one would have to run a parallel program to generate the parallaxes. The point of this discussion is to show that a well-designed spacecraft on a specific mission can do what an Earth-based community could ***never*** do in a lifetime—even if they were persuaded to embark on it at all. Gaia promises even more!

Now we have the bits and pieces with which to tackle stellar evolution. The book that fomented my desire to become an astronomer, Discovery of the Universe by Gerard de Vaucouleurs, had within its text a discussion of evolution occupying but one diagram and one paragraph. Incidentally, the author was later my teacher in grad school.

CHAPTER 10

A PATHWAY TO DIAMONDS

10.1 Boundaries

The key factor that governs the course of star's evolution is its mass. Near the endpoint of their lives, stars that are less than about 1.4 solar masses, have a completely different evolutionary path than more massive objects, while those about a tenth of the Sun's mass have yet a different endpoint. Even massive stars have two different endpoints. For this reason, we look at each mass range separately. The mass boundaries giving rise to differing outcomes are blurred for it is possible for stars to lose mass by ejecting their atmospheres by barely understood processes—though we see the results as planetary nebulae. There are three mass boundaries that govern the course of stellar evolution.

The lower boundary, approximately a tenth the mass of the Sun, defines the region above which nuclear burning can occur. Below this boundary, a star only gains its energy by slowly compressing itself to produce heat in a process we call gravitational contraction. These stars are called brown dwarfs and they end their lives as cold masses of "unprocessed material". They are unprocessed because the material at the end of the star's life is the same as at the start, though in a vastly compressed form. These stars extend down in a sequence towards objects with masses approaching that of Jupiter and blur the lines between what is a planet and what is a star. Recent observations by the VLTI are providing radii for very small stars that are approaching this lower mass boundary. This interferometer measures the size of the star in thousandths of an arcsecond. Because these small stars are intrinsically faint, they must be close for us to even see them, so in most cases we can also measure their distances directly by parallax and hence get their sizes in km.

Between the lower mass limit and 1.4 of the Sun's mass the endpoint of stellar evolution is vastly different. This is the white dwarf stage. Above this mass, termed the **Chandrasekhar limit**, a white dwarf collapses because pressure within the star cannot sustain the mass of the overlaying material.

The result of this collapse is a supernova explosion and the formation of a neutron star or a black hole about which I'll talk later. A star may start with a mass much greater than this critical value and lose most of it in its evolution, but there comes a critical time when the star either becomes a white dwarf or explodes as a supernova.

The third boundary is not clear-cut, and is perhaps at three times the Sun's mass, perhaps not—some astronomers would castigate me for being so vague, but the science is uncertain. There are clues. Later, in Chapter 14, I'll talk about merging compact objects and the detection of gravitational waves, which, in their detection, yielded the masses of the merging stars and that of the resulting black holes. Between the Chandrasekhar limit and this upper boundary, the endpoint of stellar evolution is the formation of a neutron star. Above this boundary a black hole is formed. We'd know more about this mass limit if we could find a stellar black hole and weigh it. These limits are summarised in Table 10.1.

Table 10.1. Mass limits and evolutionary destinations

Limits ($M_\odot$)		Evolutionary endpoint
Lower	Upper	
0.013	<0.075	Deuterium and lithium may burn between these limits as the star compresses as a brown dwarf
0.075	<0.8	Hydrogen burning only on the main sequence, ultimately becoming a white dwarf
0.7*	1.4	Nuclear burning, becomes a planetary nebula with its central star a white dwarf
>1.4	~3??	Nuclear burning, becomes a supernova leaving a remnant neutron star
>3??		Nuclear burning, becoming a supernova leaving a remnant black hole

* I note that this limit is uncertain
?? Strangely enough, this boundary may be best established by further studies of gravitational waves

10.2 A cosmic jigsaw puzzle

Some of these endpoints of evolution are readily available to the public for observation. Typically shown during the public nights at the DAO in Victoria BC were the Ring Nebula in Lyrae, the Crab Nebula in Taurus and the Orion Nebula. These objects appear as vast bits of expanding gas and are readily visible in a small telescope, so for this reason they are very popular viewing objects among amateur astronomers. Of these objects, the first has a developing white dwarf at its centre and the second a neutron star embedded within the wispy gas, and invisible to our eyes. Both are endpoints of stellar evolution. To complete the triumvirate, it would be great to have a "visible" example of a black hole. There are many likely black hole candidates among binary systems—the only way they can be weighed and thus verified—but it is tough to prove that the object making the other star move in orbit is a black hole when, by definition, no light can escape from it. What a bummer! Ironically, it is easier to show that black holes reside at centres of galaxies than in these binary system candidates though there must be innumerable black holes within our galaxy but undetectable so far. However, the binary system Cygnus X-1, a prime candidate for a black hole based on its X-ray emissions, has proven to be a black hole but not because of the spectroscopic measurement of this unseen mass.

The cosmic mix of stars that swim into our ken is legion. Here are a few. There are stars called cataclysmic variables that flare up thousands of times in brightness over a period of days with the light slowly decreasing back to "normal" over weeks. These outbursts occur over months or years. On the main sequence we find hot pulsating stars, though the pulsation s may be in waves travelling around the star but not swelling and shrinking. Cooler stars do their pulsating thing in hours. Off the main sequence, we see pulsating stars showing brightness changes from hours (the RR Lyrae stars) to weeks and months (Cepheids) to months and years the red giant (Mira) variables, and ultimately, we see stars that burst into brightness out of nowhere—the supernovae—and die away to leave an object even stranger than a white dwarf—a neutron star or a black hole. In trying to solve the mystery of where this strange mixture of stars fit into the scheme of stellar evolution, we are trying to assemble a puzzle of the various pieces we have in hand to form a coherent picture that can be checked. Not all the puzzle is complete, but slowly the pieces are falling into place. I'll try to tell as complete a story as I can without drowning you in a sea of details.

10.3 Stellar nurseries

The Sun condensed out of a large cloud of gas light-years across (see example in Figure 10-1) with gravity slowly pulling the material together to squish it up in the centre. At the same time, the whole mass started rotating faster and faster as it contracted in size and with this motion it began to flatten out, much like the way pizza dough gets larger as it is spun around on a chef's hand. The fledgling stars are formed within cocoons of material masking the embryo star from the UV radiation of other fully formed stars.

Figure 10-1. See Centrefold. This image, called "The pillars of creation" must be regarded as one of the iconic pictures of the 20th century. It shows a mass of stars forming within interstellar material that is the home to future glowing bodies we know as stars. It is thought that all stars formed like this within cocoons of gas and dust. Credits: ESA/Hubble.

We might legitimately ask where is the leftover material that did not form our Sun? Part of the material was absorbed within the solar system, swept up by the planets and which we see as impact craters that riddle all the planets and their moons, even the asteroids, or gobbled up by the Sun over the eons. But the remainder, largely gas and dust, was simply blown away by the Sun's radiation.

At this early time the young Sun slowly increased in temperature because of the heat generated by contraction. The HST routinely detects globules of gas and dust radiating energy in the IR. We know there are stars within the globules, just as we know there is a warm-blooded animal in the forest when, though invisible at night, we look at them with an infrared detector. Over a period of time ranging from a few 100,000s of years to more than 50 **Myr** (50 million years), depending on the mass involved, the object collapses far enough, and gets hot enough, for the star to start driving the enclosing material away by **radiation pressure**. Yes, light exerts a pressure on gas and matter. You might have read about the possibility of using large sails on spacecraft to harness solar radiation and to provide them with the initial impetus to get moving until such time that the main drives come on. We have all seen the effects of the solar radiation on comets. In the large straggly clouds, observed by the HST and shown in Figure 10-1, the stars have not contracted enough to generate sufficient heat to begin this process but they are detected as IR sources because they are warming up inside. While we may not see the effects inside the encapsulating cloud, we do see cases where nearby hot stars evaporate the outside of these stellar cocoons leaving long trails of material in the shadow of the offending star. To see these examples, scroll though the masses of images in the HST site.

10.4 How do we evolve a model star?

Let’s return to the model Sun first introduced in Section 5.5. This is a what is called a static model, once computed it does nothing and needs more physics to enable it to be evolved. It is static in the sense that it is not rotating and is the simplest model that can be calculated with a uniform composition throughout. Having calculated our initial model, we know that it must be evolved in some way. Now, differing mathematical approaches to the solution of the equations of stellar structure are available so we have choices as to how we want to build our models. The methods are robust—this may be an overstatement—and except for the pesky difficulties associated with convection, most of the physics is solid. The situation regarding computation is vastly simpler nowadays. In yesteryear, the computers—mainframes all—had capacities of about 16 kilobytes, a thousand to a million times less capacity that your laptop or telephone. It makes a difference, because, like the physics compromises we had to make to even get going, the memory capacity of the machines limited the number of instructions we could program, often demanding that we store and recover results as our program ran, or in modern terms, our app did its thing. As an example of the change, as a graduate student I got my hands on a modelling code and it took four hours on an IBM 360 to evolve a ten solar mass star to an age of 20 million years, whereas a student of mine did the same calculation using **MATLAB** on a PC while he waited. But, like the observational side of the science where progress only begets more and more questions, the theoreticians find that more and more physics needs to be included to make their calculations more realistic. The modelling is aided by huge databases involving opacity and energy generation rates which provide the necessary input to the models. These databases are generated because the physics upon which they are based is too complex to be included within a program. These databases are more reliable and complete compared to those available in the 50s and 60s. Inevitably, the computer codes grow more complex, and so the computer apps take longer to run to completion. “Run to completion”, what does this mean. Scientific programming is not like the apps that you use every day. These apps run so fast that you rarely witness them thinking. I guess searching on the Internet is the best example here. Science programming is based on computation. The programs are long and once started for some application take a while to run, from minutes to hours and perhaps days. While they run we go off and do something else. Then we say that they have run to completion—they’ve done what you told them, right or wrong.

We now need to turn our static model star into one whose internal conditions change with time. In this process our model Sun will slowly grow a core that changes to helium and with those interior changes the outer observable parameters, temperature (T_e) and luminosity (L), change. In time, the helium core will be transmuted to carbon and the star will develop internal shells of differing composition. For example, at some evolutionary stage there may be a core of carbon, a layer of helium, and an envelope of hydrogen. All these changes with time will yield a surface temperature and brightness or luminosity that will take the model in some path across the H-R diagram. While I’ve never built models—or evolved models—to this degree, I can imagine the excitement of the early pioneers who began their exploration of the H-R diagram in a way that had never been possible, or even imagined, before. In a small way I have experienced similar excitement when a model prediction matched an unusual spectrum feature in the northern primary reference star, Vega, telling me that we are looking down on the spinning axis of this star. That was ***my*** journey into the unknown. These early model-builders were indeed going into the unknown and were faced all the while with observational data that tested their assumptions and hence the validity of their models. In this process, we hope to see how evolution appears in an H-R diagram.

To handle the question of evolving our static models, we must introduce a time component, that, given a time step in millions of years, the time dependent parts of the physics kick in and a new model is calculated. The new component is the rate at which hydrogen is converted to helium, or helium to carbon and so on. For the Sun, maybe take at time step of 10 million years and compute a new model. The core will not be completely hydrogen but part of it will have been transmuted to helium. The change inside the star manifests itself "outside" by a change in luminosity and temperature. If everything goes right, we have a model of the Sun with different T_e and L. Plotted on an H-R diagram these values gives the start of what is called an **evolutionary track**, something which we will be continuously referring to as this book progresses. These are the evolutionary tracks which will come into their own when we attempt to prove this story in Chapter 13. I suggest you concentrate more on the tracks and less on the description because there are a lot of words to absorb and you may find a picture can say it all.

Since Schwarzchild's pioneering work on modelling the stars in the 50s, the physics of the nuclear reactions have been developed, along with increasingly sophisticated mathematical techniques that improve the whole process, aided of course by the rapid developments in computers. Now we routinely deal with machines whose memory is measured in **gigabytes** (10^9 storage locations) compared with the 16,000 (16 **kilobytes**) contained in the best machines when all this began in the early 60s. Not only have computing speeds and storage blossomed by at least a factor of a million, but also the sizes of these machines have shrunk. We don't operate in vast rooms of whirling tape drives and large "boxes" housing the air-conditioned central processing units (CPUs) and the disk drive, both with capacities far less than your run-of-the mill PC or cell phone. No more carting around boxes of IBM punched cards containing your precious computer codes and associated data—a flash drive in your pocket will do today. No impersonal places to pick up your results as you look through your printout cursing yourself for putting a couple of key cards out of order. Then, you resubmit the job, walk to your office, and wait for your results again. You haunt the computer lab when you really ***need*** to see the latest result. You waste time.

Now we submit our jobs to our own machine, or, if not that, we develop and run our software on some remote computer in our homeland, or overseas as I do, from the comfort of home and a view out over native bush and the sound of warbling birds. In thinking about yesteryear's walk to the computing centre, and today's sedentary existence in front of a computer screen, I see that yesteryear was not all bad. The walking at least provided some exercise and a chance to feel the breeze on your face and the soft warmth from the Sun on a winter's day. The problem for me in those days was that our observatory was about 7 km from the university's computer and a botched job submission meant another long round trip and a dreadful waste of time! It could also be dangerous. I'm thinking of a horrible day in 1966 when an ex-marine on the U of T tower killed or injured 45 people. On that day I was fortunate, not that it gives me much solace, as I had just returned across the plaza from the computer centre which sits right underneath the looming tower.

In this work, speed is the essence. Imagine it. For each mass, a model must be calculated, a time step taken and the model computed anew, Maybe, evolution is going too fast for the given time step and must be shortened. Maybe the reverse. While all this is automatically controlled by some fancy algorithm you've designed, it takes time. To help speed things up, pods of PCs can be linked together to run parts of the program simultaneously using the separate CPUs, or perhaps you have access to a supercomputer where this separation takes place in one machine. This is called parallel processing and it is demanding of the programmer since the software must be prepared in just the right way to take advantage of the special qualities of the supercomputer. Similar gains are found in spectroscopy where, by ingenious design, we can observe hundreds of stellar spectra at one time, much like we take direct images of the stars and galaxies. Again though, as with a computer program, there is a fair bit of overhead required before you parallel process. The situation is akin to the current broadband capability of the links to the Internet. Broadband means the ability for the fibre optic cable to carry many calls at once. Without this facility, as a user of the Internet doing program development remotely, I'd be forced to wait until a slot came open and my research would be dead in the water. Parallel processing is the computing equivalent of broadband data flow.

Given a computer and a computing code, with which to model an evolving star, we are in a position to take our first steps to interpret the H-R diagram and to check out evolution we see in clusters of stars, for they will provide the initial testing to see if we are on the right track. I'll begin the discussion of stellar evolution by talking about the Sun whose fate is just a little entwined in our own.

10.5 From interstellar gas and dust, to the Sun

Under gravity, a vast cloud of gas and dust, part of which are the fruits of other stellar destruction slowly compress under the inexorable force of gravity in a birthing process I've described earlier. Some of the earliest theoretical stellar models began with this scenario and the results of these calculations are shown in Figure 10-2 for the Sun's path as it compacts out

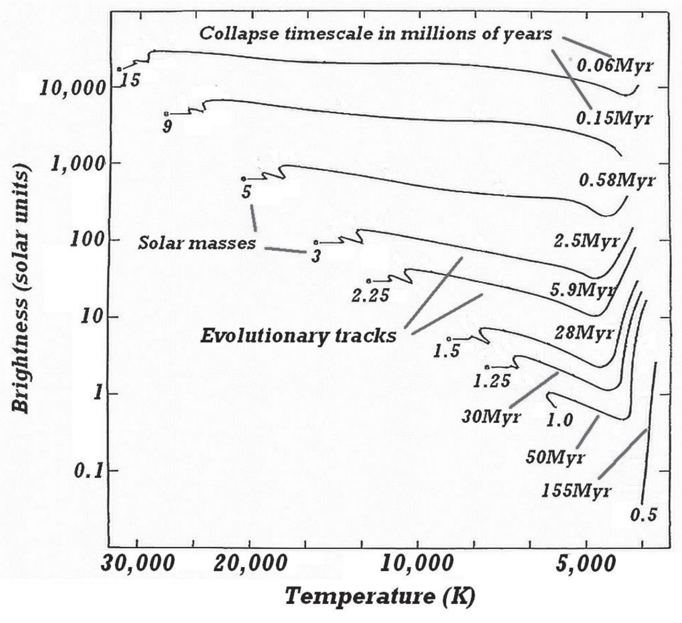

Figure 10-2. The image indicates the collapse times to the main sequence for stars between 0.5 and 15 solar masses. The Sun took about 50 million years to reach the main sequence. Credit: Iben, 1965, ApJ, 141, 993. Modified by the author.

of the interstellar medium in its march to becoming a main sequence object sustained by fusion in its core. Figure 10.2 is interesting particularly in the timelines displayed, which range from only 60,000 years for a fifteen solar mass star, yet for a solar-type star the contraction time may be closer to 50 million years. Figure 10-3 shows the evidence for the detection of stars slowly contracting from a gas cloud to become main-sequence objects. The left-hand panel is not so tidy as the stars are all differing ages as the region

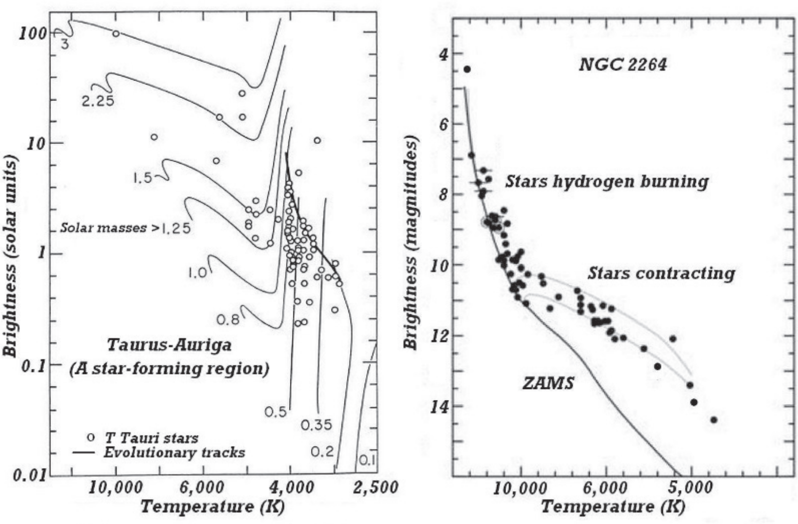

Figure 10-3. Left-hand panel shows an H-R diagram illustrating the downward path of clouds compacting out of the interstellar medium. The numbers represent mass and the stars plotted are thought to be pre-main sequence. A good example of the result of these collapses is in the right-hand panel where, in a very young cluster, the cooler stars have yet to reach the main sequence. Credit: Left panel. Stahler, 1988, PASP, 100. 147. Right panel. Wikimedia Creative Commons/Turner, 2012. Annotated by the author.

is not compacting out of a single cloud of gas, in other words it is not forming a cluster. However, these variable timelines show up nicely in the observations of the very young cluster NGC 2264 shown in the rightmost panel of this figure. And how do we know that!

Looking at Figure 10-2 you can see that a three solar mass stars reaches the main sequence in 2.5 million years, whereas less massive, and hence cooler stars like the Sun, would not have reached the main sequence. You can see that in the right panel of Figure 10-3. The models happily predict what is seen in NGC 2264, Another way to check on the age of the cluster, or at least to know that it is very young, is in the presence of a very hot star of spectral class O7—remember the sequence of spectral classes OBAFGKM going from hot (30,000 K) to cool (3000 K). The cluster must be young because an O7 star is massive, maybe 20 solar masses with a lifetime of only ~15 million years. As I'm writing this, I'm conscious that the numbers I quote are never with the surety that you would hope for in a scientist. I guess the answer to my own question is that the proclamations of science can never be cast in stone. Science moves forward, sometimes crawling, but when technology or a great mind gets in the mix, it goes quickly. But with the pace comes change for the discoveries come quickly and inevitably part of the old is overturned. Anyway, my numbers reflect a caution born of experience and perhaps a bad memory.

Now, back to the end of this pre-main sequence discussion. Given enough time, the cloud forms a sequence of stars burning hydrogen and no longer contracting. We have a main sequence. But looking at the faint end and the time it takes to compress, I wonder if the stars that take a long time to compress are evaporated by those already happily burning hydrogen in their cores, if not, then stars still compressing should be detectable in the IR.

10.6 The main-sequence Sun

The next stage awaiting the embryo Sun is core ignition, the time when conditions are right for nuclear burning to take place. The word burning does not accurately describe the process since burning for us means consuming the fuel leaving nothing but ash. The fuel in the star is transformed—transmuted—and not burnt, but the term is commonly used. In this case the ash that is left is in the form of energy that supports the Sun's outer layers against collapse and what we feel on our faces 150,000,000 km away. In this process we begin to model a star assuming it is spherical and is not rotating, which is another way of saying that there are no complications. The first thing we must decide on is its composition, that is, "What elements is it made of?" We use a mix of hydrogen, helium and heavy elements, generally in the ratio by mass of 71%, 27% and 2%, a mix deemed appropriate for the Sun, since, in terms of the age of the universe, it is a young star and prior to its birth there have been many cycles of star birth and death which seeded space with more helium and heavy elements (elements heavier than helium making up this 2%). I've blithely mentioned 2% as some sort of metal contribution (called metallicity earlier) but this number plays a critical part in how well we reproduce observations with a given theoretical track of evolution to be discussed later. (I'm sorry about all these caveats.) Note that a first-generation star would be evolved from a mix of only hydrogen and helium until massive stars started to shed newly created heavy elements into space. Out of this metal-enriched material the Sun formed 4.5 billion years ago.

The model depends on several things. We assume that the pressure inside the star, caused by the high temperature, prevents its further collapse against the force of gravity, that is, it is in equilibrium. The way mass and density changes throughout the star needs to be determined along with the way that heat moves from the interior to the outside. Whether the heat's passage is governed by radiation (remember the heat from the bar heater) or convection (bubbling water in a pot) needs to be considered—another way of saying we also need to work out how energy is transported and how do we know when each operates? Where radiation predominates, photons carry energy and are impeded by the material through which they flow (opacity). Finally, we need to know how the star is generating its energy. Is it generating it through the sole effects of gravity compressing the star, or by a "nuclear fire" in the core? When the temperature is hot enough for the star to begin to transmute hydrogen into helium, at temperatures above 10 million K, then we say that the star has begun its main-sequence life. Once hydrogen in the core starts being transformed into helium, the increased energy generated stops the collapse and expands the star somewhat as the star adjusts to this new energy source. Over time, the surrounding primal cloud shrouding the Sun is dissipated by both the solar wind and radiation, leaving a young star with its contingent of planets and residual space junk. From afar, that is from another star, we would see the Sun as a very ordinary yellow star that has now reached what we term the main sequence with enough fuel in its core to ensure a main-sequence life of about ten billion years before evolution starts to expand it, ultimately engulfing the Earth but still leaving us plenty of time to sort ourselves out unless we snuff out our existence by rank stupidity! And we seem to be heading that way.

10.7 Off the main sequence

The Sun ends its main-sequence life when the core is converted to helium and the nuclear furnace shuts down. Follow these steps by referring to Figure 10-4. It can get confusing, but remember, when the star exhausts one supply of fuel in its core, it contracts and ultimately gravity provides the energy needed to get the next set of transmutations going again. By now it has started its movement away from the main sequence and is now ready for a new phase of evolution that will see it grow to an object that will engulf Venus (see Figure 8-6 showing radius changes with evolution). When the core is devoid of immediate fuel, the star contracts under gravity and heats up. The whole interior of the Sun increases in temperature and the Sun increases in brightness beginning the loop visible in the schematic H-R diagram. When the temperature of the hydrogen gas immediately next to the inert helium core reaches about 15 million degrees fusion in a shell of hydrogen begins again, immediately changing the structure of the star by causing the outer part, the envelope, to swell in size making the Sun cooler and brighter. Cooler and brighter, means that it is getting larger—remember the giant stars that Hertzsprung and Russell discovered a hundred years ago? The shell of hydrogen gets converted to helium while the core, still lacking an energy source, contracts even more, getting hotter and more compacted while the outer parts of the Sun expand as the Sun moves upward along what is called the red giant phase of its evolution.

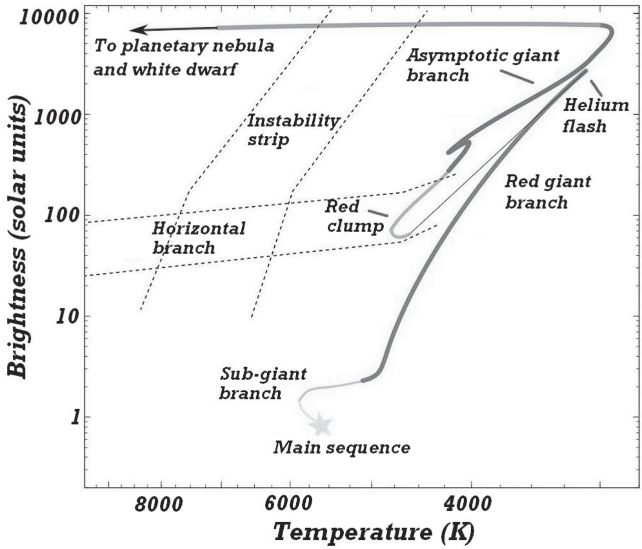

Figure 10-4. Shows the evolution path (track) of the Sun as it evolves away from the main sequence to ascend the red giant branch. At the peak of the red giant branch the core experiences what is called a **helium flash** when it fuses part of its helium core to carbon and oxygen altering the internal structure of the star, becoming less luminous but hotter as it moves downward to what is called the horizontal branch. When the core starts fusing carbon and oxygen to heavier elements, the track reverses upward to what is called the **asymptotic giant branch** and then onward shedding its mass as it becomes a planetary nebula (PN) and reveals its core—a future white dwarf. Credit: Wikimedia Creative Commons/Lithopsian. Annotated by the author.

The giant name is quite appropriate since, over a timescale of 10-12 billion years, the Sun will easily become 100 times larger than it currently is, swallowing up Mercury and almost reaching Venus as it evolves. By now the star is fully into the red giant stage of its life where is has increased in size many-fold, extending halfway out to the Earth while its surface temperature has dropped from about 5800 K to 3000 K. Remember that all this is taking place inside a computer, we cannot verify the process by looking for changes in the Sun or any star for that matter but there are other ways, even though a moment in time is all we see but we'll get to these ways later. The Sun ends its life as a red giant when its core gets hot enough to burn helium.

10.8 The helium flash

The pressure interior to the shell increases as the core continuously squishes up to compensate for the loss of nuclear energy while the shell happily continues converting hydrogen to helium. But in the core, the increased density and pressure is changing the gas into a strange form of matter termed **degenerate matter**. In this case the electrons are packed around the atomic nuclei creating a “brittle” pressure that supports the core. Once in this state, if the pressure fails to support the star, it will collapse with catastrophic results resulting in a supernova but more about this later. Normally a gas responds to an increased temperature by increasing its pressure hence forcing the gas to expand or at least to hold its own to support the overlaying gas. In contrast, a degenerate gas reacts much like a brick does when it is heated; it does not expand, or very little. Under these conditions, increasing the temperature does ***not*** produce an expansion of the gas and so no cooling takes place. And the temperature is increasing because of the continued contraction of the core.

Now to a what if? If you could get a nuclear reaction going in a degenerate gas there would be nothing stopping it from consuming its fuel and generating hotter and hotter temperatures without being able to expand and so cool down. In other words, there is no control over the fusion process.

Back to the story. The core is inert and not producing any energy, so how does the interior of the Sun reach 100 million K to enable helium fusion to take place? By gravity. ***All stellar evolution is driven by gravity.*** In the absence of nuclear heat generation, and hence supporting pressure, the star will contract causing heating and ultimately ignite some nuclear process, either in the core or in the shell about the core. When the fuel runs out of fuel for a particular transmutation then the star contracts until a temperature is achieved that starts the next nuclear reaction and so it goes on—contraction, heating, energy generation, fuel exhaustion, contraction, heating, energy generation, etc, until the star runs out of fuel or something else happens. The "something else" is the discussion we're now having.

In the Sun, as the degenerate helium core—basically a white dwarf—begins to burn, it generates energy and therefore heat which in turn increases the nuclear reactions which in turn generates more energy and so on. Under these conditions the star will transmute part of the helium in the core to carbon and oxygen, the next elements up the chain, and only stops if the helium fuel runs out, or the conditions are not enough to continue fusing carbon. This process is called a thermal runaway and is like a firestorm that only stops once it has consumed all its fuel, or, like a plague that kills until there are no more people left to kill. Because of the extreme densities found in the core, ignition spreads quickly in a matter of minutes by conduction in a process called the helium flash—check its location in Figure 10-4. Helium is transmuted in a nuclear reaction called the triple-alpha process, one in which three helium atoms combine to form carbon with a little mass left over to be converted into energy (see Figure 5-5). Oxygen is also produced as a by-product in this case. The nuclear transmutation continues until the temperature reaches over 300 million K when the enormous temperature forces the core to correct itself and revert to obeying the perfect gas law—the law that says increased temperature produces increased pressure or increased pressure produces increased temperature. Think of your bicycle pump that gets hot near the washer as you pump up your flat until it gets too hot to hold or too hard to push, whichever comes first! The core now expands and cools. Again, the total structure of the star must adjust to these changes. Why don't we see these dramatic changes, after all, the core basically explodes? The changes are absorbed within the outer envelope of the Sun because the unbelievable energies released, the equivalent of 100 billion Suns, goes into evaporating the "brick" which is the white dwarf core, turning it back into a normal gas, the very situation that normally prevents a thermal runaway. We can't verify this occurrence because the helium flash occurs in minutes, as part of an overall evolutionary process taking place over billions of years, and we'd be dead lucky to witness this! After the helium flash, and the resulting reduction in the temperature of the core, structural changes occur and what is left of the helium burns over a period of approximately a billion years. Burning helium does not produce as much energy as burning hydrogen so the outer part of the Sun contracts to compensate for this loss and the star gets less bright but hotter as it moves downward and to the left in the H-R diagram where it drops down until it reaches what is called the **horizontal branch (HB)** before sweeping back upward to its highest point in the H-R diagram at a brightness or luminosity 10,000 times that of the Sun ($L/L_\odot$) and a temperature about 3000 K (see

Section 10.10). A lovely example of the evolution to the horizontal branch for the southern globular cluster NGC 5272 (M3) is shown Figure 10-5.

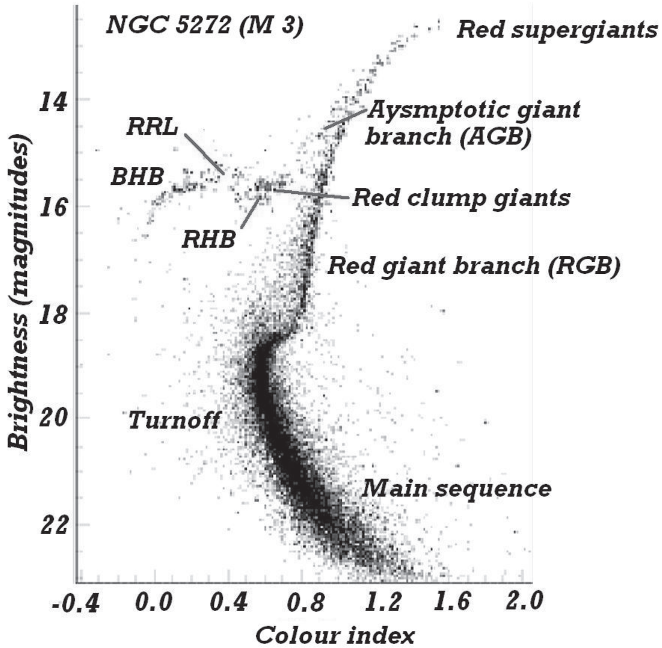

Figure 10-5. This figure shows the H-R diagram or colour-magnitude diagram of the globular cluster NGC 5272. The annotations show the stages of evolution I've just discussed. The brightness is given in the observed cluster magnitudes—apparent magnitudes. The haze of stars around the lower main sequence are stars between us and the cluster. **RRL**, **BHB** and **RHB** refer to the **RR Lyrae stars** and **blue and red horizontal branches** respectively. Credits: Rosenberg et al., 2000, A&A, 145, 451. Annotated by the author.

10.9 Pulsating RR Lyrae stars

Just think of the Sun now having descended from the red giant branch on the rightmost edge of the horizontal branch. It has a core of carbon and oxygen, but there will be no more fusion of elements past carbon as no star under 8-9 solar masses can trigger the burning of carbon in their cores because the mass overlying it is insufficient to raise the temperatures to the 500 million degrees necessary!! Stars slightly less massive than the Sun

(~0.8 $M_{\odot}$), and destined to become RR Lyrae variables, pass twice through the horizontal branch while their cores still create carbon and oxygen while their shells fuse helium and hydrogen. However, the Sun will stop just short of where these pulsating variable stars are found (see the horizontal branch in Figure 10-4 and in Figure 10-5). Now, rather than radii 100 times that of their main-sequence sizes, they will be more like ten times. The RR Lyrae positions are shown in Figure 10-5 where the letters BHB and RHB refer to the blue and red ends of the horizontal branch. RRL stands for RR Lyrae stars. Note that these variables lie in a gap in the middle of the horizontal branch in a quite localised position, indicating that evolution moves the stars quickly across this region. It also suggests that accurate modelling and excellent repeated observations of these stars might yield more insight into evolution here, after all, the stars cross this region, first from right to left and then the reverse with transmutations continuing in the shells (this is discussed in Chapter 13). This pulsation behaviour is observed in stars in globular clusters on the horizontal branch though not all globular clusters have the well-developed horizontal branch that we see in M3.

At this stage of our calculations, we have a series of models of the Sun of given temperatures and brightness as a function of time and we've been able to track the star's changes on the H-R diagram. Because it looks like an H-R diagram we are confident that we are on the right track. It seems that stars above ~0.8 $M_{\odot}$ do not become RR Lyrae stars, but I'm a bit vague on this. Maybe to be more charitable to myself, no number has caught my attention in the literature. I confess to not being sure as to whether the Sun will become an RR Lyrae star or nay but if it does, the following discussion is relevant. Alternatively, for the moment, think of the Sun as a 0.8 $M_{\odot}$ object where this discussion ***is*** relevant. The reason for my uncertainty is that RR Lyrae stars are found in globular cluster which are Population II entities, whereas the Sun is Population I. Be that as it may, let's get on with it.

When we look at the part of the diagram where the theoretical Sun ends up, we find these variable stars. What does our model say? Is it compatible with the observations? Will this model pulsate? And if it started, could the action be sustained? Would its pulsation period agree with what is observed? Think of what happens when we punch one of those small punching bags. It bounces backwards and forwards losing momentum and ultimately stops. What we look for in a pulsating star is something that once started, maintains the pulsations for millions of years. The best analogy for the pulsation processes I've seen on this is related to a pot of water boiling on a stove covered by a lid. As the heat creates the steam, the pressure under the lid builds up until the lid lifts, letting go all the steam and releasing the pressure. Then the lid settles down while the pressure builds again and the cycle repeats itself. This is what happens in a star that pulsates. That is, it shrinks and then gets larger, shrinks again and so on until it finally runs out of puff and quits. In a pulsating variable, heating is caused by the outer atmosphere cooling off, with the star contracting getting smaller as it does so. In turn this heat increases the pressure forcing the star to expand again. At a critical point, the atmosphere suddenly absorbs the heat and the pressure drops. (It is how the star absorbs the heat that is the clue for the driving mechanism that maintains the pulsation, but I won't expand on this.) Without support, the atmosphere collapses, heat is trapped, pressure builds, finally forcing the atmosphere to expand. And the process goes on, until, as the star evolves, changes to its internal structure alter the conditions that allow pulsation. The fact that we see pulsating stars in globular clusters offers a real test of the models that we build. They are an opportunity and a huge challenge. The evolutionary calculation must end up with a model that is unstable. Then the problem is in giving a star a sharp enough kick for it to want to vibrate and hence pulsate. This mechanism remains a mystery, whether for the RR Lyrae stars we are discussing here or the Cepheids that are part of the evolution of more massive stars.

10.10 To the asymptotic giant branch

In following this discussion refer to Figure 10-4. The new carbon and oxygen core do not burn because the core's temperature is insufficient to start the reaction. The core now is degenerate, which means electrons are providing the pressure to support the star. Unlike the helium flash which was precipitated by the onset of helium fusion in a degenerate core—remember the brick?—the carbon-oxygen core will not fuse and experience the same thermal runaway. The pattern of compression and heating continues, generating higher temperatures, moving the star blueward through the RR Lyrae gap. It stalls at the blueward end and begins a march redward, much like it did when it evolved off the main sequence because there was insufficient energy being generated in the core, which was contracting to make up for the loss. Now, the inside of the star is different from how it was on its blueward evolution, so there is hope that it will manifest itself in some way in the behavior of the RR Lyrae variables. At this point, the star has the following structure: a core of carbon and oxygen which is squishing up under gravity and heating, a shell of burning helium, an inert helium shell, a hydrogen-burning shell and outside this a dormant outer envelope made up gases with the original composition (hydrogen and helium and heavy elements). As the core contracts and increases the temperature, this in turn, enhances fusion in the shells and, increasing the pressure, expands the outer part of the star. This process takes the Sun back through the RR Lyrae gap to what is called the **asymptotic giant branch (AGB)**. The AGB gets this name because a whole mass-range of stars end up populating a well-defined strip in the H-R diagram (see Figure 10-5). In human terms it is like the place in our bedroom where odd socks are collected

Continued fusion in the shells expand the star even further, causing it to increase in brightness on a path that takes it up the asymptotic giant branch to a place where it is described as a red supergiant (see Figure 10-5). In terms of the star's size, this hydrogen-burning shell is large enough to encompass the Earth and the outer parts of the star reach out to engulf Mars and come close to Jupiter. The huge outpouring of energy is absorbed within the star over 10,000 years ending up in an object, perhaps varying in brightness, with a degenerate core of carbon and oxygen a few Earth radii in size, surrounded a shell of helium with hydrogen encompassing it all.

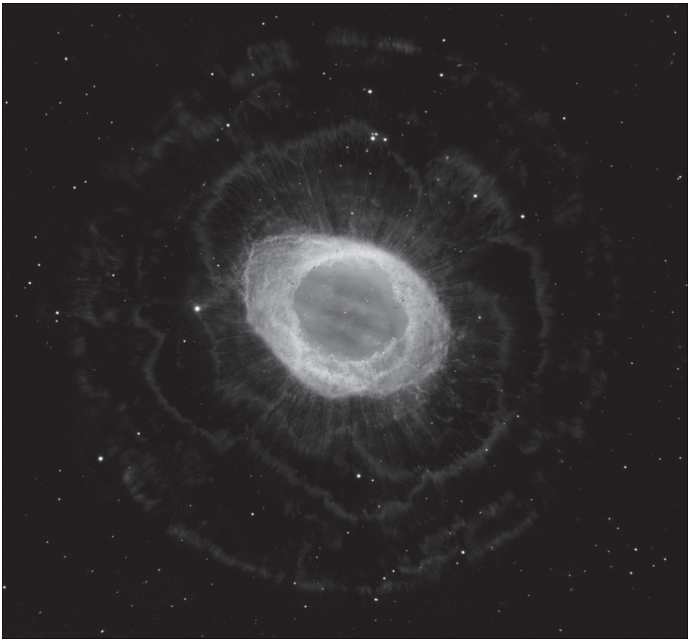

Figure 10-6. See Centrefold. The Ring Nebula in Lyrae. Look carefully outside the main image to see remnants of other explosions dissipating into space. Credit: ESA/Hubble.

10.11 Smoke rings: The formation of a planetary nebula

From this place, the Sun begins to lose its mass by forming a planetary nebula, the name deriving from the fact that these objects look round when examined through a telescope. Have a look at the Ring Nebula in Figure 10-6. Then have another look because the image is amazing, not because of the main structure, but because of the wispy rings, representing earlier explosions, standing out beyond the obvious rings. I confess to never seeing these before but my computer screen shows them beautifully. If the reproduction here is inadequate, have a look at the Hubble site on the web. The helium or hydrogen shells burn and burn hotter because of the gravitational pressure on them until the fuel is consumed. The star contracts and heats up until the temperature is enough to ignite a shell of hydrogen or helium again. This is a cyclic process taking place over hundreds of thousands of years, though the number is speculative. Each time shell-burning switches on, a pulse of energy serves to make the star pulsate over periods of months or years but also destabilizes its outer atmosphere which is slowly expelled to form a planetary nebula. During the pulsation cycle, the temperatures within the atmosphere are cool enough for carbon atoms to condense into grains that are expelled from the star by the radiation pressure from the enormously hot stellar core. The most intense radiation here is in the UV and the star begins the process of "shedding its shell" or losing mass big time. One can measure the expansion of these shells directly because, as time goes by, they slowly increase in size, which we can measure. We can also measure the velocity of the shells. We can do this because the shells are gaseous and each gas has its own particular distributions of lines though in this case the lines are bright and not dark, caused by the atoms being excited by radiation from the parent star and the releasing of energy as the electrons sink down to lower states like a ball bouncing down a series of stairs. Identifying the element by its characteristic distribution of wavelengths allows us to measure its velocity. Given this information for each of the shells we can calculate some mean time between ejections as well as the distance to the object. The composition of the ejected rings through a spectroscopic analysis basically gives one a look at the star from the inside out! By looking at these gaseous remnants, we can see what the inner part of the star was made of, since progressively, more and more layers are being exposed, much like an onion skin that we peel. In this way, remarkably, we can see into a star that ***was***. These various processes take our star from a cool, red supergiant to a very hot star (see the path in Figure 10-4). This picture of evolution was only developed after telescopes were lifted into space and they could see into the UV region of the electromagnetic spectrum where these very hot central stars radiate.

Once these telescopes were pointed at the central cores of planetary nebulae it was realised that they were very hot, much hotter than normal stars, confirming suggestions that in a planetary nebula we are looking at a hot central star on its way to revealing the white dwarf at its core. In Figure 10-7 I've chosen to display a planetary nebula with an amazingly blue and

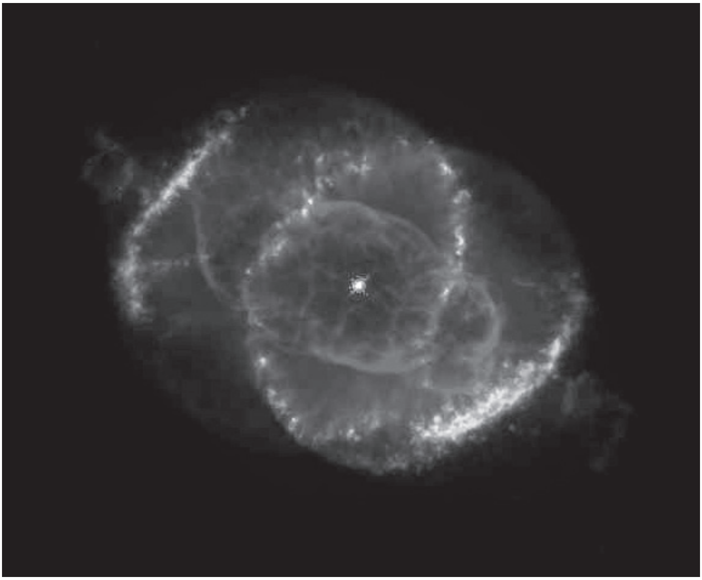

Figure 10-7. See Centrefold. This image of the Cat's Eye Nebula shows a blue-white star in the middle of rings of glowing gas. This is the exposed core of the star whose surface temperature could be 100,000 K. At this temperature, the photons, the packets of energy produced at the surface of the star, not only blow away the star's atmosphere but also excite the atoms in the surrounding rings of gas causing them to glow. The colours are specific to each of the excited elements comprising the gas—red is hydrogen gas and green is oxygen. The varying sizes of the rings show that the atmosphere has been expelled at different times over intervals of hundreds of thousands of years. Credit: ESA/Hubble.

bright central star. This colour gives me a sense of how hot the star is—it could be a 100,000 K! Not all planetary nebulae look as simple as the Cat's Eye Nebula, but, like people, they really come in all shapes and sizes as you can see from the gallery of images below. Some of the more complex shapes seen in Figure 10-8, may be caused by the presence of a companion star that changes the geometry of the whole situation. One star evolves in the way I've described and maybe it engulfs its companion—more of that later—but the presence of a massive body nearby alters the way the rings form. Each planetary nebula must be analysed—modelled—individually to match observation with theory. But I'm ignoring this, in the same way that I'd not try to characterize humankind by a detailed investigation of everyone on Earth. Whatever story I wanted to uncover would be totally swamped by the details of seven billion individuals.

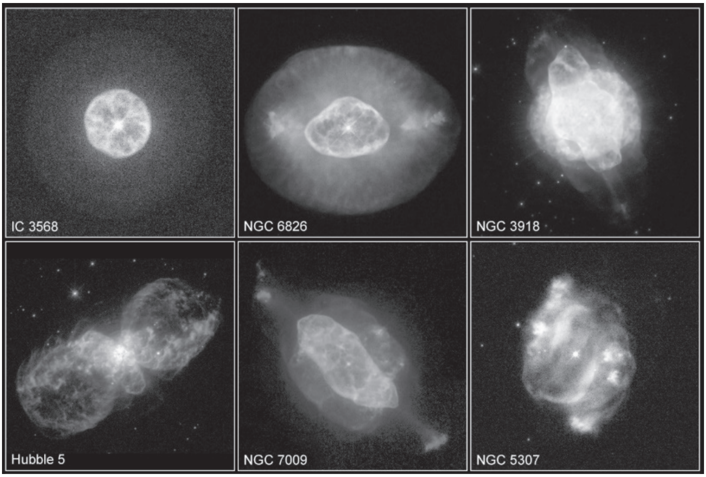

Figure 10-8. See Centrefold. A gallery of planetary nebulae showing the varied structure they present. On some of the images you can see rings of differing size illustrating that the atmospheres were ejected from the star in separate incidents. The dramatically differing shapes are thought to result from systems in which two stars are present. There is no general analysis that can be used for these quite different nebulae and each must be investigated individually. Credit: ESA/Hubble/Bond and Balick.

10.12 From under the carpet

This evolutionary scenario takes the Sun from what it is now into a supergiant object with its mass spread out into a volume perhaps engulfing Jupiter which would make its overall density rarer than the rarest vacuum we could produce on Earth. Somehow, it gets to an endpoint like the white dwarf companion to Sirius. How does it get there? Hot fast does it evolve? In the above description I offer no information backing up our central star's passage across the top of the H-R diagram. From its colour (check out the blue colour of the central star in the Cat's Eye Nebula Figure 10-7); we know it is hot but we don't know its luminosity because these objects are a long way away and the distance markers we'd normally use, spectral type for one, do not exist—Gaia may have already measured some parallaxes. A few planetary nebulae are found in globular clusters and this gives a good starting point for trying to compare observations with the theoretical modelling which takes a star from the supergiant phase to that of the white dwarf. I've noted many assumptions as the researchers try to make progress in the face of uncertain data, least of which involves somehow getting temperatures for these stars. We know the central stars are hot, but how ***do*** you measure their temperature? You can use the known distances to the globular clusters and hope that the reddening is consistent with reddening in other parts of the galaxy and that the derived magnitude or brightness of the star is free from the effects of the gas and dust within the associated nebula. Then there is the fact that most of the energy is radiated in the UV and a magnitude we use (remember the yellow glass) which only represents part of the star's energy output must be corrected for this imbalance—perhaps by a factor of 100 or more!

Despite these difficulties it appears to be a vigorous area of research with astrophysicists doing their best to match these uncertain results with models. Not only do the astrophysicists try to determine the masses of central stars but they attempt to determine the masses of the progenitors and that's cool! Here we are working with a minimum of verifiable data and the theoreticians are going even one step further! It is rather impressive what can be gleaned from a minimum of uncertain information. For four planetary nebulae in globular clusters the researchers cite current masses of about half that of the Sun and progenitors between 0.7 to 1.2 solar masses, indicating that the original stars have lost about half a solar mass. The models give a timescale of evolution from when the stars being analysed were deemed to have begun their lives as planetary nebula. (This mention of 1.2 $M_{\odot}$ points to my confusion regarding the Sun's evolution but emphasises the dependence of this RR Lyrae evolutionary stage on chemical composition.) As mentioned earlier, the velocity of these rings as well as their composition can be measured. Given the velocity of the outermost ring it can be projected back and so tell us when one of these objects shed its first skin. In addition, the measurements of other rings, can tell us the mean time between these shells being blown off. This provides a check on the reliability of a model and allows the scientist(s) to mull over the situation and perhaps make improvements to their model. Look at a spectrum of one of these stars in Figure 10-9 where the star is so hot that its spectrum will peak well to smaller wavelengths than those displayed in this figure. Here the scientist is trying to match a model against both the shape of the observed spectrum as well as the few absorption lines visible there. Obviously, this transition across the H-R diagram is difficult to buttress observationally, but we go with the evolutionary calculations simply to make progress. But now back to the story.

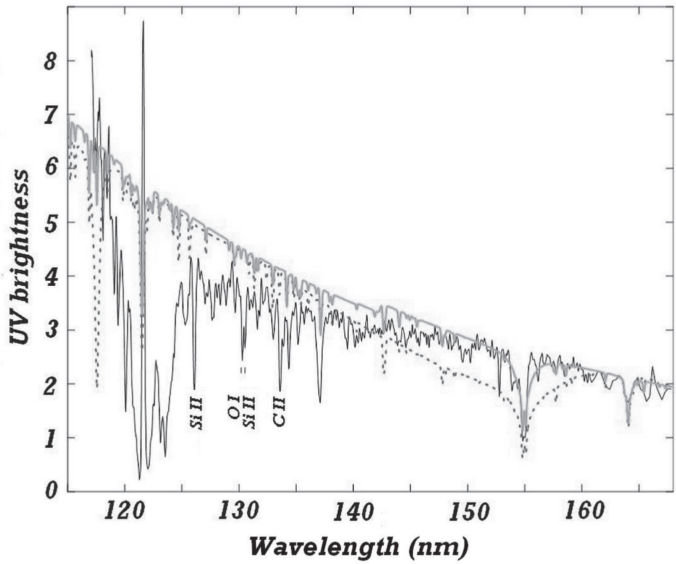

Figure 10-9. See Centrefold. This is a spectrum of a planetary nebula's central star. The green line is an attempt to match theory with these observations for a star of 70,000 K—the red data is a failed fitting attempt at 50,000 K. Note that the green line is rising at the shorter wavelengths and if this star is "only" 70,000 K it would peak at about 43 nm, way off to the left, thus there is no way to conclusively judge this star's temperature by this fit (which looks pretty good) except we know that it is very hot. Credit: NASA/ESA/Jacoby et al., 2017 ApJ, 836. 93. Annotated by the author.

10.13 The end of the line: The formation of a white dwarf

Mass is continued to be expelled from the atmosphere of the Sun by a process like the solar wind but only much more vigorously. Remember that the temperatures now are in the hundreds of thousands of degrees, twenty times or more than the Sun. For the Sun, radiation pressure has cleared out our environs, imagine that at these temperatures (~17 times that of the Sun) the radiation pressure will be even more powerful, in the ratio of the two different temperatures $(100{,}000/5800)^4$ about 8,000 times. How much material lost in this way is little understood except we know that mass is lost. Stars that are initially above the maximum mass of a white dwarf, still form white dwarfs so they must lose mass in some way otherwise they become supernovae. Mass loss leads to the blurring of the boundaries where a star of one mass goes one way in its evolution while another goes a different way. How do we know this? The Pleiades cluster is about 130 million years old and the most-massive stars we see in it are well over the Chandrasekhar limit. One white dwarf is found in the cluster and seven in the Hyades which has an uncertain age of about a billion years. Massive stars evolve faster than less massive object. These white dwarfs should be neutron stars or black holes. Two conclusions follow. One, the theory is wrong. White dwarfs ***can*** result from massive stars and there is ***no*** mass limit to their production, or the stars lose mass as they evolve. We see the evidence for this latter interpretation in planetary nebulae and supergiant red stars. This is the way out, even if getting there is difficult.

As the fuel is exhausted in the shells, the core shrinks and we see it as a very hot star whose radiation is mainly seen in the far UV (look at the spectrum in Figure 10-9 again). When the fuel is finally consumed the core remains degenerate and does not collapse. Then it slowly cools, taking a path indicated in the H-R diagram in Figure 10-4 and all the while the pressure of radiation from the extremely hot core slowly blows away the outer atmosphere. The star is now well on its way to becoming a white dwarf over a time scale of hundreds of thousands of years. The timescales of these processes are not well known for the calculations involving the dynamics of blowing away an atmosphere are very difficult, hence the vagueness of the words I've used. The white dwarf takes billions of years to cool until no heat remains when it becomes a black dwarf, unseen and a necessary object for Starship Enterprise to avoid!

Recent discoveries of white dwarfs in globular clusters—see later—reveal a wealth of objects which, when combined with theoretical calculations regarding cooling times for white dwarfs, yield a minimum age of the universe of 13-14 billion years. This is very interesting in that what ***I*** might have considered an uninteresting area of study has produced a number of fundamental importance! I must swallow my words. As you will see in Chapter 13, the study of white dwarf evolution is vibrant and fascinating.

10.14 Stars less than 0.075 solar masses

Depending on the mass of the star, there are two paths a star may take. Take these boundaries with a grain of salt as we are in the realm of speculation as much as we are in that of science. Let's start with the very long uneventful life of a star less than 0.075 solar masses where, at 0.075 solar masses, it might be massive enough to begin hydrogen burning and thus be called a star. Below this mass we are dealing with the so-called brown dwarfs which I'll visit again later in Chapter 12. While the cores of these stars are not hot enough to fuse hydrogen, the temperatures of those stars near 0.075 solar masses might be enough to fuse deuterium (heavy hydrogen) and lithium. Note that deuterium is part of the chain of nucleosynthesis that creates helium but here it fusing the deuterium that was produced in the original Big Bang, bypasses its own creation in the proton-proton reaction—or chain—thus making fusion easier—it takes a shortcut so to speak. The limits of these reactions in terms of stellar masses measured in terms of **Jupiter's mass (*M_J*)** are uncertain but the numbers quoted are 13 M_J as some sort of cut-off for these nuclear reactions. However, over time, the process will cease and the "star" will contract and cool off as a brown dwarf.

10.15 Stars less than 0.7 solar masses

Let's deal with the evolutionary cycle of a slightly more massive star destined to become a white dwarf like our Sun. Stars less massive than about 0.7 solar masses (I suspect this limit is uncertain) don't go through the evolution that our Sun will follow; evolving to a red giant and on from there. They condense out of the interstellar medium from a mass of hydrogen, helium and other debris from previous evolved stars and inevitably begin to spin because the collapse will not be symmetric. Planets will form. We know this because we can see it. The census of the current detected extrasolar planets and their host stars overwhelmingly favours red dwarfs. This is not surprising though, since they are the most plentiful. I'm thinking of the TRAPPIST system mentioned earlier (see Figure 7-15). When the internal pressures and hence temperatures are enough to trigger the transmutation of hydrogen into helium the energy from this process is enough to halt the contraction and the star reaches a stable configuration. It is now on the main sequence where it will live for eons and slowly morph into a white dwarf with its electrons packed unbelievably tightly within a lattice to provide the pressure needed to support the star. But dump enough mass on it such that its total mass is greater than 1.4 solar masses, perhaps from a companion star, and it this little baby will go boom as a supernova.

It may seem repetitive, but there is plenty of evidence in support of this happening if the star is part of a binary system (see Chapter 14) and these explosions play a critical role in cosmology and our expanding—perhaps accelerating—universe. The reason that stars of this mass don't emulate the Sun's evolution is that the mass overlaying the core is insufficient to compress it to temperatures that will trigger hydrogen fusion in a shell. Therefore, in these stars, there is no march across the H-R diagram for them to become red giants but they sit there as long-lived main sequence objects. I gather that stars like this may live longer than the current age of the universe. At least the inhabitants of these myriad planets won't be worried about being swallowed up by their life sustaining Sun. However, ultimately, it will cool down and become a cold mass like the failed stars mentioned above. Space must be littered with dark, undetectable objects.

10.16 A summary. What have we got so far?

What do we have here amid this welter of words? A star similar in mass to the Sun collapses out of the interstellar medium. When hydrogen starts burning in the core it is called a main sequence object where it will spend most of its life. Even at 4.5 billion years the Sun is still considered a main-sequence object—and young. When almost all the hydrogen in the core is converted to helium, the star swells, gets hotter and moves away from the main sequence. When there is no fuel left, the star contracts under gravity which heats the core until the temperature outside the core increases enough for hydrogen in an outer shell to begin burning. While this conversion continues, the star becomes a red giant moving slowly up what we term the red giant branch. As it evolves, the inert core contracts becoming degenerate—remember "getting like a brick" but a wee bit denser—getting hotter and hotter without expanding because temperature and pressure are not connected. When it reaches about 100 million degrees, helium atoms in the solid core begin to fuse, forming carbon and a little oxygen in what is called the helium flash but in a degenerate gas there is no regulation of the heat by expansion and cooling. The core burns quickly with the heat spread by conduction over a timescale of minutes with an energy output billions of times that of the Sun! This fantastic power is not observed because it goes into melting or evaporating the degenerate core of the star making it behave like a normal gas such that when the temperature increases, the pressure will also increase and the gas will expand and cool off. Because the process of helium burning is not as efficient in generating energy as hydrogen burning the star shrinks to compensate taking a path to the left in the H-R diagram to the horizontal branch where it doubles back once the fuel is extinguished and then, under compression, heats up and begins to fuse helium to carbon and oxygen. While going through the horizontal branch both ways, the star becomes unstable and pulsates over periods of hours becoming an RR Lyrae star. Pulsation finally stops and the star gets brighter and cooler as shells of helium and hydrogen ignite in the interior as it quickly reaches what is called the asymptotic giant branch. The star is enormous in size and would engulf Mars if placed in the solar system. From here the star may begin to pulsate, but it certainly sheds its outer atmosphere to form a planetary nebula. A nuclear furnace in a zone around the star's hugely compacted degenerate core—a future white dwarf—will provide the enormous radiation needed to drive away the outer envelope, leaving the white dwarf exposed to cool over the eons in interstellar space. The white dwarf cools slowly and ultimately, after billions of years, it reaches the temperature of interstellar space. The star itself is made of unbelievably dense carbon and has become a diamond! Not that one could ever wear it for a sugar-cube sized "rock" would weigh tonnes.

This is the evolutionary saga of a star like the Sun. There are uncertainties for sure, but while the details might be sparse in places, essentially this is the picture. It is salutary to be reminded that investigating any one of these stages of evolution requires a team of astronomers and astrophysicists, some making observations that test the theory and others who make the theoretical calculations, updating their equations as the observations reveal more unknown details. What we see in the journals as random samplings of research, then needs to be interpreted and combined to form a coherent picture.

10.17 Complications: Surprise! Surprise!

10.17.1 Rotation of the Sun

I've been using as an example, the evolution of a star like the Sun because it is a simple system that is slowly yielding its secrets to the external probes of helioseismology and neutrino emission. Our Sun revolves at a leisurely 2 km/s whereas other stars revolve much faster. When stars rotate quickly, they bulge at the equator, even the Sun does a little. A good example of this is the planet Jupiter whose equatorial bulge is most noticeable. The Earth has an equatorial bulge also caused by rotation. The point is, that we've done the calculations assuming that the stars aren't rotating at all. Adding rotation to the mix makes everything much harder as rotation causes circulation currents related to what we see in the Earth's atmosphere or in the ocean. Circulation in a star means that material is moved from one place to another; from the depths at the equator and over to the polar regions, or dredged up from the interior and moved back into the depths. This material is potential fuel. Helium initially created in the core may be moved upwards out of the fusion region while hydrogen, the fuel, moves downwards (dredged down) to be transmuted. Whenever there is rotation, and hence circulation currents, fuel is moved around leading to longer timescales because of the mixing of the interior elements. When helium is the fuel, similar complications may arise leading to altered timescales and differing evolutionary tracks in the H-R diagram. Note that pathway of the Sun in Figure 10-4 is an example of an evolutionary track. This complication creates the need for even more complex models. Material is dredged down by circulation and if the modelling of this process is not quite right, what sort of effect will it have on our conclusions? For this reason, we see more and more recalculation occurring in the literature as the physics gets better understood, or perhaps, related equations that might have appeared intractable get solved, yielding a growing list of associated publications.

Related to this in an historic first, the VLTI in Chile has measured the distorted shape of the star Achernar directly on the sky (see Figure 10-10). The result shown in this figure is ***no***t derived by modelling a star, but the star's shape is ***directly*** determined by "looking" at it with an interferometer. The result apparently tests the things I've mentioned here as ***complications.*** It is highly flattened such that the equator bulges out 50% more than its polar radius—just think of the Earth bulging out that far. We expect the currents to take material from the equatorial regions to polar latitudes and hence to circulate. Think of it in the context of the Sun, in which, for a modest rotation that hardly produces an equatorial bulge, we see the polar latitudes rotating at different speeds than at the equator. These effects will be greatly enhanced in a star rotating as fast as Achernar. We'd expect interesting structural changes inside this star as well as the likelihood of Achernar shedding mass around its equatorial regions where gravity is lessened because of the centrifugal force and the effects of radiation pressure. In this case, the models we use to evolve such a star will be only a very rough first approximation to reality. Undoubtedly there are many other variations on Achernar in the general stellar population.

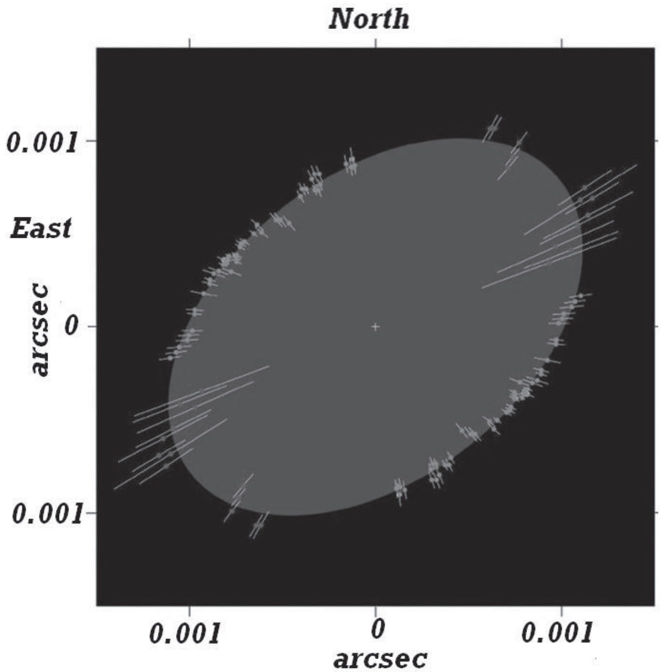

Figure 10-10. The shape of a star seen using the VLTI showing how rotation can grossly distort a star. There is a huge temperature difference between the pole (20,000 K) and the equator (10,000 K) which, to say the least, provides a challenge to be realistically modelled, let alone evolve such stars. You can see here that the resolution is below 0.00001 arcseconds. Credit: ESO/VLTI.

10.17.2 Convection, or bubbles of hot gas

The calculation of the internal structure of the Sun depends on how convection is treated—remember that convection is the transmission of energy through bubbles rising in our pot of hot water. The physical theory first used by Schwarzchild, called the mixing length theory, essentially analysed how long it takes for a hot bubble of rising material to cool off and merge back into its surroundings. In order to be treated mathematically with the computers of the day, the model had to be pretty simple. Remember the storage capacity of yesteryears computers was little better than the current crop of handheld calculators and certainly less than the organizers many people have. Despite the advances in computing and modelling power, the development of a good theory of convection to replace that used initially by

Schwarzchild is long in coming. In essence, an application of an inadequate theory allows its handling to be used as fudge factor to match the observed radius and luminosity of the Sun to the model and creates an uncertainty in the modelling since there should be no fudge factor.

Convection, like circulation, also plays a major role in stellar evolution. Consider the core of a star where convection occurs. What happens if convection is more vigorous than our calculations predict? In these cases, the bubbles of helium in a convective core end up among unprocessed hydrogen gas, which is dredged back down into the core to be consumed as the bubble heats and mixes with its surroundings. Now, with more raw materials to transmute, the core continues to do what it did before but for a longer period. This process, called convective overshooting, serves to alter the evolutionary timescales given by the calculations as well as altering the structure of the star so it evolves along a different track in the H-R diagram. It is realistic to assume that all the evolutionary scenarios will be altered, some dramatically once convection is formulated accurately and introduced in its fullness into the calculations. (I apologise to my fellow researchers if this has already been done.)

10.17.3 Energy generation

The results from a recent nuclear physics experiment conducted 1400 m underground, away from the effects of cosmic rays coming from space, have a direct bearing on one of the fusion processes that converts hydrogen into helium. In low mass stars like the Sun, it is the proton-proton chain which dominates, whereas in more massive stars, or in stars with central temperatures greater than 20 million degrees, it is the carbon-nitrogen cycle or CNO cycle (ignore the details—they both create helium). Experiments aimed at proving the physics used for evolutionary calculations, gave results at variance with the results generally used to evolve stars in the computer, in the sense that their rates of energy production were slower than expected. In this case, helium is produced more slowly and evolution proceeds more slowly, hence the timescales of evolution are increased. While such a provocative result will need verification (whether right or wrong) I mention it here because science is always at the mercy of the latest results, some of which may buttress the current accepted view and others that may challenge it. In writing this story, I too am at the mercy of the latest results, both observational and theoretical! Believe me, I'm conscious of it! Gaia is always at the back of my mind but I'm not going down ***that*** rabbit-hole because I could never keep up. In the case of stars like the Sun which gains its energy from the proton-proton cycle, the CNO cycle will be important in the post-main-sequence lifetime when the interior temperatures have risen due to core contraction and the onset of other fusion processes. Estimates by the Italian scientists involved in this experiment increase the age of the universe by about a billion years which may put them at variance with results from the COBE successor WMAP that dates the universe quite precisely at 13.7 billion years. I just love this!

10.17.4 Sunspots

The Sun is not heavily spotted over its surface. The spots are small and yet they provide visual emphasis to the way the Earth is affected by surface activity on the Sun. At best, they change the Sun's luminosity by about 0.3% whereas in other stars the spots may change the stars brightness by upwards of 10%. (As an aside I modelled the light curve of an eclipsing binary, ER Vul. using a sunspot size of 10% of the stellar surface—they can be large!) Despite these words, the tree ring data that indicate the level of magnetic activity on the Sun, or specifically the solar wind, indicates a large-scale heating of the Earth between the 10th and the 14th century. Currently solar physicists recognize the possibility that the total energy output of our Sun may be variable, not in the way of showing large sunspots or excessive flares, but in energy related to changing magnetic activity.

This all means is that our simple Sun is anything but simple, but its modelling by the methods described here can take us a long way. It is a good start. You may wonder how this talk and speculation can be proven. I'll get to this topic after the next chapter.

CHAPTER 11

ON THE FAST TRACK TO OBLIVION

11.1 Helter skelter

The collapse of a massive star out of the interstellar medium takes place faster than a less massive star. In fact, everything goes faster. The temperatures inside the stars are more extreme and transmutations impossible in stars like the Sun now readily take place. When the star forms, maybe it spins a disk from which planets form. Maybe the extreme UV radiation from the emerging star blows the whole lot away, maybe not. Who knows! Well, we ***will*** know when a planet is found rotating around a neutron star, one possible end-product of this evolution. Just after I penned that line there was an announcement that such a planet had been discovered, but a complicated history had it ***captured*** by a neutron star and not originally in orbit around it. Now the list is longer and I remind the reader that everything written here is subject to change because of the research that continues to verify and expand theories. But since I mentioned diamonds in discussing white dwarfs, a neutron star with a dense object (remnant of a star being scoffed by the neutron star) with the density of diamonds is orbiting every 2 hours. Now details of the orbit are absolutely clear-cut because the neutron star beeps with amazing precision such that the wobble produced by its orbiting companion delays and advances the normal pulsar beep. The situation is analogous to how a politician's fortunes may change as more and more information is revealed. In science, everything is developing. Consider how the origins of Homo sapiens gets pushed back further and further in time and interbreeding with the Neanderthals/Denisovans becoming a fact, even more recently. I'm sorry that these seem like weasel words but because of continued new discoveries—let alone some pretty exotic theories—no proclamations can be cast in stone.

Consider a 20 solar mass star on the main sequence and follow the process from where the star leaves the main sequence, getting brighter and cooler. Its main-sequence life ends when the hydrogen fuel runs out and the star contracts without an energy source in the core to support it. We see this

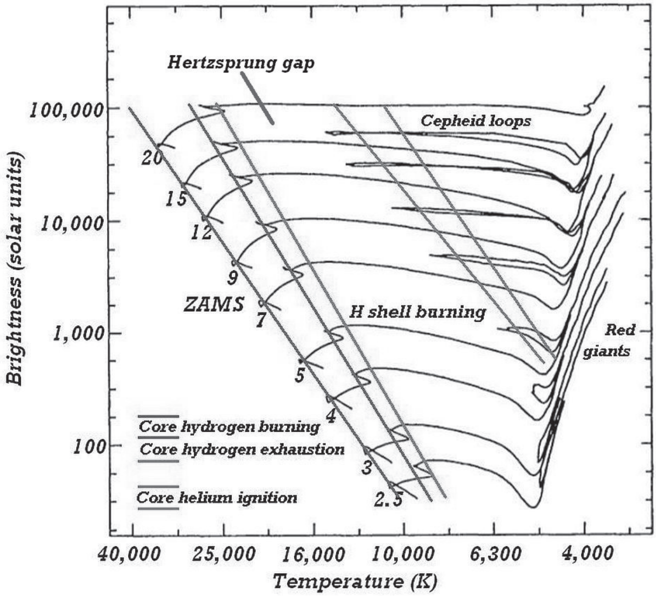

Figure 11-1. See Centrefold. Displays a theoretical H-R diagram showing the evolutionary paths of massive stars. The colour-bounded areas delimit hydrogen burning in the core, **core hydrogen exhaustion** and contraction and helium ignition in the core. Credit: Schaller et al., 1992, A&AS, 96, 269. Modified by the author.

effect in our theoretical models as a swing to higher temperatures and luminosity in an H-R diagram, shown in Figure 11-1 followed by a hook to cooler temperatures from where is moves quickly across the Hertzsprung gap towards the red giant branch. This swing ends when the inner regions get hot enough to ignite a shell of hydrogen (**hydrogen shell burning**) surrounding the core. Now the star stays at the same brightness but gets cooler and larger (see Figure 8-6 to refresh your memory). Now we have a star with an inert core slowly squishing up under gravity and getting hotter, with a shell of hydrogen busy transmuting into helium with more and more vigour as the core heats. Therefore, the helium core gets larger and so does the star because of the increasing energy coming from the shell of hydrogen. We see this manifested in the H-R diagram as a star moving to cooler and cooler temperatures. When the core reaches 100 million K, helium burns creating carbon by fusing three helium atoms together in the simplest of nuclear reactions, the **triple-alpha process**. The star is now a red giant. and it mixes up in the same region of the H-R diagram where stars like the Sun reside in their paths towards becoming white dwarfs (Figure 11-2).

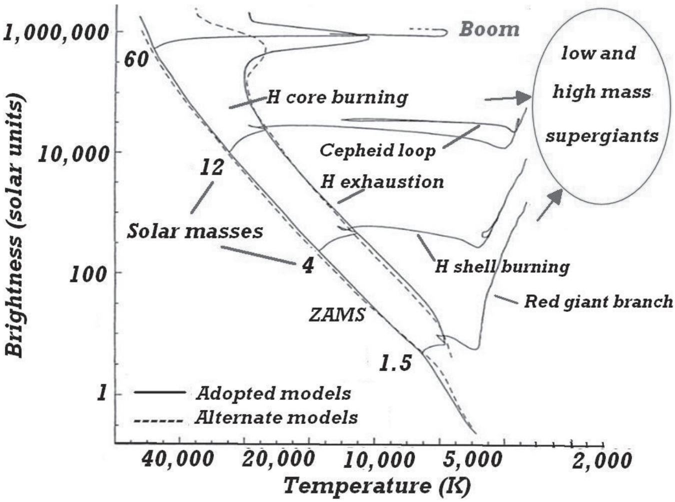

Figure 11-2. The oval to the upper right shows the overlap of supergiants evolving from solar mass stars and those that are much more massive. When observing red giant stars, initially we don't know whether they are of high or low mass. The 60 $M_{\odot}$ star never makes it to the red giant "sink" and explodes as a supernova. Two sets of evolutionary tracks are shown to illustrate the calculation uncertainty for very massive stars. Credit: Schaller et al., 1992, A&AS, 96, 269. Modified by the author.

11.1.1 Now for a slight digression. The red giant sink

Evolution takes low and high mass stars into the region of the red supergiants (Figure 11-2) where, for a given luminosity and temperature, they share the same radius; the only difference being their mass. Recall that surface gravity depends on the radius and mass of the star. Therefore, the more massive star will have the highest gravity and their spectral lines will be broader than if they were of low mass (see Figure 7-6). To differentiate between the two possibilities the spectra must be modelled to determine the gravity and temperature. Having the gravity, and knowing the radius, then gives the mass. This situation does not arise in a cluster; Yes, there will be these red supergiants in open clusters such as the double cluster in Perseus and there will be red supergiant stars in the globular clusters, but the time-lines are such that the supergiants arising from massive stars in a cluster will be long-gone before their low-mass cousins also become supergiants. The situation in the general field, that is stars not associated with clusters, is quite different. Then, you may be dealing with either alternative when faced with a red supergiant.

11.2 Back to the story

After helium is burned in the core to produce carbon and oxygen and the core contracts, the star takes a large loop to hotter temperatures in the H-R diagram before the core ignites at 600 million K to produce neon, magnesium, oxygen, and again, the star begins a march to cooler temperatures within the red giant region. It is in the region of this loop that Cepheid variables are found (see Figure 11-1 and 11-2). This is the same scenario we looked at regarding the RR Lyrae stars where a loop back after the helium flash on the red giant branch produced model stars in the region of the RR Lyrae stars, that, given a kick, would pulsate. Well, the models computed through this region of the H-R diagram would also pulsate if given a kick. In astronomy speak, these models are pulsationally unstable, that is, they're quivering, trying to decide to take a series of deep breaths, and then pulsate or to move on. Like someone pushing you forward when, all harnessed up, you're trying to make up your mind to make the bungee jump you always wanted to do—or thought you did! I can recall as a graduate student the excitement surrounding two astrophysicists doing a triumphant speaking tour announcing they'd evolved their models through this region and found that they were unstable, ignoring the fact that the masses they had derived for the stars were too low by half. Their problem, dating back to the mid-60s, has been with us for a long time. Originally, it was thought to be associated with an error in the software computing the opacities adopted for the models. (I was visiting the institution at the time where the astrophysicist responsible was coming to grips with his error, and I recall he was a mite upset!) But there is no magic bullet to solve ***this*** problem. The opacity error provided but a partial help in reconciling the mass differences which remains to this day, but more of this later. I told you that astronomy was a mess of interconnecting problems—and solutions too.

Why does the core heat up this much when in a star like the Sun 300 million degrees is about the limit? The mass of the overlaying material is the difference. While in bed we hardly get squashed by the weight of a counterpane but put a door on us! Having created these elements, the core contracts again and when temperatures reach 1.5 billion degrees (!!) oxygen burns producing silicon, sulphur, phosphorus and more magnesium. The result of these reactions is to create even higher temperatures at which time silicon burns to iron. A convenient way to imagine all this is to think of the interior of a star looking like an onion where each layer corresponds to an element. In the outer layer there is hydrogen, inside it is helium, inside that is carbon and so on until we reach the centre of the star with a core of iron surrounded by silicon. Yes, the same silicon we have in abundance on our beaches, in our windows and as well as, unfortunately, a breast augmentation substance. I show a schematic of this situation in Figure 11-3.

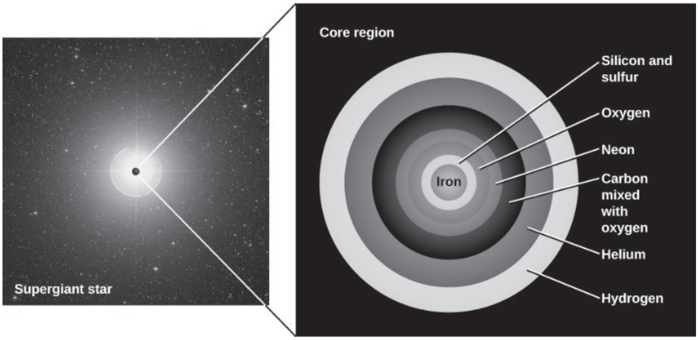

Figure 11-3. A schematic representation of a massive star just prior to it generating an iron core and becoming a supernova. The situation can be represented by thinking of the innards of a star as a series of onionskins each comprising one element. It is obviously more complex than this because of the circulation currents and the inevitable mixing of the elements. Credit; ESO, Wikimedia Creative Commons/Hall.

The reader will imagine that such a simplified scenario is quite unlikely but it illustrates the notion of nuclear transmutation. Why might this scenario be unlikely? I've talked about convection in stars, that is the bodily movement of material inside a star caused by the inability of parts of the interior to expel energy to the outside by radiation alone. I remind you of the water boiling in the kettle where the heat flow is so great that the water is displaced and comes to a rolling boil. A rolling boil in a star will mix these shells, or some of them, depending on the extent of the boiling or convective process and where it is occurring. In the Sun, convection occurs in the outer regions where we see it manifesting as those granules, but in a massive star it is the core that is in convective uproar. Think of the simplest case where a core is of helium and a shell of hydrogen is burning outside the core. When there is convection, helium moves upward into the hydrogen which is brought back to the core to provide more fuel for the star to burn. With more fuel to burn the longer a star can stay wherever it happens to be, on the main sequence, the asymptotic giant branch etc, thus throwing off the timescale calculations. Our simplistic onionskin has got to be a crazy mix of dynamic elements in the presence of mass circulation. Understanding the process of convection and treating it properly in the calculations is not only difficult but may have a profound effect on the calculated ages of the stars. This is likely an understatement!

Here, I've discussed the simplest case. What about replenishing the core with silicon on its way to being converted to iron? The whole area of research suddenly becomes very complicated. Now toss in the fact that these massive stars may rotate very quickly. At the extreme, velocities of rotation may be as large as 500 km/s, a value 250 times that of the Sun. At these speeds the stars are bloated at the equator and inside them, like with the planet Jupiter, or the oceans of our Earth, circulation currents move material from one place to another. The simple static picture I've outlined becomes a dynamical nightmare where mixing of various elements takes place throughout the star and the intermingled nuclear processes become very complicated. When I use the term "dynamical nightmare" I'm referring to the fact that formulating and hence calculating the effects of movement becomes very difficult. What we see happening quite nicely in Nature, such as our boiling water, is very complex and difficult to model in a computer. "Model in the computer". I stress here that someone works out the theory and feeds it to a computer—more easily said than done—the computer does nothing but what ***you*** tell it. But in the end, the core is likely to be made of pure iron. This process is a dead end, like the car chase that roams over the city only to stop catastrophically at a dead end road. Iron cannot burn at these temperatures and the scene is set for the mother of all explosions.

11.3 The end of the line

Prior to this point the star is slowly moving to cooler outer temperatures and staying very luminous until it too becomes a red giant. When the core is made of pure iron, it cannot burn, even at interior temperatures of billions of degrees. The star has run out of fuel! Now it follows the pattern we've established; it shrinks gaining energy by compressive heating. But in this case, and under tremendous pressure, no fusion occurs, instead the protons and electrons in the core are forced to merge into each other to form neutrons. The supporting electron scaffolding has collapsed! Thus, a core of iron is suddenly transformed into a sphere of neutrons because the electrons that provide the star's supporting pressure in the face of gravity's relentless force are absorbed into the iron nuclei. This has catastrophic consequences, leaving the star to collapse inward under the huge pressure of the overlaying material. Under these immense forces, the core of neutrons is compressed into a ball maybe only 20 km across (!) and the densities inside this ball rival that of those in the atom itself (see Table 7.1). In less than a tenth of a second the temperatures reach 5 billion degrees and the star collapses in on itself at speeds up to 15% of the speed of light! The imploding material bounces off the neutron core and in a matter of hours, lifts off the outer layers in a monstrous explosion. A star totally invisible one day, then shines so brightly that its light may be 100 times the visible light of an entire galaxy! A schematic showing the brightness changes is described as a light curve and is shown in Figure 11-4. The rise in light is sudden and the descent much slower, but this varies also. Trying to catch an event like this on the rise is something astronomers have long sought and automated telescopes are scouring the skies to try and detect them. Immediately a supernova is detected, the word goes out to the largest of the telescopes and operations immediately are transferred to make the observations with whatever instrument is available. The extraordinary luminosity that supernovae attain makes them invaluable for use in cosmological studies where the galaxies are so distant that individual stars cannot be identified except when a supernova is seen as bright star overlaying the hazy view of the galaxy. During this immolation, iron fuses as do all the other elements in succession, one from another, and the conundrum that frustrated earlier researchers on the process of nucleosynthesis is solved. Whereas nucleosynthesis in the Big Bang had to

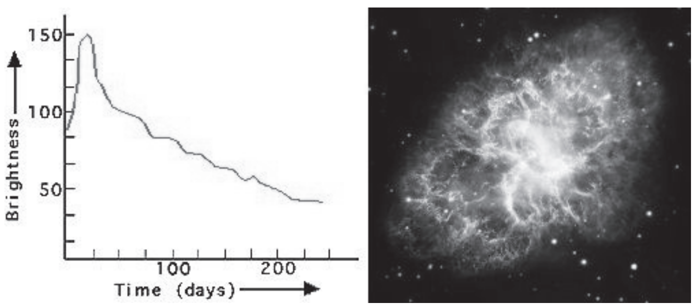

Figure 11-4. Left panel. A schematic supernova light curve. Right panel. The Crab Nebula in Taurus, the remnant of a supernova that erupted in 1054. The pulsar at its core is seen as a white spinning top-like object. This highly detailed image was created by combining data from radio telescopes (VLA), powerful X-rays as seen by the orbiting **Chandra X-ray Observatory** superimposed on the Hubble Space Telescope's image and IR data from the Spitzer Space Telescope (SST). Credit: NASA.

work in dropping temperatures, a supernova deals with rising temperatures, an ideal situation for we know that is how heavier elements are built, piggybacking from less massive elements.

The most famous recorded explosion produced a nebula called the Crab Nebula is illustrated in Figure 11-4. In the 1054 Chinese astronomers noted a new star in the Taurus constellation which became as bright as Jupiter and was visible for two years though the event is not recorded in Europe. (Had King Harold seen this he might have wondered if it presaged the end of the Saxon dynasty). In this nebula, the material is moving outward. The rate of expansion is measured by comparing images taken years apart. Knowing the expansion rate in arcsec/year, it is possible to project it back to calculate the date of the explosion and so verify that this was indeed the event recorded by the Chinese. In addition, because the innards of the star are expelled into space it is possible to analyse the chemical composition of the nebula and so verify the transmutations that have occurred.

The picture I've painted here is of a generic star twenty or so times more massive than the Sun. As I mentioned at the start of the chapter, in massive stars everything happens faster. A massive star may do its thing, that is blow up, long before it ever reaches the red giant stage of its existence—see Figure 11-2.

11.4 More about supernova

In 1987 a supernova erupted in the Large Magellanic Cloud (see Figure 11-5). The explosion was different because the star slowly rose to a maximum over 85 days instead of within a few days but the progenitor star in the LMC was a blue supergiant, not a red one. As an aside, I point out that even the model I've talked about where the immolation is immediate and the brightness increases dramatically, is already proved a lie with reference to this star. These "little" discrepancies are what make astronomers tear their hair, but they also provoke thought that always advances the science. The collapse of the core releases vast numbers of neutrinos into space, some of which were discovered here on Earth, and produces a gravity shock that is propagated through the LMC and beyond. When reliable directional neutrino and gravity detectors are in place, we'll get a direct look into the heart of a star in its death throes—but eons after the original event! (Remember, we are always looking into the past.) Having said that, the first confirmed detection of a gravity wave was in 2015 and now many events have been recorded (see Chapter 14) opening a whole new avenue of research. Back to the LMC.

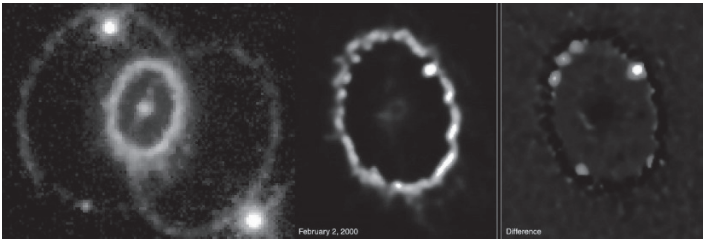

Figure 11-5. The left-hand panel shows the supernova 1987A with two rings, the large outer and the inner, both of which have no explanation and which existed before the star blew up. When the light from the supernova died down the inner ring seen in the central panel became visible with a size of 0.808 arcseconds. Matter ejected from the supernova took 12 years to reach the ring and interacted with it to give the bright spot seen in the right-hand panel. By measuring the velocity of the matter originally ejected from the supernova and the time of travel coupled with the observed size of the ring it was possible to triangulate the distance to the supernova and hence to the LMC. Credit: NASA/HST.

The event that was observed in the LMC leads to a distance determination just as observations of the Crab Nebula yielded its distance. How does this happen? In the case of "the Crab" it was observed to erupt in 1054 and astronomers measured the velocity of the remnants seen on the sky, the so-called velocity of expansion. Knowing when the explosion occurred coupled with the remnant's velocity yielded the distance between the nebula and its progenitor, then, when coupled with the measured diameter of the nebula in arcsec, this distance yields the diameter of the nebula in km. Given the angular size of the nebula in arcseconds and its size in km we can calculate its distance from us by simple trigonometry. (This is a common lab exercise in Astronomy 101.) This is the normal scenario where an expanding object is close enough for us to measure its velocity and its changing size on the sky. The supernova in the LMC provided a lovely variation on this theme. In the image of the supernova (see Figure 11-5) there is a small ring, of unknown origin surrounding the star. It was theorized that the material racing away from the supernova—its ejecta—would impact the ring about a dozen years after the explosion. By monitoring the ring, it was expected that the collision between the gases would produce a series of hot spots and lead to a travel time from the supernova to the ring. Combining the travel time with the velocity of the ejecta gives a measure of the baseline in km. By measuring the size of the ring in arcseconds we are into classic surveying with a known baseline and an angle, enabling the distance to the LMC to be calculated by geometric means! As far as I know this is the most distant triangulation ever made and with an error of only 6%. Interestingly, in reading about it on the Web, I discovered that the measurement, placing the LMC 170,000 LY away, had provoked an immense amount of interest and debate between the creationists and keen amateur astronomers. The discussion involved the accepted velocity of light and how these observations could be forced to fit a 6000-year-old universe. But like the flat-Earthers anything is possible if you ignore the facts.

Evolution in massive stars creates all the elements up to iron but the heavier elements, lead, gold, mercury etc are produced afterwards in the supernova explosion where the temperatures inside the star reach billions of degrees. Calculations reveal that nuclear synthesis ***will*** take place at these temperatures and so the material we take for granted around us, the bands of gold and platinum on our fingers, the calcium of our bones, iron in our blood, the uranium and lead all had their origins in the stars. But a supernova explosion does more than seed space with enriched material suitable for the creation of worlds, it also triggers the formation of stars themselves. The material blown away in the explosion ultimately interacts with the gas and dust permeating space from innumerable explosive events in the past, and not just from supernovae but from stars older than the Sun that have expelled their outer layers to form planetary nebula. The onrushing supernova material collides with the other stellar remnants increasing the density of the mingling gases and dust. In some cases, the density increases sufficiently for the material to start collapsing under the force of its own gravity to form more stars. Thus, a supernova event may spawn a burst of star formation.

What do we see when a supernova goes off? From a part of the sky where there is no trace of a star, suddenly within the space of a day (see Figure 11-6) there is a new beacon of light which peaks rapidly and then immediately starts to die away. The light decreases, dropping by perhaps a factor of 100 over a few years. Because of this enormous change in brightness, supernovae are used as standard candles in distant galaxies since they are easily discovered and at peak luminosity their brightness is similar from star to star. A standard candle is something whose intrinsic brightness is thought to be known. If you can prove that all the supernovae achieve the same brightness then they can be used to measure the relative distances to far-flung galaxies. I must qualify this statement; in fact, there are two types of supernovae, Type Ia and Type II, both resulting from a star exploding because the mass at the terminal stage of evolution exceeded 1.4 solar masses. A star blowing up in the manner I've just described is of Type II and only recently has proved useful as a distance marker. The other type of supernovae stems from a binary system and the nature of this event produces a reliable standard candle, but more of this later in Chapter 14. Again, this statement must be qualified—do we know anything with surety?

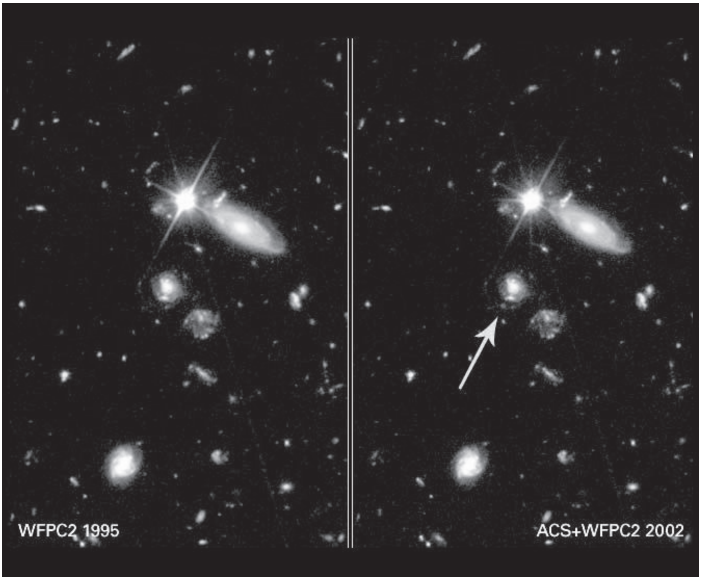

Figure 11-6. See Centrefold. A supernova in a distant galaxy. The left panel shows a galaxy with the supernova missing and the right panel shows the supernova as a red object. The bright image towards the top is a star in the Milky Way. Almost every object visible in these frames is a galaxy! If you want to garner an idea of infinity think about this statement. Credit: NASA/HST

Because of their enormous brightness, 100,000 times the luminosity of the brightest stars, considerable effort has been made to detect supernovae events using automated searches. These dedicated telescopes cover the same groups of galaxies night after night looking for changes in brightness in the star fields. Telescopes under construction will do this job very well and will support the automated searches that are ongoing with smaller telescopes. Here, I'm referring to The **All Sky Automated Survey for Super Novae (ASAS-SN)**. This program has 20 robotic telescopes in the Northern and Southern Hemispheres surveying the entire sky approximately once every night. Any changes are picked up by automated software and the results are passed on to large telescopes so that spectra can be obtained. Because they peak in brightness so quickly it is critical to observe them "on their way up". It is important to measure as much of the light curve as possible because, as noted above, there are two ways that stars can become supernovae and each type of event has its own characteristic light curve. It is remarkable really; I've talked about the difficulty of observing the helium flash in a low mass star because it takes place in minutes. The real problem is that not much happens for us to see as the changes take place ***within*** the star—a rearrangement of the furniture within a room so to speak—but in the case of a supernova we see something immediately—the room's walls blow out! Then we see a dramatic change in brightness that heralds an evolutionary event that only takes days to be revealed.

Type Ia supernovae have been used in recent studies of the expansion of the universe. These studies suggest that the most distant galaxies are accelerating away from us, leading to the question as to what is producing the acceleration. The universe formed in the Big Bang and since that time it has been expanding into space, the expansion rate being limited by the gravitational attraction of the mass within. The big question has been whether the force of the original explosion would cause the universe to expand forever or would gravity rein the expansion to a halt and then force a collapse. This picture is like a satellite failing to achieve the speed at launch necessary to take it away from the Earth's gravitational pull on its way to the Moon or beyond and so it returns to Earth. Instead, the studies of distant supernovae suggest another unknown force at work—a force of expansion—which is driving the expansion even faster. Now astronomy becomes embroiled in the world of particle physics in a subatomic world where speculation is rife and the discussion fascinating. And, always, the two disciplines of astronomy and physics are entwined.

11.5 Summary

The evolution of massive stars is more straightforward than that of stars like the Sun, but I'll recapitulate the story here: A star many times more massive than the Sun forms out of an interstellar cloud and when it starts burning hydrogen in its core it becomes a main-sequence object. Radiation pressure and the solar wind blow away the remnants of star birth. As the star converts hydrogen to helium it gets brighter, slightly cooler and larger, until the interior fuel is exhausted at which point the star's core contracts raising the core temperature. In this process it does a small hook back to the left in the H-R diagram. Contraction heats the core until a shell of hydrogen fuses, and like its low mass counterparts on their way across to the red giant branch, the star gets larger and cooler as its outer layers are forced outward by the energy produced by the shell. All the while the core is increasing in temperature until it reaches 100 million K when helium begins to burn, taking the star into the red giant region of the H-R diagram. When the helium in the core is exhausted the star does its number again by contracting, heating the core and getting hotter as it swings to the left in the H-R diagram forming the Cepheid Loop and then, once the core helium ignites to create carbon, the star moves back towards the red giant region. Whether it gets there or not depends on its mass, but ultimately, whether in a short burst of transmutation or a long evolution it ends up with a core of iron. This process of fuel exhaustion and pulsation is similar to that which triggers the RR Lyrae stars in less massive stars. Tests on the models in the Cepheid Loop reveal them to be unstable, as they pass through to hotter temperatures and as they turn back towards the red giants. Because the interior of the star is different in each case, on the turn to the left the core of carbon and oxygen is inert, but on its swing towards the red giants its core is transmuting carbon and oxygen to neon, and so the light curves calculated for the pulsation are different. Details like that enable the theory of evolution to be tested in a microscopic way, rather than by checking the overall path of evolution in an H-R diagram. While I've said that evolution goes so slowly, we can't observe its effects—excluding a star that explodes—but variable stars like the Cepheids and RR Lyrae stars also exhibit small evolutionary changes in real time that we need to understand. For example, the North Star, Polaris, is a Cepheid variable. Well, it stopped vibrating a few decades ago. Why? It was thought to be leaving the region of the instability strip and becoming stable again. However, observations of its radial velocity, or the velocity of its atmosphere towards and away from us, show that it is still pulsating or vibrating over a four-day cycle. In addition, its period is slowly changing, consistent with its movement towards the red giant region. Anticipating the chapter on proving these theories, the comments regarding the Cepheids gives an indication of the details achievable for us to be sure that we have it right! Despite my earlier words, there ***are*** real time observational changes that enable us to really check the details of our models.

A core of iron does not burn so it contracts from a size about that of the Earth and absorbs all the electrons that provide the sustaining pressure in the star. The core now shrinks to about 20 km across and is made of neutrons with a density 0.4 quadrillion times that of water (see Table 8.1)—close to nuclear densities. Without the supporting pressure of the electrons the star collapses and blows up in what we call a supernova explosion. The immolation produces all the elements we have on Earth. The remnant of this explosion is a neutron star or a black hole. Massive stars, perhaps greater than 3 solar masses, form black holes whose interior densities are greater than that of the atomic nuclei themselves—I'm sorry about these "perhapses" but we know the broad picture and not all the details, which in my world are the most interesting. I'm sure forensic criminologists feel the same way!

Parts of the processes are vague. For example, what is the mass limit above which black holes form? The problem here is that because we are dealing with very hot stars and very hot atmospheres, we are faced with trying to estimate or calculate the loss of the atmosphere by the effects of radiation pressure. That is the heat itself expelling the atmosphere. How much mass ***is*** lost over a star's lifetime? We also do not have a series of observations of black holes with which to verify their formation. When I first wrote this, gravitational waves (GWs) had not been detected so we do, in fact, have observations that give a clue as to the masses of black holes among the stellar population (see Chapter 14).

CHAPTER 12

RESULTING WEIRDOES, THE PRODUCTS OF EVOLUTION

12.1 Preamble

Now that I've raced through the evolution of stars undergoing fusion in their cores I'll back up and reprise the situation. To me, in writing this material or giving it in a lecture, it seems like I move leisurely along with a long build-up and then suddenly, the story is out and we're all wondering what has happened.

We have learned that the final stellar evolutionary products are white dwarfs, neutron stars, black holes and brown dwarfs and how a star gets there is determined entirely by its mass. We have seen that the boundaries between these end-products are blurred. Astronomers cannot say with any certainty just where the demarcations occur for each star is different: they have differing chemical compositions and they rotate at different speeds mixing the elements, or fuel, within them in ways that we don't understand. Think of the Sun in which a very modest rotational velocity (2 km/s) produces streams of matter moving from regions near its core to differing places, its equator and the polar regions in patterns not predicted though we do observe them in a variation of seismology called—surprise, surprise—helioseismology. What might be going on in stars whose rotational speeds are ten, or a hundred times this? What role does chemical composition play in a star's history where the passage of energy from within to without is variously hindered by its composition. What about magnetic fields that cross the galaxy and are captured by embryo stars to become part of their makeup. (Magnetic fields have always been conceptually problematic for me at least past the simple notion of a bar magnet and those iron filings!) Because of the infinite variations, I chose to illustrate the evolution of stars with only two masses as, by adding more, I felt I'd simply be describing the characteristics of yet another star. Somehow, we must generalize, acknowledging that covering the whole range of possibilities will swamp us in detail. This circumstance makes me feel very happy because I know that however much we might learn, there will always be work for those of us who've spent their lives studying the stars, trying to get a handle on how they live and die.

12.2 White dwarfs

White dwarfs were discovered in the early parallax surveys as very faint objects, two of them show up in the original H-R diagram (Figure 7-5). Their location in this diagram immediately classed them as some sort of weird star sitting as they do 10 magnitudes below the main sequence above them. As an aside, my teacher Willem Luyten, himself a student of Hertzsprung, is reputed to have coined the name, "white dwarf". Of the three stars known 100 years ago, two are companions to well-studied binary stars, Sirius, and a prominent northern hemisphere star, Procyon. The most prominent white dwarf is the companion to the brightest star in the night sky, Sirius, located south of the constellation Orion as seen at Christmas time. Its companion is about 10 magnitudes or 10,000 times fainter, yet it weighs only about as half as much as its brighter companion! In looking at this star in detail figuring out its size from its brightness and approximate temperature, and hence its density, astronomers were confronted with some of the extreme forms that matter could take in the larger world. Now a teaspoon of water weighs 5 gm but a teaspoon of white dwarf material would weight about 5000 kg (or five metric tonne), close to five tons—though I've seen a variety of quoted values!

There is solid theoretical evidence that white dwarfs are the endpoints of evolution for low mass stars like the Sun. (If we were not so sure of the theoretical basis for the existence of white dwarfs then the age of the universe could not have been placed between 13 and 14 billion years.) They are the cores of parent stars stripped of their outer layers, and in the process squished to unbelievable densities and doomed to cool until they are totally invisible in interstellar space. It is worth describing again the type of material comprising these stars. The stars are made of degenerate gas, material in which the electrons are packed tightly around the atoms and which provide the pressure supporting the overlaying mass of material. I imagine it as people sitting in a lattice of seats in the bleachers, all packed in together with no place to go. Replace the lattice with electrons and the people by atoms. This is a stable situation and, in a star, if there is nothing to upset the lattice like dumping more mass into it, it will remain stable. In this analogy the supernova results when more people move onto the structure and the whole thing collapses. Without a source of energy, the lattice will cool in a way as predictable as a pot on a stove. In the earliest attempt to calculate the age of the Earth by its cooling, Lord Kelvin derived the age of the Earth as 20 million years based on its mass and assumed internal temperature; though in this case the calculation went awry because there is another heat source—radioactivity—in the centre of the Earth that fouled up his calculations. Not so with the white dwarfs whose only energy must come from without if there are to be any further changes to the star. You may realise that I'm setting a scene here, but more of this later.

How do we know their mass and sizes and so confirm the densities inside them? Sirius B, the white dwarf companion to Sirius moves around Sirius A with a period of 50 years. We see its motion in two ways. Firstly, the fainter star changes its position with respect to Sirius A, just like the end of the hand of a clock moves with respect to its hub (see earlier Figure 6-3). We can see it by taking photographs or images of both stars over a period of time with reference to background stars presumed to show little proper motion. Secondly, both components slowly move across the sky performing a slow-motion dance in which both components wobble across the sky mirroring each other's motion, though in this case the more massive star wobbles less. Those of you who jive (a word from the distant past) know that the woman, the lightest of the pair, displays the most action on a dance floor. Both those situations result in the mass of each component being measured very precisely using the laws of Newton. But knowing the mass of Sirius B doesn't give the density—remember density is mass divided by volume. We need the radius which is implied by its appearance in the H-R diagram where a very rough spectral classification combined with its intrinsic brightness places it in a unique position within the diagram. Its size comes from its brightness and a judgment as to its temperature from its spectrum and colour, which was white. In this way astronomers knew a hundred or so years ago that Sirius B was a very strange Earth-sized beast.

The extreme conditions on the surface of Sirius B give rise to something Einstein predicted, namely that the frequency and hence energy of radiation arising within an intense gravitational field should be reduced. This effect is called a **gravitational redshift**. The decrease in frequency means that the wavelength of the light is increased, hence the term redshift. Said another way, light needs to expend energy to escape a gravitational field! Normally this is never a factor but in white dwarfs it is. The most extreme form of this is in a black hole where gravity impounds all light trying to escape. This frequency or wavelength shift is seen as a velocity and it appears as if the object is moving away from us. The theory indicates that the radiation is redshifted according to the strength of the gravitational field which is related in a simple way to the mass and radius of the object. Immediately this effect was predicted, verification was attempted, but, in fact, this measurement is very difficult. In a binary system, the stars revolve around each other, so you need a very accurately determined orbit to compensate for this motion and Sirius provides it. The spectroscopic orbit of Sirius B would have to be derived from the mass ratio of the system as seen on the sky, combined with the velocity orbit of Sirius A. Given this information, the velocity of Sirius B can be computed for any observation. Knowing this, the process is then to measure the velocity of Sirius B and subtract the computed orbital velocity from it. This difference is the gravitational redshift. However, the most difficult part of all is in measuring the velocity in a spectrum where the lines are hugely broad (remember how we tell the difference between main-sequence stars and giant stars, the greater the gravity, the broader the lines). Gauging where the centres of these lines are, becomes very difficult—almost an act of faith for those people who attempted this measurement 90 or so years ago! In the case of Sirius B, the expected theoretical relative shift in wavelength corresponded to 84 km/s giving a satisfactory match to the observed, or measured value of 90 km/s, reported in 1924. Another measurement came in 1954 when a relativistic shift of 21 ± 2 km/s was compared against a predicted value of 17 ± 2 km/s for a star with the strange name 40 Eridani. This prediction, and that of the deflection of starlight past a massive object like the Sun, were two of the astronomical tests that lent credibility to Einstein's theory about the distortion of space in the presence of a massive body. In the latter part of the 20th century it became possible to measure the amount of this shift by measuring the ***Earth's*** effect on the frequency of a gamma ray decreasing over a height shift of only 22.6 metres! In this case the expected relative value of the shift was "only" 2.46×10^{-15} cycles/s (Hz) against the measured value of 2.57×10^{-15} Hz. How times have changed!

Again though, having proved the reliability of a theory, it can be turned around to infer otherwise unattainable information. I'm referring here to masses which I've said can only be determined from measuring an orbit in a binary system. Certainly, that is the only direct way, but there are indirect ways. If we analyse the spectrum of a star and model the spectrum to measure its gravity—remember a model spectrum that reproduces the data yields temperature, gravity and abundance—we can infer its mass by knowing its radius. Similarly, we can infer the masses of single white dwarfs in galactic clusters whose velocity we can determine from its member stars, by measuring their velocities and hence the redshift and then their radii from their intrinsic brightness and an estimate of their temperature.

What else do we know about white dwarfs? We've concluded that they are the cooling central cores of stars, places where nuclear transmutation once took place. We should therefore expect to find some white dwarfs composed mostly of helium, others of carbon and or oxygen. The exact composition depends on the mass of the progenitor star, and therefore its evolutionary state when it lost its atmosphere, something I never touched on in Chapter 9 because the combinations are endless and the knowledge spotty. Do we see them? The only way we can verify this is by looking at the spectrum of a white dwarf. That supposes that there is an atmosphere overlaying an unbelievably dense interior. White dwarf spectra ***are*** recorded, but in general they are not very interesting in that there are not many spectral features to observe. As I noted earlier, one of the factors that determines how a spectrum line appears is the gravity within the atmosphere where it is formed. In physically large stars—stars with large radii—the surface gravity may be 10 to 100 times less than that of the Sun. Under these conditions the lines are very narrow. Conversely, where gravity is much greater than the Sun, as in the white dwarfs where the value may be 10,000 times that of the Sun, the lines are very broad, so broad that they overlap one another, at times producing an almost featureless spectrum.

The following is slightly off topic but interesting in its way. A featureless spectrum could be an additional check on the calibration of our CCDs because we also require the equivalent of a white balance that photographers use to get the best out of raw images taken with a digital single-lens reflex camera (DSLR). In an astronomical context those of us who are spectroscopists would dearly love a stellar source that would fit this bill. A featureless white dwarf spectrum might do the job but, at least for the telescopes I've accessed, they are too faint… pity.

Strangely though, most of the white dwarf atmospheres show a hydrogen-line spectrum, whereas it might be expected to be richer in helium lines since hydrogen is converted to helium in the initial stages of evolution. One might also expect that since the core is exposed there should be no hydrogen visible. Two factors are at work here. The first is that any residual hydrogen from the original envelope—atmosphere if you wish—will form an atmosphere around the hot core. Secondly, the processed elements like helium or carbon are heavier than hydrogen and the denser material will slowly sink to the centre of the star leaving any hydrogen on the outside. Much like the coffee grounds, where the grains collect at the bottom of your favourite latte. The process where heavier elements slowly sink into a star is called differentiation and is at work in the Earth, the other planets, their moons and the asteroids. In the centre of the Earth is a molten core that accumulated from the time when the Earth formed out of the vast nebula or cloud that surrounded the Sun billions of years ago. Why should the iron be at the core? Because it is heavier than the crustal material, and over eons has sunk through the hot interior finally congregating at the Earth's centre.

With their nuclear furnaces extinguished, white dwarfs cool off into blackness. How long does this cooling take? What might we learn from it? Recently, a search for white dwarfs was made in a globular cluster called M4, the 4th fuzzy object in a catalogue compiled by a Frenchman Messier in 1771 (see Figure 9-1). Recall that the globular clusters we see are comprised of very old stars, which means that many stars must have lived and died over the intervening billions of years. Therefore, we should see remnants of these stars in the form of white dwarfs, neutron stars and black holes. Neutron stars are far too faint for us to see by conventional means but white dwarfs might be. In fact, this discussion pre-empts the next chapter where I try to assemble some proofs for what I've been discussing. First, it is simple to validate the ideas of stellar evolution described here, no white dwarfs, no viable theory and you've been wasting your time reading this book! But white dwarfs ***were*** discovered in profusion in M4 (phew!), see Figure 12-1. But the astronomers wanted more; they wanted to match predictions of how slowly a white dwarf cools with what is observed. Testing the Hubble telescope to its limit, by detecting stars at about one billionth the brightness of the faintest stars we can see with the naked eye, white dwarfs ***were*** found that formed a sequence in the H-R diagram consistent with the theory that predicted a cooling time of between 12 and 14 billion years. Add a billion years for the formation of the globular cluster after the initial Big Bang gives an age of the universe of 13-15 billion years in remarkable agreement with the results from COBE's successor WMAP. Recall that these two systems measured details of the microwave background, the remnant of the energy abounding at the time matter started forming out of radiation, 380,000 years after the Big Bang. Though maybe it is not that simple. How can you have a cooling time of all those billions of years when stars like the Sun live for at least 10 billion years? Surely the cluster must be a lot older than 12-14 billion years! Think of the white dwarf already found in the Pleiades, an open cluster only 130 million years old. Bright cluster members we can see, have masses greater than 1.4 solar masses and yet some stars that were originally more massive are white dwarfs. Surely this is a contradiction! The answer is in the blurred mass boundaries and how readily stars appear to lose mass, thus avoiding an explosive fate. The globular cluster above would have started life with many stars above the 1.4 solar mass limit and if we think of the Pleiades with white dwarfs a 130 million years into its evolution, there is plenty of time for globular cluster white dwarfs to cool off giving the Hubble researchers the material from which to determine an age.

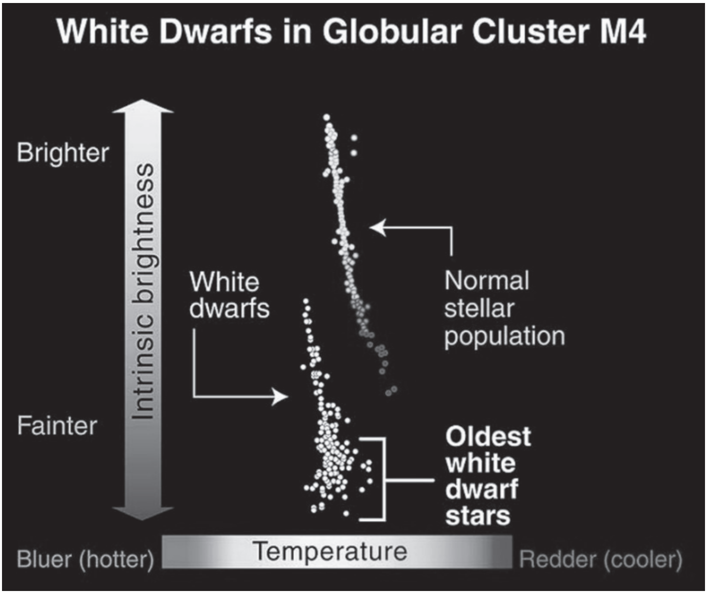

Figure 12-1. See Centrefold. Shows the relation between the white dwarf sequence in M4 and the globular cluster's main sequence. It is the lowest part—and superficially—the least interesting part of this diagram, but it holds the key to determining the age of the universe! NASA/ESA/Field.

I've talked about the pulsation of Cepheids, RR Lyrae stars and red giants. Well, white dwarfs also pulsate though not on the scale of weeks or hours but of seconds ranging from 100 to 1000 seconds or from two to 20 minutes. These stars lie on an extension of what is called an instability strip or region in the H-R diagram (Figure 8-6) that links the variable stars I've mentioned to the white dwarfs. It is fascinating to see this relation since the stars are all very different, both in mass, size and their internal structures. Don't ask me to explain it. A study of pulsation among white dwarfs is not revealed dramatically in their light variations but in the variable X-rays that they emit. It is with telescopes above the Earth's atmosphere such as the Chandra X-ray Observatory and a rival, the **X-ray Multi-Mirror Newton (XMM-Newton)** satellite observatory, that we can also pinpoint these stars. Routinely, new X-ray sources are discovered that pulsate over periods of minutes that are later investigated by the HST in the UV and visible regions of the spectrum. Again, the mechanism that triggers the pulsation is unknown though the pulsation mechanism, that which keeps everything going once it starts is known in principle, but like much of stellar astronomy, it is one thing to think you know, another to really prove it. The pulsations don't make the star's atmosphere go in and out like our lungs but may act like a wobbly wave that circles the star—think of the Mexican wave in a soccer stadium. At one time you might see a wobble going away from you, at another it will appear to come towards the viewer. How do we know this? Only by the velocities that we measure using the lines in the atmosphere of the star. Many of these pulsations are associated with stars in binary systems, notable because the white dwarf companions erupt periodically leading astronomers to notice and hence study such systems more carefully. In doing so they discovered white dwarf companions and the mechanism that produced these eruptions. These are called cataclysmic variables but more of this later.

In dealing with cooling times, studies of a white dwarf's pulsation have proven to be most useful. Against cooling times of a billion years or more it is hard to imagine how pulsation times measured in minutes could ever be of use. But timing measures, the rotation rate for neutron stars for example, provide us with the most accurate clocks attainable, far more accurate than any clock derived from the atom. Again, it is the time variation of the signals from white dwarfs that promises a lot, for it is not simply an examination of the spectra and light from these objects but the dynamics of it all; a study of how the atmosphere moves and what happens as it does. Here, I'm reminded of the stories from WWII, where fighter pilots, using examples of wing loading and stalling speeds, proved that bees couldn't fly. We know, of course, that all static theory goes out the window in the face of movement. It is the same with pulsation, a successful pulsation model reveals more about the star than we could ever hope to learn in the face of a static atmosphere. Again, going back to the Sun and the seismology that we use to investigate it, without those granules or convective elements popping up to the surface we'd know nothing about the vast streams of liquid circulating throughout the Sun, modifying its energy output and making its modelling more difficult than we might ever have expected.

I'll return to the discussion of white dwarfs later when I talk about binary stars.

12.3 Neutron stars

The word neutron star came into astronomy soon after the neutron was discovered in 1932. Two astronomers Zwicky (1896-1974) and Baade (1893-1960) suggested that neutron stars could exist and that they would be the product of a supernova explosion. Talk about being prescient! At least Zwicky got to see the prediction come true. So, what ***is*** a neutron star? The closest thing to a neutron star is the neutron itself. Recall that atoms are made up of protons (positively charged particles), electrons (negatively charged particles), and neutrons (neutral particles). If we could squish an electron into a proton then we'd have negated the positive charge and have a neutron—sort of. That's what happens during a supernova event where the core of iron absorbs the electrons providing the pressure supporting the star which then collapses. Thus, a positively charged core becomes neutral, a neutron star. What do we know about them? Despite Baade and Zwicky's prediction, neutron stars were not in the picture in terms of stellar evolution until the first pulsar was discovered in 1968. Like a lot of discoveries, this one came about by accident when a group of radio astronomers were studying data from distant galaxies. A graduate student, Jocelyn Bell, noticed there was a blip in the data showing up every 1.33 seconds. When I say a blip in the data, I'm referring to a long paper chart on which a pen draws lines (original data are shown on the Web). The pen would have drawn a series of blips on the paper significantly above the squiggly baseline. All our data were recorded on paper in those days and we had to make laborious measurement directly and build our research stories from that. Today, the data reside in a computer and we plot the results directly onto a screen either in real-time or later after the event. But paper has advantages. You can see more of it at a glance, just as when editing a book a paper copy is easier to deal with than paging through a document using many screens only seeing thirty lines at a crack—tell me about it! Later refinement of the measurements revealed a pulse that repeated itself every 1.3373011 seconds! Talk about precision. This unbelievably precise pulse gave rise to the exciting notion that Little Green Men (LGM) might be trying to contact us! The Cambridge researchers Hewish and Bell searched for more pulses in other radio sources and found three more. For this work, Hewish was awarded the Nobel prize in physics in 1974. Discovery of similar signals from other part of the sky ruled out LGM and the word pulsar was coined to describe these objects. The name, pulsing star, or pulsar has stuck. Over time many hundreds of pulsars have been discovered with periods ranging from a fraction of a second to a few seconds. In addition, because the pulses are so short, it is possible to measure their periods or cycle times with unbelievable precision. Even from the early data it was discovered that the periods were lengthening in most of the objects. It is of interest to follow the reasoning, basically the elimination of all other possibilities, that led astronomers to the notion that the pulsars represented extremely dense compact objects, particularly since their radii have never been directly measured. Such regular pulses could come from several sources, each of which was examined and ruled out. These possibilities were all investigated using back-of-the-envelope calculations. This is the thought process.

Could it be a binary system with a period of 1 second or so? Assuming the stars were similar in mass to the Sun, an application of Kepler's law relating mass, period and orbit size—the equation that allowed us to measure the mass of the Sun—gave an orbit about 2000 km, which is much less than the Earth's radius at 6,400 km and less than the white dwarf Sirius B's radius of 5500 km! If two neutron stars were orbiting each other they would radiate gravitational waves, thereby losing energy and so slowly spiral in towards each other causing them to speed up and shorten the period. But pulsars were observed to have their periods increasing, not decreasing, thus eliminating a binary system as a source of the radio pulses.

Since stars are known to pulsate, the observations were interpreted using a pulsation model, by comparing them with white dwarfs, known to pulsate. In this theory, there is a relation between the period of pulsation and the inverse of the density. Thus, a star varying over weeks or months would have a much lower density than one varying in seconds. This notion is consistent with the periods of other pulsators, the red giants pulsate over years, the Cepheids over weeks and months and the RR Lyrae stars over hours. Applying the numbers for an assumed neutron star pulsator, ignoring how this might happen or whether it was even feasible or not, ruled out pulsations because the periods would be outside the range of the longer period pulsars.

What about something involving the rotation of a star? If we assume a limit that an object could rotate without breaking apart, we have a boundary. What keeps a spinning object together? Gravity. What happens when an object is affected by rotation? It bulges out like Jupiter which is decidedly larger at the equator than at the poles. Make Jupiter spin faster and it will flatten out even more and ultimately lose parts of its outer layers to the effects of rotation. Back-of-the-envelope-calculations equate the force caused by rotation with that of gravity pulling it all together. Think of a rock twirling about on a string. You feel the tug of the rock wanting to fly away and through the string your hand provides the equivalent of gravity. The final answer relates the period and the density. At white dwarf densities, about a million times that of water, the minimum period corresponding to the fastest rotation, is 12 seconds, much too high for a pulsar. At nuclear densities (200 quadrillion times that of water!) the minimum period is about 2 milliseconds, about the period of the fastest pulsars. Making guesses as to the masses and radii involved also led to a range of possible periods between a millisecond and five or so seconds that encompassed what was observed. If we reduced the Sun to the size of a neutron star (radius ~7 km), starting from its current rotation rate of 2 km/s, how fast would it spin? About 4500 times per sec, as fast as the most rapid pulsars.

Out of this process the rotational model was the only one that survived. Pulsars were rotating neutron stars. By now the earlier predictions of the link between a neutron star and supernovae were rediscovered and searches of two supernova remnants were made, one being the famous Crab Nebula the other in the constellation Vela in the southern skies, resulting in the discovery of pulsars associated with the stellar debris. Finally, the link was established, and with it, we had the end product of the evolution of massive stars. Technically, the discovery was ***very*** difficult because the equipment was not as sensitive as it is today and the period of the Crab pulsar was only 0.033 sec! But, when light pulses were discovered in the Crab, then everyone was scratching their heads trying to figure out something rotating that would create pulses in the radio and visual regions of the spectrum. It was noted that light is created when electrons move in a magnetic field thus bringing a magnetic field into the equation. Now, there was a hazy picture developing of a rapidly rotating neutron star with a strong magnetic field producing radio and light pulses. But how do you get the radiation to pulse?

These bits and pieces led to the development of what is known as the lighthouse model based on the fact that light is emitted at the magnetic poles of the neutron star. If the rotational axis is not aligned with the magnetic axis a beam of light will sweep around as the star rotates. We see a pulse when a beam of radiation crosses the Earth as is shown in Figure 12-2. Checking this model out again I note that pulsars emitting gamma radiation don't fit this model… sigh, more work for someone to do! The object spins around and the beam crosses us again. If we are not in the beam, we see no pulse and detect no pulsar. The next question: "Why a beam?" A massive rotating star goes boom and with it goes a large part of its material and magnetic field, but part of the field remains but is rendered very intense since the magnetic field is compacted with the material left at the core of the star.

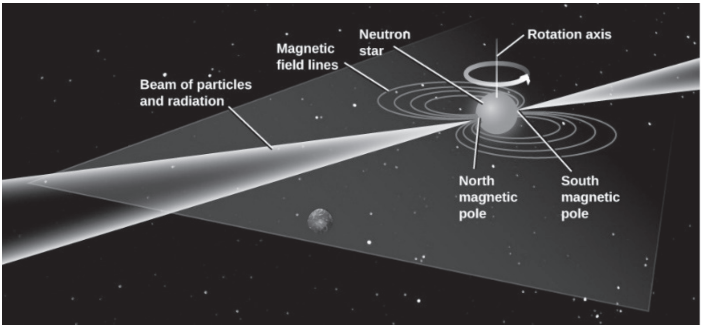

Figure 12-2. The lighthouse model of a pulsar. Note that the rotational and magnetic axes are not aligned thus producing a light beam that sweeps around the sky. We see this as a pulsar "beeping" in fractions of a second as the light passes over the Earth. Credit: Wikimedia Creative Commons/Hisgett.

Through the conservation of momentum, once what was a large rotating star is now a small star and so it rotates faster—remember the skating analogy. The magnetic axis of the star does not need to be the same as the rotational axis. Earth is a classic example of this, for we know that north by the compass is not north by the stars. If the two axes are misaligned the magnetic pole sweeps out a circle around the axis of rotation at the North Pole and South Poles. What does the magnetic field look like? Just like the Earth's magnetic field—or the Sun's—which forms lines of magnetic force joining the polar regions—like our teacher's bar magnet experiment. Presumably the magnetic field of a neutron star just formed by a massive explosion would be similar. A moving magnetic field produces electricity—electrons, which leave the surface of this star and spiral around the lines of force at each pole until they leave the system. As they spiral, they produce electromagnetic radiation, yes, that includes light, along the direction of the lines of force leaving the magnetic pole. We now have our beam. Jupiter was found to have a magnetic field long before spacecraft got there because of similar radiation produced in its magnetic field though not beamed as in a neutron star. We have a neutron star spinning. A beam spinning. We have a potential pulsar! And if the searchlight beam intersects the Earth then we will see the neutron star as a pulsar. I use the word see because we may only make an initial detection in the radio region of the spectrum where the pulses are more noticeable. The Crab Nebular pulsar has been detected throughout the electromagnetic spectrum as the Figure 12-3 demonstrates.

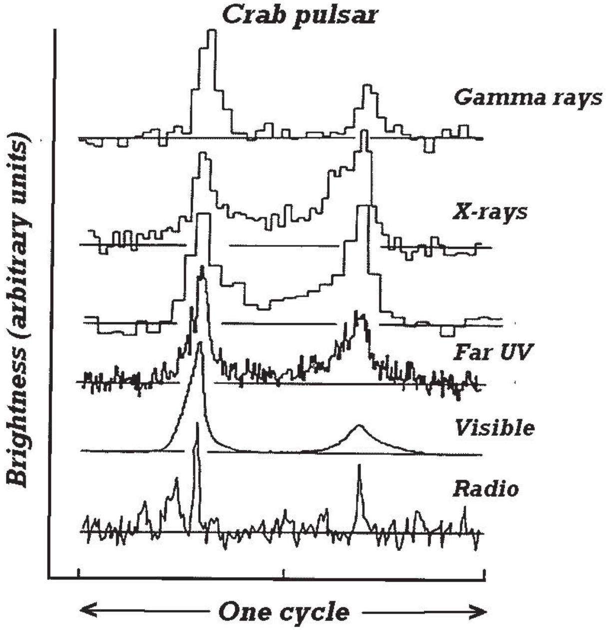

Figure 12-3. Showing the Crab pulsar pulses in various regions of the electromagnetic spectrum. Credit: Source unknown. Modified from the Web by the author.

If the cone of radiation does not intersect the Earth then we don't see the neutron star. A pulsar is always a neutron star but a neutron star is not necessarily a pulsar, since to be a pulsar we require a special circumstance where the beam of radiation sweeps across the Earth. (This is a favourite question in Astronomy 101!) Hundreds of pulsars have been discovered to date which means there are ***many*** more undetected neutron stars. Some pulsars are in binary systems rotating about another star, leading one to wonder how a close neighbour could have survived such a stupendous blast from its supernova companion. But they do, and there are plenty of them. There are cases where two pulsars orbit each other and another where a white dwarf, a pulsar and a planet are in orbit about each other! But more of this later. As I've noted, because of their intense magnetic fields, neutron stars are strong X-ray sources and because of the orbiting X-ray observatories, Chandra and XMM-Newton, we can now detect them in this part of the electromagnetic spectrum.

Neutron stars tend to move rapidly through space because of the tremendous explosion which birthed them. Any asymmetries, or imbalance in the explosion will send the newly formed neutron star hurtling through space faster than the Sun's leisurely speed of 30 km/s with respect to its neighbours orbiting the galactic centre (remember Newton's laws of motion—every action has an equal but opposite reaction!). That's one way to look at it, another is based on the observational fact that that 50%, give or take 10% or so, of the stars in the sky are binary in nature. There are stars among the hot-massive stars called runaway away stars for which a plausible theory related to supernovae explosions was developed to explain them. If a companion star explodes then it loses most of its mass, and the gravitational attraction which binds both stars together is sundered and both stars spin off into space at high speed. Just like a rock twirled around your head in a slingshot. Release the string and the rock flies off. Goliath found that out the hard way! The speeds that some neutron stars have acquired can be astonishing. The one pictured in Figure 12-4 is clocked at 1500 km/s, a speed that would allow it to be ejected from the galaxy. Modelling the explosions does not yield these speeds; so, once again, observations challenge the theoreticians. But there are uncertainties in the velocity, chiefly the distance to the nebula with which it is associated.

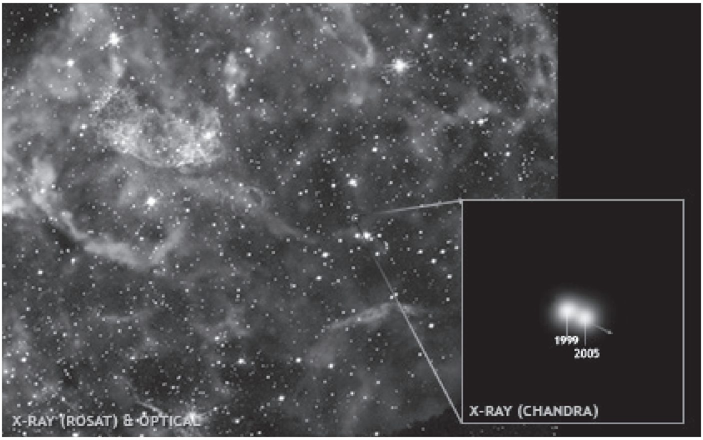

Figure 12-4. A combined X-ray and optical image of the supernova remnant in Puppis A showing the location of the neutron star and, using the X-ray data, the separation over 5 years that yielded its proper motion and a velocity of 1500 km/s. Credit: Chandra: NASA/**CXC**/Middlebury College/Winkler; ROSAT: NASA/GSFC/Snowden et al., Optical: NOAO/CTIO/Winkler et al., (Middlebury College).

In 1997 Chandra detected an X-ray source in a blank region of sky—a "bare" neutron star—but, because the positioning accuracy of an **X-ray telescope** is not as accurate as a regular telescope, it often requires a search around the position to find the likely source. Fortunately, the Hubble telescope was able to see a pinpoint of light within 2 arcseconds of the X-ray position. Over a year its position was monitored and a picture of the object racing across the sky is shown in the left panel of Figure 12-5. A parallax has been determined making it the closest neutron star to us at 61 pc or 200 LY. By measuring the "colour" of the star, by comparing its brightness in X-rays and UV against that in the visible, researchers concluded that the surface of the star was about 434,000 K!! The analysis yields a confirming small diameter of about 22 km. Neutron stars move rapidly through space. There is gas in space and one might hope that neutron stars would interact with this gas in some way as we see in Figure 12-5 (right panel). A detailed picture of the sky around the pulsar called RX J185635-3735, the numbers referring to its position of the sky, reveals a bow wave similar in appearance to what we see when a boat powers through the water. In coming to grips with interpreting what is seen, astronomers must figure how the interaction takes place, whether the heat from the neutron star is affecting the gas or whether it is a more physical connection with the surface of the star and the gas.

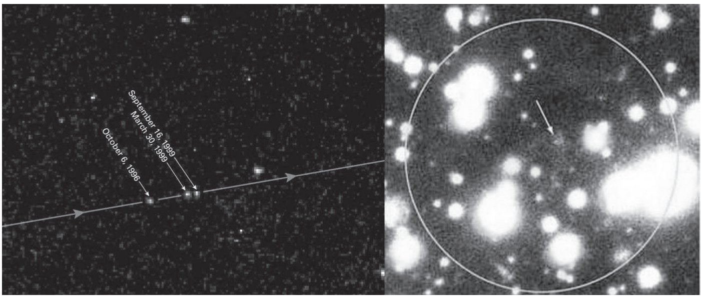

Figure 12-5. See Centrefold. Lefthand panel: The rapidly moving neutron star RX J185635-3735 captured by the HST. Righthand panel. The same object, imaged by the VLT, showing the bow wave in red resulting from a neutron star interacting with the interstellar medium. Credits: Left panel. NASA and Walker (SUNY). Right panel. van Kerkwijk (Institute of Astronomy, Utrecht), S. Kulkarni (Caltech), VLT Kueyen (one of the 8.2-m telescopes), ESO.

In addition, there are many results about high energy sources from astronomers working with NASA's **Fermi Gamma-ray Space Telescope (FGST)** and the National Science Foundation's Karl G. Jansky Very Large Array (VLA), and I quote one such result:

> "They have identified a remarkable pulsar, named PSR J0002+6216 (J0002), that was shot out from the remnant of a supernova, identified as CTB 1, at nearly 2.5 million miles an hour—it even has a radio-emitting tail that points back to the supernova that created it, drawing its path in space like a contrail."

The study of neutron stars, once a fanciful idea put forth 90 or so years ago, is in full flower with the space-borne "Great Observatories" that NASA coined, which cover the electromagnetic spectrum from gamma radiation to the visual, and buttressed by radio observations from Earth. I'll return to these objects in Chapter 14.

12.3.1 The ultimate celestial timekeepers

Pulsars are the most reliable of timekeepers. In perusing a list of periods, I found a pulsar called B1937+21 with a period of 0.0015578064924327 seconds, with an error of 3 in the last place! This time is then accurate to about 3 parts in 10^{16} or 1 second in about 1,000,000,000 years! The best atomic clock is accurate to 2 or 3 parts to 10^{14} or a hundredth of this accuracy! Because they pulse so regularly any deviation is immediately known. For example, imagine if a pulsar orbited an unseen star, what would happen to the pulses? As the pulsar moves away from us across the orbit it takes longer for the pulses to reach us so it looks like the period is slowing down. When the pulsar reaches the other side of its orbit and starts back towards Earth the distance from us is reducing and it looks like the period is decreasing. It's identical to the change of pitch that a police car's siren makes as it approaches and then leaves us. The change of period we can relate to the size of the orbit in terms of the velocity of light, or "**light-travel time**". Recall that Roemer in 1676 used the concept of light-travel time to measure the speed of light, using deviations from the predicted motions of the Galilean moons of Jupiter as the timepiece. In terms of binary stars, this phenomenon was first discovered in the famous eclipsing binary Algol where the clock, given by eclipse timings, varied over a period of just under two years indicating that the binary star itself was orbiting an unseen body. An example of this light-time effect in the first discovered binary pulsar PSR 1913+16 is shown in Figure 12-6. The shape of the light-time orbit indicates that the physical orbit is eccentric or oval shaped.

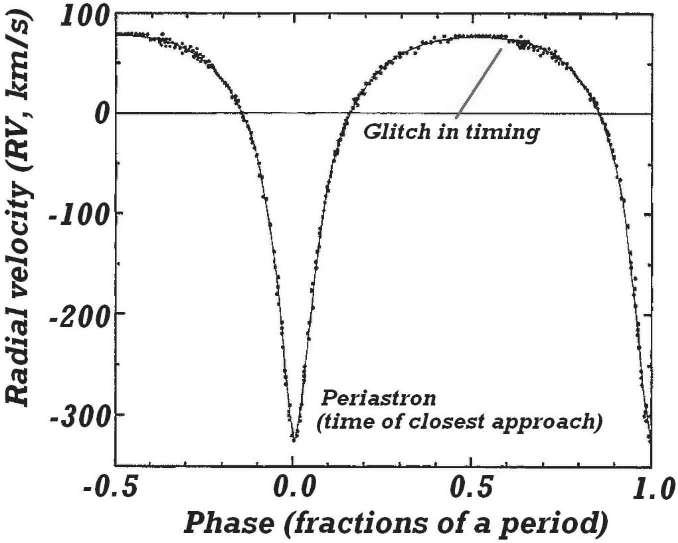

Figure 12-6. The first detection of a binary pulsar which resulted in the discoverers (Hulse and Taylor) earning a Nobel Prize. The velocities are derived from the delay-times measured from the pulses themselves as the neutron star orbits its unseen companion. Binary star velocities will only rarely match the quality of these data. Notice at about phase 0.6 that there is a slight discontinuity in the velocities caused by glitches in the pulsar timing. This is discussed below. Credit: Hulse and Taylor, 1975, ApJ, 195, L51-3.

The presence of a companion is not the only phenomenon that changes the observed period of a pulsar. The radio waves are affected as they pass through the material between us and the star. For visible light we see this effect when light travels through a prism. The red-light travels quickly through the glass and is less affected and hence is bent less. The blue light travels slower through the glass and is refracted more. Thus, the interstellar material affects the radio waves differently depending on the frequency. As the radio signal passes through the tenuous gases in space the radio waves excite or cause the electrons they encounter to vibrate. This exchange of energy slows down the radio wave. The amount that the pulse is slowed down varies with the frequency of the radiation and the delay depends on the amount of material the radio wave encounters. The more the material radiation experiences, the longer the delays and knowing the approximate density of electrons in space gives astronomers a crude idea of the distance to these objects if they are too far away to measure the distance by the parallax or trigonometric method and you are desperate to have an estimate.

The pulses are occasionally interrupted by glitches as shown in Figure 12-6, small hiccups in what is a stream of reliable pulses. These glitches are thought to arise inside the neutron star, itself a hard shell with a sea of neutrons circulating inside. The glitches are thought to be related to spasmodic interaction between the "sea" inside and the carapace of the cooling star. Data like this provide the people who model these structures the chance to test their models. If the pulsars ran like clockwork with nary a hiccup then the theoreticians would have little material to work with.

12.4 Black Holes

What is a black hole? Michell (1783) and Laplace (1795) independently suggested that perhaps enough mass could be condensed in one place so that not even light could escape. They obviously knew that light had a finite velocity to even suggest the concept of an object whose mass and radius was enough to prevent light from escaping its gravitational attraction. We can call this the velocity of escape. The velocity of escape on Earth is something that the rocket scientists need to overcome when they send probes to the Moon and beyond. We all guess that if we could just jump hard enough, we'd escape Earth's bonds. Given enough velocity, an object will escape from the Earth's gravity. Given enough impetus the galaxies currently flying away from each other will keep on going forever. This is the concept of escape velocity. What would the situation be if light could not escape the presence of a massive gravitational field? Light responds to gravity as I've commented above in discussing white dwarfs, and the natural extension of this observational fact leads directly to black holes. The energy or frequency of electromagnetic radiation is reduced in the presence of a gravitational field so the extension that perhaps light could be bound to its source is logical.

The expression for the velocity of escape relates it to mass and radius. If we turn this formula around, we can find the radius needed to make the velocity of escape equal to the speed of light. As an example, if the Sun was to become a black hole—it won't—its diameter would be only 3 km! The radius (R), measured in km, of a black hole is 3 times the mass of an object if the mass is measured in solar units ($M_\odot$); hence $R = 3\ M_\odot$ km is just about as simple a formula as it gets.

Since the 70s when the issue of **missing mass** became important and a modern theory of black holes was developed, astronomers have been trying to discover them, either as stars, or in the central cores of galaxies. In relation to missing mass, recall that the stars move in the Sun's vicinity as if there is more mass around than we can see. It is true of the galaxies also where their rotation indication the presence of more mass. Now, hot off the press as of 10 April 2019, is an image of a black hole (Figure 12-7) in the centre of the galaxy M87 produced by the Whole-Earth Array of radio telescopes that created, by some fancy software, an image of the core of this galaxy.

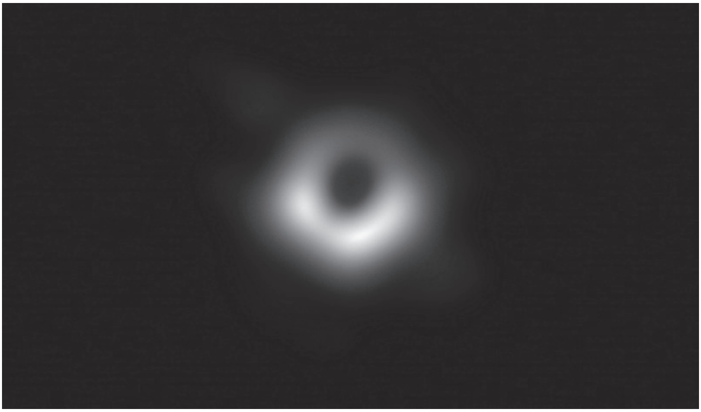

Figure 12-7. An image of a black hole at the centre of the galaxy M87. The diameter of the hole is 40 billion km—130 times the diameter of the Earth's orbit. Credit: **EHT** and collaborators.

The only way to make reliable measures of mass is through motion. For this reason, astronomers initially began looking among binary stars to find black holes. The problem is daunting because only one spectrum is visible and two are necessary to determine minimum masses. In a binary system the mass of the assumed black hole must be inferred in some other way. The best example of a system that includes a black hole is Cygnus X-1 which I'll discuss in Section 13-13. The second, and much more promising line, is to look at the centre of galaxies which are often regions in turmoil. The advantage there is that we can literally look ***into*** the centres of galaxies, much like we can watch the soapy water spiral out of our bathtub. Given a favourable viewing angle, allows us to measure the size of the central core of the galaxy and to measure the velocities of the gas, or the stars orbiting it providing we can resolve the stars—see them distinctly. The HST has uncovered a number of galaxy cores (including our own) that seem to harbour black holes. In Figure 12-8 is shown the orbit of a star (S2) moving around what is considered a black hole at the centre of the Milky Way. The orbital solutions provide a minimum mass of four million solar masses for the black hole in the galactic centre.

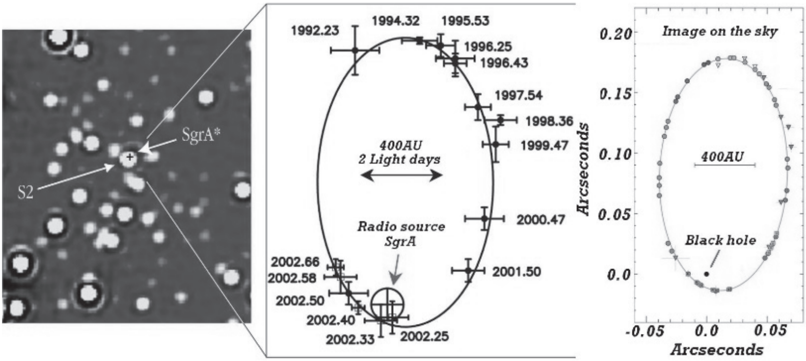

Figure. 12-8. This diagram shows the motion of the star S2 around the super-massive black hole at the centre of the Milky Way. It was compiled from observations with ESO telescopes and instruments over a period of more than 25 years. The star takes 16 years to complete one orbit and was very close to the black hole in May 2018. Note that the sizes of the black hole and the star are not to scale. The right-hand image is based on data from the VLTI and are much more accurate than those shown in the centre panel. Credit: Left and centre panel. ESO. Rightmost panel. ESO/MPE/ GRAVITY Collaboration. Commentary from the scientists. Modified by the author.

Thus, while black holes exist in the core of galaxies (Figures 12-7 and 12-8), we have not conclusively shown their existence among the general stellar population. Below is a picture (Figure 12-9) from the HST which shows the gravitational bending of light from an unseen object thought to be a solitary black hole in interstellar space. I confess to being underwhelmed by this evidence. Nevertheless, while the assertion is made, it will require more evidence to verify the identification. If it turns out to be a strong X-ray source then the statement gains more strength. But again, it is hard to detect something which by its nature is black, unless it is associated with other material that will reveal the monster's presence. However, it is worth making a few comments regarding this image: Think about the immensity of the sky and then (I presume) the sophisticated automation required to detect the changes in the left-hand panel. I smile, because my mentor Willem Luyten spent his life comparing images of star fields taken by the Schmidt telescope on Mt Palomar about twenty years apart, looking for positional changes, in the case here, it would be for brightness changes. The second point is this microlensing event is a one-off because the black hole is still moving across the sky but we can't see it, at least optically. The last comment involves how astronomers use diverse techniques to gain the knowledge they desperately need. I see my fellow astronomers as highly imaginative, persistent scientists who won't take "it can't be done" as a satisfactory answer.

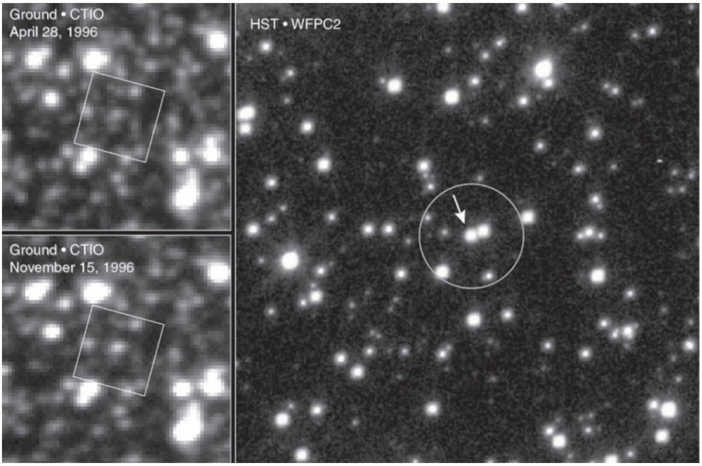

Figure 12-9. Two international teams of astronomers using the HST and ground-based telescopes in Australia and Chile have discovered the first examples of isolated stellar-mass black holes adrift among the stars in our galaxy. The brightening event is shown on the left. Top: Un-brightened, bottom: brightened. The image on the right shows the star which was lensed. Credit: NASA/ESA/Bennett (University of Notre Dame, Indiana). Commentary from Bennett.

If we fell or flew into a black hole tidal forces would destroy us and we would be falling into a singularity, a place where density is infinite or where the volume is zero! I think of a singularity in a mathematical sense as a place where Nature has divided by zero. When you reach such a place mathematically, anything is possible—remember the algebraic proofs of 2 = 1! which are all based on a division by zero. It has been conjectured that passing through a singularity might propel you through time and/or space. There is talk in physics of parallel universes just as New Age teachers suggest. As an aside, I'd say that if time travel is possible through a black hole or any other mechanism, then future time travellers are already here on Earth! Think about it. After writing this I downloaded an article from the Internet claiming that black holes can't act as portals to other universes or for time travelling. In travelling through a black hole, presuming it was possible, the traveller would encounter two singularities and they'd end up in either one or the other that would effectively bar their way! Pity. You win some and you lose some! But maybe not. I don't believe everything I read on the Internet, which is ironic because this book owes a lot to this source. The discussion of black holes is taken up again in Chapter 14.

12.5 Brown dwarfs: Little stars that couldn't

We know that temperature and pressure at the centre of a star must be enough to allow the proton-proton chain to begin its work of generating energy. If the conditions are not right, that is the overlying material does not create enough pressure, combustion will not occur. In the absence of fusion, these stars can only generate their energy through gravitational contraction and compression. At the lower mass end, ten times the mass of Jupiter (M_J) these stars start to look like planets and then the question is, "How many times more massive than Jupiter does an object have to be to be called a star?" Working downward in terms of the Sun's mass, the cut-off point, where nuclear fusion involving hydrogen alone cannot be initiated seems to be about masses 0.075 $M_\odot$ or ~75 M_J. Fusion though can still occur using deuterium which is what is called an isotope of hydrogen, a remnant of the Big Bang found in interstellar space from which the stars are seeded. Deuterium is similar to hydrogen except it has an additional neutron in its nucleus and this helps to push down the limits where fusion is possible. Because deuterium is part of the proton-proton cycle that produces helium, the star already has a "leg up" in fusing to create helium. This cut-on point for deuterium fusion is about ~0.075 $M_\odot$ and the limit for the end of deuterium transmutation into helium is 13 M_J or 0.013 $M_\odot$. As an aside, deuterium is called "heavy water" and thus the German interest in using it to bypass part of the fusion process in their abortive attempt to build an atom bomb in WWII. Additional to deuterium fusion, is also possible to fuse lithium at these masses as the temperatures required for the process are lower than that for hydrogen fusion.

It is hard to judge the age of these stars, remember the only way we have a handle on the ages of normal stars is when they form in clusters where we can compare the observational data with the theoretical evolutionary models over a range of masses and evolutionary times. **Brown dwarfs** have been found in the Pleiades cluster and we know its age is about 130 million years (I keep on seeing differing ages for this cluster). This says nothing about their lifetimes so we must resort to theoretical models that track the luminosity of a star over time showing that brown dwarfs may be long-lived—billions of years. Discovery data show there could be millions of these little suckers sprinkled throughout our galaxy. Not only would our interstellar Starship have to negotiate its way past these dead stars, but white dwarfs and the all but invisible neutron stars.

12.6 Missing mass: Yet more of it!

The **Wide-angle Infrared Survey Explorer (WISE)**, launched in 2009, sent into hibernation and reactivated in 2013, has discovered many brown dwarfs in the solar vicinity though apparently not as many as the researchers anticipated. The hope was that one would be found closer than 4.4 LY, the distance to the α Centauri system (the nearest and brightest star in the constellation Centaurus) but this was unsuccessful, The search did identify a pair of brown dwarfs rotating around each other at 6.5 LY. The hope is that these stars will show the same level of binarity (stars gravitationally linked) as their bigger siblings around them. Remember that approximately half of the stars we see are binaries and without this happy circumstance, we'd have no easy way to measure stellar masses, the very driver that governs any star's life cycle.

Why the infrared? It's the same story repeated earlier; Brown dwarfs are cool objects therefore they radiate in the infrared (remember our body heat is detected by infrared detectors) and the stars are unbelievably faint and any successful detection is noteworthy. Why bother with these objects, they are hardly interesting? The real interest that drives the hunt for brown dwarfs is the question of missing mass, or dark matter, in the universe. As it stands now, there is insufficient detected mass in the form of galaxies and gas in the known universe to decide whether it is open or closed. In an open universe the galaxies race outward and the universe would ultimately suffer what has been described as a "**heat death**", where it expands into infinity. A closed universe is one where the galaxies expand away from us, and, like a ball tossed upward to be returned by gravity, the galaxies slow down as the gravity of the whole system overcomes the expansion and ultimately, the universe collapse on itself to begin its cycle again. We know, by dynamical means, or simply said, an application of Newton's laws of gravitation, that the mass we can see in clusters of galaxies is smaller than what the great wheeling motion of the cluster implies. The estimated amounts of the missing mass differ but it is surmised that ~90% of the universe is unseen. In the face of these uncertainties, trying to decide between these cosmologies is impossible.

It was hoped that the missing mass, whose unidentified existence bedevils astronomers, might be found in these brown dwarfs. To this end, the remarkable observing project OGLE is currently underway trying to find these brown dwarfs by detecting gravitational lensing events. I'll talk more about this program in Chapter 15. But apparently, these "failed stars" as they have been called, are not numerous enough to close the census gap between what we see and what the stars and galaxies react to gravitationally. Mass is also missing closer to home. For example, taken as a group, the motions of the stars that move upwards away from the galactic plane in the solar neighbourhood into the North and South Galactic Poles, can be used to calculate the restoring force—the gravitational attraction—that governs the behaviour of these stars. The observational results cannot be reconciled without postulating more unseen mass that controls their movement through the galactic plane. On large scales, missing mass is a fact, and on small scales such as in the solar neighbourhood mass is also missing.

Aside from missing mass, there is another complication. The universe is accelerating (see Figure 5-2). With the use of supernovae as seemingly reliable distance markers, it is found that the more distant galaxies are accelerating so the open universe is going to reach its heat death sooner. It exposes a whole new area of physics involving some form of a repulsive law that is at work at great distances. I'll offer a comment, stupid it may well be, but I'm looking at all this from what I see on Earth and extrapolating it into cosmology. We have finally measured gravitational waves that literally shake the space within which we exist. At some level they are continuously with us. For us it is a quiver we have no hope of ever experiencing ourselves but what about events on a large scale where the quiver becomes a wave? A tsunami if you will. The galaxies ride on this tsunami, a series of gravitational waves erupting during the formation of the universe resulting in the outer galaxies riding the downward slope of such a wave and appearing to accelerate. This leads to a prediction that some galaxies will be slowing on the upslope and others accelerating on the down—unless there is only the one wave. How many waves there are is unknown. If what I've said is not stupid, the problem of verifying such a suggestion, is that, because the distances to the galaxies are based on their velocities, my simple-minded notion of detecting waves in the extragalactic velocities becomes difficult. However, there could be nodes at particular velocities, much like periodic traffic jams, that could be detected, statistically. This ends my venture into cosmology.

Recalling how stars form out of the interstellar medium, we see in the H-R diagram the main sequence of stars extending to about 3000 K. Even Jupiter, if it were twice as massive, might be considered a star even though nuclear processes would not turn on. They may have some nuclear reactions in the same sense as the Earth whose interior is heated by radioactive release (through the weak nuclear force) in the molten core, but they do not fuse hydrogen, deuterium or lithium to form helium. Until the issue of missing mass arose, little attention was paid to the study of stars cooler than 3000 K. Part of the reason was their faintness and the fact that detectors efficient in the red part of the spectrum were not sensitive enough to be useful. With the strides in detector development it has now become feasible to search for these objects. They condense, collapse, heat up as they contract and then begin to cool. The light they generate is invisible to our eyes and they radiate faintly in the infrared. The HST has also managed to image some of these faint objects. In terms of evolution, their history is boring. They condense out of the interstellar medium, heat up, and if massive enough, fuse deuterium or lithium or both to completion and last in this almost stable state for an unknown number of years! Sorry about this but I can find no timeline… These stars are fully convective which means that whatever fuel they have in the form of deuterium or lithium will eventually migrate to a region hot enough for fusion. This will extend the star's lifetime.

How do we know what is observed is a brown dwarf? Two tests are used, one involving the presence of methane and the other, the absence of lithium. Because the atmospheres of brown dwarfs with temperatures less than 1000 K should contain methane, astronomers have been looking for the gas. Two surveys in the far-red part of the spectrum have turned up six methane dwarfs. These identifications were confirmed when their spectra were shown to contain methane. Thus, these stars fill the gap between stars and planets. Also, part of the test used to identify brown dwarfs, is the absence of lithium in their atmosphere. Lithium is present in the Sun's atmosphere but the Sun is not fully convective so its lithium is not fused and therefore can be detected spectroscopically, whereas in a fully convective atmosphere of a brown dwarf, the lithium is circulated into the furnace in the core of the star and consumed. Obviously, in a young star you'd find lithium so what is called the lithium test is not precise.

Now it is time to have a look at the proof of the story that has been told so far. Through the discussion of the endpoints, it seems that part of the truth has already been established. Let's have a good look at the rest of it from a more critical viewpoint. After all it has been such a struggle for the astronomers and astrophysicists to create this picture, now, like a runner beginning to run the final leg of a relay race, we can't say the job is finished yet.

CHAPTER 13

PROVE IT!

13.1 How do you know you've got it right?

The verification of the evolutionary picture described in the previous chapters is critical. Evolution has been described in terms of events that are cataclysmic such as supernovae or as simply beautiful static images of planetary nebulae; both representing the endpoints, or the march towards, the dynamic world of stellar evolution. I've talked about white dwarfs, neutron stars, black holes and brown dwarfs and given details of these objects. How do we really know that these objects may be the endpoint? You cannot simply tack these objects on to whatever theory has been developed and say they are the endpoint. You get there incrementally via computer modelling and matching the data against what is observed, or in the case of white dwarfs, you wait for a space-borne telescope to give you an answer, or until the instrumentation has a sufficiently quick reaction time to record events that take place in fractions of a second. I'm talking here about white dwarfs, pulsars and neutron stars. Those of us doing spectroscopy in the 60s were always hampered by the lack of digital equipment. It was there for photometry—though one measurement at a time—but what we all needed was a panoramic digital detector that could do what our phones do every day; capture a two-dimensional image that we could readily process. Though, even if such a detector had been available all those years ago, the computers of the time could not handle a 4 K screen. The memory was not enough to process the data in one shot and the storage—hard drive if you will—was never more than a **megabyte**. The first hard drive I saw in the 70s with a megabyte of storage was as large as a dishwasher. With its arrival we all thought we had died and gone to heaven. Our storage was on those whirling tape drives that movie makers use to serve as visuals for a computer. We get the answers that I've talked about, not only from the brains of the scientists trying to work things out, but we are equally dependent on technological advancement both on Earth and in Space. Aristarchus must have felt that way when his naysayers posed the question, "Why don't we see the stars wobble as the Earth moves through the seasons?"

Given that the models represent pretty much what is observed, though it is never exact—stars are sort of round, they rotate and they have mates—but you gain confidence as you go. On the way, something shows up that you hadn't thought of and an analysis of that phenomenon confirms your calculations in some unexpected way. Alternatively, you end up with an inconsistency that acts like a burr under you.

We cannot unlock the secrets of stellar evolution by looking at one star. Well, there is the Sun of course, but it is just a small part of a whole range of masses that comprise the universe of stars as we know it. We see neutron stars, planetary nebula, white dwarfs, variable stars like the Cepheids and RR Lyrae stars, all the objects we believe are necessary to form a reliable description of stellar evolution. Just as we garnered an understanding of the evolutionary process by studying these diagrams using modelling techniques, we need to convince ourselves that the results are robust, that is, that some new fact is not going to collapse the whole theory.

The reason that clusters, either open or globular (see Figure 9-1 for direct, representative images) are used in the verification process is because the stars are ***assumed*** to have formed at the same time with similar chemical composition. This may not be absolutely true in that the rate of collapse and formation of a star is a function of the mass of each cloud fragment that formed the individual stars (see timelines in Figure 10-2). But because this process takes place quickly relative to the stellar nuclear ages, ranging from a few million to many billions of years, it is probably a good assumption. Therefore, given what is called **coeval star formation,** any changes we see among the stars must then be related to the aging process. This ignores the influence of rotation, which varies from star to star.

13.2 The data

Since cluster colour-magnitude diagrams are at the heart of everything that follows, it is worth commenting on how they came about. In the 50s and 60s, when it became possible to make measurements of stellar brightness and colour to about 1%, then the study of open clusters really took off. The seminal paper that launched the massive observation studies through the 50s to today was by H.L. Johnson and W.W. Morgan (1906-1994) who presented photometry and spectroscopy of stars chosen as standard stars, that would place everyone's observations on the same scale—termed a photometric system—that set the stage for what we have today. They provided lists of magnitudes and colours of many star along with their spectral classifications (Morgan was a master of this work). Johnson made his initial mark by designing stable electronics that allowed reliable and repeatable observations to be made. As far as I am concerned, he sparked the massive observational program of the 60s spearheaded by astronomers at the Kitt Peak observatory in southern Arizona—mentored by Bengt Strömgren (1908-1987)—and astronomers in Capetown, South Africa. In reading their paper anew, I was struck by the fact that they'd already assembled, aside from all the standard stars and their magnitudes and colours, a zero-age main sequence (Figure 9-5) which was the bible for many years.

I've mentioned the early observations being made through pieces of coloured glass, and they formed what we call the ***UBV* photometric system,** a standardized way of calibrating our data. (Unfortunately, the standardisation depended also on the atmospheric cutoff in the UV and the photomultiplier response in the red. Sigh… I need a droopy mouthed emoji here). Our world is full of standardized systems, dress and shoe sizes, distance and weight that is almost universal, bed and pillow sizes, etc. Other regions of the electromagnetic spectrum were also defined (there is a profusion of standardised systems, but I'll stick with the *UBV* and its extension). In part, the extension was possible because the original photoelectric photometers (spectral response: 320 to 650 nm) were replaced by ones that could reach 1000 nm; the Earth's atmosphere produces a cutoff at the short end near 320 nm. The name of this extended setup, credited to Johnson, and Cousins in Capetown, is the *UBVRI* photometric system with filters centred on 365, 435, 548, 635 and 880 nm (Figure 13-1) and quite broad in their response. In practical terms, as astronomers reach out to observe fainter and fainter objects, this system, because of the broad width of each of these passbands, allows them to go fainter than most of their counterparts. Telescope time is precious, and the faster you can observe, the more data you can assemble or, alternatively, you can tackle fainter objects. There are always trade-offs when we observe. As I mentioned earlier, the telescopes are never big enough and the detectors never fast enough to give you what you want. You are always at the edge. Just listen to people bleating about their phone's bandwidth never being enough; you'd think you were listening to observational astronomers going on about their equipment and telescopes!

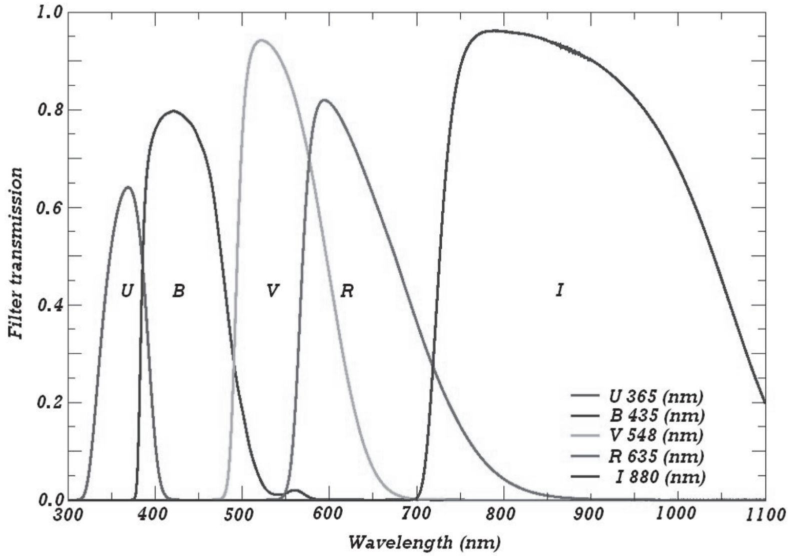

Figure 13-1. The UBVRI passbands. The actual passbands are a movable feast because the photomultipliers and CCDs have evolved as the detectors have changed from the original system. These are the filters most often used and are reproducible, unlike the early pieces of glass that defined this photometric system. Credit: Multiple sources. Annotated by the author.

13.3 Obtaining cluster data

Open cluster observing was long and tedious, my stints in Chile in the 60s and 70s involved observing one star at a time: checking the finding chart for identification and going on to the next one. Each observation took about five or six minutes, including finding the star, centring it in a circular diaphragm and making two observations, each through three filters, one group of the star and another of the sky. It was a classic time-and-motion exercise; night after night for six weeks. I talked about it earlier, but for those people who used photometers in those days that was the common experience. But globular cluster observing was always harder, since the clusters are fainter and hence it takes longer to "soak up the light in two or three-minute intervals" to observe a sample of faint stars with enough precision to be useful. Before the advent of CCDs observations of globular clusters were largely made photographically in order to get data on as many stars as possible (look at the number of stars visible in the ground-based exposure of M3 in Figure 10-5). But these data were augmented and the quality enhanced by observing a selection of cluster stars photoelectrically over a wide range of magnitudes in order to convert the sizes of photographic images to magnitudes. The “reduction sequence”, converting image size to magnitude, needed to be established for each observation separately, because every exposure on a photographic plate results in different image sizes than the previous one. Whereas photoelectrically, the accuracy of the data is about 1%, photographically it is about 10%. If, as has been done, you do more than measure the diameter of the star but fit the whole shape with some three-dimensional function, the accuracy can be improved, to more like 5% or better. To get colours, the whole business of photographing the cluster had to be repeated another night through another filter assumed to have the same characteristics over the plate. That was a daunting task as it meant additionally measuring the size of each star in a machine designed for the task for all plates, or if using the fitting technique, by scanning the plate and then dealing with the complexities of identifying each star and measuring the whole shebang in one shot. Coupled with this difficulty was the fact that the atmosphere smears the star images so the interior of the cluster is rendered opaque by these stellar images merging into each other. It is a measure of the quality of the HST images that they have recorded individual stars in the centre of nearby globular clusters (see Figure 13-2). For this reason, before the HST, or a telescope equipped with adaptive optics, measurements were limited to the outer reaches of globular. clusters. Studies, now aimed at checking differences between stellar populations in the central region compared to the outer, were not possible.

It was not until the advent of the CCD camera that first-rate data came available that bypassed the need to scan a photographic plate and go through the laborious process of calibration in order to generate an H-R diagram suitable for comparison with models. From these data came the first reliable H-R diagrams of globular clusters. But this fancy new detector produced its own hold-up, because, given these lovely data, astronomers were unwilling to simply measure the stellar diameters to get magnitudes, they wanted to match the 3-D profiles of each star image with some sort of model image. And more, they wanted software that would automatically scan the whole CCD, locating the stars and fitting some reliable profile to each stellar image and so derive a magnitude. Also, in the process, they wanted to be able to get magnitudes for stars with blended images. Developing that software was a huge job, but these tools are used today converting raw data on a CCD image to lists of magnitudes, colours, and positions for thousands of stars at a time.

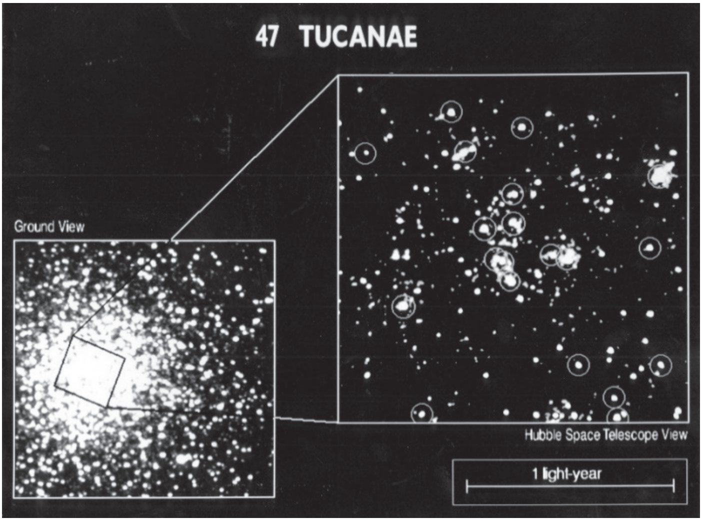

Figure 13-2. Showing the improved (!!) resolution of the HST over ground-based telescopes. The circled images are from a study of stars called **blue stragglers (BSS)** which are identified in the right panel. Note the light-year scale. The nearest star to the Sun is at 4.37 light-years. This give you an idea of the compact nature of a globular cluster. Credit: Left panel, Ground Image: ESA/**STScI)**/ESO/Meylan, Right panel, NASA, ESA/Paresce, ESA/STScI/Shara.

Again, the CCD is not a panoramic detector like the photographic plate, and so the observer will take selected frames distributed around the cluster; their location depending on the observing program. Earlier, we've seen clusters displayed in colour magnitude diagrams (see Figure 9-2), and, as you've seen, it wasn't until star clusters were studied using these diagrams coupled with preliminary stellar evolution calculations, that an understanding of how evolution proceeded, with these diagrams providing a clear picture of the situation. But this simple temperature-luminosity H-R relation is multi-dimensional. Other axes could be drawn: a third would be mass for any spot within a colour-magnitude diagram. Similarly, elemental abundances affect the results. You can imagine that a star forming when the universe was young, would come from gas clouds barely enriched by the heavy elements created from early supernovae and we would expect these stars to evolve differently from others forming later with abundances like those found in the Sun. This means that there are whole populations of stars with gradations of metallicity out there waiting to be studied. Gaia will do this and perhaps show us, through these gradations and their location within the Milky Way, the chemical evolution of our galaxy.

Basically, we have a four-dimensional grid, incomplete with respect to known masses at the hot end, and abundances that must vary from place to place in our galaxy, since we can hardly expect a uniform distribution of elements common to each gaseous cloud. I'm getting a strong feeling as to how researchers in this field must feel. I've used the word daunting a lot. In my area of research, the measurement of abundance in stellar spectra, complications also arise. A lot of fundamental laboratory data are still needed to generate a spectrum that precisely models a real spectrum. We are continually at the edge, pushing forward and making assumption that will allow us to make some sort of progress. Making stellar models that incorporate rotating stars that we know are in any given cluster is a very difficult complication, making the modelling of spherical stars seem simple by comparison. But again, the physics of all this is incomplete and therefore we aren't there yet with accurate models that will represent the real world.

13.4 Generating the models

Let's have a look at some evolutionary calculations. They seem to be coming thick and fast in the literature for reasons implied here: largely improvement in the physics, sometimes in the calculation of the rates of energy generation in the stellar cores, the improvement of opacity calculations, and improved modelling of convection. Undoubtedly there are other issues that require the continued recalculation of model evolutionary sequences. The effects of rotation must be considered. At the end of these calculations, the evolutionary models must reproduce the complex cluster colour-magnitude diagrams I've shown earlier (Figure 9-2).

If we were to change something like the abundance, then we can use the just completed model results to begin again, thus we piggyback a new model star from the old one. The question of abundance seems to be problematic as the formulation used has been vastly simplified and in a way is often used as some sort of fudge factor to overcome some difficulties that I will bring up a little later. What we students did in graduate school produced a very crude model in comparison with what can be generated in a fraction of a second in a home computer or with a more sophisticated mainframe. I repeated this model building process a few years ago while watching TV, converting a basic evolutionary code to run on MATLAB, a useful programming code used throughout the North American college system, augmenting the software to plot pretty little graphs showing the run of temperature and density as it slowly zeroed in on a solution. I guess I did it as a challenge to see that I ***could*** do it. Subsequently, a grad student (Alex

Rimoldi) extended the code to handle evolution for his master's thesis. The number that I use for the age of the Pleiades comes from his thesis.

I'll mention here another approach to generating stellar models with different abundances or masses once a starting model is available. With this method, you run a solution and compute the differences from what you put in, or started with, against what you just calculated. The mathematics of these differences point the way to a better solution with different starting values that tend to be larger near the outer boundaries of the model. The process continues until either a new solution blows up and the numbers become nonsense, or each new iteration produces smaller and smaller "corrections". Update the differences to your model and compute it all again. And again, and again until some prescribed limit of these differences is attained. This technique is also used in computing the pulsational models and the atmospheres of the stars and through much of the varied analyses in astronomy and astrophysics. It also can be very unstable against a poor set of starting values. I've found the technique to be most temperamental when I've been trying to generate a stellar atmosphere that gives the run of temperature and density against depth in the atmosphere, a necessary beginning in order to calculate a stellar spectrum. That's enough of the vicissitudes of model generating and unstable mathematics.

13.5 On the way to evolution: Generating a ZAMS

Given a modelling code and a starting model for a star of given mass, we have the capacity to model stars from brown dwarfs to the most-massive stars that can form. The complications come from the physics required because they are not necessarily complete, especially for the brown dwarfs where convection rules. To attempt the calculation of any evolutionary sequence such as that shown in Figure 13-3 below, we need the range of mass covering the observed data, say 0.6 to 30 solar masses. We have a single model, probably based on the Sun. Generating a main sequence is straightforward as we increment the mass of our starting model, thinking that the temperatures etc, from the previous model would be a good starting approximation. If we change the mass too much what we calculate will not converge, that is, the mass will not go to zero when the radius does. If the steps are small enough it is possible to automate the process so the computer does your bidding while you do something else. At the end, you have a zero-age main sequence covering perhaps the range I quoted earlier. This whole business of steps is akin to a police search looking for a missing person. If your grid is too large you may miss the person. Make a grid small enough and your chances of success are markedly better. Make it too small and you'll get nowhere. The question, "What is small enough?" is only answered by trial and error. Now we'd like to compare our newly generated ZAMS with the theoretical calculation.

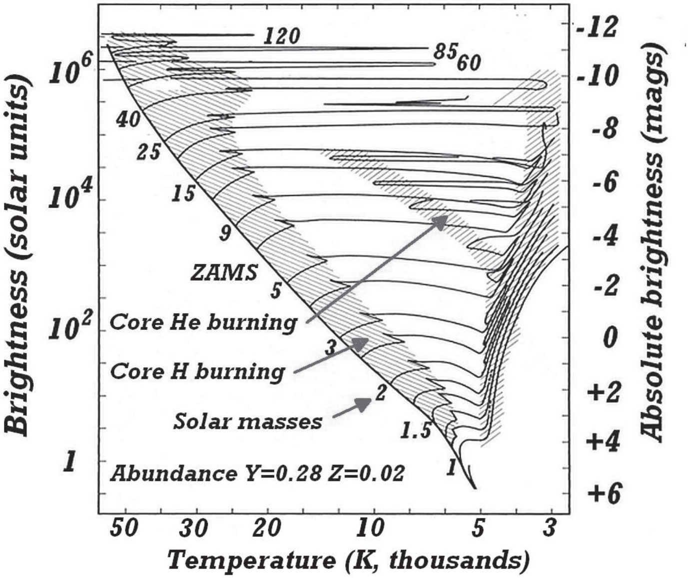

Figure 13-3. Showing how stars of masses 1 $M_\odot$ to 120 $M_\odot$ evolve. Note how the track for the 120 $M_\odot$ model is quite different from the rest. I suspect that the model is having trouble getting started and wants to blow the star-forming material away. The ZAMS is the left-hand line where the evolutionary calculations begin. Credit: Maeder and Meynet, 1989, A&AS, 210, 155.

But before we do this comparison, I'll reprise what I talked about in Chapter 9. Observations deal with absolute brightness and colour (M_V and *B-V*); both measures related to observations of the star made through yellow and blue coloured glass filters, whereas the models results are given in total energy output and temperature ($\mathbf{M_{bol}}$ and T_e). These data must be reconciled before any comparison between observations and models can be made. M_{bol} refers to the energy produced through the whole of the electromagnetic spectrum and the absolute brightness or magnitude M_V refers to the radiation that is measured through a piece of yellow glass which does not record the infrared or the ultraviolet. Corrections are necessary to compensate for these deficiencies. The corrections can only be gained by comparing data for the same stars measured from space and on Earth, thereby getting the correction factor. I won't go into detail about the complications but linking M_V to M_{bol} requires for the calibrating stars, distance measures. Relating colour to temperature is a little more of a song and dance as it also requires a measured angular diameter in milliarcseconds (mas) as well as the calculation of theoretical spectra for the calibrating stars. This is a simplification and the process is very complicated but I don't want to get bogged down in what is done, it is enough to know that the calibration is interwoven between observations and theoretically derived stellar spectra.

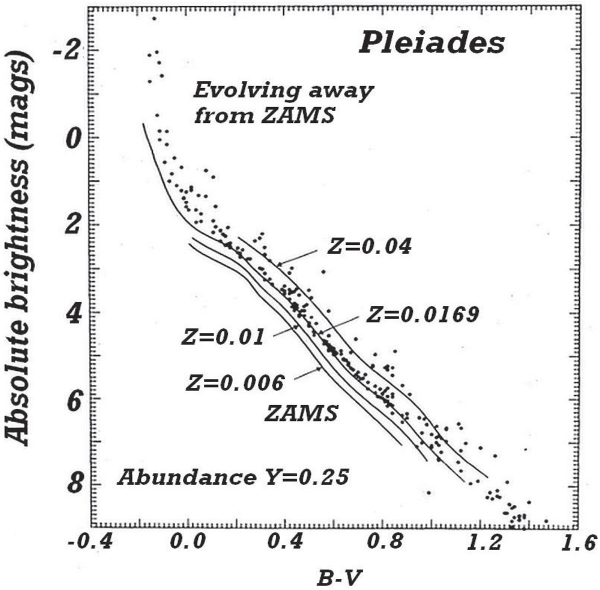

Figure 13-4. Compares the Pleiades ZAMS with those from several theoretical models computed with various metal abundances (Z). Small values of Z represent lower metal abundance. The wiggles in the data are well represented by the theoretical results. Note the effects of evolution at the bright (upper) end. Credit: Vandenberg & Bridges, 1984, ApJ, 278, 679. Modified by the author.

Now, let's see how the colour-magnitude data for the Pleiades is fitted by the models; see Figure 13-4 where we plot the data and hope that the two sequences will sit atop one another. In this diagram have a look at the dots—the data—that waver a little but the theoretical calculations mimic these small changes very nicely. Agreement like this makes you feel good. But look again and check the metallicity in Figures 13-4, which, when changed, moves the fit up and down but rule out the extremes. An error in the distance to the Pleiades will also mimic these changes in Z (metallicity), whether it is fitting a ZAMS to that of a globular cluster or to a cluster like the Pleiades where these interleaving effects provide a lot of opportunity for error.

Now evolve the models. You supply your code with a time-step and recompute your model; again, using the previous model to begin the evolutionary process. If the time step is small enough—though the amount will differ because everything happens faster in more massive stars—and the model converges (gets an answer); some hydrogen is fused, converted into helium, and the structure of the star changes. As the time steps continue, the core gets transmuted, the structure changes, and we see this as a change in luminosity and temperature. We are on the way to producing a theoretical H-R diagram, such is shown in Figure 13-3, that we can match to the data. With a suitable algorithm much of this can be done automatically, though devising the recipe may be a little bit tricky. In all these automatic calculations, it is the failure of a model to converge—to get an answer—that causes problems and then it is back to the drawing board. I'm sure the designers of these driverless cars are still sweating over situations they may have not envisaged. At the end of all this, you have created what is called an evolutionary sequence, or when plotted, called evolutionary tracks. At the end you have a grid of masses with values of M_{bol} and T_e for each time-step.

To see what a cluster might look like at a given age we go through each of the evolutionary sequences to interpolate the M_{bol} and T_e corresponding to that age. The results of this process as applied to the tracks in Figure 13-3 are shown in Figure 13-5. These are called **isochrones**— lines of equal age. To find an age to a young cluster you'd overlay the cluster data (M_v, *B-V*) with a series of isochrones and interpolate an age. The effectiveness of the process depends on the accuracy of the transformations between *B-V* , T_e,

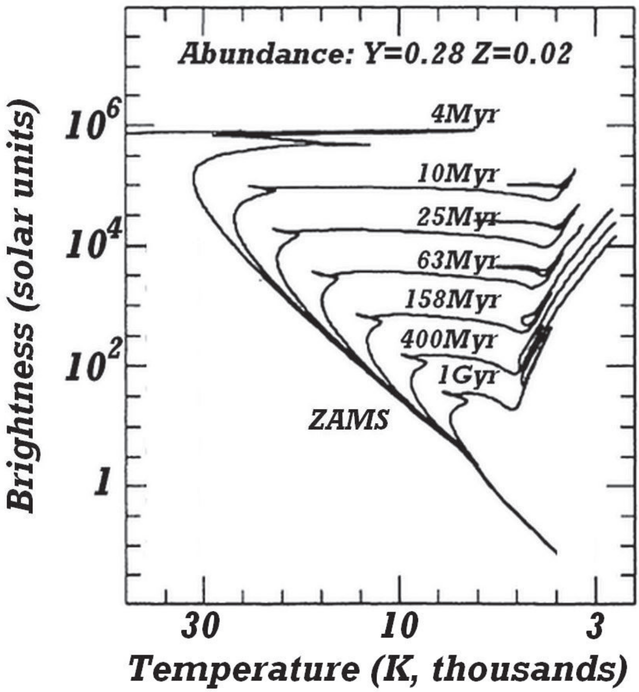

Figure 13-5. Isochrones interpolated from models like those shown in Figure 13-3. The isochrones cover a range in age of 4 million to one billion years. Credit: Bertelli et al., 1994, A&AS, 108, 275.

M_{bol} and M_V. The use of isochrones is shown for the Pleiades and the Hyades in Figure 13-6. I'm not trying to produce any definitive results here but am content to try to show the principle behind getting ages by this method. The only thing that is constant are the data, the models are always changing along with the calibration links between the theory and observation. Because observational astronomers are unlikely to have access to evolutionary codes, there are databases of isochrones for researchers to use. These databases are updated as the model builders improve their realism.

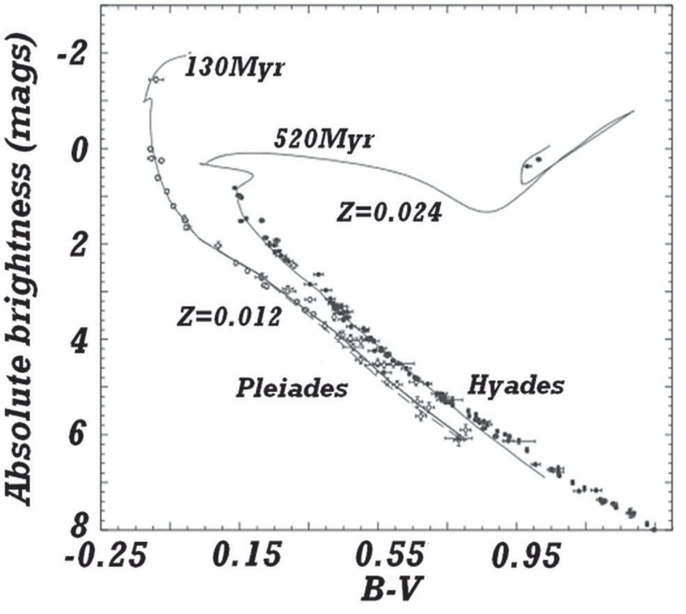

Figure 13-6. Shows model fits to the Pleiades and Hyades cluster data. Note the difference in metal abundance (Z) between the two clusters (0.012 and 0.024) illustrating the point that the observed ZAMS has been created by overlapping clusters with different abundances. Note also, the difference in the Pleiades abundance between here and in Figure 13-4. Credit: Castellani et al., 2002, MNRAS, 334, 193. Modified by the author.

13.6 How do you match theory with observations?

In addition to fitting the cluster sequence, your models must represent the observed colour-magnitude diagrams as well as, being able to predict the characteristics of specific stars e.g. M_{bol}, T_e and mass, within a cluster which have parameters derived from some other study. For example, there is an eclipsing binary in the Pleiades whose characteristics are well-established. The calculated models must match these data very well. If they don't, perhaps it indicates a failure of the physics, perhaps the stars are evolving faster because the rate an element is being transmuted is in error, maybe the derived distance to a cluster is incorrect, maybe it's a shortfall in the quality of the opacities, or the convection theory being used. Moreover, the cluster stars, at least for these young clusters, are all rotating upwards of 200 km/sec though these rotational effects are masked by the random orientation of their axes, from looking down on the spinning axis or side on. I'll show you the effects of rotation a little later. The science is much more complete than I ever could have imagined when I wrote a partial draft of the book more than 15 years ago.

Now for a far more stringent test, the matching of theory to a globular cluster billions of years old. Any errors or shortcomings in the process must surely be exacerbated here. Consider the H-R diagram of Messier 68 (M68) in Figure 13-7. The same evolutionary turnoff takes place in globular clusters. In this figure we see the turnoff near M_V of 4.8 on the left-hand scale. This is fainter than where it should be because the Sun still has 5 billion years to run before it starts moving away from the main sequence. The 4.5 Gyr age of the Sun has given ample time for more massive stars to evolve to the right and for the even more massive stars to disappear as neutron stars and white dwarfs. The figure shows the fit between data and theory in two colours *B-V* and *V-I*. Recall that data may be obtained at different wavelengths; in this case the letter *I* represents a measure in the near infrared (see the passbands

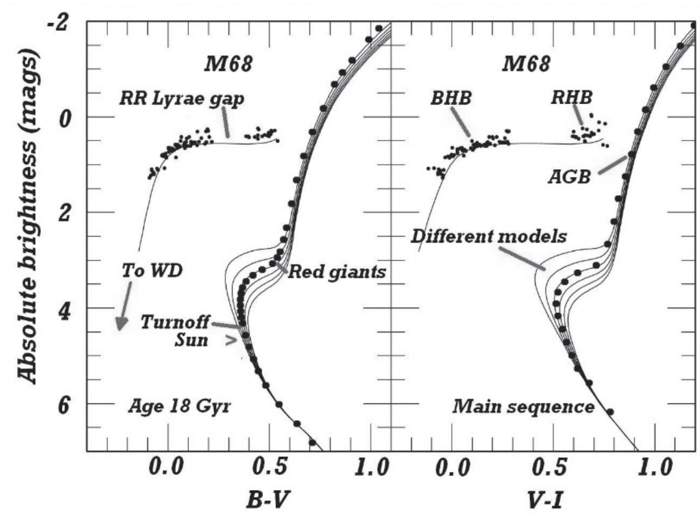

Figure 13-7. Showing the fits to a simplified globular cluster sequence in two colours (*B-V* and *V-I*). Aside from the horizontal branch to the upper left, the fit is superb. Note how the different models represent differing abundances. Of note is the quoted age (18 billion years) which is larger than the current accepted age of the universe. The models in the right-hand panel go a long way to representing the data. Credit: Vandenberg and Clem, 2003, ApJ, 136, 778.

in Figure 13-1). The data are averaged over small intervals to simplify analysis (look back at the image of NGC 5272 in Figure 10-5 to see why).

Getting back to this figure. This whole fitting process relies on several variables: the distance to the cluster, reddening, the abundance and undoubtedly convection parameters, all of which can be adjusted to produce the fit we see in this figure. It looks good. But there is a problem. There always seems to a problem whenever we look closely at any aspect of astronomy. The age of the theoretical sequences required to make the fit is greater than the age of the universe. I quote from the authors of this paper.

> "The transformation of the luminosities and temperatures predicted by stellar models into the various magnitudes and colour indices that can be directly observed is of vital importance for our understanding of stars and stellar populations. Both to test theoretical models using empirical data and, conversely, to interpret observations using evolutionary computations, it is essential to have reliable colour-T_e relations. Unfortunately, the uncertainties associated with such transformations have continued to be quite large, despite the efforts made by many workers over the years."

Let's turn to the Cepheids, giant stars that pulsate and which have gone a long way towards helping us understanding the overlaying universe.

13.7 The Cepheids

Aside from the usefulness of Cepheids in the study of cosmology, their existence provides other tests of evolution and pulsation theory. As noted earlier in reviewing distance markers, these pulsating variables were discussed along with their position in the H-R diagram (see Figure 8-6 and Figure 11-1). This position in the H-R diagram is called the instability strip because that is where the RR Lyrae stars and Cepheids are found, though at much differing luminosities; evolution takes stars across this region. For the RR Lyrae stars it is quite clear-cut because they are found in what is called the horizontal branch; a well-defined region in a globular cluster H-R diagram (Figures, 8-6, 10-4 and 10-5). Unlike the RR Lyrae stars, Cepheids in open clusters are not in well-defined regions because the number of these variables is small; itself an indication that evolution takes place rapidly through the Cepheid part of the instability strip, and that galactic clusters are not rich in stars anyway. Considering that fewer than thirty Cepheids have been discovered in open clusters it is surprising that ***three*** are found in the cluster NGC 7790 (see Figure 13-8). In this Figure the brighter stars are moving away from the ZAMS shown as the solid line and the location of the Cepheids indicates a rapid evolution to that point otherwise there would be stars within the gap. Incidentally, their presence within a galactic cluster allows their absolute brightness to be determined though, as you see in both panels of Figure 13-8, the cluster main sequence is not as well-populated or as well-defined as the horizontal branch and the RR Lyrae stars within it. Can we fit these data with an evolutionary track? Yes, as we see in the right panel of Figure 13-8. It is reassuring to see that like with the Pleiades data earlier (Figure 13-6), the evolutionary tracks pass through the data, so we are on the right track. There are several points to make here.

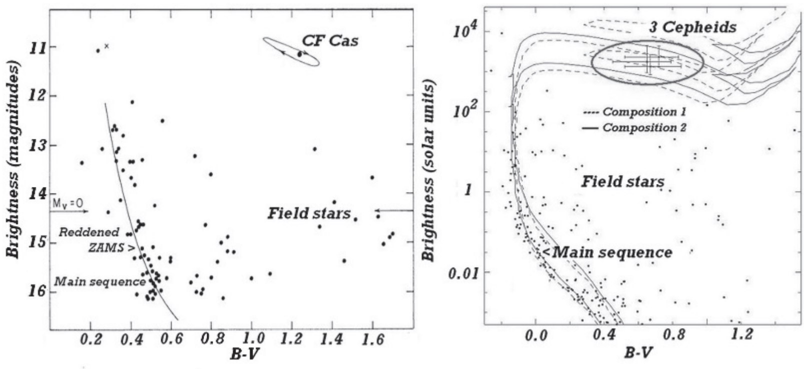

Figure 13-8. Two colour-magnitude diagrams for the cluster NGC 7790. The left-hand panel shows early data and the Cepheid CF Cas with its changing position as it brightens and changes colour. In both diagrams the empty space between the Cepheid(s) and the main sequence indicates that evolution is rapid across this region. There are two additional Cepheids in the cluster data shown in the right-hand panel along with two sets of evolutionary tracks differing only in the assumed abundances used for the calculations. From this fit, the age of the cluster can be derived from these calculations. Note that, because of **interstellar reddening,** the colours in each panel do not align. Because of this, there is no temperature scale in the left-hand panel. Credit: Left panel. Sandage, 1958, ApJ, 128.150. Right panel, Gupta et al., 2000, A&AS, 145,369.

First. When plotted on a theoretical H-R diagram, the Cepheids of known absolute magnitude and colour (M_V, *B-V*), should fall within the bounds of the instability strip (see Figure 13-9). Inevitably some will fall outside these boundaries and will immediately draw researcher's attention. This will lead to another question. "Why?" No theory comes out as tidy as an immaculate ball gown or slick dinner suit.

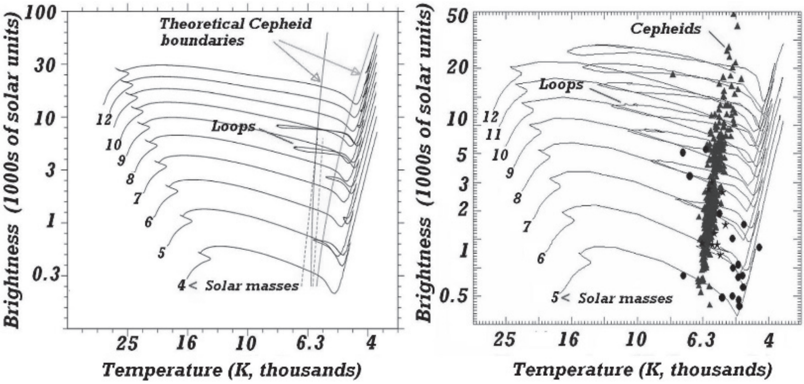

Figure 13-9. Both panels show a series of evolutionary tracks for masses ranging from 5 to 12 $M_{\odot}$. Note the "Cepheid loops" to the right in each image. The tracks move from left to right (higher to lower temperature) up the red giant branch and down to form a loop before the stars migrate back up the red giant branch. The left panel shows the boundaries of the calculated instability strip. In the right panel, the observations are plotted on these tracks. Note that these data fall directly into the region where we see the loops and within the instability strip. The difference between tracks in each image, notably the size of the loops, result from the various researchers adopting different physics. Credit: Left panel. Valle et al., 2009, A&A, 507, 1541. Right panel. Halab et al., 2012, ApJ, 761, 1.

Second. The models coincident with the instability strip must be pulsationally unstable—sorry about this mouthful, all it means is that the stars in this zone must pulsate (vibrate if you will) if given a kick.

Third. The masses of the evolutionary models must agree with those needed for the pulsational models to represent the behaviour of the Cepheids, which means reproducing their periods (the cycle time needed for the pattern to begin again), the amplitude of the light curve and its shape. I'm ignoring the fact that light curves are of different shapes and like a bell that is struck may resonate in different harmonics. Observed changes in the periods of some Cepheids occur. It is the behavioural variations of these stars that spawns more observations and a plethora of theory in the evolutionary and pulsational modelling of these stars. I cannot deal with this material here, as the research is dynamic and worthy of a book and, like this one, will be out-of-date as it is being written. Where possible, the modelled masses must be identical with those ***measured***. Observationally, masses are derived by observing a double-lined spectroscopic binary that is also an eclipsing binary. There are two known Cepheids that fulfil these requirements and disentangling the intrinsic Cepheid velocity variations and light changes with orbital velocity changes and eclipses has been done for them both. The hunt is on for these very beasts for they will be game changers in this whole discussion. I'll talk about it in more detail later in this chapter.

Fourth. Is it possible to find out what triggers the pulsation, not only in the Cepheids but in all stars that are pulsationally unstable?

Consider the evolutionary tracks and the observations. We have enough data (M_V, *B-V*) for the Cepheids to place them in an H-R diagram and check if they fall in the instability strip (Figure 13-9, shown earlier). You will notice that the red line in the left panel of this figure shows a narrowing of the range near 4 $M_\odot$ (about 200 solar luminosities) and is one of those research projects directly aimed at checking when pulsational instability ends. This immediately leads to a prediction that there should be few, if any, Cepheids below about 4 $M_\odot$. In fact, looking at the right panel we see that no Cepheids plotted there are below this limit. Notice that the models don't look the same in each panel. Earlier, I mentioned the plethora of models, each differing in some small way but all showing the same characteristics. I could illustrate these varied results by showing more and more graphs but then I'd be in a Neverland of research myself.

13.7.1 The pulsational and evolutionary model mass discrepancy

Now let's turn to the question of a mass discrepancy. You might recall earlier when I mentioned a model pulsating Cepheid that reproduced what was observed in terms of its period and amplitude but the mass it implied was incorrect when compared against evolutionary calculation. How does this work, where do the pulsational masses come from? Have a look at Figure 13-9 where the Cepheids are plotted. The mass increases as the luminosity increases, which is what we call a mass-luminosity relation. Now have a look at the loops on either panel. The Cepheid luminosity for a given mass could be on the top of the loop or below. There is a small error here and astronomers try to determine in which crossing the star in question is located. But there is also the period-luminosity relation that enables us to determine a Cepheid's luminosity from its period alone, thereby providing us with a healthy distance scale that could reach out into our galaxy neighbours; we talked about this in Chapter 9. These two relations link the mass to the pulsational period through the common parameter, the luminosity. Alter the theoretical luminosities and you alter the predicted mass and hope that the changes that occur go in the right direction! Making that happen has helped stellar astronomy a great deal because many aspects of the subject have been re-examined. This is never a bad thing, in stars or in human relationships. To increase the mass from its pulsation characteristics requires the mass-luminosity relation to be in error. The mass depends on the period and the luminosity. If there is an error in the luminosity then the mass will be incorrect. Over the years the evolutionary models have improved and have closed this gap to between 10 to 20%. It is still not good enough and provides a continual irritant that seeks an answer. The actual mathematical modelling of the stellar pulsations in a radial pulsator (swells and shrinks), like the Cepheids and RR Lyrae stars, appears to be on a solid footing. In addition, the type of pulsations: radial (inward and outward) or non-radial (waves sweeping around the surface of the star) had already been covered in detail sixty or more years ago before data were available to see if these travelling waves even existed in the stars. This follows a long tradition of theoreticians making predictions long before there was a hope of substantiating it in one's lifetime. Consider Aristarchus and the solar system, Halley and his comet, Einstein and gravity waves and Zwicky and Baade with neutron stars to name but a few. Subsequently, these negative results lead to improvements in the physics within the modelling software. But to this day the exact reason for the discrepancy is unresolved though attempts to find a solution are ongoing. In its way this is good because the evolution people are taking a hard look at what might be going on in these stars that they hadn't considered.

Just having written these words I find a paper that suggests a solution involving rotation. Again, it involves the mixing of the elements within a star by the circulation effects of rotation. In these calculations the luminosity of a rotating star is greater than a non-rotating star thus giving the lift to the pulsational mass needed to solve the problem. Figure 13-10 shows images from two papers that imply a solution to the problem of which I first became aware in that seminar at U of T fifty-five years ago. But again, the court of public opinion resides with other astrophysicists who will check these calculations.

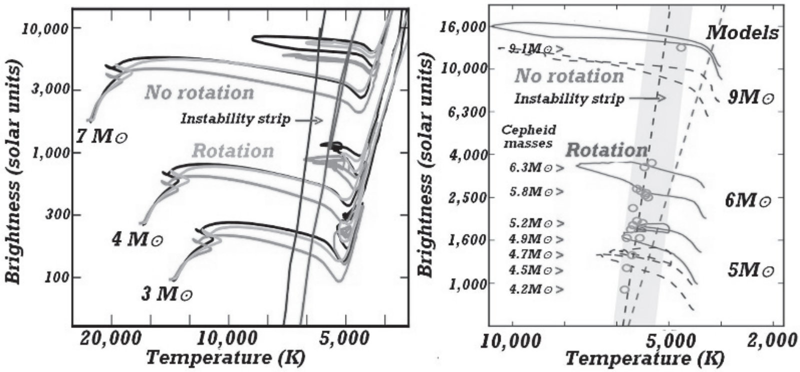

Figure 13-10. See Centrefold. Left panel shows the effects of rotation on evolution through the Cepheid loops. Notice how the rotational tracks (yellow-black lines) sits above the non rotating results (green line). Right panel. Cepheids with measured masses plotted as cyan open circles onto the blue loop portions of evolutionary tracks. Tracks corresponding to models rotating at about 200 km/s are shown in red to the right. Non-rotating tracks are shown in blue. The stars and the instability strip (shaded area) are nicely encompassed by the loops. Because the full evolutionary tracks are not shown it is difficult to tell just how closely the two sets of masses agree but it is very close. Credit: Left panel. Anderson et al., 2017, Proceedings of the 22nd Los Alamos Stellar Pulsation Conference "Wide-field variability surveys: a 21st-century perspective". Right panel. Anderson et al., 2014, A&A, 564, 100.

13.7.2 What triggers pulsation?

What triggers the pulsation will be difficult to ascertain. Models are computed on nuclear time scales whereas the process that creates instability, though unknown, must operate within seconds to begin the pulsation, much like a landslide on a seabed that produces a tsunami. Even though the Cepheids pass through this region relatively quickly (tens of thousands to millions of years), finding that key moment when your model receives that kick will be like trying to find a needle in a haystack. It will require non-stop computing with time-steps in seconds opposed to ones in thousands of years. As I've described above there are shells of material fusing above the carbon core being affected—stirred up if you will—by rotation and convective overshooting. There will be sudden bursts of energy released as some element switches on to nuclear burning, perhaps similar to the process that expels the rings in planetary nebulae. Surely amid that fusion—or confusion—there will be a magic moment that will set the star quivering and be seen by us as a Cepheid.

13.7.3 A brief aside: OGLE

Before turning to the masses of the Cepheids I need to talk about a Polish observing program in the "**galactic bulge or galactic central bulge (GCB)**", the central region of our galaxy, and expanded to the Magellanic Clouds. Its scope is so great that it offers stellar astronomers unprecedented opportunities to practice their craft in measuring fundamental stellar properties, radii, masses, absolute magnitudes and distances of stars in nearby galaxies. Personally, it brings to fruition what was started in St. Andrews with Hilditch and his collaborators more than 25 or so years ago. I can recall an evening about that time in a pub, when Paczyński, the father of modern lensing and OGLE, spoke about microlensing, hoping to get observing time in Chile to begin an observing program that would help detect what still bedevils cosmology—missing mass. Then it was just an idea in a theoretician's mind but he brought it to pass. This ongoing Chilean-based Polish observing project did much, much, more than detecting microlensing events, it took the whole field of stellar astronomy into an extragalactic environment. Incidentally, writing this and mulling over the past is creating a bit of envy in me, seeing what can be accomplished using the massive database and the possibility that stellar astronomers may now have easier access to large telescopes that was so hard to get 25 years ago. Prior to OGLE, few were willing to spend the time to monitor the sky in the hope of picking up the increase in brightness of a star as it was focussed or lensed by a foreground object. The notable exception being the continued nightly search for stars whose light is increasing in some supernovae outburst. Now we have these lovely data that have also been mined for just the opposite effect, dips in light that might be related to eclipses or other forms of variability. The material is beautifully catalogued and any researcher has ample material from which to extract data for analysis, just like the **Search for Extra Terrestrial Intelligence Program (SETI)** that offers anyone interested access to radio data in order to search for meaningful signals that may herald the existence of life out there.

I'm sorry for disturbing the flow of the story but the results from this exciting observational program are rippling through stellar astronomy and have a relevance to Cepheids and their masses.

13.7.4 Cepheid masses

There are at least two eclipsing binaries found in the OGLE database that contain Cepheids, both stars are in the LMC. Let's follow through the analysis of one of them OGLE-LMC-CEP0227 whose light curve over many pulsation cycles is shown in Figure 13-11. (I'm cheating here because I don't have the complete data for this star and need to use the results from another to fully illustrate the analysis.) Because the components of the system are well-separated, the region outside of eclipse is constant except for the Cepheid variations. Because of this, one can just deal with these data and find the period of pulsation using some canned program. In looking over these data it is clear that the observers are making more than one observation/night in order to facilitate this period-finding. Making only one observation nightly opens you up to problems when you try to find the true period of variation of a given star. They are avoiding getting alias periods; say for example finding a period less than a day when the true period is much longer. A perfect example of this is afforded by a movie of a moving car's wheel. Often, they look like they are rotating backwards. This is called an alias period. The results of an identical process for another OGLE star (OGLE-LMC-CEP1812) are shown in Figure 13-12 and look exactly like the schematic archetypical Cepheid light curve seen in Figure 9-6. Given a Cepheid light curve, as shown in the left panel in Figure 13-12, these variations are subtracted from the original data (not shown) to yield the data through both eclipses (right panel Figure 13-12) which can now be analysed with a program that solves light curves.

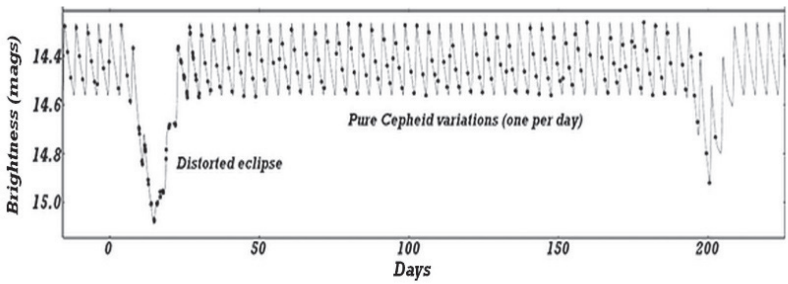

Figure 13-11. The light curve of a Cepheid (OGLE-LMC-CEP-0227) that is also an eclipsing binary. The Cepheid cycles are shown along with two obvious eclipses. A Cepheid light curve is derived from the non-eclipsed data and subtracted from it to show the eclipses. Credit: Pilecki et al., 2013, MNRAS, 436, 953. Modified by the author.

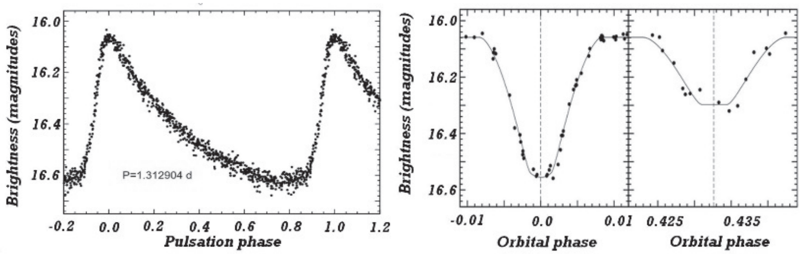

Figure 13-12. Left panel showing a Cepheid light curve extracted from observations of OGLE-LMC-CEP1812. The right panel shows the eclipses (primary on left and secondary on right) that are solved to yield the relative sizes of each star in terms of the separation between them and, critically, the inclination of this system to us. Credit: Pietrzynski et al., 2010, ApJ, 742, L20. Modified by the author.

The second ingredient needed to derive the masses is the radial velocity orbit. I don't have an image of the radial velocities with time similar to Figure 13-11, which will be a combination of the pulsational and orbital RV changes. Given these data, and knowing the pulsational and orbital periods, it is possible to separate out the two sets of data. These are shown in Figure 13-13. By combining the data from the solution of the light curve and the joint orbital motion of each star, we get the individual masses and radii and hence that of the Cepheid, which we can compare to the pulsational mass. The results from these studies have been shown to be consistent with pulsational masses but in 2018 these results have been challenged. The whole discussion is unbelievably complex with evolutionary models being

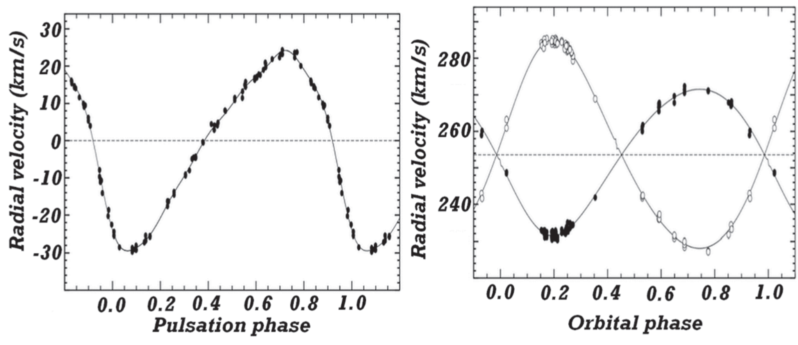

Figure 13-13. The left panel shows the RV pulsations of OGLE-1812 and the right panel the orbital motion of the primary star (filled circles) and the secondary less massive star (open circles). Credit: As in Figure 13-12.

altered this way and that (see the variations displayed in Figure 13-14). Typically, there are the usual suspects, the free parameters: mass loss through this region of the H-R diagram, chemical composition, and convective overshooting. I'm just a reporter and will watch with interest to see how it works out. But the masses, radii and derived gravities for these Cepheids are solid. To give you the idea of what is involved, have a look at Figure 13-14 where graphs of the loop area in the H-R diagram show results for OGLE-LMC-CEP-0227. Displayed there are four models with varying amounts of convective overshooting and mass loss. The panel to the lower right with maximum mass loss does not meet the brief but the others do. This comparison would seem to be most promising but we lack the instability strip which itself would depend on the parameters giving rise to these models. Despite all the uncertainties these results give me confidence that we are getting it all right, that our theory of stellar evolution is on the right track.

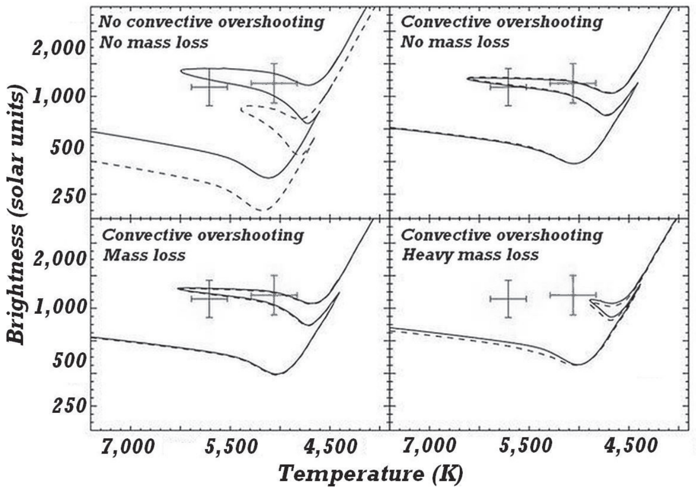

Figure 13-14. See Centrefold. Evolutionary results for OGLE-LMC-CEP-0227 plotted in the "loop region" of Cepheid evolution. The Cepheid is plotted in blue and the red giant, which is not pulsating, is in red. Clearly, the loop with maximum mass loss produces a loop that does not encompass the data. All other models are possibilities. Credit: Moroni et al., 2012, ApJ, 749, 108.

We have a wonderfully diverse and complex series of models which now include rotation (I have seen others that include magnetic fields) and four good masses with which to make progress. Remember that the isochrones must satisfy the data for both stars in each system. Having written that, I pick up a paper that challenges the assumption that the stars formed together at the same time (coeval birth). Sigh…

13.7.5 Period changes

Period changes are observed in Cepheids and this requires a lot of observing by measuring the peaks of the light curves over many years. The archetype that gives rise to the name Cepheid is the star ǒ Cephei which was discovered to be variable by Goodricke in 1784 and its period has been monitored ever since—Goodricke was the young man who observed the eclipsing binary Algol and correctly explained the reason for the light changes. Given a period change, these measures easily reveal a period shift. Models show that such shifts are related to a star's passage across the instability strip. I mentioned earlier that we see no "live evolution" because of the timescales involved, except for the supernovae which blossom forth and which we only recognise after their explosion is well underway. Well, maybe Cepheids and their period changes, negate this statement and reveal something about a Cepheid's evolution as it moves across the instability strip. A hundred years ago, it was suggested by Eddington that because there was a relationship between period and the mean density of a star that any changes in period would also indicate structural changes within a star. He couldn't have known how right he was because in each of the three crossings of the instability strip the star is quite structurally different. Ignoring the first crossing to the red giant branch when the star is still converting hydrogen to helium in a shell about an inert helium core which is contracting and heating while the outer shell of the star is cooling and the star swells in size. This crossing from the main sequence to the red giants goes very quickly, in the order of 10,000 years. This absence of stars can be seen in Figure 13-8 which shows Cepheids in the cluster NGC 7790 with few stars between them and the main sequence. This paucity of stars was noted by Hertzsprung and is called the Hertzsprung Gap and it's quite noticeable in Figure 8-2. The star gets brighter at some point and moves upward in the H-R diagram to become a red giant—what happens here has been the subject of much research. There, at the red-giant stage at a temperature near 600 million degrees, the core switches on to begin transmuting helium to carbon and oxygen. The outer envelope of the star stops convecting and we see the star moving to higher temperatures and beginning its blue loop (see Figures 13-3 and 13-4) at which time it starts fusing carbon into oxygen as it begins its movement back towards the red-giant phase, ascending the asymptotic giant branch and into the supergiant realm before it begins its march towards becoming a white dwarf or a supernova. This story is slightly more complex than what I described earlier in Section 11.2 but in reading a summary paper by Cesare Chiosi I see that the whole story of Cepheid evolution is unbelievably complex. Giving this evolution in detail would wear me out and we'd all lose interest, so please settle for what I've offered here and ignore the slight inconsistencies you'll discover if you check back.

The internal structure of a star is quite different in each of those crossings; initially **hydrogen-core burning**, then helium-core burning, and finally carbon-core burning. There are at least 400 Cepheids that exhibit period changes that hold out the possibility that given enough data, observational analysis will identify groups within each of the crossings. The astrophysicists who build pulsation models have their hands full, because many of the Cepheids vibrate in harmonics of the fundamental period, leading to a whole interwoven study linking the observations with the theory. The observations show many variations which might be considered a bane for the theoreticians but I think they welcome these difficulties because that really test their calculations. As I mentioned earlier, the story of the Cepheids is huge and I have no hope of doing any more than this broad-brush discussion. But the way period changes give a glimpse into the core of an evolving star is the driver that has created a desire for studies of period changes in Cepheids within our galaxy and our galactic neighbours the Magellanic Clouds. I can add no more to this.

There is proof here about the validity of stellar evolution because you can see in the foregoing discussion astrophysicists are now worrying about the details. A quote from the abstract of a paper by Neilson and Langer beautifully summarizes the situation that faces the researchers in this field.

> "The Cepheid mass discrepancy, the difference between masses predicted from stellar evolution and stellar pulsation calculations, is a challenge for the understanding of stellar astrophysics."

Progress ***is*** being made. Let's turn to the next important group of variables, the RR Lyrae stars that will aid us in affirming the picture of evolution generally accepted by the astronomical community.

13.8 RR Lyrae stars and the Horizontal Branch

When we look at a globular cluster, we find variable stars in a flat part of the H-R diagram called—imaginatively—the horizontal branch (check Figures 10-4 and 10-5). These are the RR Lyrae stars, stars less than a solar mass but at an advanced stage of evolution. Unlike the Cepheids, which pulsate over periods of weeks to months, these similarly pulsating stars do their thing in less than a day and exhibit dramatically different light curves. For a given star each type of light curve may morph into the other. Sample light curves are shown in Figure 13-15. The location of these stars is shown in Figure 13-16 (left panel) and the evolutionary path is shown in the right panel. From this diagram we see that the RR Lyrae variables enter the instability strip from the right and evolve blueward before returning to ultimately move up the asymptotic giant branch to the red giant tip and onward, shedding mass in the form of planetary nebula on the way to becoming white dwarfs. The main-sequence timescales for the stars displayed (0.7 $M_\odot$ and 0.8 $M_\odot$), are seven billion years (7 Gyr) but the ascent to the red giant tip (RGT) takes less than a billion years.

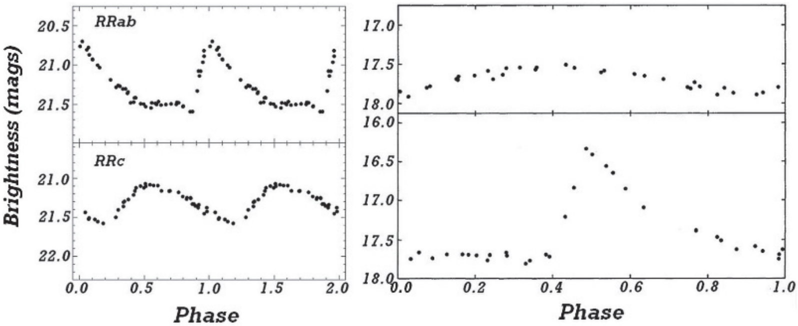

Figure 13-15. Two types of light curves shown for RR Lyrae stars. RRab stars are more common than the RRc. Credit: Left panel. Unknown source. Right panel. Hartwick et al., 1972, ApJ, 174, 537.

There is no ambiguity about associating these variable stars with where the theoreticians say they are in the H-R diagram and they do pulsate when they're kicked. Now we'd like to see if there is any further evidence of evolution because the stars exhibit period changes and it would be nice if these changes could be associated with a star's location in a particular part of the RR Lyrae gap in their direction through the gap, or with their differing light curve shapes. Model builders find that to generate an RR Lyrae star requires just the right mix of mass and mass loss for evolution to carry a star through this region of the H-R diagram. Because the models are sensitive to this fact, along with sensitivity to the "metallicity", or fraction of heavy elements that the model uses, makes the RR Lyrae stars a very sensitive test of evolution and pulsation theory. In addition, because evolution takes stars through this region twice, both contracting and heating, moving blueward or moving redward in the H-R diagram, this circumstance opens up the prospect of perhaps finding variable stars going both ways through the instability strip and relating this to the period changes. But, as with the Cepheids, more is demanded than just having the calculated evolutionary and pulsational models agreeing but the masses must agree to give the whole analysis a lovely consistency check.

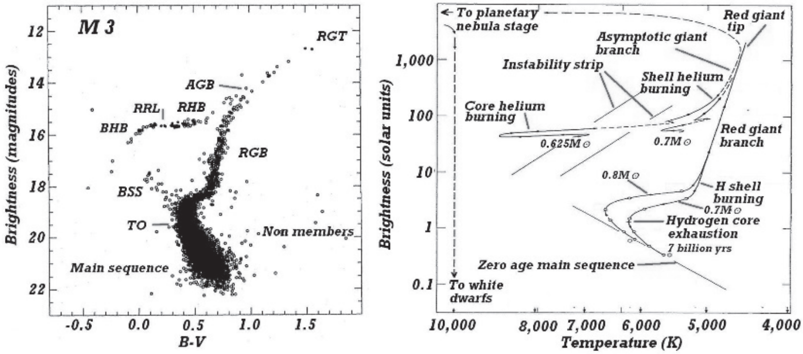

Figure 13-16. Left panel. An annotated H-R diagram of the globular cluster M3 showing the location of the RR Lyrae (RRL) stars on the horizontal branch (BHB, RHB—blue and red horizontal branches respectively) and the blue straggler stars (BSS). Right panel. Shows the evolutionary track of a 0.8 $M_\odot$ star on its way to the horizontal branch to become an RR Lyrae star. Follow its evolution upward on the right-hand side to the helium flash where it swoops down quickly to the left and the horizontal branch and a life as an RR Lyrae star. From there, evolution takes the star upward to the right to the **red giant tip (RGT)** and then has a long march to the left as a slowly exposed hot core imbedded in a planetary nebula. Note that in the process the star the 0.7 $M_\odot$ star has lost 0.175 $M_\odot$ of its mass. Credit: Left panel. Buonnano et al., 1994, A&A, 290, 69. Right panel. Iben, 1991, ApJS, 76, 55.

13.8.1 The data

Observations of RR Lyrae stars are made photoelectrically and with CCDs. As an observer myself, I've enjoyed observing them because they don't need continuous attention and I could intersperse their observation with stars in another observing program, These variables are good to observe because their periods range from six hours to perhaps eighteen. Thus, for the shorter periods, there is the hope of observing a complete light curve in one night. For the longer periods, one needs data over more than one night which are pieced together once the period has been determined. This is how eclipsing binaries and Cepheids are observed—over days. When dealing with a variable star for which no information is available—except that it ***is*** variable—finding the period is a challenge and one is happy to use a software system that gives a period. Any period-finding process is hugely gluttonous on computing time and on the quantity of fan-fold paper spewing forth from the massive printers of yesteryear. Often the labour in getting data into a form harmonised by the period that can be analysed is a larger problem than the analysis. Given a period, if you are observing through two passbands, say *B* and *V* the colour data (*B*-*V*) tell you if the star is changing its temperature through a cycle. An RR Lyrae light curve obtained at one epoch is generally insufficient, because, over time, the period of a star might change, either increasing or decreasing and even the shape and amplitude (difference between maximum and minimum) of the light curve might change. Given these varied data it is then a task to make sense of it all.

13.8.2 Evolution at work

Evolutionary calculations indicate that the periods of stars evolving to the left on the horizontal branch should shorten by approximately 7 hours/million years whereas stars evolving to the right should have increasing periods. There are difficulties in proving this observationally. Firstly, one needs to have an historical base of data good enough to detect period changes and excellent data have only been around for six decades or so. Secondly, the stars aren't beating like metronomes, sometimes they change their mode of vibrating—think of a guitar string. Given the right internal conditions, a star can vibrate at different frequencies. The period changes occur essentially because a star is changing size or something else is happening inside it. The speed a wave propagates, or travels through a star, is related to the speed of sound in the star's interior such that the larger the star, the longer the period. As I mentioned earlier in discussing the Cepheids, almost a hundred years ago Eddington related the period to the density of a star, so that period changes are related to the current evolutionary process at work within the star. If a star is moving from left to right across the horizontal branch, then it is getting larger since its brightness is constant and the temperature is decreasing. Conversely, evolution at constant brightness and increasing temperature produces a smaller star. Therefore, evolutionary changes should be detectable and be related to blueward or redward movement across the instability strip. I can also hear the "but". Yes, there is a "but". It turns out that there are happenings inside a star, perhaps related to convection, that also produce changes in an RR Lyrae star's period. These changes mask the evolutionary changes so that the study of one star in a cluster cannot be used to verify evolutionary predictions. At best we must look at a lot of variable stars and try to prove the effect statistically.

The difficulty with observing the period changes in stars can be overcome by looking at the variable stars that vibrate at two or more frequencies at the same time and which change shape. When this happens, it provides a real test of pulsation theory since the ratios of the various frequencies are sensitive to the structure of the stars. A prediction of the evolutionary models is that the ratio of these frequencies should evolve in a specific way and with that, the amplitudes of the observed oscillations should change with time. Such analyses have verified the predictions of stellar evolution through the horizontal branch but with lots of contradictions.

What is really needed is to measure the mass of an RR Lyrae star and check it against what the models predict. This requirement is hard to fulfil. There is no question that evolution studies are on the right track in the interpretation of the RR Lyrae stars in globular clusters and we can see this as a verification of the theory. Maybe not in all the details, but as I've said before, enough of it is correct and we know we are getting there. Unlike the Cepheids discovered in the remarkable OGLE survey, I have uncovered no similar published eclipsing data for the RR Lyrae stars, but among the 45,000(!!) RR Lyrae stars identified by OGLE in the LMC, SMC and the GCB, there must be many such systems.

13.9 What can eclipsing binaries tell us?

13.9.1 Binary stars amid the isochrones

In the foregoing discussion I've not dealt with the nitty-gritty of deriving a stellar mass. The subject is important, crucial for studies of evolution, but also in determining the distances to our extragalactic neighbours. With the advent of massive telescopes, this subject gains in importance, because it puts high resolution spectroscopy "in the frame". Light curves of eclipsing binaries and radial velocity orbits yield distances as well as masses. A successful analysis of these data gives absolute magnitudes, and with them the ability to measure distances free from the effects of interstellar reddening. In the 90s my colleagues and I made the first attempts to measure the distance to the LMC and SMC with this approach so I have a great interest in how this subject is developing in the 21st century. This technique has now been used to measure reliable distances to the LMC, SMC and M31 (the Andromeda Galaxy), but more later. I'll use as an example, six binaries for which masses, radii and temperatures have been derived. From these masses and radii, surface gravity was calculated for each star. The results of this analysis are shown in Figure 13-17, where we see for each system a plot involving gravity (log g) and mass (log mass) along with isochrones—lines of equal age. Note that the problematic temperature is not included here. Five of the systems plotted have experienced no interaction between their components and are called **detached systems**; in this case the evolution of each star has proceeded unimpeded by their companion. I'll talk more about this in the next chapter. We'd expect to find the components of these systems at the same age and lying on the same isochrone. As an example, look at the components of DH Cep which sit between the 1 Myr and 2 Myr isochrones; this system then is ~1.5 Myrs old. Similarly, the age of the oldest system, CW Cep, is about 6 Myr. The one exception is the system V3903 Sgr whose primary—the most massive star in a pair—sits on the 1 Myr isochrone and the secondary—the least massive—on the 3 Myr. How does this happen? There has been an interaction between the two stars, they are ***not*** detached and some form of **mass transfer** has occurred between the components, but more of this later.

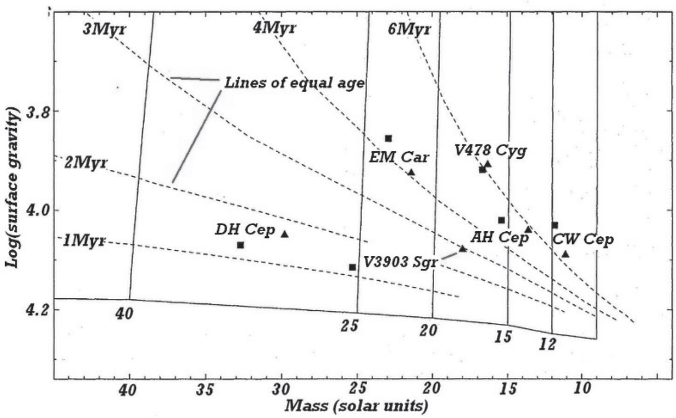

Figure 13-17. Comparison between observation and theory for six stars in a plot of gravity against mass (log g or surface gravity vs log mass). The primary components are denoted as squares and the secondaries as triangles. If they are at the same age, both components should line up along the same isochrone. Except for V3903 Sgr this requirement is largely met. In this case, the reason for the failure is because there has been evolution and interaction between the components (see next chapter). The ages of the stars range from 1.5 to 6.0 Myr. Credit: Hilditch et al., 1996, A&A, 314, 165. Modified by the author.

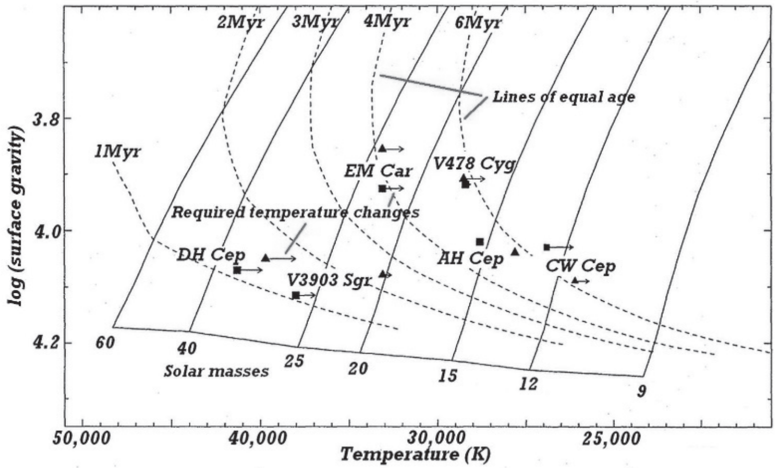

Figure 13-18. A plot like the previous figure except it is gravity plotted against temperature (log g against temperature). Everything is the same except for the small arrows that show how the temperature should be adjusted for the stars to line up along the isochrones as shown in the previous diagram. Credit: As in Figure 13-17.

Now look at Figure 13-18 in which gravity (log g) is plotted against temperature and it illustrates the temperature problem that these researchers faced at the time, but it may have been resolved by now. The small arrows are what my colleagues needed to align each star's temperature with isochrones in the H-R diagram. Diagrams like this yield suggestions as to how the temperature scale should be modified. But the problem might be alleviated, as some researchers have already done, by comparing the component spectra with theoretical spectra, or if you're lucky enough, a spectrum extending into the UV from the HST to derive the temperature. It would seem to me that the approach of deriving temperatures from observed colours are ready to be retired.

13.9.2 Measuring distances

So how do these diagrams help us get a distance to the SMC or LMC? Well, the solution of the light curve gives us the relative sizes of the components with respect to the orbit and its inclination to us. To get the size of this orbit in km, we analyse the radial velocity data and for this to work we need two orbits, one for each star. Combine all these data together and we have the size of the orbit and each star in km. The temperatures of each component come from the colours of each star or by modelling the spectra. Knowing the temperature and size of each star gives the total luminosity of each, that is, the luminosity embracing all the radiation from the electromagnetic spectrum. Can you see a problem looming here? Now we're in the theoretical domain of stellar models and face the difficulty of transferring the total luminosity (in magnitude speak, M_{bol}) to the observations that are made through some modern version of yellow glass, that is, we must correct M_{bol} so that it can be compared to the *V* magnitude of the data. After the correction, M_{bol} becomes something we're familiar with, the star's absolute magnitude M_V ($M_V = M_{bol}$ - correction). Given these data, we can calculate the distance to each system by comparing the observed *V* magnitude from the parts of the light curve outside of eclipse with the combined light our solution has given us. But in getting to this point we are now at the mercy of our temperature scale. Errors in distances can be directly attributed to this uncertainty. So how do we get the distance knowing M_V? Remember when we measured distances using trigonometry and moved all those stars with known parallaxes and observed brightness (*V* magnitudes) to a standard distance (10 pcs or 32.6 LY) to obtain the absolute magnitude? Now, given M_V and *V*, we turn the process around to get the distance.

Eclipsing binaries with observed light curves and spectroscopic orbits give astronomers the ability to measure distances but limited by the same corrections needed when we compare theoretical evolutionary tracks against their observed counterparts. Despite these uncertainties, given an eclipsing binary in a cluster, we can verify any other distance that has been determined for it, just as we can measure the distance to the SMC, LMC and M31. Now there are plenty of these extragalactic data which I will talk about in Chapter 15.

13.10 White dwarfs

13.10.1 White dwarfs in clusters

From the foregoing discussions of the evolution of stars we see that the "pathway to diamonds" is not limited to masses below the critical mass of 1.4 $M_\odot$. A lot happens to stars greater than this limit on their evolution shown in a H-R diagram. When white dwarfs were found in galactic clusters where the main sequence extended to higher masses than the 1.4 $M_\odot$ limit it caused a bit of a kerfuffle because it tossed the then current ideas of evolution into a cocked hat. The only way out was to postulate the occurrence of mass loss that, over the course of its evolution, would take the star's mass below this critical limit before it went boom. Now all the calculations incorporate mass loss as part of the evolutionary scenario after the stars final rise up the asymptotic giant branch to become red supergiants. We saw this earlier when we looked at models within the Cepheid loops to see how the results were susceptible to mass loss, see Figure 13-14. Now these red supergiants are gigantic and the cores of these stars, shells of material are mixing like water bubbling in a pot resulting in nuclear furnaces switching on and off as new fuel-rich materials are suddenly available. Such jolts suddenly increase radiation pressure and lift layers of materials away from the weak gravitational bonding at the outer parts of the star. That this happens, we know. The images of planetary nebula show that many episodes of mass loss occur—check the various expelled rings in Figures 10-6, 10-7 and 10-8. If the star sheds enough mass to take it below the critical limit, then we have a white dwarf. Above the limit, the pressure lattice of electrons holding the star together fails under the weight of the overlying material and we have a supernovae explosion. This scenario then leads to the prediction that we should be able to see white dwarfs in direct images of nearby galactic clusters. And we do. A series of white dwarfs are shown in the star-rich open cluster NGC 6791 shown in Figure 13-19. Furthermore, we would also expect to find white dwarfs everywhere in the Milky Way, and we do (shown in the same figure).

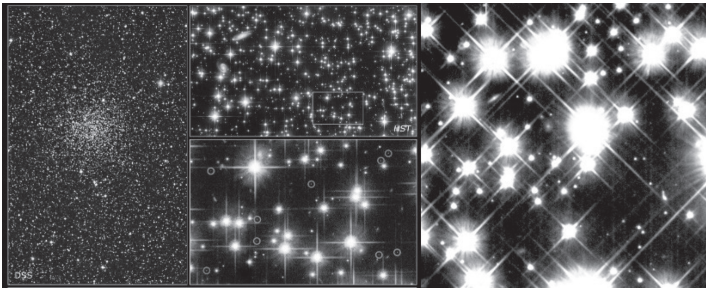

Figure 13-19. See Centrefold. The left panel shows the galactic cluster NGC 6791 with the green oblong expanded in the top centre image. The colours of the stars are not particularly noticeable but in the centre panel they are obvious. Without plotting a colour-magnitude diagram it looks like we have a lot of bright blue stars forming the hot end of the main sequence with even brighter red stars that have evolved away from the ZAMS. In the lower centre panel white dwarfs are identified within the red circles. The right panel shows white dwarfs in the Milky Way appearing as small dots as in the previous figure. Credit: NASA/HST/Richer (UBC).

The same prediction must be fulfilled for the globular clusters because all the massive stars have gone into the great beyond. In the globular cluster Messier 4 (M4), shown in Figure 13-20, the supernovae remnants, like the planetary nebulae shells have been swept from the cluster by its continued yoyo-like passage through the Milky Way disk over billions of years. But despite the eons of gas interacting with gas, about four planetary nebulae have been found in globular clusters. The one shown in M15 (see Figure 13-21) was found in 1929.

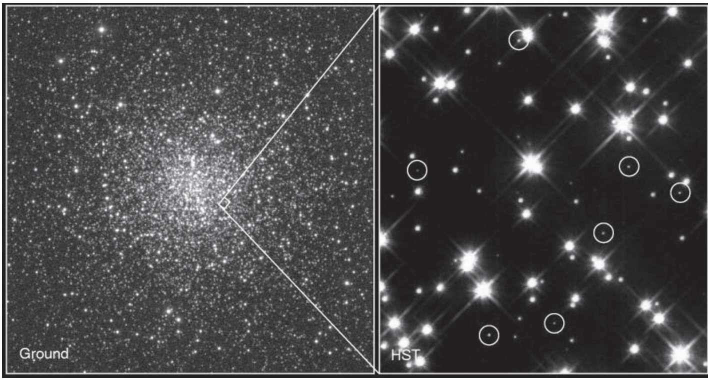

Figure 13-20. A view of globular cluster M4 (Messier 4) the nearest globular cluster to Earth (7,000 light-years away) containing more than 100,000 stars. The globular cluster was the target of an HST search for white dwarfs. The box (right of centre) shows the small area that the Hubble telescope probed. The right-hand panel reveals a total of 75 white dwarfs some of which are identified. The cluster is predicted to contain a total of about 40,000 white dwarfs. Left panel. Credit: Kitt Peak National Observatory 0.9 metre telescope, NOAO; courtesy Bolte (UCSC). Right panel. Credit: NASA/HST and Richer (UBC).

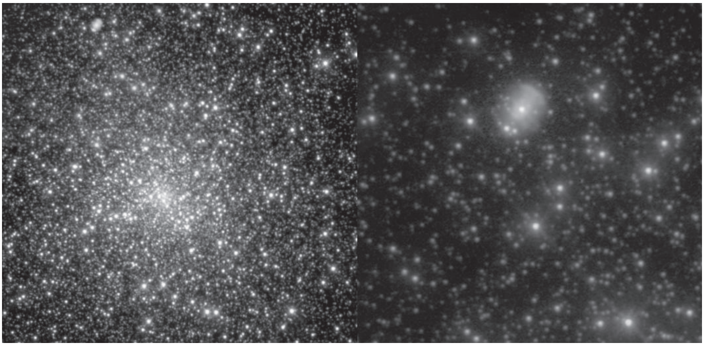

Figure 13-21. See Centrefold. An HST image of the globular cluster M15 is shown in the left panel. Notice the fuzzy orange tinted object in the upper left. This is the planetary nebula discovered by Pease in 1929 and shown in the right panel. The colour has been altered to show the image as it would appear to the naked eye. Credit: NASA/HST.

13.10.2 The cooling sequence and the age of the Universe

White dwarfs in globular clusters also provide limits to see how faint they are with respect to the main sequence. In Sirius B, the pup, is about 10 magnitudes fainter than its companion. What is it like for cooler parts of the main sequence? I confess to getting a little nervous here because these studies are not "my bag". I'm not doing a survey of the field but just trying to give you the reader a sense of it all. Out of the study of white dwarfs in globular clusters has come a measure of the age of the universe that I've mentioned before. As usual, a picture is worth a thousand words. Look at the lower main sequence of the globular cluster NGC 6397 in Figure 13-22. The data in the centre panel have been cleaned by removing all the stars that do not share the proper motion of the cluster—mull over the centre panel, look how tidy it is. These words stun me, because when I started my astronomical training, I was measuring proper motions from images taken 50 years apart—and that was hard going and thoughts of measuring the

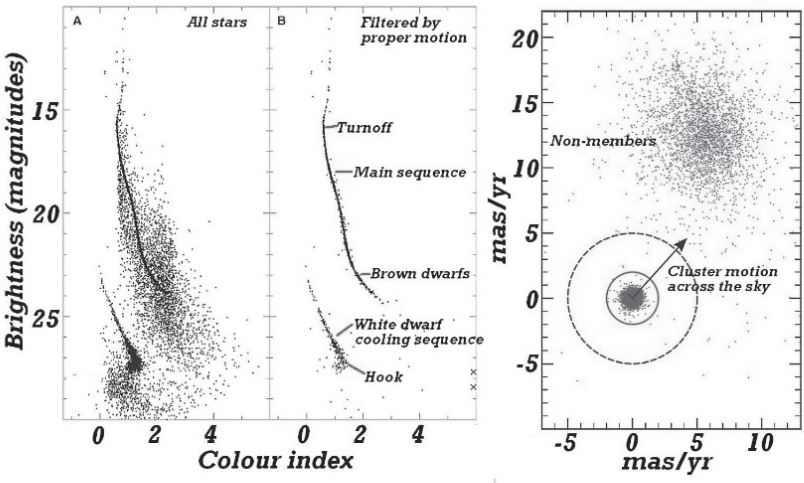

Figure 13-22. Left two panels showing the lower main sequence of the globular cluster NGC 6397. The leftmost panel shows measurements made of all the stars in the cluster field. The middle panel shows the data "cleaned" by the removal of all the interlopers. To my eye, this graph is a thing of beauty and I cannot honour the researchers enough for this work. Note the "hook" at the bottom of the white dwarf sequence. The right panel demonstrates how the data are cleaned by measuring the proper motions of all the stars in the field. Here mas/year refers to motion measured in thousandth of an arcsecond over one year. Credit: Left panels. Richer et al., 2008, AJ, 135,2141. Right panel. Heyl et al., 2012, ApJ, 761, 51.

proper motions of stars over the face of a globular cluster was beyond comprehension. But here it is, a powerful advance in the measurement of stellar positions, based entirely on digital technology and the HST providing sharp stellar images and therefore increased positional and photometric precision. Think about the labour involved here developing the software needed to measure, not only the positions but magnitudes from an automatic 3-D analysis of the images themselves. I admire the "geeks" in backrooms who do this stuff—I know some of them but won't mention their names. Given these data for every star that is measurable (some are too close together to be measured) from early and later HST material, gives the sideways motion in the sky for each star. No wonder astronomers are a little odd! Fortunately, once you can register separate images of the same field on top of each other, the proper motion measurements are easily made in the computer using someone's software—or your own if you are that way inclined, not that I'd recommend it, the labour is extraordinary—but worthwhile. That the method was successful can be seen by the lovely sequences of stars in the centre panel. The right panel of Figure 13-22 demonstrates the method of cleaning where you see a clear separation between the (non) cluster motion and the other stellar "contaminants". The main sequence appears to fizzle out opposite the top of the white dwarf sequence and indicates the limit of nuclear fusion. Below about 23th magnitude—check the left-hand scale—will be the region of brown dwarfs, the wannabe stars that couldn't.

As a newbie to all of this, it was with interest that I found another image that blew me away. Figure 13-23 is remarkable as it shows that, at least for the two clusters 47 Tucanae and NGC 6791, the white dwarf sequences overlap even though the main sequences are of different ages as can be seen in the turn-off points identified in the left panel. Even more, the differences in the region around the hook reflect the ages of the white dwarfs and hence the age of the cluster. Leading on from that, these clusters yield a lower limit to the age of the universe.

White dwarfs add an interesting twist to the debate on the age of the universe. One imagines as objects cool off that they would appear to move redward towards the cooler regions of the H-R diagram. Not so as theoretical calculations of a UCLA astronomer Hansen predicted. As you can see in the centre panel of Figures 13-22 and also in Figure 13-23, cooling white dwarfs ultimately form a sequence angling to the left in the lower part of the H-R diagram. These measures of the white dwarf cooling time predict very sweetly a lower limit to the age of the universe of 12 to 14 billion years. Therefore, any expansion age derived from the motions of the galaxies racing away from each other, must be larger than the ages of these globular clusters, the oldest stellar groupings in our galaxy.

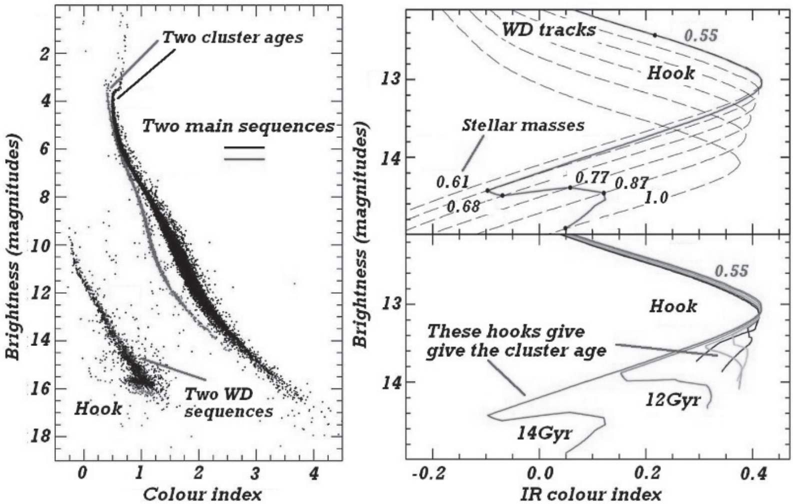

Figure 13-23. Left panel compares two globular clusters, 47 Tucanae (light) and NGC 6791 (black). Note the remarkable overlap in the two white dwarf sequences (WD) while the main sequences show marked differences and the turnoff points are quite different. At the bottom of the WD sequence is a feature I term the “HOOK". The right-hand panel shows a theoretical blow-up of this region to show that the extent of this hook is a measure of the age of the system. Credit: Left panel. Richer et al., 2013, ApJ, 778,104. Right panel. Bono et al., 2013, A&A, 549, 102.

It was a coup detecting white dwarfs in a globular cluster as they are very faint and extend down to the limit of detection of the HST (see previous Figure 13-20). This critical detection is the ultimate proof of the theory of the fate of our Sun and others. Details may be uncertain, such as the calculation of mass loss through the stellar wind at the red supergiant stage, or the slow shedding of the star's outer atmosphere as it forms a planetary nebula, but in a broad fashion, the theory is on a sound footing. Routinely, we’ve found white dwarfs in galactic clusters (Pleiades and Hyades for example) where the masses of the stars along the main sequence range upwards to about 3 $M_\odot$ and detect white dwarfs there, so mass loss is a fact. Let’s turn to the neutron stars.

13.11 Neutron stars and pulsars

The same arguments hold for neutron stars as were offered for the white dwarfs. They should be found in open and globular clusters. Having them discovered in the general field is hardly a proof, because, like the white dwarfs in the field of the Milky Way, there is no connection to other stars around them to put them in some sort of evolutionary context. There is little to show by way of images of pulsars but their pulses in the radio spectrum make them easy to detect. Pulsars are common in globular clusters. X-ray sources heralding neutron stars which abound also, see 47 Tucanae in Figure 13-24. Many pulsars, single and binary are found. One census, probably well out-of-date, in 47 Tucanae, finds that 68% of pulsars are binaries. From this one cluster we see ample proof of their presence in globular clusters.

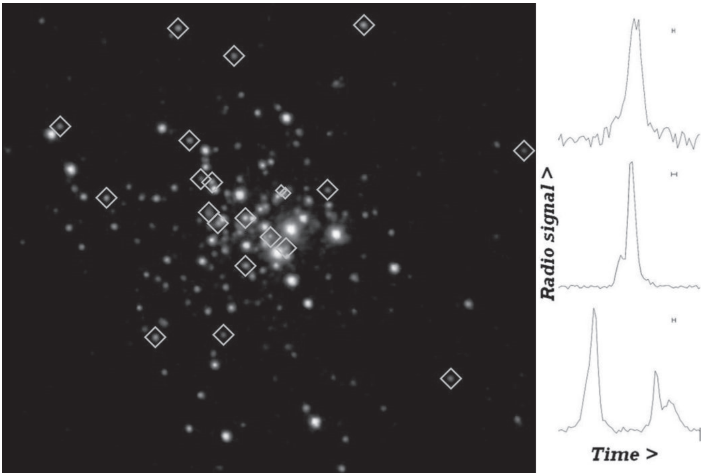

Figure 13-24. The left panel shows an X-ray image of the southern globular cluster 47 Tucanae with locations of some of the known pulsars indicated. The right panel shows what a few of the pulsar pulses look like over one cycle. Credit: Left panel. Chandra, NASA, edited by Heinke. Right panel. Freire et al., 2017, MNRAS, 471,857. Modified by the author.

As for pulsars in open clusters, that is more problematic because if there is any asymmetry in the supernova explosion then the remnant will experience a reactive force that may see the neutron star ejected from the cluster environs. There are neutron stars moving very fast and attempts are being made to project their passage backwards with the hope of finding their birthplace. The fact is, though, that I've not found a reference to neutron stars being in galactic clusters though there are many in the general field. There is no question that pulsars and hence neutron stars exist in globular clusters, therefore fulfilling the predictions of evolutionary theory.

13.12 Black holes

This has always been difficult for me, starting with the question my colleagues at the DAO tried to answer, “Is Cygnus X-1 a black hole?” It is, but it has taken many years to prove it. I’ve touched on the difficulty that those of us face who do traditional stellar astronomy involving photometry and spectroscopy when trying to unravel the mystery of Cygnus X-1. The spectral lines of only one star are seen, and, by definition, the black hole emits no light and we need the orbit from two sets of spectra to weigh the components. We have an oblate star, see next chapter, that produces light changes as it rotates, presenting different-sized cross-sections to us. There are no eclipses as we’ve seen earlier when discussing extrasolar planets. Therefore, there is no indication of the presence of a companion by these means and we’re stymied, although its oblateness, caused by rotation and the gravitational attraction of the unseen companion, offers a plan of attack. It turns out that the Cygnus X-1 black hole is about 15 $M_\odot$ and invisible. Perfect. When I say “invisible”, it’s not invisible at all because it was the X-ray emissions that brought this variable star to astronomer’s attention in the first place. The conclusion regarding the system came from other than the traditional means available in the 70s. There are several other stars that also fit the bill so I’m happy at last to shed my scepticism. Undoubtedly, a black hole is an endpoint of evolution for massive stars. The illustration, shown in Figure 13-25, is of an evolved star pressing hard at L1, the place of no return where the gravity of the black hole prevents the material from returning to the host star. As shown, this lost material will stream across the intervening space to orbit the black hole, forming what is called a **circumstellar disk** that will ultimately be absorbed by this invisible companion. The same situation occurs if replace the black hole with a star such as the fainter component (Algol B) to its more massive companion Algol A. Then the material orbits the star, in fact, this image is an archetypical representation of the evolution of a close binary system. Back to Cygnus X-1. The black hole was formed, we presume, from a supernova explosion, then why wasn’t the companion star obliterated also? We may not have the answer to this but there are many combinations of white dwarf—pulsar, pulsar—pulsar, pulsar—star, each involving supernovae, so whatever happens, there is a commonality about it. I’ll talk more about the evolution of binary stars in the following chapter. The image of the black hole illustrated here with its beam, follows what astronomers think about quasars, quasi-stellar objects that are found in the centres of what are called active galaxies and are seen at vast inter-galactic distances and are known to have beams. These beams have been inferred from X-ray studies of other black hole systems such as SS433 giving rise to the name **microquasars**. Cygnus X-1 is being studied by its X-ray emissions which adds another dimension in deriving its mass from details of the gas stream interacting with the circumstellar disk. Out of this work comes that extra bit of information that gives the mass of the unseen object, determining it to be a black hole. The list of X-ray emitting objects within binary systems is growing, making the subject which has always been difficult in a stellar context, more tractable.

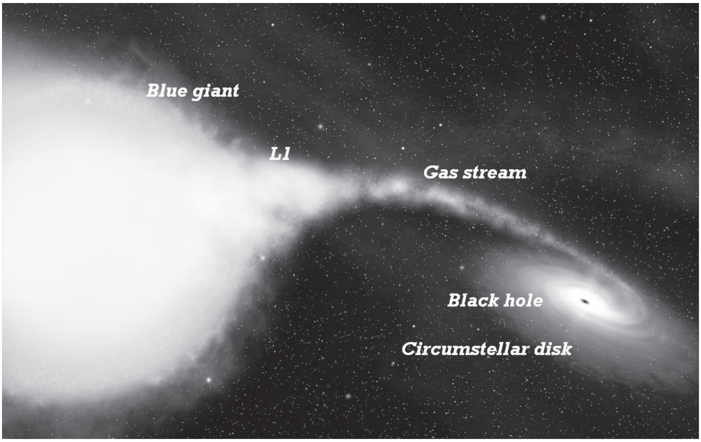

Figure 13-25. See Centrefold. An artist's impression of Cygnus X-1 comprising a bloated star that is losing mass through L1 to a black hole as it evolves. We are familiar with this scene as most stars grow in size as they evolve. It you look carefully you will see a beam coming from the black hole. Credit: NASA/ESA illustration. Notation by the author.

13.13 Summing up

In this chapter I've attempted to "prove it" but this is not like finding the villain and laying all doubt to rest. I can say though that I have no doubts. Some details may be sketchy but the science is moving forward on a sound foundation. This story is about a series of hypotheses each one leading to another and to another so that in the end they form a coherent whole. Yes, there are many holes in our understanding, or even in our ability to be able to do the calculations that we hope would lay another difficulty to rest, but the edifice is built on tying together observations within a framework of physics so that the end-result is satisfying. The science is built on small successes. I can recall the excitement of the astronomical community when the IUE went up into space and yielded the first observations of the core of a planetary nebula to prove the hypothesis that the central stars of these objects were very, very hot. Up to that point there were obviously very hot white stars at the heart of planetary nebulae but we had no way of measuring their temperatures. They were too difficult to observe spectroscopically and the photometric results (magnitudes and colours) were outside any calibration because all their energy was radiating in the ultra-violet. The observations were aimed at proving the central stars were white dwarfs getting hotter and hotter as they shed their atmospheres to reveal the core within. No, they were not heating up, just taking some clothes off. And so, it proved, the central star of a planetary nebula should be ***very*** hot and it was. They are. That then tied the previous stage of evolution to the red supergiant tip to mass loss as a very tenuous atmosphere was expelled by thermal pulses related to fusion occurring within the layered "bowels" of the star. These pulses produced the nebula and by their appearance we knew the approximate timescales of the expulsions. That led the theoreticians to model those losses and predict the masses of these stars and even work out what their masses might be prior to their march to becoming white dwarfs. So, we have white dwarfs. faint stars of unbelievable density and generally at the limit of detection, whether from space or on Earth, whose observation leads to the determination of the age of the universe in happy accord with an age derived from the observations of microwaves from space.

The process we follow is straightforward. If your theory is wrong, then have another try. Make changes. To a cynical appraiser of this research, it might mean trying to shoehorn your data into a theory you don't believe in, and not doing as I've said—propose a theory, make predictions and then verify it. If that fails, try another angle. Ptolemy tried to shoehorn his geocentric cosmology to fit a simpler heliocentric cosmology. How many of us have arrived in a strange city and even with our GPS, made errors and then corrected them?

Through the second half of the 20th century, astronomy has moved from a horse and buggy world to that of Ferraris. Once we were bound to the Earth, now space offers us unimaginable opportunities—I suspect, too much for us to digest. Since graduate school, I've lived long enough to see how these building blocks, the white dwarfs, pulsars, planetary nebulae, have completed a building. Some of the walls may be ragged, but the foundation of the structure is sound. I’m very happy with what I see.

CHAPTER 14

AND SO THEY CAME, TWO BY TWO

14.1 Binary star evolution: The Roche model

There are two wonderful examples that set the scene for this discussion. I've talked about both systems before. Sirius and its white dwarf companion, and Algol, an eclipsing binary with evolution pushing one component hard against the inner Lagrangian point L1. Sorry about "Lagrangian" but to refresh your memory have a look at Figure 1-4 at the start of the book, or the illustration in Figure 13-25. In contrast, there is Sirius A, a 2 $M_\odot$ main-sequence star which has yet to evolve, with its white dwarf companion. This companion has undergone its evolution and will slowly cool down over the billions of years left to it. The white dwarf must have started out as a more massive star, otherwise there'd be just two main sequence objects in the system, which emphasises the fact that Sirius B must have lost mass to become a white dwarf otherwise it would have become a supernova. Another quite different example of a binary system in the form of a stellar dumbbell was displayed earlier in Figure 7-13. So, we have pairs of spherical stars, systems where one component is definitely not spherical, and others where both components are not spherical, giving astrophysicists enough variation to test any evolutionary scheme.

When discussing the evolution of binary stars, we are looking at various systems—I've mentioned three of them in the previous paragraph—and try to work out how evolution got them to what we see today. It is an interesting challenge, because, unlike the evolution of single stars, we don't have the simplifying circumstance that clusters of stars bring to the problem. In a binary system we have a light curve, which we can generally solve for inclination and relative radii and a spectroscopic orbit that we hope will yield masses. In the past, because of the huge disparity in brightness between the two components in an Algol system, it was not possible to measure their masses because one spectrum, that of the cool star, was unseen. But mathematical techniques stretching back to the time of Fourier miraculously give us a view of the faint secondary spectrum and with that, the ability to measure its orbital velocities and so get a complete orbit. The dumbbell-shaped systems provide a different problem but again new mathematical techniques render what only yielded crude results in yesteryear now give much better results. Thus, we start the process of discovery with masses, radii, separation between the components and the orbital period. In coming to grips with the evolution, we must consider what happens when one of the component stars evolves and encounters the Lagrangian point L1. The trailblazer of this type of analysis, Mirec Plavec, was at the DAO at the time he was exploring this type of analysis and it was with great interest that John Hutchings and I used the results of his extensive calculations to determine the progenitors of the Algol system.

In discussing binary systems, it is useful to consider three situations first defined by Kopal in his book, Close Binary Systems, about sixty years ago. This book was my bible when I first started studying the mathematics behind the eclipse geometry and stellar shapes so I could begin to model them to replicate the eclipses—solve them if you wish. The situation is best described by a diagram (see Figure 14-1). Kopal's classification system makes sense of all the varied eclipsing binary light curves, just as the H-R diagram gives a framework for the study of stellar evolution. These classifications are displayed in Figure 14-2.

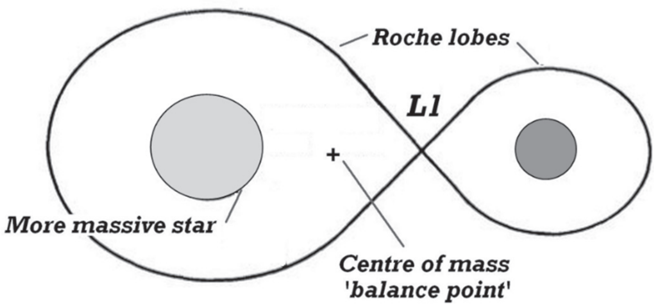

Figure 14-1. A schematic illustrating the Roche-lobe geometry. Shown is a cross section of the unique surface that shows the realm where each star's gravity holds sway. These realms form lobes which make contact at a junction (L1, see Figure 1-4) along the line joining the centres of the two binary components. Credit: By the author.

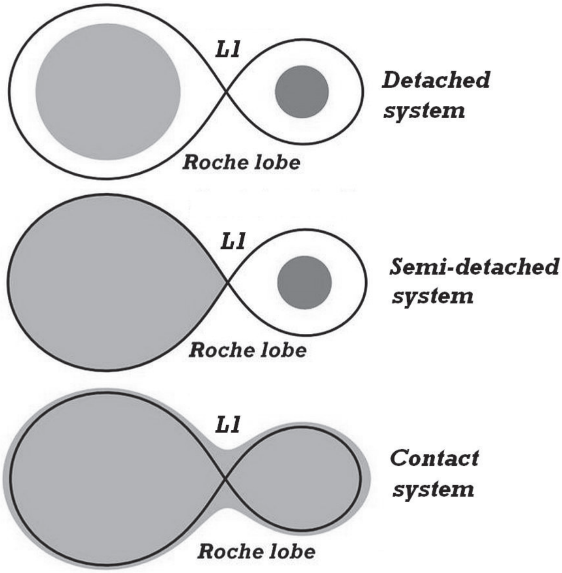

Figure 14-2. The three situations involving Roche geometry that are used to describe the many types of binaries we observe. Increasing interaction with the gravitational balance point between two stars (L1), brings more complex light curves and spectra. Credit: Wikimedia Creative Commons/Hall. Modified by the author.

Detached systems. These are stars we see whose radii are within those lobes and they remain detached until one evolves into the Roche "barrier". A wonderful example of a detached light curve was shown earlier for the Cepheid binary in Figures 13-11 and 13-12.

Semi-detached systems. When one star evolves and fills one of these lobes then the binary configuration is like the illustration of Cygnus X-1 (Figure 13-25), producing an Algol-type light curve seen earlier in Figure 7-12. Matter then leaves the evolving star and is captured by its companion. Much of what I'll talk about in this chapter involves this scenario.

Contact systems. In this case both stars evolve to fill their respective lobes, see the light curve displayed in Figure 7-13 earlier. With such characteristic light curves these stars are easy to identify and, given a large enough telescope, their spectroscopic orbits are easy to determine, leading to a ready database of fundamental data for them, such as masses, radii and temperatures.

In summary, the factors governing the evolution of binary systems are: the Roche lobe, and what happens when the evolving star pushes against it. Let's look at these three types of binary stars which result in distinctly different light curves and figure out how to work backwards from what we see now to what they were when they started their lives.

14.2 Modelling a binary system: Getting started

Whenever we look at a binary system that is not detached, it has already evolved, so you can see the difficulty here. You may see where a car has finally been parked, but where did it come from? The observed light curves reflect two stars of differing masses, but not necessarily the masses they started their life with. "Where ***do*** you start?" They are linked together, so how far apart do you place them before you start their individual evolution. Then you have that pesky critical gravitational boundary between the two stars. Evolution proceeds, and we know how that works for independent stars. One thing is known for sure, if the separation between the two stars is less than 10 or so solar radii—remember a red giant is 100 solar radii—then ultimately one star will reach the edge of its Roche lobe and then we'll have mass loss to the other star. We've seen this process displayed in the Cygnus X-1 illustration (Figure 13-25). How, in the real world, do we model a stream of gas going from the evolving star and into orbit around the other star to become part of the orbiting circumstellar disk, ultimately to be absorbed by the star as additional mass? If you decided that modelling this hydrodynamic problem should be solved before doing anything else, we'd be still agonising over it and ignoring the possibility of making progress by taking an expedient approach.

To deal with this mass exchange business, what say we remove a small amount of mass from the evolving star and add it to the other? Assuming our models shake themselves and stabilise after these unexpected intrusions and keep on going (evolving), there is our mass loss for one star and an equal mass gain for the other. Now, continue to evolve the models. Is it at all realistic? Who cares? Let's see where it takes us, after all the essence of understanding how a pulsar works was worked out on the back of an envelope! Given that the models can handle the mass loss and mass gain, then how ***do*** we start? The problem involves nothing but variables—the two masses and their separation. But we know a little more. From our photometric and spectroscopic analysis of the system we have measured the individual masses, the period, and the separation between the two stars. So, rather than being faced with a blank page with which to investigate our binary's evolution we know the sum of the masses—assumed to be what the system had at the beginning of its evolution. This circumstance confines the range of possibilities. I can almost hear your question. "Does this mean that the sum of the masses you end up with is the same as what you started with?" Sigh… For a first go around the answer is, ***Ye*s**. But once the researchers gained confidence that this approach gave realistic answers, then this restriction was relaxed. ***No***, I believe the systems do lose mass. Back to the story.

Provided the masses add up to what was observed, any values can be chosen. The only way to proceed is on many fronts at once. Assuming a range of separations between the stars and Newton's law of binary motion relating the masses and separation gives the period! Or, given the sum of the masses and the period, enables the orbit size to be used as a variable. There are two guesses you need to make, the individual masses and the starting separation that kick off your evolutionary calculations. Knowing these values, the period can be computed from Newton's laws governing binary motion. When this was done fifty years ago, it tested the computers because of the number of evolutionary models that had to be computed. Some models went nowhere and were abandoned. More promising ones were computed to their end. The stars we're looking at have evolved as binaries, we know their masses, but don't know how they got there. Sounds like a Jason Bourne movie doesn't it? We're looking at the endpoints of evolution over many years and need to limit our options, otherwise the computations could go on forever. There are too many unknowns. But there is hope. How evolution proceeds in a binary system depends what is going on in the evolving star when the Roche limit is encountered. Is it burning hydrogen in its core or in a shell? Furthermore, calculations show that it is possible to have more than one episode of evolutionary mass transfer exchange. There are enough variables here to guarantee that there will be no simple evolutionary picture that can explain the variety of binary stars we see. The modelling is demanding, because how a system evolves involves the continued recalculating of stellar evolutionary models as mass is lost and gained during the various interactions. There are other possibilities such that the system overall is losing mass.

From the foregoing you'll see that I can't hope to cover all the varied possibilities, nor shall I try, otherwise the book will be describing a room full of people and not giving an overview of the scene as a whole. I'll track the evolution using a few examples.

14.3 Detached systems

Even though a system is detached now, it doesn't mean that it will ***always*** be that way, it depends on how separated the component stars are. But there will have been evolution in most detached systems and, where identified as significant, could be treated simply with the type of model-building we've employed earlier for clusters of stars, only in this case it would be a "cluster" of two! Whereas a cluster is assumed to have been formed at the same time (coeval star formation), we've already seen in Figure 10-2 that stars like the Sun take about 50 Myr to condense out of the interstellar medium whereas more massive stars collapse and form in a few millions of years or less. Thus, for young clusters a few millions of years old we'd expect to see evidence for this disparity in collapse time, and we do, as shown earlier in Figure 10-3. For binary stars then, there is no such concern, they both form out of the spinning cloud or they don't form at all. This makes them useful for study in evolutionary terms because we know the masses of each component and we know that mass is the primary driver of stellar evolution. Earlier, I showed results for a series of eclipsing binaries (Figures 13-17 and 13-18) showing how the component stars lie, within the errors, on the same evolutionary timeline (an isochrone—line of equal age) as a proof of stellar evolution. The same proof—not shown—has been used for Cepheids in detached binary systems in the LMC, e.g. the OGLE variables LMC-CEP0227 and LMC-CEP1812 (see Figures 13-11, 13-12 and 13-13). A similar set of detached binaries containing at least one RR Lyrae star must exist in the OGLE database of more than 40,000 of these variables. In fact there must be hordes of detached binary RR Lyrae stars and Cepheids.

Sirius is a perfect example of a detached system. It is a system where both stars are now evolving without influencing each other. In this case, there will never be a physical interaction outside of a supernova because the separation between the stars is about 20 AU, a distance nigh out to the orbit of Uranus, whereas the largest red supergiants may reach radii of "only" 4-5 AU. On this basis there is no chance that Sirius A will grow to engulf its companion. What we see now has essentially been the evolution of two stars linked gravitationally but evolving totally independently. Let's have a closer look at Sirius. We know that evolution takes place independently between the two components, so how come the white dwarf has already evolved and is now at the end of its life? What happened? The white dwarf component started life as the more massive star, evolving through the red giant phase, through the Cepheid loop and then moved up the asymptotic giant branch becoming a bloated, red supergiant. It lost mass by expelling its outer atmosphere as it compacted, gaining temperature by shedding its clothes—

its outer layers—as the core slowly became exposed through the planetary nebula stage, leaving a nude, very hot white dwarf core. Which is what we see now.

Interestingly, there is a mystery about the system originating from Roman times.

14.3.1 A brief aside: Red Sirius

In about 150 CE, Ptolemy described Sirius as "red" along with other obviously red stars such as Betelgeuse, which is 30 degrees north in the nearby constellation, Orion. The reason for the "uproar" is that, as a main-sequence object, Sirius has never evolved to become a red giant. But, aside from the Sun, it is the brightest star in the sky, so it is hard to imagine an error. There is a whole discussion of this in the literature; enter "**Red Sirius**" into your browser and look through the responses. It is an interesting mystery. Before I reviewed the material, my take on it was to note that Sirius is seen far to the south from the Mediterranean and its colour does depend on ***where*** it was observed. Was the viewer seeing it standing proudly in the sky or low down on the horizon? I've had plenty of phone calls on public nights at the observatory where people were concerned about a coloured object dancing around on the horizon. They were viewing a star through the prism of the atmosphere refracting the starlight into many colours and it was suffering the effects of seeing. Back to the story. But Sirius A is white and evolving slowly, while the pup has taken hundreds of thousands of years to become a white dwarf after it went through the red supergiant phase of its evolution; there are no remnants from its being a planetary nebula. As I commented earlier when discussing the Leonid meteor shower (see Figure 1-15), people who had never witnessed that extraordinary event might accuse those who recounted the experience as being fanciful. My comment is that everything that has been recorded in the past, which appears fanciful to us, may, in fact, be real. I'd like to think that the evolutionary pathway from planetary nebula to an exposed white dwarf might yet hold some surprises. For me, the observation stands, strange as it is. Now onto the semi-detached and contact systems.

14.4 Back to detached systems

The detached systems are what give us the simplest solutions to the light curves and the measurement of radial velocities. As the stars get closer to the Roche lobe you can see from Figure 14-2 that the stars will no longer be spherical. This results from a combination of rotation, and the gravitational attraction of the companion distorting the shapes of both stars, makes modelling a little more complex. An extreme example a star's distortion was shown earlier (Figure 10-10) where Achernar's shape was measured by interferometric means to reveal a flattened system caused by extreme rotation.

Detached systems have particularly straightforward light curves because the stars are far enough apart so there is little physical interaction between them. But if the stars were closer, what might this interaction be? From the Roche diagram we know about the gravitational distortion, just as we know that the Moon lifts the surface of the Earth, as it passes over us. I'm ignoring of course the Moon-driven tides we're all familiar with. Any gravitational distortion produces a change in the light curve outside of eclipse because the distorted star will produce a varying cross-section to an observer and hence a changing light curve. The next effect is that of heating. A very hot star's radiation pouring down onto a cooler companion will produce a heating effect such that the cool star's surface will present a heated face to us at times in its orbit. An example was shown for Algol (Figure 7-12). In a detached system, these effects are minimized so that when photometric or spectroscopic data are presented for any detached system it is readily analysed and tested against evolutionary models as I showed in the previous chapter for the even more complex situation regarding a Cepheid.

Let's turn now to situations where there ***is*** interaction.

14.5 Semi-detached systems

I'll talk about Algol, as this is the archetype for a semi-detached system and the first system Hutchings and I analysed with our computer program. We have a cooler and less massive companion hard up against the Roche critical boundary losing mass to its more massive companion. It started life as the more massive star with its expansion limited by the Roche boundary. With nowhere to go it then lost material to the companion through L1. With the changing mass, the critical boundary moved even closer to the mass-losing star, only exacerbating its problem. What happened then depends on how much mass the "loser" had lost and therefore which of its innards had been lost. Is hydrogen flowing between the stars or is the mass loss affecting a helium rich atmosphere? I'm not following such variations as it will lead me down yet another rabbit-hole and we'll all get confused by the details and various alternatives. When the mass-loser reaches the red giant phase of evolution where things happen "quickly", mass transfer speeds up and the masses of the two stars have reversed. Check the timescale in the left panel of Figure 14-3. What might have started out as a system starting life as a pair of stars of 1.5 $M_\odot$ and 2.5 $M_\odot$ are now of masses 3.3 $M_\odot$ and 0.7 $M_\odot$. The system will look very much like Algol we now observe where the less massive star is still hard up against the Roche lobe and is trickling mass onto its companion. In time, the more massive star will evolve into contact also unless the system loses mass as a whole—yet another free parameter to play with. What happens after this depends on the evolutionary state of the mass losing star. Is it burning hydrogen in its core? This is Case A. Is there a shell of fusing hydrogen? Is the helium-core burning and the star is in the Cepheid loop? This is Case B. Is the star near the top of the asymptotic giant

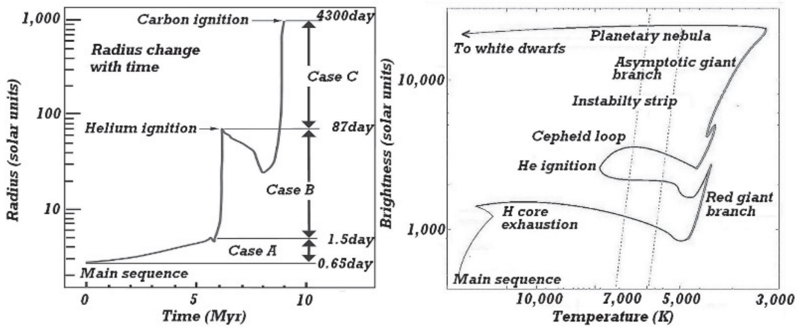

Figure 14-3. Left panel shows the relationship between radius and age for an evolving 5 $M_\odot$ star. Also displayed are the timelines governing the definitions of mass transfer for Cases A, B and C. The right panel shows these cases in terms of the H-R diagram. Notice how big the star is when carbon ignites. One thousand solar radii is the distance from the Sun to Jupiter. Credit: Left panel. Paczynski and Podsiadlowski, 1969, A&SS, 3, 14. Right panel. Wikimedia Commons Contributors/Lithopsian. Annotated by the author.

branch (AGB) and carbon is burning? This is Case C. These options are shown in Figure 14-3 though the boundaries or definitions of the transitions, particularly between Case A and Case B, are often blurred.

How evolution proceeds, depends on the total mass of the system which, through Newton's laws of gravitation, in turn depends on the orbital period and the separation of the two stars at "birth". Applying Newton's law of gravitation for a range of masses we find that in systems with short periods, say less than 3 days, the primary will encounter the Roche limit while evolving across towards the red giant phase. For short periods, Case A applies. Case B is defined for longer periods from 3 days out to some 100 days. In this case the Roche limit may be encountered when the star is ascending the red giant branch and things are happening quickly. For initial periods longer than 100 days the stars may evolve separately and we are in the case C situation even though the stars may be enormous. These are almost arbitrary limits based on the sum of the initial masses of the stars forming the system. Because of this, the modellers run grids of many evolutionary scenarios covering a range of stellar masses and periods that may encompass the task in hand, which is trying to interpret a group of binaries that exhibit the same characteristics. Most of the calculations are aimed at specific stars within an identifiable group such as Algol systems or pulsar and white dwarf binaries. I'm not going to refer to these three options again but they may prove useful if you roam around in the Internet where an amazing amount of material is found. With a bit of sleuthing, the original journal articles are available, or you can use the references cited in some figures as a kick-off point.

14.5.1 A confession

I'm already tired of talking about these infinite possibilities. Now, for a confession. I've reviewed what I've said and begun this section several time and have been unhappy with all the versions. The stories have ended up stultifying me and would surely similarly affect you, the reader! This is my best shot without the "what ifs" leading to more words, but at the end of it all, the many evolutionary variations will lead to pairs of stellar combinations involving a white dwarf, a pulsar, a black hole and perhaps a brown dwarf. But you can be sure that the discussion will be short. Parts of it are interesting, particularly the pulsars, because that is where the full force of astronomy and astrophysics can be applied in trying to explain what these weird things are like. For them, along with black holes, data are combined from many sources: X-ray, radio, optical and on the horizon—gravitational waves—which development excites me. I told you astronomers are weird.

14.6 Contact systems (W UMa binaries)

As we already know, if the stars are massive whatever happens will happen quickly and there is also the possibility of a supernova tossed into the mix. For stars around the Sun's mass the process will be long. In all cases the most-massive star of a pair will evolve faster than its companion until it reaches the Roche lobe. There, it loses mass to the other star shown previously in Figure 13-25. The companion star absorbs this new material and with its increased mass will evolve faster than it had been. Maybe it will evolve so that it too reaches the Roche lobe leading to a **contact binary** or what are called **W UMa binaries** named after the first of these variables discovered. as shown in Figures 7-13 and 14-4, with the overflowing mass from both stars spilling out of the gravitationally bounded lobes to surround the system, held in place by each star's gravity. The gas there will be held tenuously because the rotational forces from these stars which revolve in under a day will disrupt gravity's grip and so the stars will leave a spiralling trail of ejected material as they move through space. The light curves of these systems are readily identifiable (see Figure 7-13 shown earlier) and easy to solve when they are uncomplicated, though often the light curves are asymmetric and present problems of analysis, undoubtedly related to us viewing such a system through veiling blobs of surrounding gas.

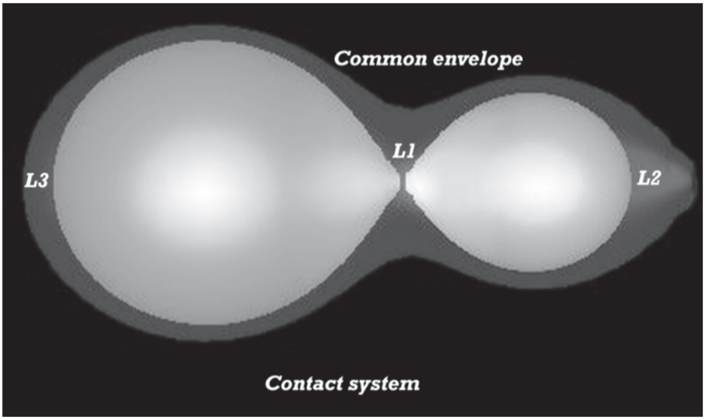

Figure 14-4. An impression of a contact system where stars have evolved into contact at L1. Continued evolution produces a common envelope of gas which is lost to the system because of its rapid rotation. Credit: Image created with Mathematica—Wolfram Demonstrations Project/Dutton (Penn. State). Annotated by the author.

14.7 End-of-life variations

If initial evolution does not take the mass gainer to the Roche limit, then what? The mass loser transfers its envelope onto the companion and ends up as a white dwarf. The situation may not end there because the mass gainer is evolving and may reach the Roche limit and start spilling material back onto the white dwarf. (dog-eats-dog-eats-dog) which, if still receiving mass, will either tip it over the 1.4 $M_{\odot}$ limit creating a Type Ia supernova, differing in appearance from that resulting from a single star's evolution. ***This is a***

critical happening for cosmology. These are the supernovae used to extend the distance scale beyond the Cepheids because of their amazing brightness and they erupt to similar absolute magnitudes. The reason they all erupt to the same absolute magnitude is because of the 1.4 $M_\odot$ limit. Not 5 $M_\odot$ or 3 $M_\odot$ but 1.4 $M_\odot$. Because of the stricture of this mass limit, the brightness achieved in an eruption is likely to be consistent between similar systems. If its mass is less than this critical limit the infalling material reaches the surface of the star and if it is hot enough, and we know that the surfaces of white dwarfs at the start of their cooling phase are searing hot with temperatures in the millions of degrees—remember they are the exposed cores of stars. Given this circumstance, the hydrogen fuel falling onto the star begins to fuse which we will see as a burst of light. This process is repeated over months or years as the accumulating material again reaches a critical point and erupts again as a cataclysmic variable (originally called a Nova or new star). There is also a "spin-up" effect as the material falling onto the mass-gainer will spin up the other star. These are complications that I'm avoiding now. All the while the mass loser is evolving, ending up as a white dwarf itself or a neutron star. Which leads to the prediction that there should be many white dwarf pairs, neutron star pairs, or white dwarf—neutron star pairs. All have been observed.

Consider the pairs just mentioned. These orbiting compact objects cyclically bend space around them, resulting in the production of gravitational waves which, in turn, suck energy out of the system causing the stars to move in an ever-tightening inward spiral. Inevitably, they will coalesce or merge. We detect these mergers. Now that there is a gamma ray observatory in space that can detect the most energetic of explosions, perhaps resulting from the ultimate merging of these compact objects, we've gained another window on the universe. Massive explosions are being detected now, but what caused them if no rise of a supernova is concurrently observed? What happens in the radio or X-ray domain? Given combinations of these data, then the theoreticians come into their own by researching questions such as, "What can we expect when white dwarfs merge? What about combinations of neutron and white dwarf stars?" Ultimately though, when a system forms a pair of compact objects, it will affect the larger world we all exist within and they'll radiate away their orbital energy as gravitational waves. In time, they will coalesce and then erupt as a new type of supernova. An image from the Chandra X-ray Observatory is shown in Figure 14-5 showing regular X-ray pulses presumed to be from a pair of orbiting white dwarfs which in turn radiate gravitational waves.

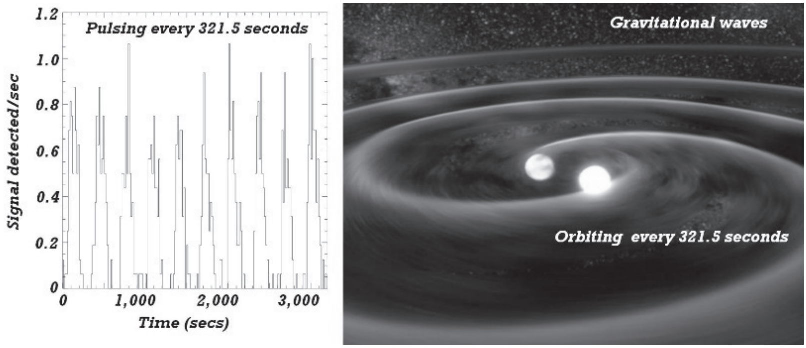

Figure 14-5. Left panel showing X-ray pulses from a source thought to be two white dwarfs in orbit (right panel). Because of their incredible density they will radiate gravitational waves as they orbit. Credit: Left panel. Light curve: Strohmayer, 2005, AAS, 37, 792. Right panel. NASA/CXC/GSFC/Illustration: GSFC/Berry. Annotations by the author.

14.8 Detecting neutron stars in orbit

Years ago, it was thought that it would be unlikely to find a neutron star in an orbit as it was imagined that any gravitational connection would be sundered in the extraordinary explosion which is a supernova. Not true, as Hulse and Taylor found in their ground-breaking discovery of a pulsar binary (Figure 12-6). But how do we know that a neutron star is in a binary system? In a pulsar or a neutron star we can either see its light pulses or detect its radio pulses or perhaps detect its pulses in the X-ray domain from an X-ray observatory in space. In a binary system the pulse's timing changes because the star is sometimes coming towards us and later in the cycle it is moving away. A spinning pulsar is the best clock in the universe and any orbital motion is reflected in the timings as the frequency of the pulses stretch out as the pulsar moves away and compress as it approaches—think of sitting at a railway crossing listening to the pitch of a train's whistle increasing as it approaches and decreasing as it recedes. The quality of the data is wonderful as you can see in the earlier diagram Figure 12-6, where data from the first pulsar binary are displayed. As mentioned earlier, getting an orbit in this way is not new, the archetypical eclipsing binary Algol is really a triple system and the early astronomers used a similar analysis but used eclipse timings as clocks to conclude that the variations seen in them were caused by the eclipsing pairs motion around a third body. In stellar astronomy it is called the light-time effect—remember Roemer in 1676. Getting the orbit of a pulsar is wonderful compared to using eclipse timings simply because of the quality of the data. There is no noise (uncertainty) in the pulse timings—or at least at the level I'm used to!

Since the initial discovery of binary pulsars radio astronomers and, latterly, the growing X-ray community, are having a field day detecting the combinations I've mentioned: white dwarf-white dwarf, pulsar-white dwarf, pulsar-pulsar, white dwarf-ordinary star and pulsar-ordinary star combinations. All of these combinations noted above produce relativistic effect such as orbit decay noted in Figure 14-5 and with this development comes the unexpected—at least for me—the possibility of measuring stellar masses with unprecedented accuracy, even in the absence of knowledge of orbital inclination which always bedevils those of us who observe binaries. After the comment on **periastron** we'll look at this different way of measuring stellar masses.

14.8.1 A comment on periastron

Periastron is when two orbiting celestial objects are closest to each other, whether in binary stars, or in the Earth's motion around the Sun. For us, periastron is in January, and, incidentally, this is not the reason why it is hot in the southern hemisphere in January. We get a "super moon" when the Moon is at periastron and brought even closer at times because of the Sun's effect on its and the Earth's orbit. In the following discussion I'll be talking about how this time of periastron passage changes with time and it can be illustrated by tossing a marble into a large bowl. You'll see the high point of the marble's rotation moving around the bowl. That changing high point can be called the advance of periastron referred to in the stars. When we measure this effect in normal binaries, we call it **apsidal motio**n, but it is nowhere near as pronounced as is seen in the remnant binaries being discussed here.

14.8.2 The advance of periastron and gravitational waves

A good example as to where I'm going with this discussion is a pulsar with the name PSR1913+16, where PS stands for pulsar, the R for radio, and 1913 the position in the sky in longitude 19 hours and 13 minutes. The +16 is its latitude in celestial coordinates—remember the Earth is tilted by 23 degrees so latitude and longitude do not simply correlate with the coordinate system of the Earth. This binary has been observed over 30 years, long enough for astronomers to notice its changing orbit. Notably, because the time of closest approach, periastron, has been systematically changing (see Figure 14-6). It was quickly realised that these changes in periastron passage, first noted in ongoing observations of the "Hulse and Taylor's pulsar", were caused by the generation of gravitational waves that removed energy from the system. This energy loss is systematically altering the orbit in such a way as to ultimately bring the two objects into contact and to another stupendous explosion giving more material for the gamma ray and X-ray observers to drool over! At the time this result was announced, it was the only observational evidence that gravitational waves existed. Now that gravitational detectors feel the shudder of space, we have a more direct verification of their existence.

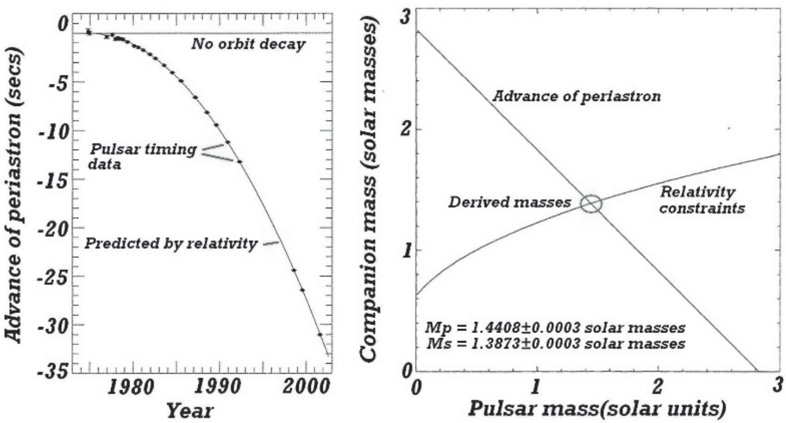

Figure 14-6. Left panel show how the time of periastron is advancing. The line is a prediction from the theory of relativity. The match between data and theory is unreal. The right panel shows how a combination of the observed orbit, the advance of periastron, and other relativistic constraints predicts the mass of each component with unprecedented accuracy. Credit: Weisberg and Taylor, 2003, ASP Conference Series, 302. 93. Annotations by the author.

The results of these observations and relativistic predictions are seen in Figure 14-6. I'm now out of my comfort range here as I point you to the right panel of this figure. It is here where relativity again provides information that enables the masses of the components to be measured. The authors of this work state that uncertainties in the data are within the thickness of the lines in the graph! There are two lines in the diagram based on Keplerian information—the observed orbit of the star—and relativistic data based on the rate of periastron advance, that provide constraints on the masses of the stars. Where the lines cross gives the individual masses. You can see that the masses have been determined with unbelievable accuracy! It's quite amazing for me to see this, as the best measure of mass among normal binary stars is only accurate to about 5%. Similar advances in perihelion are detected in other binary pulsars, all implying the existence of gravitational waves. The detection of gravitational waves in 2015 has confirmed all of this. We turn again to neutron stars and black holes.

14.8.3 Compact binaries. The detection of gravitational waves

To interpret gravitational waves, the theoreticians must have developed theories based on the merging of black holes and neutron stars as the only scenarios capable of shaking the fabric of our universe. Model results are displayed in Figure 14-7.

Notice the extraordinary speeds that the orbiting stars attain, amounting to a significant fraction of the speed of light, before they go off-scale in the moments before they coalesce and shake the universe. Now that this remarkable detection has been made, and was so long sought, the scientists have a completely new way of exploring the universe outside the electromagnetic spectrum. See the discovery records in Figure 1-13. These are exciting times for astronomers. The results presented here come from theoreticians in this field modelling the expanding database of detections now available after four years of observing. Some data are displayed in Figure 14-8 which will be modelled according to the appearance and amplitudes of the signature chirps (see Figure 1-13 earlier) and more are available up to June of 2019. Looking at this figure you can see that the signature of the merger of two black holes in the upper two panels is significantly different from that of a neutron star merger shown in the lower one. Like many things, getting the first result seems superhuman, but after the initial mountain is surmounted later it becomes routine—I guess the mountain imagery makes me think of Everest and the queues awaiting a successful ascent. These events lead to masses of the individual components being computed; the details can be found in lists of these detections found in the LIGO and Virgo websites. Figure 14-9 shows the masses of black holes derived from gravitational wave detections and X-ray binary observations and start to resolve the question I raised earlier about not knowing the boundaries between the formation of a neutron star and a black hole. Using the scale for masses given in Figure 14-9 (I love the title!) you can judge that the minimum masses predicted from the modelling are about 5 $M_\odot$. But the data as presented leave one wondering about the gap between the measured masses of the neutron stars that lie entirely below ~3 $M_\odot$ and the black hole masses that lie above 5 $M_\odot$. These discoveries show that black holes are real among the stellar population, not that we've been able to detect many in the optical region of the electromagnetic spectrum.

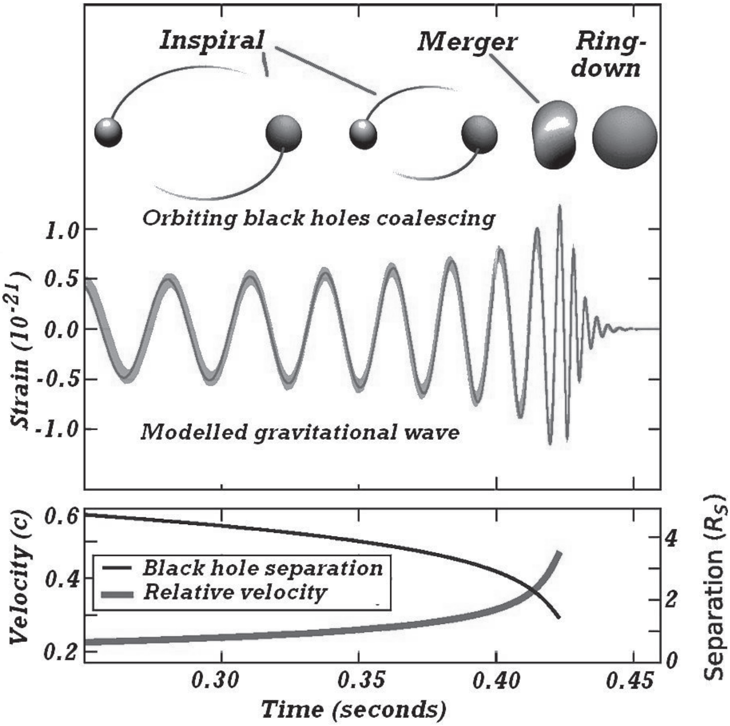

Figure 14-7. Shows the merging model developed to interpret the catastrophic event leading to the production of gravitational waves. Check the scale on the lower panel which shows the relative orbital velocity between the black holes as a fraction of the speed of light before going "off-scale" after 0.4 seconds. The separation ("strain") is in some undefinable unit—at least for me! Credit: **LIGO/Virgo**. Modified by the author.

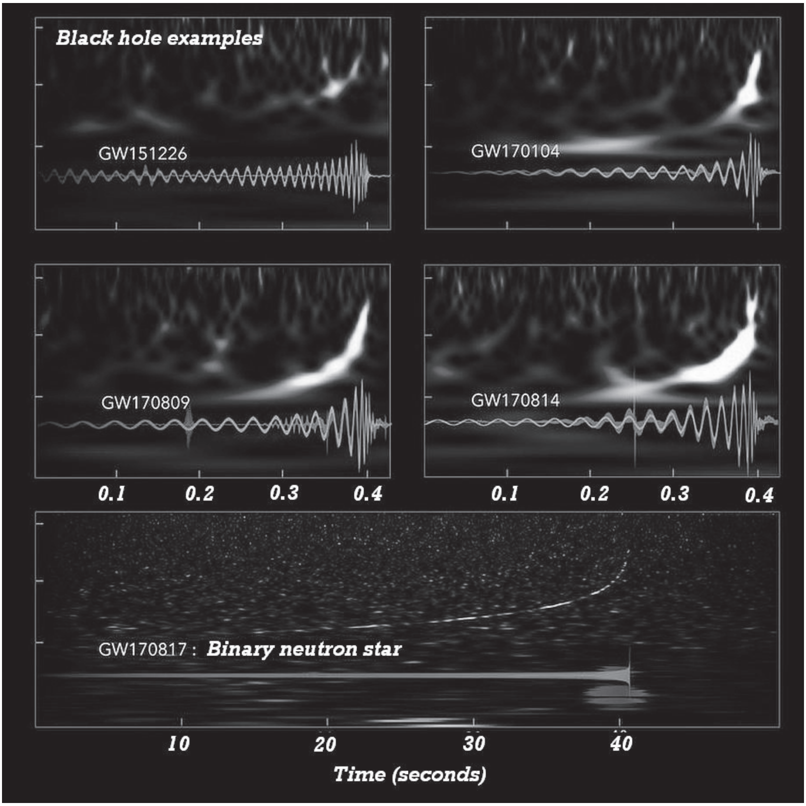

Figure 14-8. See Centrefold. Shows a series of gravitational wave detections interpreted and modelled in the context of mergers within black hole and neutron star binaries. The difference between the two types of mergers is dramatic where we see a long leadup to neutron stars merging, in contrast to the merging of two black holes. Among the black hole traces—the wiggly line—we see marked differences undoubtedly providing necessary data for theoreticians to determine individual masses for the merging objects. Credit: Wikimedia Creative Commons. LIGO Scientific Collaboration and Virgo Collaboration/Ghonge and Jani (Georgia Tech.). Modified by the author.

To sum up, neutron stars are regularly discovered in the radio domain and we know that they produce gravitational waves as they orbit one another. This leads to the hypothesis that this loss of energy will affect the orbit, sucking energy from it, ultimately leading to a collision that annihilates the two stars, which is exactly what we see in the GW and X-ray observations. For those who predicted this scenario years ago, the discovery of gravitational wave must be a great source of satisfaction and it also buttresses the notion that we know what is going on in stellar evolution.

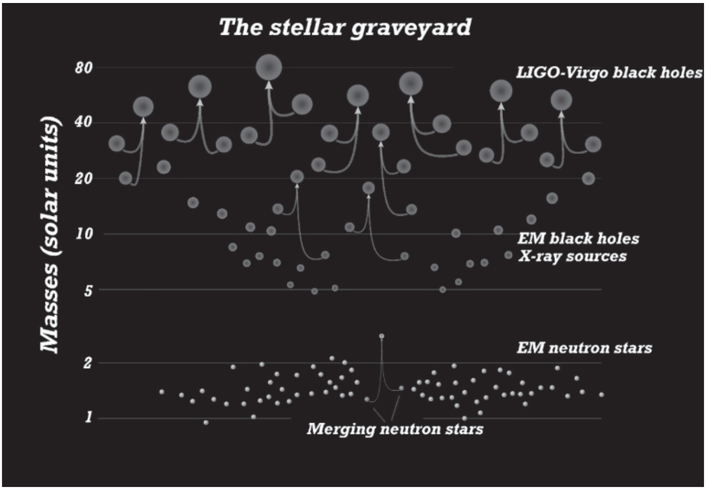

Figure 14-9. See Centrefold. The commentary comes from the LIGO/Virgo website. "This graphic shows the masses for black holes detected through electromagnetic observations (purple); the black holes measured by gravitational-wave observations from LIGO and Virgo (blue); neutron stars measured with electromagnetic observations (yellow); and the masses of the neutron stars that merged in an event called GW170817, which were detected in gravitational waves (orange)." Credit: LIGO/Virgo/Elavsky (Northwestern University).

14.8.4 Planets among the remnants

There are many examples of white dwarf and pulsar binaries derived from X-ray and radio data, and because of the precision of the timings within the range of a millionth to a billionth of a second, this happy circumstance produces many possibilities. Because of this precision, changes in the orbits caused by relativistic effects and third bodies readily stand out—even the discovery of planets orbiting a pulsar have been detected. The left panel of Figure 14-10 shows the position of a binary white dwarf-pulsar combination thought to have a planet orbiting every 62 years or so. The right panel shows a typical pulsar orbit—that is an orbit with no noise and displays perfect data! This display is ***not*** of the pulsar in M4 and I show this in lieu of the original data given in the discovery paper of 1988. How could they figure out that there was a planet in the system? Because the data are so wonderful, any anomalies show up in the same way that anomalies in the orbit of

Uranus led to the discovery of Neptune. That's why, in Figure 14-10, the astronomers could deduce the presence of a planet in the system purely from the timing data. The planetary period is uncertain because the data have only been available since 1988 and we are only thirty years into the data acquisition. The mass of the planet is about 0.6 M_J. There are at least four planets discovered in this way.

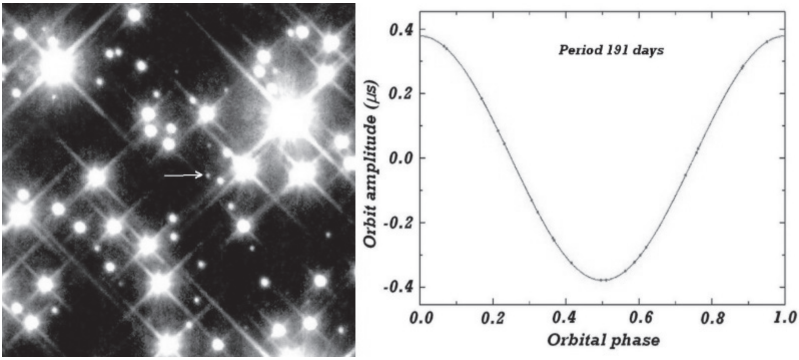

Figure 14-10. The left-hand image shows part of the globular cluster M4 where a white dwarf is orbiting a pulsar and a planet is orbiting them both with a period of ~62 years! The right panel shows faux light pulse variations of a pulsar consistent with an orbiting object and with a period of the orbiting white dwarf and pulsar. Note the times on the vertical scale that are measured in millionths of a second (μs)! Credit: Left panel. NASA/HST/Richer et al., 2003, Science 301, 5630. Right panel. Diagram source unknown. Modified by the author.

14.9 A brief wrap-up

This seems like a squib of an ending but there is plenty of activity "out there" related to binary stars. The high energy observatories in space are measuring outbursts of gamma radiation and X-rays thought to be the result of merging compact objects, whether they involve white dwarfs, neutron stars or black holes. These events will generate GWs that we hope we'll be able to identify and therefore tie together with other observations one day.

I've gone as far as I can in this saga of binary star evolution. It is a massive topic, particularly at "the end-of-life" which is in the realm of gamma ray, X-ray and radio astronomy and latterly gravitational wave observatories. The wealth and variety of research into compact binaries that continue to test and verify relativistic predictions staggers me. I can only suggest you enter any of these words, white dwarf, neutron star, black hole and mergers into your browser and go from there. In the end, although evolution in the real/scientific world is through a maze of possibilities, pathways and dead ends, we see only the endpoints. These pathways I've just mentioned must be inferred because real-time in astronomy is in millions of years and we are always working backwards with our models, though not with our imagination.

CHAPTER 15

WHERE IS ASTRONOMY HEADING?

15.1 Big data

Already within this book there are clues as to where astronomy is heading. It's heading to "big data", really BIG DATA, ever augmented by bigger, and bigger, ground-based optical and radio telescopes and more sensitive satellites working across the electromagnetic spectrum. Let's deal with big data because we're already experiencing it, both in the world of OGLE and the ongoing data factory known as Gaia. Once we get a handle on what is involved in big data I'll turn to big telescopes and see what they will bring. For sure, their output will dwarf all that is being currently gathered.

15.2 OGLE

The work of the OGLE observational program really sets the scene. Let's have a look at what has already been accomplished because the future will truly be built on this. The OGLE program is based on data from a dedicated telescope in Cerro Las Campanas, Chile, that has been cycling through fixed zones in the sky for twenty years taking image after image, initially of the **galactic central bulge (GCB)**—the stars in the outskirts of the galactic centre—and then the SMC and LMC. As an example, see the fields surveyed in the LMC in Figure 15-1. The program involving this dedicated telescope did not start that way but began with the allocation of telescope time on another telescope in Chile. Initially the astronomers worked on the GCB, and with its success, managed to fund the telescope now in use. Figure 15-1 shows the zones in the LMC so you can judge for yourself the extent of the coverage. On every clear night, and in Chilean skies that amounts to about 330 plus per year. The stars are imaged using drift-scans which have only been made possible by technological advances in the current crop of CCD detectors and the ever-increasing capacities of storage. Think of drift-scanning as like streaming video that gives us an almost seamless video experience. It is a passive form of observing where the telescope sits there and, as the Earth rotates, the sky drifts across the detector. Clever software and the hardware advances allow observers to get the equivalent of a movie over a great swath of sky, gathering the data in blocks of approximately 2000 by 8000 pixels or an area on the sky of approximately 0.25 by 1 degree. The same images are repeated night after night and typically upwards of 45 million photometric observations are made per night with the goal of having the data in final form available within 24-hours. (I'm choking on these numbers!) These totals will have changed by the time you've read this book; the original CCD detector has been replace by one about 16 times larger (262 megapixels). Goals like this, while hard to achieve, are necessary, otherwise one would be overwhelmed by the flood of data. This drift-scan observing repeats similar stretches of sky night after night simplifying the detection of stellar variability or positional changes. I got the details of the technique from an amateur astronomer's site. These days, the amateur's equipment is often as good as their professional cousins and they have access to similar software. The technique is easy in principle but fussy to set up and has been adapted by amateurs for their searches for comets, asteroids, supernovae, microlensing events and Near-Earth Objects.

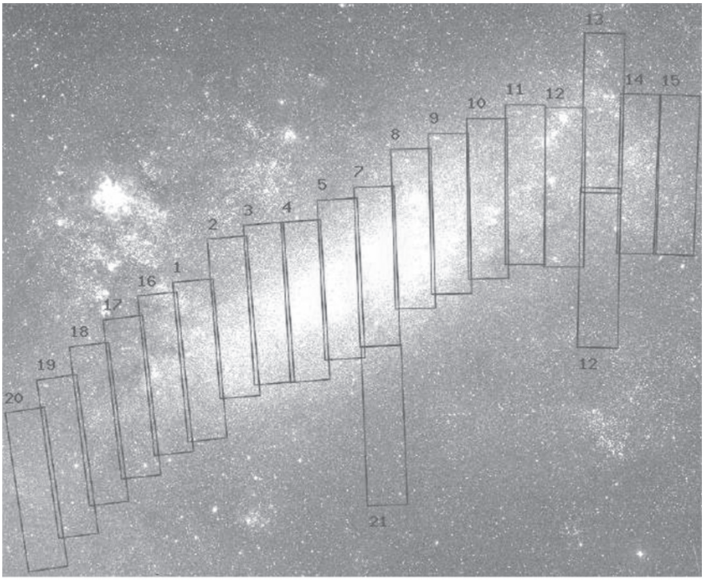

Figure 15-1. Shows the fields in the LMC covered by OGLE. Credit: Udalski et al., 2000, AA, 50, 307.

I felt good on a photometric observing run if I'd measured 80-120 stars a night—compare this number with about 15 million/per night in the LMC and ~45 million observations in the galactic bulge! Even between OGLE 1, the initial program in the GCB, and the present (OGLE IV), the data rate (observations/night) have increased 30-fold. Cumulatively, the numbers are staggering. The last number I saw from the SMC observing program was for 7 million stars, undoubtedly it is way bigger now as equipment has improved. 38,000 RR Lyrae stars have been discovered in the GCB, or galactic bulge. In some way these numbers are meaningless because they are simply too large to comprehend! But what is recorded? A typical frame in a non-crowded field is shown in Figure 15-2. These are not the nicely shaped star images we're used to with the HST observing program but were

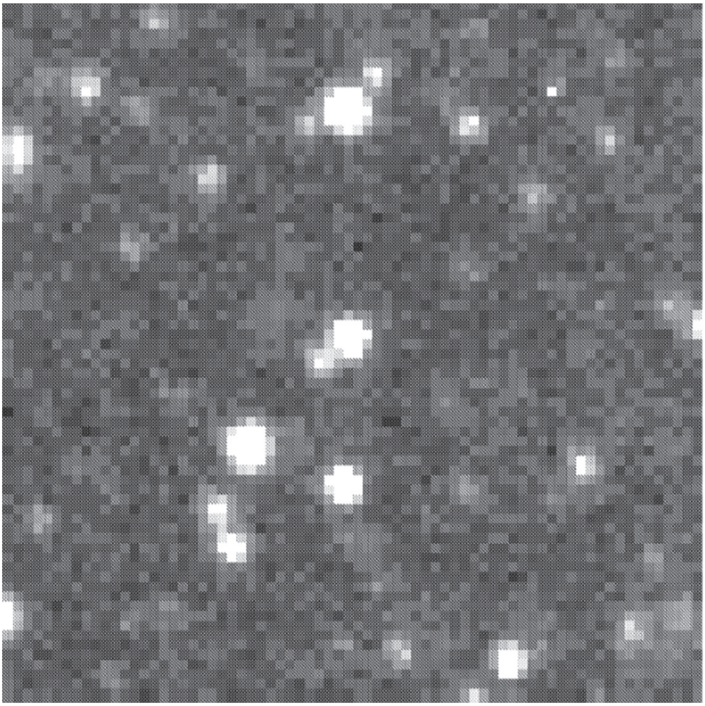

Figure 15-2. A typical OGLE frame or image from a field in the SMC. While the images look pretty pixelated many tests would have been made to see how good the magnitudes would be from these images, and, given these magnitudes, could the project work. For specialised work on specific stars such eclipsing binaries, the errors are less than 1% but for the general field, the best results for the brighter stars (~12 mag) is about 2% with the errors increasing at fainter magnitudes, and also in crowded fields where the software has trouble separating out partially merged images. Credit: Udalski et al., 1997, AA, 47, 431.

established as a minimum required to complete the project in a given time, knowing that with the march of technology, OGLE II, III and IV could repeat the task better. I can't express more my appreciation and admiration of what these Polish astronomers are giving to the astronomical world. When the drift-scan images are compared over all the observing nights, they yield a treasure-trove of variable stars that Paczyński hoped would answer the **missing mass** query but, aside from recording many microlensing events, some of which yielded planets, it achieves something quite different.

To get a feeling for what this "add-on" is, I quote the abstract of a recent paper by Soszyński:

> "During its long history, the OGLE survey detected, classified and published more variable stars than all other astronomical projects put together. Currently the OGLE Collection of Variable Stars contains nearly one million objects: Cepheids, RR Lyrae stars, long-period variables, eclipsing binaries and other variable sources in our Galaxy and in the Magellanic Clouds. These samples have been used in countless analyses focusing on the stellar variability itself and on the structure of galaxies to which they belong…"

All these data are available, so what is accomplished? Well, we've already seen the detection of binary Cepheids in the LMC, something that would be a fluke to achieve without OGLE. The eclipsing binary data, when combined with spectroscopy, are critical in revealing shortcomings, or proof, regarding stellar evolution. There are issues of improving the distance scale of the universe which is related to the distances to our closest extragalactic neighbours the SMC and LMC galaxies with their content of Cepheids and RR Lyrae stars. The original topics involved the detection of microlensing events of both single and binary stars and they also wanted to test how sensitive the technique was in crowded fields such as those found in the galactic bulge. They described as side projects the use of their photometric database. The boost this database gives to stellar astronomy has been enormous, not only with lots of data, but it has taken us from the Milky Way environs into the extragalactic realm.

15.2.1 Getting follow-up data related to stellar evolution

The following comments pertain to OGLE and all the other programs that will produce light curves of eclipsing binary stars. Measuring many light curves at once is straightforward because, in the crowded fields of the SMC, many stars are visible on the CCD at one time which produces its own problems—a real problem—the follow-up data requiring a larger telescope to complete the project. For example, a recent paper that used observations of forty eclipsing binaries detected in the LMC, needed spectroscopy to complete the project. Without the follow-up the project was dead in the water. Remember that solving a light curve combined with spectroscopic orbits for the component stars yields, mass, radii in solar terms as well as temperature and distance—all the necessary data to compare the results with those predicted from evolutionary models. The problem is something I've touched on—you can take direct images to much fainter limits than you can get spectra. In the case I've just mentioned, the spectroscopic side of the project was only completed when the collaborators were able to prove to the telescope-time granting committee that the spectrograph would produce spectra adequate to do the job. As one collaborator later told me, "emphasise the word barely". It is always like that. You've got forty stars, each requiring ten spectroscopic observations that need to be taken at just the right time so that you can see and hence measure two spectra. That adds up to a lot of observing time—time you'd never be allotted. But what say you take a direct image of the sky and measure the positions of all the stars you're interested in and, with a fancy bit of engineering, replace the detector with a device that places glass, or optical fibres at each star's location? (Look at Figure 7-3. We want to replicate that with high quality spectra). Then you can pipe the light from each star through the spectrograph to stack them directly onto your CCD. Observing many stars at once in this manner is called **multiplexing**—our wives claim that that is what they do all the time, doing more than one job at once. Obviously this engineering and optical advance can vastly improve the efficiency of your observations by enabling you to observe dozens of stars in one shot. The **James Webb Space Telescope (JWST**)—yet to be launched—has the capacity to measure a hundred objects at once and this is all done remotely! For an observer, it was an absolute treat when I first used it on the Big Island twenty-five years ago. Multiplexing made it possible to complete the project. Here, I'm touching on the optical technology that makes the difference between getting a result or not even getting started, because you would never get the observing time to observe each star sequentially. In writing this and trying make things clear, it is proving quite difficult because the interleaving of hardware, optical advances and software complicates the story. I'll finish this part of the story with reference to these forty stars because it shows that a successful result not only depends on the light curves and their solution and the multiplexed spectra, but on software that miraculously separates the component spectra. These spectra then yield the velocities which in turn give the orbits and then lead on to determining the fundamental data necessary for interpretation in terms of stellar evolution. The spectroscopic results are displayed in Figure 15-3.

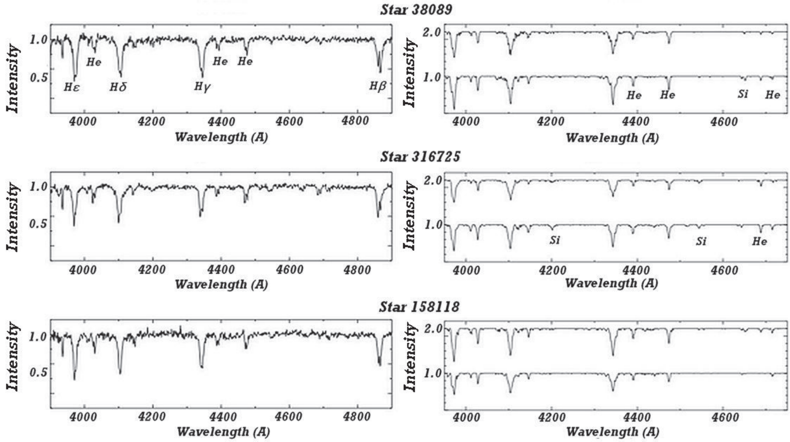

Figure 15-3. A sample composite spectrum of each eclipsing binary is shown in the left panel. In the right panel an iterative disentangling process (separating out the individual spectrum of each star) yields a spectrum for each star based on an analysis of all the spectra for each system, finally ending up with the velocities at each phase. These velocities give a spectroscopic orbit, which, when combined with the light curve solution, yields the masses and radii needed for the evolutionary discussion. Credit: Harries et al., 2003, MNRAS, 339, 157.

The images in the left panel show sample spectra where the velocity differences between the components are at a maximum. Said differently, we can now see both spectra. When the whole dataset of observations are processed using powerful mathematical techniques, out pops the separated spectra shown the right panel and a set of velocities for each observation. I mention this, because this type of analysis will also need to be multiplexed in some way to handle the immense amount of data coming from OGLE and Gaia. This mathematically rich processing, gives much better results than those obtained in the past and demonstrates the way that astronomy is going; process vast amounts of data with as little intervention as possible ***is*** the future. Which again has its own problems because in my experience, automation can fall over because of the unexpected exceptions… I'm still worried about the driverless car here.

15.3 Gaia

The replacement to the earlier astrometric space-based observatory Hipparcos (1989-93), is called Gaia (see Figure 15-4) and was conceived in

1993 and finally launched in 2013 to sit at L2. Well, not fixed there, because it wouldn't be able to see either the Earth or the Sun because of the Moon blocking its view. It does a little orbit around the line joining L2 to the Sun to accomplish two things, one to get the sunlight that powers the satellite, and secondly, to be able to download its data to Earth-based radio telescopes tasked to gather the observations and to make adjustments to Gaia's operation. Though you've rocketed the spacecraft to reside beyond the Moon, you still must be able to control it, unlike the Russian dog that was launched into space and left to die. It is a passive telescope, spinning in orbit and measuring every object it encounters. Because it precesses just like a top, it covers a lot of sky and over the years it will repeat the observations many times. There is propellant on board to sustain the spacecraft till 2025. Over the mission life, deemed to be five years, it is expected that each of the billion stars will be observed 70 times!

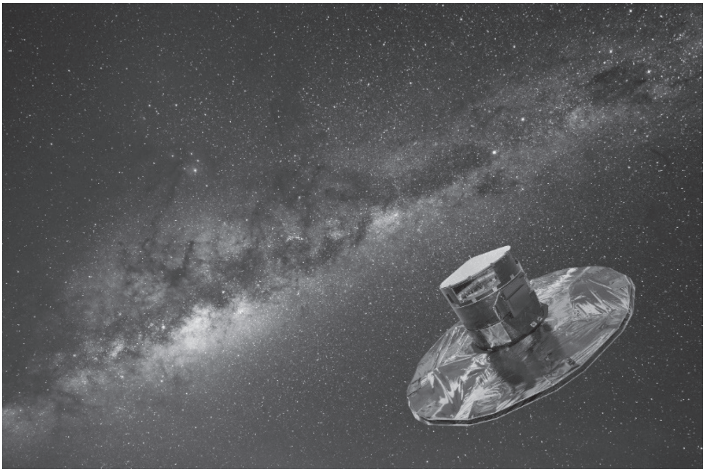

Figure 15-4. The spaceborne observatory Gaia, tasked with measuring the position, brightness, colours, spectra and velocities of a billion stars. Credit: ESA/ATG Medialab; background image: ESO/Brunier.

This is Gaia's mission statement.

> "Gaia is an ambitious mission to chart a three-dimensional map of our Galaxy, the Milky Way, in the process revealing the composition, formation and evolution of the Galaxy. Gaia will provide unprecedented positional and radial velocity measurements with the accuracies needed to produce a stereoscopic and kinematic census of about one billion stars in our Galaxy

and throughout the Local Group (our nearby galaxy neighbours). This amounts to about 1 per cent of the Galactic stellar population."

Reading this gives me a burst of excitement and extreme indigestion when I think of the labour involved in dealing with these data… But it is also inspirational! This is BIG SCIENCE This observatory, bold in its plan to map 1% of the Milky Way's stellar content, reflects confidence in technology: in the CCD detectors (106 of them on board, equivalent to a 1000 megapixels, or one gigapixel), computers, and the ready availability of massive storage in the **terabyte** range (a million-million bytes). And all this based on the experience of Hipparcos, its father in the world of astrometry. But, whereas Hipparcos yielded reliable data for about 120,000 stars with extensions to one million less-accurate stellar data in a program called Tycho, Gaia's developers took a leap of a 1000-fold in their goals—much like Boeing did when they introduced the 747. And what will Gaia's offspring—probably already being planned—yield? But all this would be useless without the confidence that the massive data associated with a billion stars could be handled. In my view OGLE had set that very stage.

A Gaia presentation, given after 18 months of the telescope's operation, reveals a lot more than what is given in Gaia's mission statement. They hope to create catalogues of:

- One billion stars—already done.
- 100,000 to a million galaxies.
- 500,000 quasars (quasi-stellar objects)
- 100,000 solar system bodies
- Tens of thousands of new Jupiter-mass sized exoplanets
- As well as providing information on fundamental physics and general relativity.

Gaia will also be able to use Hipparcos and Tycho data to extend their analyses over a baseline of thirty years, a critical aid in measuring proper motions of stars in common with these programs. As of August 2019, this observatory has measured the positions of a billion stars and from these data derived distances and proper motions for one million of them—undoubtedly there are many more completed astrometric data available such as visual binaries and the masses they will produce. As of the time of writing the project has already yielded almost 2000 scientific papers, many of which involve the structure and evolution of our Milky Way, as well as studies required to calibrate the data for more detailed studies of stars, such as measuring temperatures, surface gravities and chemical composition. In terms of stellar evolution, these data are key to many studies, for example, the location of Cepheids in the framework of theoretical evolutionary tracks, or a close examination of clusters in order to measure their age and chemical content. From my perusal of recent papers these are some of the varied topics that have been covered outside those I've already noted. I've not pursued Gaia's results, because they're pouring forth into the literature and, if I attempted to keep up, I'd be going down a rabbit-hole from which I'd never emerge.

The preparation for the stellar astronomy side of the operation, aimed at gaining knowledge of the chemical evolution of our galaxy, has spawned work on stellar atmospheres so that observations can be properly interpreted using a consistent reliable set of standard stars based on known angular sizes and bolometric magnitudes. These data lead to reliable temperatures and surface gravities. You've heard me go on about the temperature scale and the need to relate observations in the real world accurately to those in theoretical world. In this process they have established a reliable set of comparison stars which they call Gaia FGK benchmark stars (a subset of OBAFGKM) with which to make the comparisons.

Using quasi-stellar objects, otherwise known as quasars, distant galaxies that appear as stars in a telescope, Gaia astronomers want to anchor and/or confirm the reference system that provides the angular measurements giving the positions of the stars. Quasars are so far away that they can be considered fixed reference points in the sky. There were very few quasars observed by Hipparcos so their use was limited in that survey.

I mentioned how astronomers are very imaginative in dreaming up unexpected applications of data. One researcher has suggested that the stars will reflect the passage of gravitational waves passing through their location. By synthesising the effects of gravitational waves on a Gaia data subset they show a pattern. Given a source of gravitational waves like the compact binaries I mentioned in the previous chapter, and comparing these patterns against those observed, it might be possible to see GWs passages amongst the stars.

In thinking about OGLE and Gaia and the unbelievable amount of data that is pouring out, I know that researchers will have to be selective in what they decide to study. The powers-that-be will have to make the same decisions they made when deciding on the question of observing programs that favour those astronomers and astrophysicists at the very forefront of research. Much like the selected people who used the 200-inch all those years ago when the telescope was used almost exclusively for extragalactic studies. I suspect that the days of research papers with, but a few authors, will give way to a more impersonal presentation of papers with pages of contributors. There will be plenty of crumbs for researchers like me, but for follow-up observations on large telescopes, the thrust of grants and telescope-time, should be behind those that are at the cutting-edge of research. I hate to have said this, but can smile a little though, because there ***is*** so much data out there that nobody can cosset it to themselves. Maybe there is hope for someone like me.

The question arises, "Is there anyone on Earth who has a vision that encompasses all of what BIG DATA is bringing?" There will be so much data available that I wonder how it will be dealt with. For the teams dealing with the primary research goals that justified the telescopes in the first place that will handle itself. There will be many spinoffs. In the past we worked in little groups observing what took our fancy. I can't see that particular model working in the future, we will need to be more disciplined than that and be prepared to be subsumed within someone's larger vision. This occurred in the 60s when Strömgren had a vision about where stellar astronomy should go and a team based at KPNO, of which I was a small part, fulfilled his dream. But there is more. The quartet of 30-metre-class telescope about to come online will bring even more data that, by necessity, will require some form of overarching authority to handle.

Let's have a look at the telescopes.

15.4 The behemoths: Ground-based

These monster telescopes improve the resolution currently achievable by at least a factor of four over the current crop of 8-m telescopes, taking a value of about 10 mas to ~2 mas, just a short step from the theoretical resolving limit of the VLTI. This is ignoring the improvement of light-gathering power that will make the limiting magnitude about 3 magnitudes fainter. This magnitude extension is important because it will take us closer to observing the beginnings of our universe.

15.4.1 What's on the way

Now I'll turn to the thirty-metre-class of telescopes for which ground has already been broken. These telescopes are remarkable, in fact I can't comprehend their size. It was enough to stand inside the dome enclosure looking with awe at the sight of a 4-metre telescope moving soundlessly as it tracked the star that I was observing before I wandered out onto the catwalk to view the sky and so free my mind from the cobwebs that accumulate after too many hours of observing. I can't image the 8-m and 10-metre telescopes currently in operation, let alone ones with more than ten times the light-gathering power and the increase in size to boot. But they're all almost ready. The **Extremely Lage Telescope (ELT)** for which the ground has already been broken at Cerro Armazones, and similarly the Large Synodic Survey Telescope (LSST) which will soon be erected at Cerro Las Campanas, along with the **Great Magellan Telescope (GMT)** nearby at Cerro Pachón, will be online soon. These are all in Chile, the exception being the Thirty Metre Telescope (TMT) hoped to be erected on Mauna Kea on the Big Island of Hawaii.

A telescope can image objects fainter they can get spectra, though they can if they are prepared to spend long times to get them. I talked about this with respect to the binaries in the LMC but these new telescopes, with gains of more than a factor of ten in their light-gathering power, will be able to do the spectroscopy languishing right now. But of course, the imaging component of the instruments associated with these 30-m telescopes will, in their turn, be hampered by the lack of spectroscopy. Our telescopes are getting bigger but like halving the distance in each moment to some destination never gets you there—the original infinite series upon which much of mathematics is based—always results in not being able complete the task.

We want to see more detail within distant galaxies, or nearby to resolve disks around exoplanets (and everything in between). To meet these goals is simple, build larger and larger telescopes—ignoring the prohibitive costs of course—and to maximise the possibilities in the telescope optics to defeat the Earth's atmosphere if you will. The need to see more detail in nearby objects is currently being achieved by the VLTI interferometer, creating wider eyes with the four telescopes forming the VLTI in Chile. This interferometer is tasked with detecting planetary disks around nearby stars or looking into the centre of galaxies to resolve or separate out the stars there and to examine the black holes at their core. At the moment the interferometer is limited to the IR because of technical difficulties involved with using it in the visible region of the electromagnetic spectrum where the resolving power would be much, much better, allowing us to see more distant disks or to examine closer ones in more detail. There are plenty of planets now detected in the Goldilocks zone to provide ample objects for study. Just recently a new instrument specifically designed for the search for water-bearing planets in the α Centauri system has been commissioned for use with the VLTI. There is a real hope that soon one of these yet to be resolved planets will appear blue!

The VLTI has still a long way to go in achieving its full resolution in the visible region—recall my comments earlier on the extraordinary difficulty of selecting that single wavefront that gives you the resolution you dream about. Once the technical problem has been solved then the VLTI will achieve its full resolution of 0.001 arcseconds. But success here will have much larger implications in that having been successfully done for a 100 metre separation, there is no reason why the distance couldn't be doubled, tripled etc. by combining other telescopes within sight of each other on the same peak on Cerro Paranal. The point being, that, like the initial gravitational wave detection, having done it once, there would be no reason why it couldn't be done again. Once the principle has worked on Earth, then the baseline can be increased a millionfold in space and the resolution taken to unbelievable levels. For nearby stars with known planets, we could see their surfaces and orbiting moons. If life existed there, we'd see the evidence. So, there is an absolute gamechanger riding on optical experts attempt to crack the problem of interferometry in the visual part of the electromagnetic spectrum. The reach of such an interferometer in space would take us to nearby galaxies, yielding images of unprecedented detail. A NASA proposal to do just this was scrapped in 2010 but one day it will be done. That is the future.

Astronomy progresses based on prioritising resources—grad students, post-docs, research grants—to those astronomers using the largest of the telescopes and then devolving to the users of the remaining panoply of telescopes. The large telescope results spill over into areas that demand more detailed study, the sort that generally you can never get the time (observing time) to complete, simply because of the "oversubscription of applications for time" or, even given the time, the weather. We, the remainder, feast on these opportunities like the remora that accompany their shark hosts. All our contributions are needed to further astronomy as a whole and I think that what has happened in the past will be continued, that is the large telescopes should be pushing the boundaries of what we can observe, whether it is looking back to the earliest stage of the Big Bang or to see planets as distinct objects around nearby stars and, given a long enough time exposure, be able to examine their atmospheres spectroscopically.

Of course, the study of black holes remains at the top of any research program—both observational and theoretical—and, since they've been discovered in the centres of galaxies and globular clusters, more aperture

(LSST, GMT, ELF and TMT) and more resolution (VLTI), will give us a good look at the close surrounds of these objects, not only visually, but in the X-ray domain with the Chandra and XXM-Newton X-ray observatories and in the IR domain with the JWST as well as with radio telescopes on Earth. Some of the details surrounding a black hole, like that seen in our galactic centre with the motion of the star called imaginatively S2 gives a measurement of the interior mass that produces the orbit, that is, it weighs the black hole. Remember, when there is an announcement that a black hole has been discovered weighing millions of times the Sun's mass, it is not a fanciful figure but is based on Newton's law of gravitation and some very clever interpretation of observed gas or stellar motion in its vicinity. Note that matter is not directly sucked into a black hole like you suck water up a straw but it is like the water going down a plughole where it swirls around getting closer and closer to the hole until it disappears—this analogy also works for merging compact objects emitting gravitational waves. The centres of globular clusters will be subject to such scrutiny and any current results updated and improved. Everything done now will be altered in the future. My own research supplanted earlier results just as mine have been replaced in turn, not only with better data, but in more refined methods of digital analysis.

Because all the major telescope initiatives have their own mission statements, I'll touch on touch on a bit here and another there, like the smorgasbord complete with everything you love but you know you must settle for just a few titbits here and there. Because the LSST seems remarkable, and is already under construction in Chile, I'll start with it.

15.4.2 Large Synodic Survey Telescope (LSST) renamed The Vera C. Rubin Observatory

15.4.2.1 Petabytes and teraflops

Conceived in the 1990s and proposed in 2001, this is the US ground-based flagship, an 8.4-m telescope with an enormous detector that enables it to be able to survey the sky every few nights! Have a look at the detector in Figure 15-5! This image was presented in 2009 and I wonder if the current crop of detectors will produce even more pixels! As it stands, the whole operation is fully in the realm of **petabytes** and beyond—a thousand terabytes or 10^{15} bytes, where a terabyte is a million-million or a thousand billion or a British billion. There is so much data, that once stored, may be sampled but not moved around. Users will interrogate the database to get what they want,

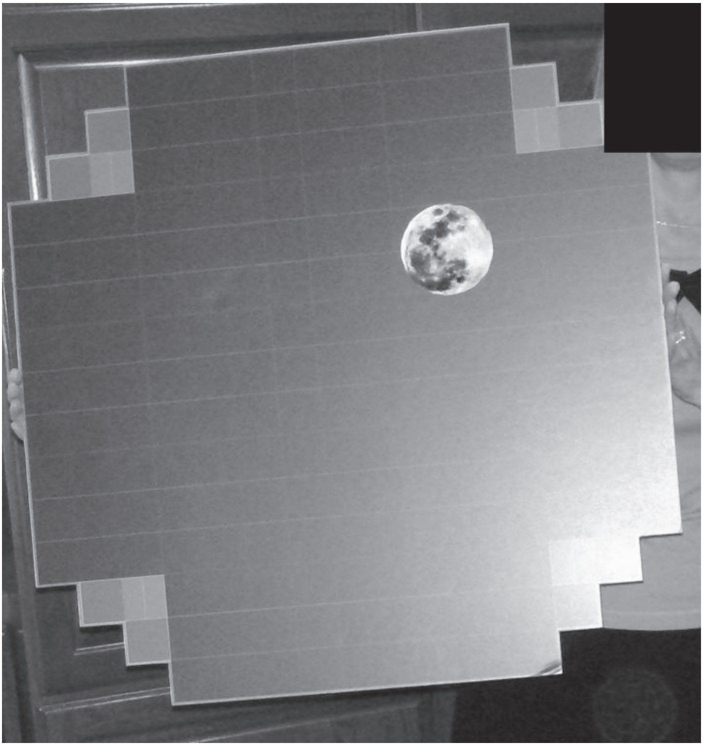

Figure 15-5. The LSST focal plane detector array with a diameter of 64 cm. This mosaic will provide over 3 gigapixels per image. The image of the moon (30 arcminutes) is present to show the scale of the field of view. Credit: LSST Project/NSF/**AURA**.

like going to a buffet to get your meal or scooping water in a cupped hand from a lake—the latter imagery is more accurate since you can't move the lake! Back to petabytes. You are used to mega, the millions of pixels in your camera or cell phone, gigabytes, in terms of the storage in your computer where giga is an American billion. And it gets worse—that is if getting too much data could be "worse"—because over the years of operation the numbers get bigger and there is a real challenge trolling through the database to retrieve what you want. What follows is a quote from an article by Evelyn Lamb about the LSST database and the challenges it brings:

> "Back in the days of **SDSS (Sloan Digital Sky Survey)**, scientists often downloaded data to their own institutions' computers and ran analyses on their own equipment. That won't be possible with LSST. 'At half an

> **exabyte**, people are not going to be able to put this on their laptops,' Yusra AlSayyad, technical manager for the Princeton branch of the data management team, says of the LSST data. 'Instead of bringing the data to scientists, LSST will need to bring scientists to the data.'
>
> The LSST data management team, consisting of approximately 80 people spread over six sites in the United States, is responsible for turning this deluge into something scientists can access and analyse."

This, in addition to dealing with the computer-challenge that requires a computer to perform an estimated 250 **teraflops** (250 million-million arithmetic operations/sec) and require 100 petabytes (100,000 terabytes) of data. Yes, the numbers are just like the universe we live in. Large. Billions and billions of galaxies with their billions upon billions of stars and with these stars, billions of solar systems.

15.4.2.2 The Programs

The LSST will be unique, a huge telescope that will sample the whole visible sky every night and repeat it night after night. The expectations of this observing program that follows comes from the LSST website. It is impressive.

- Variability information. Detecting supernovae on the rise, cataclysmic variables, all sorts of stellar variability, stellar detonations…
- A compact description of light curves
- A catalogue of roughly 6 million solar systems objects, with their orbits
- A catalogue of approximately 37 billion sky objects (20 billion galaxies and 17 billion stars), each with more than 200 attributes—positions, parallaxes, temperatures, shapes, colours…

Given these data, the goals of this project are huge. An original paper, with a vast number of researchers listing what they expect to do with the data, is too long even to contemplate! The observations and studies flowing from them are taken directly from the LSST homepage and are aimed at:

- (Studying) the nature of dark matter and understanding dark energy.
- Cataloguing the solar system
- Exploring the changing sky
- (Studying the) Milky Way structure and formation

Each year there will be summaries of data available to help researchers plan future observations or to simply "mine" the material for their own purposes. This project, along with OGLE, Gaia and the thirty-metre telescopes in the pipeline will overwhelm the astronomical community and provide them with data for decades. It is similar, but of course orders of magnitude (many multiples of 10) larger than the Henry Draper Catalogue published between 1918 and 1936 which contains about 360,000 entries but with limited information: position, magnitude, and spectral type. Each year the LSST project will release an overview paper including in part, measurements of positions, fluxes (brightness), and shapes of objects observed. Remember that there are billions of galaxies out there.

The mind boggles at the quantity of data and the grandeur of the plan and vision that has brought this project close to first light.

15.4.3 The Extremely Large Telescope (ELT)

This European initiative aimed at building a thirty-nine-metre telescope in northern Chile is a wonderful addition to the other telescopes in northern Chile, but located at Cerro Armazones in the Atacama desert. (I'm now paraphrasing part of the commentary from the ELT website.) The design consists of a reflecting telescope with a 39.3-metre diameter (130 foot) segmented primary mirror and a 4.2-metre (14 ft) diameter secondary mirror, and will be supported by adaptive optics, eight laser guide star units and multiple large science instruments. As I write these words, the foundations for this extraordinary telescope are being laid and many of the pieces of glass making up the primary mirror have been finished. Like the other large telescopes, the ELT will study the early universe as well as probe the formation of planetary systems hoping to detect water and organic molecules in the disks around these exoplanets, thus giving an insight as to how planets formed and evolved. Going outward—or back in time—the goals are to look at the mixture of primordial stars, galaxies, and black holes to see how they relate. The list goes on involving the expansion of the universe and its early chemical evolution. This following paragraph, derived in part from the ELT website, succinctly summarises the situation for the ELT and the other giant telescopes under various stages of construction:

> "Extremely large telescopes are considered worldwide to be one of the highest priorities in ground-based astronomy. They will vastly advance astrophysical knowledge, allowing detailed studies of subjects including planets around other stars, the first objects in the Universe, super-massive black holes, and the nature and distribution of the dark matter and dark energy which dominate the Universe."

It's worth having a look at this monster telescope, see Figure 15-6.

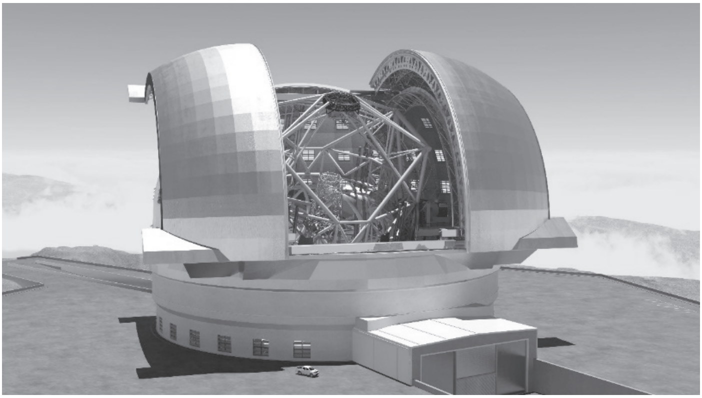

Figure 15-6. The Extremely Large Telescope (ELT) as it will appear “in situ” on Cerro Armazones in the Atacama desert in northern Chile. The automobile in the parking lot gives us an idea of the scale of this telescope. Credit: Swinburne Astronomy Productions/ESO.

15.4.4 The Thirty Metre Telescope (TMT)

It’s hard to know what to say about this telescope that got the go-ahead in 2014 but has been hamstrung by protesters who do not want the telescope constructed on the peak of Mauna Kea. The whole situation is politically fraught. I guess I’ll leave it there. The situation leaves the Northern Hemisphere short of this extremely large class of telescopes.

15.4.5 The Giant Magellan Telescope (GMT)

The current crop of large telescopes is quite diverse in their designs but are all aimed at getting large pieces of glass shaped and looking at the sky. The GMT represents one of these differing optical arrangements as can be seen in the illustration of it in situ on Cerro Las Campanas (Figure 15-7). Rather than use segments of a large mirror pieced together to form a whole, this telescope uses seven monolithic 8-m mirrors to form a telescope of 24-m equivalent diameter.

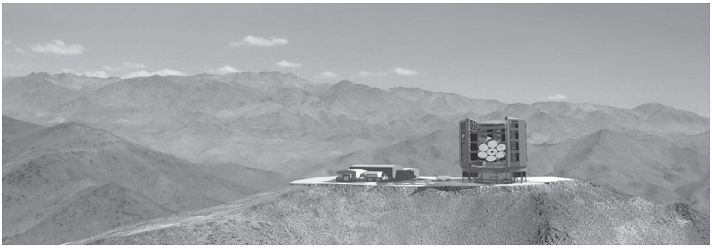

Figure 15-7. An illustration of the Great Magellan Telescope (GMT) in situ on Cerro Las Campanas. There are two things to note. The seven mirrors that make up the primary and the vast area of desert surrounding this observatory that provides perfect viewing for the GMT and the others in Chile. Credit: Great Magellan Telescope Organisation.

These are the major projects for Earth-based research, now what is happening in space?

15.5 Satellite-borne telescopes

Aside from the major project, the James Webb Space Telescope (JWST), I'm not going into any detail in describing these satellites. By now we all know what can be accomplished from space… The thought just struck me about the previous sentence and how easy it all seems now. "Accomplished from space". Nobody there to twiddle a knob or to point the telescope, no hands, just the electromagnetic reach from Earth that starts and stops exposures: safely moves the telescope to new targets, makes the observation and directs the stored data stream to radio telescopes when they come within range. These are a few of the activities implied by the phrase which is so easy to say but doesn't come close to describing the gigantic operation from design, construction and operation, implicit in any satellite-borne telescope. That it ***is*** almost routine, is exemplified by the launches of relatively simple, time-limited purpose-built space telescopes.

15.5.1 James Webb Space Telescope (JWST)

This is the planned replacement for the HST which has been hobbled by political inaction. By the time you read this the project may well be a no-go. As a replacement, because of its size, 6.5 metre against the HST's 2.4-metre mirror, it will peer more deeply into the universe than its predecessor though it will not have the capability of working in the visual or UV region of the electromagnetic spectrum. This telescope, a product of a joint effort by NASA, ESA and the Canadian Space Agency (CSA), will look outward, largely in the IR, where, unlike the Hubble with its limited IR capability, it will be able to look into the vast clouds of gas where stars are birthed. Armed with more up-to-date hardware—which incidentally is already out-of-date—it will provide advances in the larger world of cosmology. The telescope's broad goal comes from the JWST website.

> "The James Webb Space Telescope will be a giant leap forward in our quest to understand the universe and our origins. Webb will examine every phase of cosmic history: from the first luminous glows after the Big Bang to the formation of galaxies, stars, and planets to the evolution of our own solar system."

Also stated there are more details; it seems that there are four main goals. These I'm quoting directly from the JWST webpage also.

- The JWST will be a powerful time machine with infrared vision that will peer back over 13.5 billion years to see the first stars and galaxies forming out of the darkness of the early universe.
- The JWST's unprecedented infrared sensitivity will help astronomers to compare the faintest, earliest galaxies to today's grand spirals and ellipticals, helping us to understand how galaxies assemble over billions of years.
- Webb will be able to see right through and into massive clouds of dust that are opaque to visible-light observatories like Hubble, where stars and planetary systems are being born.
- Webb will tell us more about the atmospheres of extrasolar planets, and perhaps even find the building blocks of life elsewhere in the universe. In addition to other planetary systems, Webb will also study objects within our own solar system.

The telescope's optical train must be cleverly designed because it doesn't ride the rocket into space fully assembled but is like one of those Transformer-things. When in orbit, it unfolds and combines the 18-separate light-weight mirrors into one unit to produce a 6.5-metre diameter primary with about seven times the light-gathering power of the Hubble. It is also multiplexed—remember the light piped down fibres to produce many spectra at once—with programmable micro-windows that enable observations of up to 100 objects simultaneously. These innovations—the light-weight mirror segments made of beryllium, and the programmable viewing ports feeding the CCDs—represent a big advance in engineering and optics. The limitation, true of the Hubble and the now dormant Kepler/K2 telescopes, is the propellant required to manoeuvre the telescope in space. The JWST will be sensitive to a range of wavelengths from 600 nm (orange light like that peaking from the Sun) to 28 µm which is deep infrared radiation corresponding to a peak temperature of about 130 K or -140°C (remember this Kelvin scale starts at -273°C). Astronomers are waiting to witness a successful launch and deployment within the next few years.

15.5.2 The Spitzer Space Telescope (SST)

The Spitzer Space Telescope is an IR telescope launched in 2003 with aims much the same as the JWST. These goals are to: observe galaxies, and the origin of the universe, examine stars within their dust-shrouded cocoons, detect and examine planetary disks, study comets and planets within our solar system, and, surprisingly, something the Spitzer scientists had not considered—the study of exoplanets and the discovery of planets transiting the faces of nearby stars. In this regard, the discovery of many planets orbiting the TRAPPIST system (Figure 7-15) were augmented by Spitzer observations. When the James Webb Space Telescope was approved part of its mission was diverted to locating targets better investigated by the JWST.

The SST is a small telescope with a main mirror or primary of only 85 cm (2.8 feet or 0.85 m) and was launched into what is called an **Earth-trailing orbit**, i.e. is not at the preferred L2 but trails the Earth in its orbit slowly dropping behind at about 15 million km/year orbiting the Sun in 273 days. As an aside, the Kepler telescope was launched into a similar orbit 6 years later. A spacecraft in this orbit, as opposed to an Earth-centred orbit, has the advantage of not having to counter the Earth's heat in addition to that of the Sun and can view about a third of the sky at any one time. In planning the orbit, which was decided purely on a cost-cutting and mission-saving basis, the engineers had to consider communications with the Earth—something not a factor when you're orbiting the Earth, and to provide an observing routine that always minimized the use of propellants needed to direct the antennas towards the Earth when downloading data. The major limitations on all the missions are the positioning of the heat shields with respect to the Sun and the direction of the solar panels that power the observatory. As far as I can see, that with funding an issue (it always is), the final decision was driven by making the best of a bad job because in such an orbit there is no means of replenishing the cooling liquid helium or the propellant for manoeuvring, unlike the Hubble that got a new lease on life with a refurbishment of equipment and a resupply of consumables. The KEPLER observatory died with the expenditure of its consumables and the SST will be decommissioned in 2020 just when the James Webb telescope takes up its duties. For this telescope, the liquid helium used to cool the telescope—body heat—to 4 K (-269°C or -450°F) ran out in 2009 and since then until its retirement in 2020 it has operated under what was called a "warm-mission" (-243°C or -405°F)—some warmth!—using one of its remaining instruments.

15.5.3 Chandra X-ray observatory

This telescope was launched in 1999 as one of NASA's "Great Observatory" projects which include the Hubble, Spitzer and **Compton Gamma ray Observatory (CGO)**, with a goal to detect and examine radiation coming from gases at millions of degrees. These hot, tenuous, gases emit X-rays and permeate the environs of giant conglomerations of galaxies. Even the Milky Way has an "atmosphere" of hot, X-ray emitting gas; regions around black holes emit X-rays along with pulsing neutron stars, supernovae and other exploding stars caused by merging of dense orbiting pairs. The data cover the end-of-life of the stars as well as the inner workings of clusters of galaxies. A vast cloud of hot gas in a cluster of galaxies can be several million light-years across and contain enough matter to make hundreds of trillions of stars. X-ray telescopes can also trace the hot gas from exploding stars or detect X-rays from matter swirling as close to the event horizon of a stellar black hole—the place a photon gets to and can't get away.

I expect what the original planners hoped to achieve has been a lot more than what they might have anticipated. I don't think that they expected their observations would yield information on merging neutron stars and/or white dwarfs.

15.5.4 XMM-Newton (ESA's X-ray Observatory)

This observatory was launched by the Europeans in 1999, and after a series of refurbishments and a scare when it went off-line, it will go until 2022. The system observes the spectra of X-ray sources as well as having an optical telescope that allows direct imaging of the source being examined. In its study of clusters of galaxies, this telescope discovered a cluster of galaxies 10 billion LY away—not far off in time from when the universe was formed. Observations of black holes have been fruitful, and the observatory has been able to measure the spin-rate of a black hole. Continued observations of Cygnus X-1, the X-ray binary I mentioned in Chapter 13, led to it being identified as a black hole along with other candidates originally identified by their X-ray emissions. Stars have been observed emitting material giving off X-rays that have been ingested by a companion neutron star. It's a bizarre world out there. These X-ray satellites have produced a plethora of papers and there is no point in my doing anything but comment on those took take my interest.

15.5.5 Transiting Exoplanet Survey Satellite (TESS)

TESS is a purpose-built system aimed to replace KEPLER, looking for star-crossing planets located above and below the Earth's orbit so that they are observable all year round. TESS, will be able to study the mass, size, density and orbits of large numbers of small planets, including rocky planets in the Goldilocks zone about their host stars. It's expected to discover about 20,000 new planets and has already seen success since it went operational in 2018. It is planned for a 2-yr mission, but if history is any indicator, it will last a lot longer than that. Where promising, follow-up observations of these stars will be made by the SST and JWST and ground-based telescope described above. Most exoplanets discoveries have been of Jupiter-type objects but TESS is specifically aimed at detecting small Earth-type planets around the nearest stars in the sky.

Here is a description of NASA's goal for the satellite TESS with reference to KEPLER, its predecessor:

> "NASA's Kepler Mission was, during its 4-year prime mission from 2009-2013, a statistical transit survey designed to determine the frequency of Earth-sized planets around other stars. Kepler revealed thousands of exoplanets orbiting stars in its 115 square degree field-of view, which covered about 0.25 percent of the sky. While Kepler was revolutionary in its finding that Earth-to-Neptune-sized planets are common, the bulk of the stars in the Kepler field lie at distances of hundreds to thousands of parsecs, making it difficult to obtain ground-based follow-up observations for many systems.
>
> The TESS Mission is designed to survey over 85% of the sky (an area of sky 400 times larger than covered by Kepler) to search for planets around nearby stars (within ~200 light-years). TESS stars are typically 30-100 times brighter than those surveyed by the Kepler satellite. Planets detected around these stars are therefore far easier to characterize with follow-up observations, resulting in refined measurements of planet masses, sizes, densities, and atmospheric properties."

15.5.6 Wide Field Infrared Survey Telescope (WFIRST)

This 2.4-metre primary survey telescope, designed to research exoplanets dark matter and dark energy, was due to "fly" in 2025. Again, like the JWST there is no guarantee that this space-telescope will be launched.

15.6 Telescopes: A census

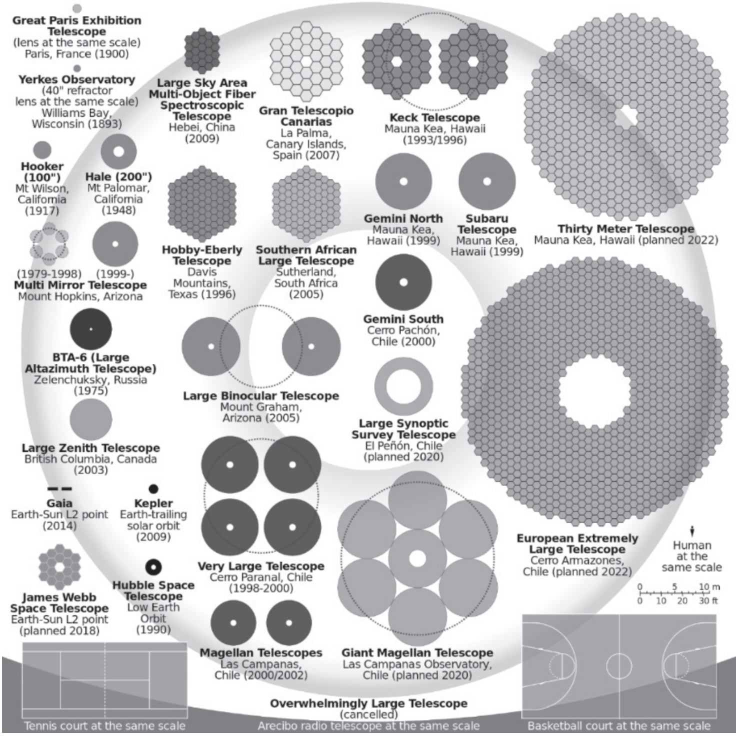

Figure 15-8. Summarizes the current crop of telescopes built or planned. Judge their size against the tennis court to the lower left or the basketball court in the lower right. The existing 4-m telescopes that appeared enormous to me don't even show up! The circles around some of the mirror pairs and the GMT represent the equivalent aperture of the combined telescope. Credit: Wikimedia Creative Common/Cmglee.

To summarize the telescope situation, consider Figure 15-8 which shows the existing, and planned, telescopes against the backdrop of the now defunct Overwhelmingly Large Telescope (OWL) 100-metre monster.

Some of these are in limbo awaiting political decisions. From an observer's point-of-view the current situation looks lovely but I'm guessing there is a fair bit of angst regarding the major US initiatives, not only because the science is at risk, but because of the enormous—and perhaps fruitless—labour involved in even bringing one of these projects to the fore where they may be judged.

15.7 A fantasy? The Overwhelmingly Large Telescope (OWL)

This was a telescope of 100-meters diameter suggested by the European astronomical community in 1998 and thought to be technically feasible by 2010-2015 (see an artist's impression in Figure 15-9). As with all the large telescopes it will peer back further in time than the current behemoths. The "pitch" was to help unlock the mystery of dark matter, to witness the birth of the first stars and galaxies, and, I quote Gilberto Gilmozzi in Scientific American as saying:

> "It has been estimated that a telescope with a diameter of 80 meters would be able to spectroscopically analyse Earth-size planets around the forty nearest sun-like stars. As such, this could help in the exploration of exoplanets and extra-terrestrial life because the spectrum from the planets could reveal the presence of molecules indicative of life."

It's easy to see why people were excited by OWL.

A monolithic mirror of this size creates its own problems, not just in its construction, but more simply, in it being transported from A to B to get erected. When its replacement ***is*** built, it will be a segmented mirror in which each of the 3000 plus segments, will need to be individually adjusted to handle the deformations caused by the telescope's movement, as well as minimizing the twinkling of the stars. Now, because many mirrors are constructed this way, the exacting optical/mechanical difficulties have been worked out, it is the scale of these processes that is the difficulty. It will be expensive, costing at least €1.5 billion dollars. At 100 meters it will have the resolving power of the VLTI without the necessity to match the wavefront to gain optimal resolution (see Section 2.8).

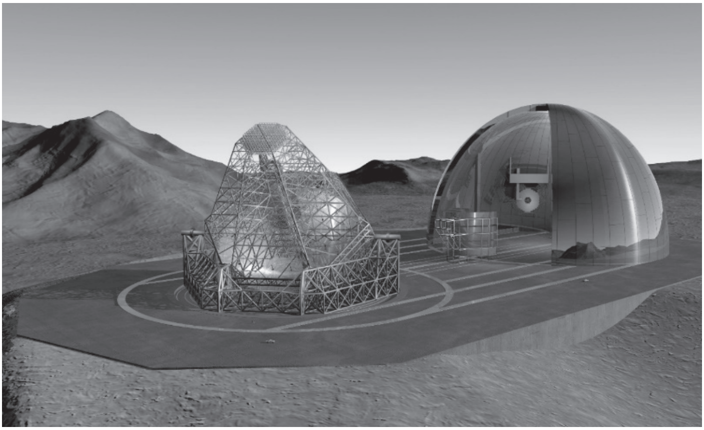

Figure 15-9. An artist's impression of the Overwhelming Large Telescope (OWL). The enclosure to the right will house the telescope and provide access to the secondary mirror which is visible. The lattice is described as an **adaptronic structure** designed to save cost and weight. It looks like the telescope sits in a cradle that rotates and tips. Pretty neat all around I'd say! Credit: ESO Telescope Systems Division.

15.8 Where is astronomy heading?

Maybe I shouldn't have posed the question because it is unanswerable, but from my limited vantagepoint it is defined by the hardware and the technological advances that are now with us—or about to be. Specifically, I'm thinking of the unbelievable industry and imagination that made the detection of gravitational waves a reality. Ever since Weber raised the hope of detecting GWs decades ago it has been the holy grail of astronomers wanting to extend knowledge into the unknown. Enough data involving the advance of periastron in neutron stars within binaries provided ample evidence that gravitation waves existed but like suspecting there was a continent to the west across the Atlantic it only remained a strong likelihood until a European first landed there—the native Americans already knew, along with the Vikings! But now detected, and with groups in the US, another in Italy, and one soon to be online in Japan, it will only be a matter of time before other groups develop interferometers and join with the others to triangulate the positions of each source. Given observations of enough compact binaries detectable in the radio and X-ray domains that are radiating gravitational waves, and knowing the rate of orbit decay, we'll be able to predict the explosions as well as anticipate the gravity waves as we watch the orbits decay. Perhaps the mass limit where black holes form or don't form will be clarified. The extensive surveys of OGLE and Gaia have already detected black hole candidates and the LSST will do likewise. These detections will, in their turn, be thoroughly examined across the electromagnetic spectrum.

Accurate parallaxes and velocities extending outward across the Milky Way will be a huge factor in the study of stars and the motion of the stars orbiting the galactic bulge. Right now, we generalise and identify only two broad groups of stars, those that formed from enriched materials from the first supernovae during the formation of our galaxy (Population II) and those that formed billions of years later over many cycles of supernovae events (Population I). There will be gradations of metallicity variation throughout our galaxy requiring us to study not only its dynamical evolution but also its chemical evolution. The possibilities could go on but I'll only be repeating what has been suggested within these pages. You may want to do your own research by looking at the journal articles identified in the Credits for the various figures. I'm not prescient and make no claim to even guessing about what will unfold, such is the nature of exploration and analysis.

Closer to home, we will look more at the planets in the Goldilocks zones, taking direct images in the hope of seeing a lovely blue planet, but more importantly are the spectroscopic data which will reveal the nature of these planet's atmospheres—the atoms and molecules there, some of which may (will) reveal the existence of life, or at least the likelihood that life is present on the planet's surface. Times have changed. Once we looked outwards towards those galaxies scooting away from us at fractions of the speed of light but now a whole new world closer to home has opened to us. Maybe it is a time to feel nervous, or maybe I've read too many science fiction novels which were my staple reading sixty-five years ago when people like Arthur C Clark, John Wyndham and Theodor Sturgeon—amongst others—gave me the willies with their imaginative stories.

This concludes my overview of which awaits us in the coming decades, not in the content, because that will be full of surprises, but mainly in the way that technology will drive the subject as it always has. From the first sightings using a plumb bob, a tree or a stick in the ground, or a distant horizon and the Sun's seasonal motion along it, to a stone circle, an elegant brass sighting instrument, a telescope; always larger and larger ones, once Earth-based and now in space. And with this growth, the equal expansion of the optical and mechanical hardware, and latterly, computers, for without these commensurate developments the science would be hobbled.

15.9 My omissions

As for the overall content of the book I make no claim to have definitively covered what is going on the field. I have not talked specifically about radio astronomy, the Very Large Array (VLA), ALMA and the **Square Kilometre Array (SKA)** and other major radio astronomy initiatives, like the recently successful Whole-Earth Array that gave us the first direct image of a black hole. The reasons for this, and other omissions, are based on having to limit the topic. Because of this, I have not covered parts of stellar astronomy such as population types based on whether the objects were formed early on in our galaxy's existence or much later. Another topic I've omitted is a discussion of how we correct for interstellar reddening and have just glossed over it hoping the omission will not irritate anyone. In addition, there are many types of variable stars which fit into the evolutionary scheme of things that I've ignored; one was my thesis topic. Two groups of stars show up in the globular cluster H-R diagrams, the blue stragglers (Figure 13-2) and the **red clump giants** (Figure 10-5). I've not developed any stories about these groups but tried to keep what is a vast and complex subject manageable, so that with but a little exercise of memory and concentration, you, the reader, can get through this book without rolling your eyes and giving up in despair. You've seen differences in some of the quoted numbers, mainly in defining limits where this or that happens. They don't reflect sloppiness on my part but the fact is I've not found definitive sources for many of the numbers. This circumstance doesn't sit well with me but I'm stuck with these uncertainties.

15.10 Last words

In science, because of its exploratory nature, what you know today will not predict the future. There is no linear way forward, though what you know now provides the necessary roadmap to get going. The explorers in Africa knew that the Congo river was the kicking off point in their quest to explore central Africa, but what was in the hinterland was outside the range of prediction. Those explorers knew, just as the scientists today know, that the future path of the science will take them into strange places. The detection of gravitational waves makes my point, as it has spawned a whole new area of research, taking it from the theoretical realm into matching predictions with the data and going from there. I admit being stunned by the inter-agreement of observation and theory seen in Figures 1-13, 14-7, and 14-8, let alone the masses of black holes derived from such agreement (Figure 14-9). These (unexpected) developments (for me) are what drives my contemporaries and feeds our fascination with the science. Not just astronomy though, but developments in other science disciplines. There is a strange world out there, a world of the present and that of the past. Within the Earth, and within our history, whether it is studying the Earth's geological, zoological, and biological evolution, the history of the nations of the Earth or the human mind, we have gleaned answers, but much is unknown. The world about me is fascinating. But just as I've attempted to address the question, "What use is astronomy?" our fellow scientists walking different paths, face the same question. For me, I would happily have found a pathway into any subject whose aim was learning more about the world in which we live, whether it involved exploring the past by digging around in ancient ruins, studying the interwoven chronology of ancient cultures, liberating fossils from encasing rock, or exploring the ocean depths… I'm inquisitive and hope that the seeds of exploration that have sprouted in others will continue to be taken up by those in the wider world. If this book serves this hope in any way, I'll feel the labour has been worth it.

GLOSSARY

aberration. How images are distorted by optics. One form of aberration is how a square grid appears curved when photographed. Colour distortion is also a form of aberration. Our eyes are tested for aberration.

absolute magnitude (M_V). The brightness in magnitudes stars have when they are placed at a distance at 10 pcs or 32.6 LY. At this distance, the Sun's absolute magnitude is 4.83.

absorption lines. The dark lines in a spectrum, formed above the photosphere, caused by the atoms of an element selectively absorbing light over narrow wavelength ranges.

active optics. The primary mirrors of modern telescopes may be made up of many individual mirror segments or a monolithic mirror that all sag under their own weight. Active optics is the technology that corrects for these deformations of the primary mirror caused by gravity as the telescope changes position.

adaptive optics (AO). These are optics that can react instantaneously to overcome the twinkling of the stars by using as a guide star a laser beam reflecting from the upper atmosphere. This correction is accomplished by what are called deformable mirrors which react to the slight shifts of the returning laser beam in the focal plane caused by the twinkling.

adaptronic structures. A structure which can adapt automatically to variable operating and environmental conditions using feedback control. They are characterized by multifunctional components that are preferably integrated into the structure with a goal of achieving a lightweight and simple construction which also conserves material and energy resources.

Algol. The archetypical semi-detached eclipsing binary identified in 1783. All semi-detached systems are called Algol systems.

All Sky Automated Survey for Super Novae (ASAS-SN). As the name says, an automated observing program searching for supernovae. The program involves robotic telescopes in the Northern and Southern Hemispheres that survey the total visible sky every night. Detections are found by comparing images taken over successive nights for significant brightness changes.

aperture. The size of the collecting area of a telescope, whether it be a mirror or a lens.

aperture synthesis. When light from a group of telescopes are bundled together in just the right way, they act like a larger telescope in terms of size and resolution. Note that the greater the separations of these telescopes, the greater the resolution. The "Whole-Earth Array" that linked radio telescopes together to see a black hole had an equivalent aperture of the diameter of the Earth.

apparent magnitude. The brightness of a star as seen in the sky. In our scale of brightness, we can see down to magnitude 7. Aside from the Sun, the brightest star is at a magnitude of -1. The smaller the number the brighter the star. The large telescopes in current use have limiting magnitudes of about 22-23.

apps. Applications typically found on a cell phone.

apsidal motion. In binary systems, the slowly changing time of perihelion is called apsidal motion. In a compact binary it is caused by the release of gravitational energy from the system. In normal stars it is caused by the long-term interaction of the component stars on each companion's equatorial bulge. There's some imagery here about humans that I won't delve into.

arcsecond (arcsec). There are 360 degrees in a circle, 60 minutes of arc in a degree and 60 seconds of arc in a minute. Thus 1 arcsecond is 1 part in $360 \times 60 \times 60$ of a circle. When an angle subtends one second of arc it is the equivalent of viewing an object one metre high from 206,265 metres or ~206 km!

asteroid belt. The space between Mars and Jupiter where thousands of rocks are orbiting the Sun. They may be the debris of a planet that did not form, or a planet formed which was subsequently disrupted by Jupiter's massive gravitational influence.

asteroids. Hunks of rock, though of substantial size, orbiting the Sun between Mars and Jupiter, thought to be either a planet disrupted by Jupiter's gravitation or one that never formed. All show impact craters.

astronomical unit (AU). The distance from the Earth to the Sun (149,600,000 km).

asymptotic branch or asymptotic giant branch (AGB). In the context of an H-R diagram, the asymptotic giant branch is formed when stars evolve away from the horizontal branch and end up along a line termed an asymptote on their way to becoming supergiants at the red giant tip and then planetary nebulae.

Atacama Large Millimetre/submillimetre Array (ALMA). Is the world's largest ground-based facility for observations in the millimetre/submillimetre region of the electromagnetic spectrum, located on the Chajnantor plateau, 5000 m altitude in northern Chile.

Atoms. Are made up of combinations of subatomic particles called protons, neutrons and electrons. The protons and neutrons form the nucleus and the electrons fly around the nucleus in a small cloud.

attenuation. How much a star's brightness is diminished by the Earth's atmosphere.

Association of Universities for Research in Astronomy (AURA). Is a consortium of universities and other institutions that operate astronomical observatories and telescopes. Its mission statement is "To promote excellence in astronomical research by providing access to state-of-the-art facilities".

Aurora Australis. The southern lights caused by collisions between the solar wind and atoms and molecules in the Earth's upper atmosphere.

Aurora Borealis. The northern lights caused by collisions between the solar wind and atoms and molecules in the Earth's upper atmosphere.

band head. This refers to molecular spectra where the lines fall on top of one another forming what is called a band head.

beryllium. This is an element used to make a light mirror for use in telescope construction.

Big Bang. Coined by Fred Hoyle, describing the beginning of our universe which blossomed forth from nothing to what it appears today.

Billion. The American definition which is a thousand million (1,000,000,000 or 10^9)

binary stars. Two stars, gravitationally bound, rotating around each other.

blackbody spectrum. Its shape is defined mathematically and represents a hot object that radiates perfectly. Stars radiate as blackbodies but what we observe is not that neat and tidy because of the presence of an atmosphere that absorbs and re-radiates the light flowing through from the photosphere.

black hole. An object where gravity is so great that not even light can escape. They are created during a merger of two compact stars or as a remnant of a supernovae explosion.

Blue horizontal branch (BHB). The hot or blue end of the horizontal branch.

blue sky research. Research undertaken with no thought as to its utility.

blue straggler stars (BSS). A main-sequence star in an open or globular cluster that is more luminous and bluer than stars at the cluster's turnoff point and which has undergone some strange evolution.

Brown dwarfs. Stars with insufficient mass to support normal nuclear reactions in their cores, though they may burn deuterium and lithium. The stellar limits for these latter processes are between approximately 0.013 $M_\odot$ (13 M_J) and 0.075 $M_\odot$, where M_J is Jupiter's mass (0.001 $M_\odot$) and $M_\odot$ is the mass of the Sun.

calculus. The mathematics that deals with continuous change, developed independently by Newton and Leibnitz.

cannibalised. When one star slowly takes mass from the other. Described as dog-eat-dog by Fred Hoyle.

Carbon-14. Is a radioactive isotope of carbon with an atomic nucleus containing 6 protons and 8 neutrons. Its presence in organic materials is the basis of the radiocarbon dating method used to date archaeological, geological and hydrogeological samples.

Carbon-Nitrogen-Oxygen (CNO) cycle. The recipe for converting hydrogen into helium using carbon, nitrogen with these elements as catalysts to facilitate the process. Operates efficiently for high mass stars.

Case A mass exchange. The exchange of mass during a star's evolution to the red giant branch.

Case B mass exchange. The exchange of mass during a star's descent from the red giant branch to horizontal branch and the onset of helium ignition in the core.

Case C mass exchange. The exchange of mass post-helium ignition.

Cassegrain focus. Where the light passes through a hole in the primary mirror and is focussed there, named after its designer Cassegrain (1629-1693).

Cassini's probe. The spacecraft that explored Saturn and its moons and dropped an imaging camera (Huygens) into the atmosphere of Titan to reveal seas of liquid of ethane and methane at a temperature of -170°C.

CCD or charge coupled device. An electronic device that records light falling on it. While these detectors are much smaller than the photographic plate, they give much more accuracy (to 0.01% or better) and can record much fainter stars.

celestial mechanics. Applies the mathematics of Newtonian physics to predict the interactions between the Sun, planets, and their moons. It was an application of celestial mechanics on anomalies in the orbit of Uranus that led La Verrier and Adams to predict the position of Neptune, leading to its discovery in 1846.

Celsius. Abbreviated as C. A measure of temperature based on water freezing at 0°C and boiling at 100°C.

centre of mass. A point representing the mean position of the matter in a body or a binary system.

Cepheid variables. A massive star that pulsates, varying in light over timescales from days to months. Found in clusters and in the general field of galaxies. They are very luminous and because their periods are related to their brightness, they are very useful distance markers when found in other galaxies.

Chandrasekhar limit. The maximum mass of a white dwarf, named after the theoretician who made the original calculations. White dwarfs with masses greater than 1.4 $M_{\odot}$ at the end of their evolution will explode as supernovae.

Chandra X-ray observatory. A NASA space telescope capable of detecting X-rays, which are generally emitted in supernovae explosions, and by neutron stars.

chromatic aberration. Light passing through a lens is dispersed into its constituent colours, each of which focusses at a different place. This is chromatic aberration. Compound lenses, like those found in cameras, are made of different types of glass to minimise this problem.

chromosphere. The lower part of the Sun's atmosphere immediately above the photosphere. It gets its name from the red appearance of glowing hydrogen gas, first seen in total solar eclipses.

circumstellar disk. The disk of material that forms around a star in a binary system when its companion has evolved and is losing mass to it. It is also found in stars surrounded by planet-forming material.

coeval star formation. The assumption that the stars in a cluster all form at the same time, or close enough, considering the timescales of stellar evolution.

colour indices. The measurement of the colour of stars by observing their brightness in two wavelength regions. Typically, the wavelength regions are defined by pieces of coloured glass, or nowadays by a sophisticated equivalent.

colour-magnitude diagram. The diagram formed when the colours of stars in a cluster are plotted against their apparent or visual magnitudes. Such a diagram is like an H-R diagram, except the absolute magnitudes are replaced by their observed magnitudes and the spectral types by their colours.

comets. Objects coming from the far reaches of the solar system, but in orbit about the Sun. They are noticed because of the glowing tails of material that always point away from the Sun. Most make it back "home" but some are gobbled up by the Sun or by Jupiter.

Compton Gamma Ray Observatory (CGO). Was a space observatory (1991-2000) designed to detect photons with energies from 20 keV to 30 GeV. It was one of NASA's four main telescopes housed in one spacecraft, detecting X-rays and gamma rays,

Computer Aided Design CAD). Is the use of computers to aid in the creation, modification, analysis, or optimization of a design. This software allows the user to build things in a computer and get a 3-D picture of the finished product.

constellations. Star patterns in the sky defined by the ancients. A good example is Scorpio (The Scorpion) seen in the southern sky in July and August. Known in New Zealand as the Hook in Māori lore.

contact system. A binary system in which both stars fill their Roche lobes, otherwise called W Uma binaries or W Uma systems.

Convection. The transfer of heat by the motion of material. A pot of boiling water is a good example.

convective overshooting. This occurs when convective bubbles expand into the hydrogen gas outside the convective zone of a star. In this process, they dredge down more fuel for the star to burn, thus extending the lifetime of hydrogen burning. Convective overshooting creates uncertainty in derived evolutionary timescales.

corona. The outer part of the Sun's atmosphere; a region of very hot gases (one million K), first seen during a total eclipse.

coronal mass ejections (CME). Matter is ejected from coronal bubbles that routinely explode from the Sun's surface sending streams of particles outward. When they reach the Earth, they spiral down lines of force at both poles, interacting with the atoms in our atmosphere to produce the aurora, and occasionally disrupting communications.

Cosmic Background Explorer (COBE). The original satellite tasked to measure the distribution of the universe's background radiation in the microwave region.

cosmic background radiation. (CBR). The same as CMB, the residual radiation from the Big Bang.

cosmic microwave background (CMB). The residual radiation stemming from the Big Bang.

cosmic rays. Enigmatic, extremely energetic particles (protons and atomic nuclei) moving from the Sun and from across the galaxy. Perhaps from supernovae.

cosmology. The study of the structure and evolution of the Universe.

Coudè focus. The place where light is directed and then "piped" for examination in a laboratory-type setting. Many mirrors, or a long fibre feed, are necessary to make this transfer.

Coudè mirror. The mirror that sits at the Coudè focus (or Nasmyth focus) that begins feeding light to the Coudè room.

Crab Nebula. The most famous supernova remnant that was seen by the Chinese in 1054 and easily seen through an amateur's telescope. There is a pulsar imbedded within this remnant.

critical point. The place between gravitationally bound objects such as the Earth and the Moon where the attraction from both objects is in balance. There are also critical points outside two orbiting objects where gravity is counteracted by centrifugal force to create a stable orbiting position. L2, is a favourite observing station.

CXC. Chandra X-ray Centre.

degenerate matter. A gas in which the nuclei and electrons are packed tightly together. The pressure of this gas does not dependent on temperature. This situation is found in the interiors of white dwarfs and during other stages of a star's evolution. It is the collapse of this structure caused by an unsupportable, overlaying mass, that creates a supernova.

Detached system. A binary system in which both stars are inside their respective Roche lobes.

deuterium. A variant (isotope) of the hydrogen atom with one extra neutron in its nucleus. Known as heavy water, it is one of the elements formed during the Big Bang and may play a role in aiding nuclear burning in brown dwarfs.

differential rotation. The difference between rotation at a star's equator than near its pole which causes circulation currents within a star.

differentiation. The settling of heavy elements, notably iron, towards the core of the Earth, the Sun, or the stars.

diffraction pattern. In an astronomical context, the ringed appearance of light when it passes through a hole or seen about a pinpoint of light.

digital detectors. A detector such as a CCD, or the variant found in a digital camera.

disentangling. A technique similar to tomography but more effective in reconstructing individual spectra from a series of combined spectra taken throughout a spectroscopic orbit.

Doppler-Fizeau principle or the Doppler effect. The determination of a star's line of sight velocity by measuring the small displacements of wavelength caused by such motion.

dwarf star. A small unevolved star with no special qualities. Average, like the Sun, burning hydrogen in its core

Earth-crossing asteroids or Near-Earth Objects (NEO). Asteroids whose orbits take them across the Earth's orbit about the Sun. These objects pose a great threat to us but there is little we can do about it.

Earth-trailing orbit. An orbiting position following the Earth where a space telescope can be placed, avoiding the continuous concerns about the Earth and the Moon "getting in your face" when you are in an Earth orbit.

echelle spectrogram. A spectrum produced by some clever optics that divides up a long spectrum into shorter lengths and stacks them down a CCD. This counters the difficulty of trying to measure a long spectrum by butting together many CCDs to cover the spectrum. A difficulty is the curvature of the individual spectra and the way their ends shade away across the CCD. Handling this in software to achieve what it promises is a real challenge.

eclipsing binary. A binary star in which one star periodically occults the light from the other star and vice versa. These stars are revealed by characteristic light curves showing two dips, the deeper one occurring when the brighter star is eclipsed.

electric field. A region around a charged particle. I think of the electrostatic field that makes our hair unruly in very dry climes.

electromagnetic pulse (EMP). Experienced first in 1989 when a massive "storm" on the Sun created electricity in the earth to bring down the eastern Canadian electrical grid. As a result of this, the electricals systems have been hardened to prevent a reoccurrence. A similar effect results from an H-bomb detonation.

electromagnetic spectrum. The total range of the electromagnetic radiation covering gamma-rays, X-rays, ultraviolet, visible light, infrared, microwaves and radio waves.

electron. A negatively charged tiny fundamental particle.

elliptical galaxies. Ellipsoidal conglomerations of millions of generally old stars.

escape velocity. The velocity required for any object to escape the bonds of gravity on Earth, or any celestial body. The escape velocity from the Earth is 11 km/s, the Moon 2.4 km/s and that of the Sun is 618 km/s.

European Southern Observatory (ESO). The southern station for the massive European astronomical presence in northern Chile in the Atacama Desert.

European Space Agency (ESA). The agency overseeing European space programs which is linked with NASA.

Event Horizon Telescope (EHT). Is a large telescope array consisting of a global network of radio telescopes.

evolutionary track. The theoretical path a star makes when it is evolved and plotted on an H-R diagram.

exabyte. One followed by 18 zeros, or 10^{18} bytes.

exoplanets. Planets around other stars, or otherwise called extrasolar planets.

exponentially. Rapid growth, like compound interest.

extinction. An astronomical term describing how much light is absorbed by the Earth's atmosphere. Another word for attenuation.

Extragalactic distance scale. The distance scale, extending from stars within our Milky Way to encompass distant galaxies.

extrasolar planets. Planets around other stars, or exoplanets.

extra-terrestrials. Beings from another world.

Extremely Large Telescope (ELT). A massive telescope, of 39-metre diameter, under construction, located at Cerro Paranal in northern Chile.

eyepiece. A lens used to view the image projected onto a telescope's focal plane. It is similar to a jeweller's loupe.

Fermi Gamma-ray Space Telescope (FGST). A NASA gamma-ray (high energy detecting) telescope.

flat-earther. A group of people who believe the Earth is flat. Conspiracy believers in the extreme.

Gaia. An ESA project using a space telescope observing at L2 on the other side of the Moon. Tasked to measure the positions and velocities of a billion stars in the Milky Way and the distances to a million others.

galactic central bulge (GCB) or the **galactic bulge**. The term refers to the group of stars found on the outskirts of the galactic centre.

galactic cluster or open cluster. A loose cluster of stars moving together in the galactic plane.

galactic plane. The plane swept out by the Sun as it orbits the galactic centre.

galaxy. A conglomeration of billions of stars linked gravitationally. They come in three shapes, pinwheels or spirals, elliptical, or undefined shapes (irregulars).

Galileo spacecraft. An American spacecraft that studied Jupiter and its moons, as well as several other solar system bodies. It consisted of an orbiter and an entry probe that was launched into the atmosphere of Jupiter.

gamma rays. Very high energy radiation from the shortest wavelengths of the electromagnetic spectrum. This radiation results from cataclysmic events such as, thermonuclear explosions, stars merging into one another, or from supernovae explosions.

gaseous nebulae. Gases between the stars that form part of the interstellar medium and are revealed by their coloured glow when their atoms react to radiation from illuminating stars.

geocentric theory. The notion advanced by Ptolemy, circa 150 CE, that the Sun revolves around the Earth. It was finally debunked by Copernicus in about 1540.

giant star. A star of large diameter and high brightness or luminosity.

gigabyte. Is 1024 megabytes—a billion bytes.

Global Oscillation Network Group (GONG). A global network of solar astronomers studying the Sun's internal structure and dynamics using helioseismology.

globular clusters. Spherical groups of hundreds of thousands of very old stars that oscillate through the galactic plane. Generally found in what are called the halos of galaxies.

Goddard Space Flight Centre. (GSFC). A necessary part of NASA's chain of command centres. Named after Goddard, an early developer of US rocketry.

Goldilocks zones. The planetary zones around stars thought to be conducive to life. We live in one.

Grand Unifying Theory (GUT). A theory able to relate the four fundamental forces of Nature: the force of gravity, the electromagnetic force, the strong nuclear force that binds atoms together and the weak nuclear force that binds radioactive elements together. There is a possibly of a fifth force which is causing an acceleration of the most distant galaxies.

granulation. The convective cells that bubble up to the Sun's surface.

gravitational redshift. The effect of gravity on light. A white dwarf's gravity shifts its light to longer wavelengths. In the extreme, when light cannot escape, you have a black hole.

gravitational wave (GW). Disturbances in the curvature of spacetime, generated by accelerating masses, such as orbiting compact objects, that propagates gravity in waves outward from their source at the speed of light.

gravity. The force of attraction that wants to pull objects together. A fundamental force of Nature. The basic driver in stellar evolution.

gravity waves (GWs). Disturbances in the curvature of spacetime, generated by accelerating masses, such as orbiting compact objects, that propagates gravity in waves outward from their source at the speed of light.

Great Magellan Telescope (GMT). An equivalent 24-metre telescope being erected at Cerro Pachón, Chile, made up of 7 8.4-metre mirrors.

Great Red Spot. A massive, enduring cyclonic storm on the surface of Jupiter.

Gyr. A giga year, or a billion years.

heat death. The death of the universe if it expands forever.

heliocentric theory. The notion that the Earth revolves around the Sun. Suggested by Aristarchus about 260 BCE and finally proved by Copernicus in about 1540, but not without some resistance from Rome.

heliopause. The boundary in interstellar space where the Sun's influence is countered by the interstellar medium.

helioseismology. The study of the Sun's interior through the measurements of velocities over its surface.

helium. An element created during the Big Bang and transmuted from hydrogen in the stars. It was first discovered in the Sun.

helium flash. At the end of a star's red-giant stage of evolution the interior of a star undergoes a rapid structural rearrangement transmuting its core of helium to carbon over a few minutes.

Henry Draper Catalogue. A star catalogue giving positions, spectral types, and magnitudes of about 360,000 entries, assembled between 1918 and 1936.

Hertz (Hz). Named after Heinrich Hertz (1857-1894) and used to describe the number of cycles/s in a radio wave.

Hertzsprung-Russell diagram or **H-R diagram.** A diagram in which is plotted spectral type or temperature against absolute magnitude or luminosity.

HEXOS. Part of an observing program on ESA's Herschel satellite.

High-reflectance coatings. Every reflection produces a light loss of about 4%. Many reflections degrade the overall light-gathering power of a reflecting telescope. This is counteracted by coating the optics with materials that raises the reflectance to more like 99%. But a coating that works over one wavelength range will not necessarily work as well over another, so generally there are two sets of optics, one of which you choose to use.

Hinode spacecraft. Is a Japan Aerospace Exploration Agency solar mission in collaboration with the US and UK.

Hipparcos. A space telescope (1989-1993) designed to measure the positions and distances of 100,000 stars with a precision of ±1 mas.

Hobby-Eberly Telescope (HET). A large 10-m telescope located in West Texas. It is a modern example of a transit telescope.

horizontal branch (HB). A stage in the evolutionary life of a star just after it becomes a red giant. RR Lyrae stars are found among the stars that pass through this region on the way to becoming red supergiant stars.

Horrendous Space Kablooie. The Big Bang as coined by Calvin, of Calvin and Hobbes cartoon fame, or infamy, depending on how you were interacting with the precocious little genius.

Hubble constant. The constant in the Hubble law that relates a galaxy's velocity to its distance. The inverse of this number gives the age of the universe.

Hubble Space Telescope (HST). A 2.4-m telescope that NASA has been operating in space since 1990.

hydrocarbon compounds. Any of a class of organic chemical compounds composed of the elements carbon (C) and hydrogen (H).

hydrogen. The fundamental element in the Universe. An atom with a nucleus of one proton and one orbiting electron from which all the other elements are built.

Hydrogen core burning. The core of a star transmuting hydrogen to helium.

hydrogen exhaustion. The situation where a star's core has completed transmuting hydrogen to helium.

hydrogen shell burning. The transmutation of hydrogen to helium in a shell surrounding a star's core.

impact craters. The craters we see on the Moon, planets and their moons, and asteroids, resulting from collisions, over eons, with the orbiting rubble of the Sun's formation.

inclination. The angle that a binary orbit is inclined to us, ranging from face-on (looking down the axis of rotation), an inclination of 0 degrees, to side-on, an inclination of 90 degrees.

infrared (IR). Part of the electromagnetic spectrum between the visible and radio region (1000 nm to 1 cm). Our bodies radiate IR in the form of heat. The atmosphere blocks most of the IR but there are a few partial windows that astronomers make use of when observing at altitude above the Earth's surface.

infrared telescope. A telescope that detects heat from the stars.

instability strip. The region in the H-R diagram where stars are unstable and may pulsate.

interferometer. The linking of two telescopes to achieve greater resolution. Used initially with radio telescopes decades ago and only recently with optical telescopes.

International Ultraviolet Explorer (IUE). A joint NASA/ESA telescope launched in 1978 and decommissioned in 1998.

interpolation. The method of generating new data points within a set of existing data.

interstellar gas. The gas between the stars.

interstellar space. The space between the stars.

interstellar medium. The material, gas, dust, grains, and molecules between the stars. Originating from the remnants of supernovae explosions, the dissipation of planetary nebulae, and grains expelled from the atmospheres of very distended cool stars.

interstellar reddening. The dust between the stars that reddens their colours.

isochrones. Lines of equal age in an H-R diagram. Derived from the evolutionary tracks computed for the differing mass models. These isochrones give cluster ages when they are superimposed on observed cluster data.

isotope. Isotopes are variants of a chemical element differing only in neutron numbers. The number of protons remain the same.

James Webb Space Telescope (JWST). The replacement telescope for the Hubble but specialising in observations just redward (IR) of the visual region in the electromagnetic spectrum.

Japan Aerospace Exploration Agency (JAXA). Is the Japanese national aerospace and space agency.

Jet Propulsion Laboratory (JPL). Is a federally funded research and development centre that also serves NASA, located in Pasadena, California.

jet stream. A narrow band of wind that operates at high altitude in the Earth's atmosphere and in other planets. It is readily visible on Jupiter.

Jupiter mass (M_J). 318 Earth masses and 0.001 solar masses ($M_\odot$)

K2. A currently dormant space telescope associated with KEPLER originally tasked to detect and measure the transits of planets across their host star.

Kelvin. Abbreviated as K. Based on a Celsius scheme going upward from the point called absolute zero (-273°C) where the atoms or molecules are motionless. Water freezes at 273 K.

KEPLER. A currently dormant space telescope originally tasked to detect and measure transits of planets across the face of their host star.

kilobyte. A 1024 bytes

Kitt Peak National Observatory (KPNO). The national observatory located in southern Arizona with offices in Tucson.

L1. The inner Lagrangian point, or the inner junction of the Roche lobes.

L2. In the context of a spacecraft, L2 is the critical point on the other side of the Moon where the orbital motion of the spacecraft balances the forces of attraction from the Sun, the Earth, and the Moon.

Large Magellanic Cloud (LMC). One of two galaxies near the Milky Way. Part of what is called the local group of galaxies.

Large Synodic Survey Telescope (LSST) renamed **Vera C. Rubin Observatory.** An American initiative placing an eight-metre telescope at Cerro Las Campanas, in Chile.

Large Zenith Telescope. A unique telescope where the primary was formed by spinning a puddle of mercury into a parabolic shape. Was decommissioned because of poor observing conditions.

Laser Guide Star Facility (LGS). Will be a subsystem of the Adaptive Optics Facility (AOF) on UT4 (one of the 8.4-m telescopes of the VLT), using four sodium laser guide stars to correct the twinkling in the individual VLT telescopes.

Leonids. A trail of material, debris from a long-gone comet, that produces a wondrous shower of meteors every thirty-three years.

light. The region of the electromagnetic spectrum to which our eyes are sensitive.

Light-gathering power. The larger the telescope's lens or mirror, the more light it collects. Like a large bucket collects more water than a small bucket.

Light-travel time. The time it takes for light to cross a stellar orbit. First used by Roemer to measure the speed of light.

light-year (LY). The distance light travels in one year which is 10^{13} km or 6 trillion miles. Multiply the speed of light (300,000 km/s) by the number of seconds in a year ($365 \times 24 \times 60 \times 60$).

limb darkening. The darkened appearance of the Sun's limb caused by the fact that we are looking tangentially to the solar surface and not directly into it.

limiting magnitude. The faintest magnitude that a telescope can detect. For our eyes, the limiting magnitude is 7, whereas for the Hubble it is 31! The Hubble sees ~3 billion times fainter than what we can see but remember the Hubble can take a time exposure which our eyes can't do and that's where the magnitude 31 comes from. While the calculations are awkward, the limit of the telescope should be about magnitude 21-22.

lithium. An element, the product of the Big Bang. The presence of lithium in the atmosphere of a brown dwarf is an indication of its mass.

LMC the Large Magellanic Cloud. One of two companion galaxies to our Milky Way, noted by Magellan in the early 1500s on his ill-fated circumnavigation of the Earth.

Local Group. The group of galaxies that are associated with the Milky Way, includes the SMC, LMC and M31.

luminosity class. A separation of spectral classes into another coordinate which depends on the surface gravity of the stars. The main-sequence objects (unevolved) are classed as V, more evolved stars—bigger, with lower surface gravity are giants classed as IV or III. The final classes correspond to what are termed supergiant stars with surface gravities a hundred times less than the Sun. These are gigantic objects and classed II and I.

lunar occultation. The passage of the Moon occulting a celestial body, generally stars.

Magellan spacecraft. Also known as the Venus Radar Mapper, was a space probe launched by NASA in 1989, to map the surface of Venus using radar and to measure Venus's gravitational field.

magnetic field. The Earth has a magnetic field and the metal in our compass aligns along what we call the lines of force that go from the North Magnetic Pole to the South Magnetic Pole.

magnitudes. A system of defining the brightness of stars devised by Hipparchus in 150 BCE. The smaller the number the brighter the star. The Sun sits at -27 and the faintest star we can see is about 7. The difference of one magnitude represent a brightness change of 2.512. Believe it or not it is still used today!!

main sequence. A band in the H-R diagram running from hot and bright (luminous) to cool and faint along which most stars reside. The reason the band is well-populated is because this is the place where stars spend most of their lives.

Mariner 10. A spacecraft that flew by Venus on its way to photographing Mercury. Later, astronomers were able to measure the masses of both planets by observing how these bodies affected the orbit of the spacecraft.

Mars Reconnaissance Orbiter (MRO). Is a multipurpose spacecraft designed to conduct reconnaissance and exploration of Mars from orbit.

mas. Milliarcsecond or 0.001 arcseconds.

mass. A measure of the amount of material contained in an object. Given in kilograms (kg).

mass loss. The loss of mass of a star during its evolution.

mass-luminosity relation (MLR). A relationship between the mass of a main-sequence star and its brightness or luminosity. The more massive the star is, the more luminous it is.

mass transfer. The transfer of mass from one star to another in a binary system.

MATLAB. A useful programming language used throughout the US college system.

Maunder minimum. The period between 1645 and 1715 when the number of sunspots was almost zero. It also corresponded to a period of intense cold in the Northern Hemisphere. The Sun affects our weather but its cause is unknown.

M_{bol}. The total luminosity of a star given in magnitudes. The value for the Sun is 4.75 magnitudes.

megabyte. A million bytes.

megapixels. A million pixels in a detecting device.

meteors. Bits of space junk that the Earth sweeps up and which burn up in our atmosphere. Occasionally, some are so large that they cause a lot of destruction like one that struck Siberia about a 100 years ago, or the earlier catastrophe that wiped out the dinosaurs 65 million years ago!

metallicity. The amount of metals assumed to be in a star. Young objects like the Sun are assumed to have ~2% by weight of metals and reflect the number of supernovae events that provide their building materials. Stars in globular clusters are assumed to have a tenth of this. Measurements of metallicity are difficult. Many values come from fitting of theoretical models to open cluster and globular cluster colour-magnitude diagrams.

microarcseconds (μarcsec). One millionth of an arcsecond. Gaia is measuring parallaxes with accuracies to this level.

microlensed galaxies. Galaxies that are seen beyond a foreground galaxy that acts as a lens by curving space and focussing the light from this more distant galaxy. By observing this focussed image with a spectrograph, astronomers can piggyback back further in time.

microquasars. A compact region surrounding a black hole.

microwaves. Part of the electromagnetic spectrum in the radio region. We cook food with them.

milliarcseconds (milliarcsec, mas). A thousandth of an arcsecond. The accuracy limit for Hipparcos.

Milky Way. This is where we live; in the vast pinwheel of stars spinning about the galactic centre 25,000 LYs away. The Sun takes about 250,000,000 years for one revolution.

Mira variables. Giant red stars that pulsate over periods of 100s of days. During the cycle they may expel grains of carbon from their atmospheres.

missing mass. The difference in mass between what can be “seen“ and added up and what stars feel dynamically. Shows up in rotation curves of galaxies, the rotation of clusters of galaxies and the motion of stars in the NGP region near to the Sun.

multiplexing. In an astronomical sense, it is observing spectroscopically a group of stars at once, rather than one at a time. The fibre that feeds TV to our homes also covers many other homes at the same time is an excellent example of multiplexing.

Myr. A mega year, or a million years.

nanometre (nm). A unit of measurement equal to 10^{-9} m.

Nasmyth focus. The place in front of the primary mirror that uses a large mirror to deflect and focus converging light from the main mirror to the side and downward to be focussed in a laboratory. Note that the Newtonian focus also deflects light to the side but is viewed at the top end of the telescope.

National Astronomical Observatory of Japan (NAOJ). This national astronomical research organisation comprises several facilities in Japan, as well as an observatory in Hawaii.

National Optical Astronomy Observatory (NOAO). The national observatory centred at Kitt Peak in southern Arizona with its offices in Tucson.

National Radio Astronomy Observatory (NRAO). This is a federally funded facility run by AURA for the purpose of radio astronomy.

Near-Earth Objects (NEO). Pieces of rock orbiting the Sun that pose a risk to Earth.

neutrinos. Massless particles, the by-product of nuclear reactions, traverse the galaxy hardly interacting with matter. Their detection was necessary to prove that the reactive nuclear chains in the core of the Sun were modelled correctly.

neutrons. Subatomic particles of mass close to that of a proton with no electric charge.

neutron star. The object that remains in the aftermath of a supernovae explosion.

North Galactic Pole (NGP). Is on a line through the Earth at right angles to the plane of the Milky Way. This plane is defined by the motion of the Sun around the galactic centre.

nuclear furnaces. Describes the interiors of stars where the nuclear transmutation of one element into another occurs.

nuclear reaction. The process of transmuting one element into another. The primary transmutation involves the conversion of hydrogen to helium.

nuclei. Atomic nuclei, combining protons, neutrons and electrons to form the elements such as hydrogen, deuterium, iron, etc.

nucleosynthesis. The creation of an element from other elements, e.g. the CNO cycle produces helium from hydrogen.

nucleus. The core of an atom about which electrons move.

nova. The name given to a star that brightens out of nowhere.

objective. The lens, or the main mirror of a telescope.

objective prism. A thin prism placed over the end of a telescope which disperses the incoming light so that star images in the focal plane appear as miniature spectra.

opacity. The way radiation or energy is impeded by matter in its flow through a star.

open cluster or **galactic cluster.** A loose cluster of stars moving together in the galactic plane.

Optical Gravitational Lensing Experiment (OGLE). A Polish initiative operating in Cerro Las Campanas, Chile, aimed at detecting microlensing events in the hope that their discovery might account for the missing mass. The volume of data resulting from this program has transformed stellar astronomy.

optical telescope. A telescope that detects visible light.

optics. The mirror, or lens trains within a telescope.

Overwhelmingly Large Telescope (OWL). This was a telescope of 100 meters in diameter suggested by the European astronomical community in 1998 and thought to be technically feasible by 2010-2015. Currently cancelled. I believe, that because Europe thinks big, as shown by their facilities in Chile and the transformative spacecraft Gaia busy at L2, that this remarkable project will go ahead one day.

panspermia. The seeding of life from space.

paraboloid. The shape of a mirror that brings the light to a focus in one place.

parallax. The sideways reflective movement of nearby stars seen against the distant stellar background caused by the Earth as it revolves around the Sun.

parsec (pc). The distance corresponding to a parallax of 1 arcsecond. That is the distance an observer must be so that the angle seen between the Earth and the Sun is 1 arcsecond (or the Earth-Sun distance subtends an angle of 1 arcsecond). One parsec is equivalent to 3.26 LYs.

passbands. The wavelength region over which light is gathered. Usually defined by some sort of filter that lets only one colour through. Think of a piece of red glass that only transmits red light.

penumbra. The radial parts of a sunspot just outside the sunspot centre (umbra).

periastron. The point in a binary star orbit where the stars are closest.

periodic table. Is a tabular display of the chemical elements, which are arranged by atomic number, electron configuration, and recurring chemical properties.

period-luminosity relation (PLR). A reliable relation that links the Cepheid's period to its absolute magnitude such that the longer the period, the brighter the star.

petabytes (PB). Is a measure of memory or data storage capacity that is equal to 2 to the 50^{th} power of bytes (10^{15} bytes). There are 1,024 terabytes (TB) in a petabyte—or 1 million gigabytes (GB)—and approximately 1,024 PB make up one exabyte.

photocathode. A light-sensitive metal coating a negatively charged conductor. When light falls upon it, electrons are emitted—the more light, the more electrons. This is the principle upon which a photomultiplier operates.

photometry. The process of measuring the brightness of stars. Usually through a system of filters that each define a specific wavelength range.

photomultiplier. The photomultiplier is a highly sensitive light detector which generates an electric current proportional to the intensity of the light falling on it.

photon. A particle of light, or best described as a package of energy, from the electromagnetic spectrum whose energy depends on its wavelength.

photosphere. Literally, "the sphere of light". The region below the atmosphere that radiates light or electromagnetic radiation.

pixel. The small picture element (pixel) in our telephone's screen or our TV screen.

planetary nebulae (PN). Stars with shells of gas surrounding them, seen towards the end of their evolutionary lives. This gas glows because of its reaction to the radiation from the parent star.

plate holder. A device that holds the glass plate used in photography, whether a direct image or a spectrogram.

Population I stars. Young stars born in a metal-rich environment. The Sun is a Population I object.

Population II stars. Stars born in a young galaxy when the metals were just being formed and dispersed into interstellar space by supernovae explosions. Globular clusters are Population II objects.

precesses. The motion that spinning tops display as they rotate about some axis. The Earth precesses around an axis over 26,000 years and in the process moves the constellations with respect to the Earth's coordinate system. Precession was measured by Hipparchus 22 centuries ago!! We must correct for these changes when pointing our telescopes.

primary component. Refers to the more massive component in a binary system.

primary eclipse. In an eclipsing system this is the eclipse of the primary component by the secondary component.

primary mirror. The main mirror in a reflecting telescope.

prime focus. The place at the upper end of a telescope where the light from the primary mirror is focussed.

prism. A wedge of glass that spreads light into all its colours.

proper motion. The motion of a star across the sky, measured in seconds of arc per year.

proton. One of the subatomic particles (protons, neutrons, and electrons) that form an atom.

proton-proton chain. The process of converting hydrogen to helium in a solar-type star.

pulsar. Is a neutron star emitting light through its polar regions, seen only because the beam from it sweeps across the Earth like a lighthouse. The neutron star's rapid rotation is revealed by the light flicking on and off during this process.

quadrillion. A petabyte or 10^{15} bytes.

quantum mechanics. Is a fundamental theory of physics that describes the nature and behaviour of matter and energy on the atomic and subatomic level.

quasars. These are very luminous point sources, so-called active galaxies, located at vast distances. Because they appear star-like in a telescope, they are useful in anchoring the coordinate systems adopted in space telescopes like Gaia.

radial velocity. The motion of a celestial body along our line of sight (motion towards and away from us)—its Doppler-Fizeau shift. Measured in km/s.

radiation. Electromagnetic radiation in the form of gamma rays, X-rays, ultraviolet light, visible light, heat, and radio waves…

radiation pressure. The force radiation exerts on matter. The cause of the tails seen in comets and the evaporation of the debris left after the Sun formed out of the interstellar medium.

radio domain. The long-wavelength region of the electromagnetic spectrum. Unblocked by the atmosphere, radio telescopes can freely observe the universe.

radio telescope. A telescope that detects radio waves. Can be one "dish ", or many of them linked together.

red clump giants. Stars in the H-R diagram that form a clump at the cool end of the horizontal branch. As a group in any globular cluster they are useful distance markers.

red giant. A cool, luminous star that is much brighter and larger than the Sun (~100 $R_\odot$).

red giant branch (RGB). The place in the H-R diagram where stars find themselves after having exhausted the hydrogen in their cores. Represents the end of a stars first stage of evolution.

red giant tip (RGT). The star's final evolutionary state before it starts shedding its mass through the planetary nebula phase.

red horizontal branch (RHB). Stars at the red or cooler end of the horizontal branch.

redshift. Distant galaxies are receding from us. This recession moves a spectrum to longer wavelengths. If the galaxies were coming towards us, they would be described as "blue-shifted".

Red Sirius. The report, that in biblical times, Sirius was described as a red star.

red supergiants. Cool, gigantic stars, thousands of times the size of the Sun. They're at the stage of evolution just before they lose mass as planetary nebulae.

reflecting telescope. The type of telescope that collects the light with a parabolic-shaped mirror. Radio waves are collected the same way—think of your TV dishes on the roof.

refracting telescope. The type of telescope that uses a lens to collect the light.

remote sensing. This is what we do when we can't touch the object we are observing. It is true for astronomers observing the stars or an observer in a deep-sea bathysphere. Similarly, a geographer surveying the Earth's resources from space.

resolution. The detail you can see. Improve your eyesight and improve the resolution. Increase the number of pixels and you increase the resolution. Alternatively, do the impossible, make your eyes spread further apart. Or technically, the resolution of an optical system is related to the smallest angle between, for example, two stars that can still be seen by the observer as separate entities.

resonate. The situation when a natural vibration (think of a swing) is enhanced by a judicious use of force—like your legs swinging out at just the right time.

Roche lobe or Roche surface. The surface surrounding the two stars in a binary system where the material is gravitationally bound to the associated star. Outside of these lobes anything goes.

RR Lyrae stars (RRL). White giant stars that pulsate with periods of less than a day. They are found in the general field and in globular clusters falling between the red and blue horizontal branches in an H-R diagram. They, like the Cepheids, are useful as distance markers.

scientific method. The essence of it is simple. Present a hypothesis, make a prediction and test that prediction. The hypothesis rises or falls on the success of this prediction.

Search for Extra Terrestrial Intelligence (SETI). As its name says, a radio-based program that is searching for signs of extra-terrestrial life. It has morphed into Breakthrough Listen and is well-funded. Data are being continuously collected and analysed.

secondary component. Refers to the less massive component in a binary system.

secondary eclipse. In an eclipsing system, this is the eclipse of the secondary, or cooler, component by the primary, hotter, component.

secondary mirror. In a reflecting telescope, this is the mirror that reflects the light from the main mirror to a place where it can be viewed or recorded.

seeing. The motion of the star as it dances around in the viewing eyepiece of the telescope or, as we see it outside, a twinkling star. When we use a detector to capture the twinkling image this effect produces a large image. like a poor focus in your camera.

semi-detached. A binary system in which one star fills its Roche lobe. Algol is the archetypical example.

signal-to-noise. Is a measure of reception. Think of the static on your radio. A clear signal means high signal-to-noise. A static-riven signal means a low signal-to-noise. Are our pictures clear or grainy? For photometry, a signal-to-noise value of 1000 to 1 is very good but for spectrophotometry a value of 10,000 is necessary and with some care can be routinely accomplished.

Sirius. Aside from the Sun, this is the brightest star in the sky. The companion to the first white dwarf ever discovered.

Sloan Digital Sky Survey (SDSS). A major redshift survey using a dedicated 2.5-metre wide-angle optical telescope in New Mexico.

SMC the Small Magellanic Cloud. One of two companion galaxies to our Milky Way. Noted by Magellan in the early 1500s on his ill-fated circumnavigation of the Earth.

Solar and Heliospheric Observatory (SOHO). A space telescope, operated by ESA and NASA, that monitors the Sun.

solar atmosphere. The region outside the photosphere where spectral lines are formed. In the solar spectrum, these show up as dark lines because the atoms absorb light at specific wavelengths characteristic of the element involved.

solar constant. The amount of heat falling on the Earth measured in Watts/square metre. This value oscillates between 1365 and 1367 W/s.

solar cycle. Reflects magnetic activity on the Sun over an 11-year cycle. In this time sunspots numbers are a maximum at the peak of the cycle and drop away to a minimum near mid-cycle.

Solar Dynamics Observatory. The SDO is designed to help us understand the Sun's influence on Earth and near-Earth space by studying the solar atmosphere on small scales of space and time.

solar dynamo. Caused by electric fields in the rotating molten iron core of the Sun.

solar flares. Eruptions on the Sun caused by magnetic disturbances. Flares are seen on other much cooler stars.

solar irradiance. The amount of heat falling on the Earth measured in Watts/square metre. This value oscillates between 1365 and 1367 W/s.

solar luminosity. The amount of energy the Sun emits in one second is 3.828×10^{26} W.

solar mass ($M_\odot$). The mass of the Sun is 1.99×10^{30} kg.

solar prominence. A prominence is a large, bright, gaseous feature extending outward from the Sun's surface, often in a loop shape defined by the magnetic field which carries it.

solar radius ($R_\odot$). The radius of the Sun is 6.96×10^5 km.

solar seismology. The study of the Sun's interior using motions (velocities) of convective granules measured on its surface and is related to how seismologists study the Earth's interior.

solar system. The Sun and its retinue of planets.

solar wind. The stream of atomic nuclei flowing out of the Sun. This wind creates the comet's tails by pressing on the dust and gas surrounding the object.

South African Large Telescope (SALT). An example of a 11-m transit telescope.

South Galactic Pole (SGP). Is on a line through the Earth at right angles to the plane of the Milky Way. This plane is defined by the motion of the Sun around the galactic centre.

Space Telescope Science Institute (STScI). The institute that supports the Hubble, Webb and WFIRST space operations.

speckle photometry. Seeing moves the focussed image over the CCD. If you record the image in short exposures, typically ten a second, which is the timescale over which each image moves, you can stack each exposure onto one selected as the master to produce a very sharply defined image. In this way, stellar diameters have been measured as well as reliable separations of visual double stars. Using this method, amateur astronomers get great pictures of Jupiter and Saturn.

spectra. The appearance of light when it is dispersed through a prism or a water droplet—think of a rainbow.

spectral classes. The nomenclature of these temperature classes is OBAFGKM representing O stars as hot (40,000 K) and M stars as cool (2,500 K). The system is subdivided such that the Sun on this scale is classified G2. Another part of this scheme involves luminosity classes to refine the system further.

spectral type or spectral class. Stars are classified into spectral types according to the appearance of their spectra which in turn reflect a star's temperatures.

spectrograph. A device based on a prism or a grating (a series of parallel lines drawn on a reflective surface), that spreads the light out into all its colours. Check your stainless-steel benchtop.

spectrophotometry. The process of acquiring spectra by using either a CCD or a photoelectric scanner.

spectroscopic binaries. Binaries revealed by the appearance of two spectra in a spectrogram or by detecting varying cyclic radial velocities in one or two spectra.

spectrum. Sunlight spread out into all its colours forms a spectrum. Violet (UV) at one end and deep red (near-IR) at the other.

spiral galaxies. The pinwheel-shaped galaxies.

Spitzer Space Telescope (SST). An infrared telescope that is playing a role in the discovery of planetary companions around nearby stars. I believe it will be retired soon.

Square Kilometre Array (SKA). Is a radio telescope project proposed to replicate arrays built in Australia and South Africa. If built, sometime in the 2020s, each array would have a total collecting area of approximately one square kilometre.

standard candle. A star whose absolute magnitude is known, allowing it to be used as a distance marker. The most notable standard candles are Cepheids, RR Lyrae stars and supernovae originating in a binary system containing a white dwarf.

standard stars. Stars for which we have reliable data that can be used to calibrate observations. There are standard stars for the varied calibration of brightness, colour, velocity, spectral type, and abundance.

starbursting galaxies. A galaxy undergoing an exceptionally high rate of star formation. Most noticeably during a collision or a near miss between galaxies where gas common to both systems collide, coalesce, and collapse to create a burst of star formation.

stars. Hot, self-gravitating masses of gas. Our Sun is a star.

Stellar astronomy. This is the study of the stars.

stellar densities. Densities inside stars (density is mass/volume).

stellar evolution. The lifecycle of stars from their birth out of the interstellar medium to the end of their lives as slowly cooling, compact bodies or as black holes.

Sun's limb. The edge of the Sun which looks darker than at its centre. This darkening is called limb darkening.

sunspots. A dark, cool region on the Sun's surface caused by intense magnetic fields which impede the rise of hot gasses from below. The spot numbers increase and decrease over an 11-year cycle.

supergiant. Gigantic stars, thousands of times the size of the Sun. They're at the stage of evolution just before they lose mass as planetary nebulae.

supernova or supernova explosion. The light that suddenly appears from a star that has blown up and formed a neutron star or a black hole. There are two types of supernovae. Type Ia originating in a binary system and Type II from a single star whose mass is above the Chandrasekhar limit at the end of its evolution.

T_e. The surface temperature of a star is called the effective temperature. The Sun's effective temperature is 5770 K.

telescope. A combination of lenses and/or mirrors that magnify an object. But it is more than that, a telescope gathers more light than our eyes, so it can "see" fainter stars or reach fainter magnitudes.

terabyte (TB). Is 1024 Gigabytes or 1,000 billion bytes.

teraflop. The speed that a computer can do arithmetic operations.

terrestrial telescope. Reflecting and refracting telescopes invert the image so using one to observe objects on the Earth requires the insertion of an additional lens to provide an upright image.

Thirty Metre Telescope (TMT). An American venture to put a thirty-metre telescope on the top of Mauna Kea in Hawaii.

tomography. Reconstruction of individual spectra from a series of blended spectra taken throughout a spectroscopic orbit.

TRACE (Transitional Region and Corona Explorer). A space telescope that observes plasma events associated with the Sun's magnetic field.

transit telescope. A passive form of observing where the telescope only moves in one direction and makes no attempt—or but a little—to compensate for the Earth's rotation. Two hundred years ago the positions of the stars were originally measured by timing their passage as they moved across a crosshair in the focal plane of a telescope. A variant of this technique was used by the space telescope Hipparcos, and its successor Gaia currently at work on the other side of the Moon.

TRAPPIST. Transiting Planets and Planetesimals Small Telescope.

TRAPPIST-1. Is a planetary system, discovered by the spacecraft TRAPPIST, located about 39 light-years away from the solar system.

trillion. A trillion is a million-million or a UK billion (1 followed by 12 zeros or 10^{12}).

triple-alpha process. The creation of carbon by the fusing of three helium nuclei.

tritium. A variant of the hydrogen atom with two extra neutrons in the nucleus.

turnoff point. The place in the H-R diagram where a star starts to evolve away from the main sequence.

twinkle. The blinking of starlight caused by its passage through the Earth's atmosphere.

Tycho. A program associated with the spacecraft Hipparcos that extended positional measurements to a million stars but at reduced accuracy.

***UBV* photometric system.** A photometric system where the passbands are defined by a combination of filters, the Earth's UV cut-off, and the response of the photomultiplier used in the photometer. Originally glass, these passbands have created a world of hurt but are now replicated by more reproducible filters.

ultraviolet rays (UV). The part of the electromagnetic spectrum between X-rays and the visible spectrum. The rays from the long wavelength end of the UV are what burns us. The shorter wavelengths are blocked by the Earth's atmosphere.

umbra. The dark centre of a sunspot.

variable stars. Stars whose brightness varies intrinsically like the Cepheids, or extrinsically, like eclipsing binaries where the light changes come from the geometry of the situation.

Vera C. Rubin Observatory, formerly the **Large Synodic Survey Telescope (LSST).** An American initiative placing an 8-m telescope at Cerro Las Campanas, in Chile.

Very Large Array (VLA). A massive array of radio telescopes located in the New Mexico desert which acts as a huge interferometer.

Very Large Telescope (VLT). A group of four 8.2-m telescopes located at the ESO station on Cerro Paranal in Chile. They can work independently or together as an interferometer.

Very Large Telescope Interferometer (VLTI). The VLT when used as an interferometer. In this mode they function as if they are a 100-m telescope with a resolution in the near IR of 0.001 arcseconds.

Very Long Baseline Array (VLBA). An interferometer formed by linking radio telescopes in the USA with a 100-m telescope in Germany.

visual double stars. Binary stars seen as double on the sky and whose orbits can be directly measured.

visible light. Is the part of the electromagnetic spectrum to which our eyes react. The wavelength of visible light is around 600 nm.

visual magnitude. The same as apparent magnitude. The brightness of a star (V) when measured in a standard photometric system.

VLT (Very Large Telescope). A group of four 8.2-m telescopes located at the ESO station on Cerro Paranal in Chile. They can work independently or together as an interferometer.

Voyagers 1 and 2. Launched by NASA in 1977. Voyager 1 did a flyby of Jupiter and Saturn before zooming outward from the plane of our solar system to explore the heliopause. Now it is in interstellar space. Voyager 2 did a grand tour out to Uranus and Neptune and presented us with the stunning pictures we view today. It is still in communication with the Earth and is near to, or in, the heliopause.

wavelength. The distance between two wave crests. Light is a wave and its wavelength, unlike those at the beach which are tens or hundreds of meters from crest to crest, is about 6×10^{-7}m from crest to crest.

white dwarf. The endpoint of the Sun's evolution, yielding an Earth-sized star with a mass about that of the Sun leading to densities beyond comprehension.

Whole-Earth Radio Telescope or Whole-Earth Array. A radio telescope formed by linking telescopes across the Earth to form a single coherent telescope with a diameter that of the Earth.

Wide-angle Infrared Survey Explorer (WISE). An infrared space telescope that has found many brown dwarfs in the solar vicinity.

Wide Field Infrared Survey Telescope (WFIRST). An infrared space telescope yet to be launched aimed at researching dark matter and exoplanets.

Wilkinson Microwave Anisotropy Probe (WMAP). A high-resolution version of COBE aimed at mapping the background radiation from the early universe in the microwave region of the electromagnetic spectrum, additionally, measuring its temperature at 2.7 K.

W UMa binaries. The archetypical contact (dumbbell-shaped) binary system.

X-rays. High energy radiation shortward of the UV in the electromagnetic spectrum. These are the rays that see through our flesh to reveal our skeletons.

X-ray Multi-Mirror Newton (XMM-Newton). An ESA space telescope capable of detecting X-rays from space, generally from neutron stars and supernovae explosions.

X-ray telescope. A space telescope that detects X-rays.

Zeeman effect. The splitting of a single spectral line into two or more lines when the radiation originates in a magnetic field. It is most noticeable in sunspots but detected in some stars.

zero-age main sequence (ZAMS). A sequence of stars in the H-R diagram we think of as stars of zero-age.

Journal Abbreviations

A&A	Astronomy and Astrophysics
A&AS	Astronomy and Astrophysics Supplements
A&SS	Astrophysics and Space Science
AA	Acta Astronomica
AJ	Astronomical Journal
AAS	American Astronomical Society Meeting
ApJ	Astrophysical Journal
ApJS	Astrophysical Journal Supplements
ASP	Astronomical Society of the Pacific Conference Series
MNRAS	Monthly Notices of the Royal Astronomical Society
NASA	National Aeronautics and Space Administration
Nature	British multidisciplinary scientific journal
PASP	Publications of the Astronomical Society of the Pacific
PDAO	Publications of the Dominion Astrophysical Observatory
PNAS	Proceedings of the National Academy of Science
PRL	Physical Review Letters
RA	Royal Academy of Arts
Science	The science journal of American Association for the Advancement of Science
STScI	Space Telescope Science Institute

LIST OF ILLUSTRATIONS AND FIGURES

Figure 1-9. The electromagnetic spectrum. Note the narrow band of wavelengths through which we view the universe. Now observations with new detectors launched on satellites allow us to observe the whole of the displayed spectral range (see Figure 1-10 also). Note that the wavelength scale is displayed in nanometres (nm or 10^{-9} m) rather than astronomy's traditional Angstroms (10 A is 1 nm). Credit: Image from the Web. Redrawn and modified by the author.

Figure 1-10. The electromagnetic spectrum and the Earth's blocking atmosphere. The upper panel shows the blocking effect of the Earth's atmosphere on the electromagnetic spectrum. A glance at the lower panel reveals that our view of the universe, if limited to the visible and radio regions, leaves out most of the electromagnetic spectrum. Airborne observatories fly at high altitudes to reach part of the IR. Radio telescopes "see" right through the Earth's atmosphere. It is not surprising that since space-borne telescopes have opened the whole of the spectrum, a picture of the universe is forming that contains many surprises. Credit: NASA/ESA Modified by the author.

Figure 1-11. The distribution of energy within a heated body is shown for three temperatures. As the temperature increases, the peak of the energy moves to shorter and shorter wavelengths, or to higher frequencies. Our eyes are attuned to the region of the spectrum peaking near 6000 K, which is the approximate temperature of the Sun's surface. The wavelength scale is given in units of a billionth of a metre. Credit: Unknown source. Modified from the Web by the author.

Figure 1-12. The shape of the electromagnetic spectrum (called a blackbody function) at 2.7 K compared with the observed microwave data. The fit is so perfect that the observations are under the theoretical line! I can't recall ever seeing data so beautifully represented by theory. Credit: NASA.

Figure 1-13. The original wobbles of gravity that confirmed the existence of gravity waves. The two sites, one in an old nuclear facility in Washington State and another in Louisiana, recorded the same signal with a 7-millisecond delay in Washington State. Gravity travels at the speed of light so we'd expect—and get-- a perfect coincidence in time as well as the "wobbles" to be in perfect tune (excuse the pun!). I can't describe the vertical axis called "strain", but whatever it is it is unbelievably small! The final few vibrations are called "chirps". Credit: Abbott et al., 2016, PRL 116, 061102-1. Modified by the author.

Figure 1-14. Upper panel. The Milky Way from above, showing the spiral arms which have been mapped using radiation from neutral hydrogen gas within the arms. Lower panel. The Milky Way is like a giant pinwheel. The Sun's orbit is indicated and it takes about 250 million years to orbit the galactic centre 25,000 LYs away-. Credit: NASA/Chandra. Modified by the author.

Figure 1-15. Early lithographs depicting the Leonid meteor showers in 1799 and 1833. These are accurate depictions of what I saw in 1966. Credit: In the public domain.

atmospheric distortions of the twinkling light from actual stars—a process called adaptive optics. Credit: ESO. The author modified original comments.

Figure 3-1. At the time when the shadow of the Sun bisects the Moon (exactly First Quarter) we have a right-angled triangle with the right angle at the Moon. Measuring the angle at the Earth between the Earth-Moon and the Earth-Sun (angle A) gives a measurement of the Earth-Sun distance (D) in terms of the Earth-Moon distance (d). Credit: Redrawn from Discovery of the Universe, de Vaucouleurs 1956.

Figure 3-2. Illustrating the basis of Eratosthenes' method for measuring the diameter of the Earth. When the Sun is directly overhead at noon at (Cyrene) it is not directly overhead at a different latitude (Alexandria)—if the Earth were flat then the angle would be the same as measured at both places. The measurement of the angle away from the vertical at Alexandria, A in this figure, combined with the known distance between the two sites (D) gives a measure of the Earth's circumference and hence its diameter = $360 / A \times D$ in the units of distance D. Credit: Redrawn from Discovery of the Universe, de Vaucouleurs 1956. Annotated by the author.

Figure 3-3. The moon Dactyl orbiting the asteroid Ida as seen from NASA's Galileo spacecraft in 1993. Ida is the large object to the left and Dactyl is the small object to the right. This portrait was taken about 14 minutes before Galileo's closest approach to the asteroid from a range of 10,870 km (6,755 miles). Ida is 53 km long and Dactyl, the small image to the right of Ida, is 1.6 km. The insert shows a close-up of Dactyl taken when the spacecraft was almost at its nearest point. Credit: Commentary and image NASA/Galileo.

Figure 3-4. The triangulation of Venus after Halley, showing the views of the planet Venus transiting the Sun as seen from Greenwich and Tahiti in 1769. The measurement of the size of the arcs on the Sun (we know the size of the Sun in arcseconds) gives the angular distance to Venus (A) as seen between Greenwich and Tahiti. Knowing the distance in km between these places, then gives the distance to Venus in km, and, therefore, that of the Sun. Credit: Redrawn from Discovery of the Universe, de Vaucouleurs 1956. Annotated by the author.

Figure 3-5. The beginning of two modern transits of Mercury. In the left panel, as imaged by the Japanese Spacecraft Hinode in 2006, Mercury is seen against the limb of the Sun. The limb looks darker because we are looking at an angle into it and into the cooler upper solar atmosphere. The effect is called limb darkening. The right panel shows Mercury about to begin its transit in November 2019. The image is from a NASA movie. Credit: Left panel. JAXA/NASA. Right panel. NASA.

Figure 3-6. The partial echellè spectrogram of a cool star. The star's spectrum is white and the lines of the star appear dark (discussed in next section). The bright white lines beside the stellar spectrum come from the comparison spectrum needed to convert the horizontal scale into wavelengths. Each of the 6 spectra displayed here cover different wavelength ranges which overlap at each end and so they can be

Orion. Angling down from the left are three stars forming “Orion’s Sword”. The large fuzzy central object in the sword is not a star but a gaseous cloud called the Orion Nebula. Credit: NASA.

Figure 4-3. An image of the solar photosphere showing the granulation, or convective bubbles near a sunspot. The bright patches are bubbles of hot gas rising from within the Sun. The darker areas among the patches are cooler gases dropping back into the interior. Similarly, the darker areas in the sunspot indicate that they are cooler than the surrounding gas. The black centre of the sunspot is called the umbra and the radial parts are called the penumbra. The sunspot is about 20,000 km across and the granules about 1500 km. Credit: NASA. Modified by the author.

Figure 4-4. These are images taken towards the limb of the Sun by TRACE. The loops represent some of the millions of magnetic lines of force (called field lines) erupting from the Sun’s surface. Gases move along these field lines and are heated to millions of degrees as they rise upwards to 500,000 km above the photosphere. Credit: NASA/TRACE.

Figure 4-5. Left-hand panel. Image of the solar corona during a total solar eclipse on Monday, August 21, 2017 above Madras, Oregon. Right-hand panel. Image of corona from NASA's Solar Dynamics Observatory showing features created by magnetic fields. Credit: Left panel. NASA/Gemignani. Right panel. NASA.

Figure 4-6. A CME interacting with the Earth. Note that the objects are not drawn to scale. Credit: NASA/ESA.

Figure 4-7. The image on the left is a picture of a sunspot. The dark line running through the middle of the picture is a slit which feeds the spectrograph to produce the rightmost image. The three vertical lines are from a single line, due to iron, split into three because of the magnetic field in the sunspot. Outside the sunspot the line is single and is unaffected by the Sun’s magnetic field. By measuring the amount of this splitting, we can find out the strength of the magnetic field across the sunspot. Credit**:** NOAO.

Figure 4-8. The Maunder minimum, a period when the Sun had few sunspots and Europe experienced very cool weather over about 50 years. Credit: Wikimedia Creative Commons/Rohde. Modified by the author.

Figure 4-9. The panel shows Comet Neat and a large CME. The small white circle to the lower left represents the Sun which is blocked from view by a disk in the telescope. The white spots are stars. Check in at the SOHO website and maybe download a screensaver showing the Sun in real-time, which will do nothing to allay any insecurities you may have about the world “out there”. Credit: ESA/NASA/SOHO.

Figure 5-1. Plots of Hubble’s Law showing the relation between galaxies recessional velocities and distances, illustrating the expansion of the universe. The left panel is

the motion of the faint white dwarf around Sirius A. The haze of open circles represents the observations made at the telescope. Credit: Left panel. A common diagram on the Web. Right panel. Unknown source. Images annotated by the author.

Figure 7-1. A spectrum of a star like the Sun. The graininess of the three spectra comes from the silver halide crystals intrinsic to the photographic process. The outer spectra come from the telescope where an iron arc has been produced and provides a wavelength scale with which to calibrate the stellar spectrum seen in the centre. Also note that the stellar lines are shifted to longer wavelengths when compared to the arc. This indicates that the star is moving away from us. Credit: A spectrum from the Dominion Astrophysical Observatory (DAO). Annotated by the author.

Figure 7-2. Emission lines characteristic of some elements. The sodium lights, which are familiar to us, radiate in the yellow-orange region of the spectrum. The now outmoded mercury lights shine in the blue from the lines to the left in this figure. Note that these are emission lines whereas in the stars it is the atoms of these elements that absorb light flowing outwards from the hot photosphere. Credit: Source unknown. Adapted by the Author.

Figure 7-3. Example of an objective prism or getting more bang for your bucks. With an objective prism there is no more getting one spectrum at a time! In this way it was possible to examine the whole sky to below about a factor of 10 what we could see with the naked eye and multiplexed to boot. Credit: Unknown.

Figure 7-4. Representative stellar spectra. The spectra here show the differences between the hot stars (B0) with temperatures about 30,000 K and cool stars with temperatures near 2,500 K. In hot stars, hydrogen lines predominate but below 10,000 K iron lines become more and more prevalent. For even cooler stars like Betelgeuse near M6, iron is replaced by lines due to carbon-based molecules and titanium oxide. Credit: Assembled from various source and annotated by the author.

Figure 7-5. The Hertzsprung-Russell diagram (H-R diagram) as Russell first presented it. The main band of stars is called the main sequence. Upwards and to the right are the **red giants** and **red supergiants**. In contrast in the lower left we have the white dwarfs. Note the difference in magnitude between the white dwarfs and their main-sequence spectral counterparts above them and the crude classification scheme available at the time. The main sequence is well-populated because stellar evolution is very slow there. Credit: Russell, 1914, Nature, 93, 252. Modified by the author.

Figure 7-6. A series of spectra showing the change in appearance of spectral lines depending on temperature and luminosity. Here, main-sequence stars (dwarfs) are compared with giants, while the letter to the right indicates a broad spectral type. The giant designation reflects the star's gravity. The main-sequence stars have larger gravities than the giants. The three prominent lines in the upper images are due to hydrogen and those lines in giant stars are sharper than in dwarfs. Credit: Morgan. Yerkes Observatory. Modified by the author.

as a fill-in observing program while you do other things. Credit: Hill, 1979, PDAO, 15, 297. Annotated by the author.

Figure 7-14. Illustrating the detection of three exoplanets from radial velocity measures. Notice the radial velocity scale given in metres/sec, the equivalent of running 100 metres in 20 seconds! Credit: Source unknown. Modified by the author.

Figure 7-15. Illustrating the detection of seven exoplanets in the TRAPPIST-1 star system from eclipse observation made with KEPLER and the Spitzer Space Telescope (SST). The eclipses are clear-cut; the depths show the relative sizes of the planets and the lengths of the flat bottoms indicate the planet's orbital velocity and where they are transiting across the face of the star. Credit: ESA/NASA/TRAPPIST/ Spitzer Space Telescope.

Figure 7-16. This is one of the most striking examples of gravitational lensing, where the gravitational field of a foreground galaxy bends and amplifies the light of a more distant background galaxy. In this image, the light from a distant galaxy nearly 10 billion light-years away, has been warped into a nearly 90-degree arc of light by the galaxy cluster RCS2 032727-132623 which lies 5 billion light-years away. A spectrum taken from this arc would allow us to look back 10 billion years. Credit: NASA, ESA/Rigby (NASA GSFC)/Sharon (Kavli Institute for Cosmological Physics, University of Chicago)/Gladders and Wuyts (University of Chicago).

Figure 8-1. Eddington's original mass-luminosity relation based on masses derived from astrometric orbits (orbits seen on the sky) and eclipsing variables. When Eddington discovered this relationship, he knew immediately it said a lot about how stars evolve, and thus seeded more productive studies of stellar evolution. Credit: Eddington, 1926, The Internal Constitution of the Stars. Modified by the author.

Figure 8-2. A Hertzsprung-Russell diagram showing the masses along the main sequence in terms of the Sun. The spectral types are shown as broad bands along with the temperatures. The diagram already gives clues as to the evolution of stars. The Hertzsprung gap is almost devoid of stars so whatever happens there happens quickly. Where there are lots of stars, as along the main sequence, evolution must proceed slowly, but slightly faster in the red giant region. Credit: NASA/Chandra. Modified by the author.

Figure 8-3. A schematic diagram showing how the elements come and go as a function of temperature. If you look at the helium (He), iron (Fe) and calcium (Ca) spectra you'll see how the less energetic atoms are excited (He I, Fe I, Ca I). They peak at some temperature and decline just as the high energy parts of each spectra (He II, Fe II, Ca II) grow and peak and decline as the electrons that form the spectra are not excited because of the higher temperatures (see text). Credit: Redrawn from Carroll and Ostlie, 1996, Modern Astrophysics. Modified by the author.

Figure 8-4. Left panel. Using ESO's Very Large Telescope Interferometer, astronomers have constructed this remarkable image of the red supergiant star Antares to match

Figure 9-5. Left panel. The colour-magnitude diagrams of the Hyades and Pleiades. The curled parts of the diagram represent stars that have evolved. The little rows of points just above each main sequence are binary stars which are brighter because there are two of them. The main sequences are defined to be unevolved, or of zero age. These unevolved sequences are the key to extending the distance scale to the most luminous stars in our galaxy. If we slide the Pleiades upward to piggyback onto the unevolved part of the Hyades then what is termed the zero-age main sequence (ZAMS) can be extended to hotter temperatures. Right panel. The results of the piggybacking process where various clusters have been assembled to show how the ZAMS was formed. Thus, given a new cluster, we can slide its main sequence onto the one derived from here and so derive its distance. Credit: Left panel. ESO Projects. Right panel. Sandage, 1958, RA, 5, 41. Both figures modified by the author.

Figure 9-6. A schematic light curve of a classical Cepheid. Because the light curves of these stars are easily recognised in distant galaxies, and there is a relationship between their periods of oscillation and absolute luminosity, they are invaluable in extending the distance scale outward to the galaxies. Adapted by the author.

Figure 9-7. Left panel. The relation between the periods of the Cepheids and their apparent magnitudes in the SMC. There are two lines, the upper one is the star at its brightest and the lower line is the star at its faintest. The right panel shows the period-luminosity relation (PLR) as derived in 2007. The funny scale on the bottom of both graphs is a logarithmic scale. This relation is fundamental to establishing the scale of the universe and was a monumental discovery not fully utilized until the 50s. Credit: Left panel. Leavitt, et al., 1912. Harvard Circulars. Right panel. Fouqué et al., 2007, A&A, 476, 73. Both figures are modified by the author.

Figure 9-8. The effects of reddening on starlight are beautifully revealed in these pictures of two obscuring dust cloud. Around the edges of the clouds you can see the stars appear red, just as distant headlights appear red in a heavy dust storm. The unreddened stars are between us and these clouds. By observing the stars in three colours UV, blue and yellow we can largely correct the observed colours for reddening as it is called. Credit: ESA/Hubble, ESO.

Figure 10-1. This image, called "The pillars of creation" must be regarded as one of the iconic pictures of the 20^{th} century. It shows a mass of stars forming within interstellar material that is the home to future glowing bodies we know as stars. It is thought that all stars formed like this within cocoons of gas and dust. Credits: ESA/Hubble.

Figure 10-2. The image indicates the collapse times to the main sequence for stars between 0.5 and 15 solar masses. The Sun took about 50 million years to reach the main sequence. Credit: Iben, 1965, ApJ, 141, 993. Modified by the author.

Figure 10-3. Left-hand panel shows an H-R diagram illustrating the downward path of clouds compacting out of the interstellar medium. The numbers represent mass and the stars plotted are thought to be pre-main sequence. A good example of the

at the shorter wavelengths and if this star is “only” 70,000 K it would peak at about 43 nm, way off to the left, thus there is no way to conclusively judge this star’s temperature by this fit, (which looks pretty good) except we know that it is very hot. Credit: NASA/ESA/Jacoby et al., 2017 ApJ, 836. 93. Annotated by the author.

Figure 10-10. The shape of a star seen using the VLTI showing how rotation can grossly distort a star. There is a huge temperature difference between the pole (20,000 K) and the equator (10,000 K) which, to say the least, provides a challenge to be realistically modelled, let alone evolve such stars. You can see here that the resolution is below 0.00001 arcseconds. Credit: ESO/VLTI.

Figure 11-1. Displays a theoretical H-R diagram showing the evolutionary paths of massive stars. The colour-bounded areas delimit hydrogen burning in the core, core hydrogen exhaustion and contraction and helium ignition in the core. Credit: Schaller et al., 1992, A&AS, 96, 269. Modified by the author.

Figure 11-2. The oval to the upper right shows the overlap of supergiants evolving from solar mass stars and those that are much more massive. When observing red giant stars, initially we don’t know whether they are of high or low mass. The 60 $M_{\odot}$ star never makes it to the red giant “sink” and explodes as a supernova. Two sets of evolutionary tracks are shown to illustrate the calculation uncertainty for very massive stars. Credit: Schaller et al., 1992, A&AS, 96, 269. Modified by the author.

Figure 11-3. A schematic representation of a massive star just prior to it generating an iron core and becoming a supernova. The situation can be represented by thinking of the innards of a star as a series of onionskins each comprising one element. It is obviously more complex than this because of the circulation currents and the inevitable mixing of the elements. Credit; ESO, Wikimedia Creative Commons/Hall.

Figure 11-4. Left panel. A schematic supernova light curve. Right panel. The Crab Nebula in Taurus, the remnant of a supernova that erupted in 1054. The pulsar at its core is seen as a white spinning top-like object. This highly detailed image was created by combining data from radio telescopes (VLA), powerful X-rays as seen by the orbiting Chandra X-ray Observatory superimposed on the Hubble Space Telescope's image and IR data from the Spitzer Space Telescope (SST). Credit: NASA.

Figure 11-5. The left-hand panel shows the supernova 1987A with two rings, the large outer and the inner, both of which have no explanation and which existed before the star blew up. When the light from the supernova died down the inner ring seen in the central panel became visible with a size of 0.808 arcseconds. Matter ejected from the supernova took 12 years to reach the ring and interacted with it to give the bright spot seen in the right-hand panel. By measuring the velocity of the matter originally ejected from the supernova and the time of travel coupled with the observed size of the ring it was possible to triangulate the distance to the supernova and hence to the LMC. Credit: NASA/HST.

ESO telescopes and instruments over a period of more than 25 years. The star takes 16 years to complete one orbit and was very close to the black hole in May 2018. Note that the sizes of the black hole and the star are not to scale. The right-hand image is based on data from the VLTI and are much more accurate than those shown in the centre panel. Credit: Left and centre panel. ESO. Rightmost panel. ESO/MPE/ GRAVITY Collaboration. Commentary from the scientists. Modified by the author.

Figure 12-9. Two international teams of astronomers using the HST and ground-based telescopes in Australia and Chile have discovered the first examples of isolated stellar-mass black holes adrift among the stars in our galaxy. The brightening event is shown on the left. Top: Un-brightened, bottom: brightened. The image on the right shows the star which was lensed. Credit: NASA/ESA/Bennett (University of Notre Dame, Indiana). Commentary from Bennett.

Figure 13-1. The UBVRI passbands. The actual passbands are a movable feast because the photomultipliers and CCDs have evolved as the detectors have changed from the original system. These are the filters most often used and are reproducible, unlike the early pieces of glass that defined this photometric system. Credit: Multiple sources. Annotated by the author.

Figure 13-2. Showing the improved (!!) resolution of the HST over ground-based telescopes. The circled images are from a study of stars called blue stragglers (BSS) which are identified in the right panel. Note the light-year scale. The nearest star to the Sun is at 4.37 light-years. This give you an idea of the compact nature of a globular cluster. Credit: Left panel, Ground Image: ESA/**STScI)**/ESO/Meylan, Right panel, NASA, ESA/Paresce, ESA/STScI/Shara.

Figure 13-3. Showing how stars of masses 1 $M_\odot$ to 120 $M_\odot$ evolve. Note how the track for the 120 $M_\odot$ model is quite different form the rest. I suspect that the model is having trouble getting started and wants to blow the star-forming material away. The ZAMS is the left-hand line where the evolutionary calculations begin. Credit: Maeder and Meynet, 1989, A&AS, 210, 155.

Figure 13-4. Compares the Pleiades ZAMS with those from several theoretical models computed with various metal abundances (Z). Small values of Z represent lower metal abundance. The wiggles in the data are well represented by the theoretical results. Note the effects of evolution at the bright (upper) end. Credit: Vandenberg & Bridges, 1984, ApJ, 278, 679. Modified by the author.

Figure 13-5. Isochrones interpolated from models like those shown in Figure 13-3. The isochrones cover a range in age of 4 million to one billion years. Credit: Bertelli et al., 1994, A&AS, 108, 275.

Figure 13-6. Shows model fits to the Pleiades and Hyades cluster data. Note the difference in metal abundance (Z) between the two clusters (0.012 and 0.024) illustrating the point that the observed ZAMS has been created by overlapping clusters with different abundances. Note also, the difference in the Pleiades abundance between here and in Figure 13-4. Credit: Castellani et al., 2002, MNRAS, 334, 193. Modified by the author.

Figure 13-7. Showing the fits to a simplified globular cluster sequence in two colours (*B-V* and *V-I*). Aside from the horizontal branch to the upper left, the fit is superb. Note how the different models represent differing abundances. Of note is the quoted age (18 billion years) which is larger than the current accepted age of the universe. The models in the right-hand panel go a long way to representing the data. Credit: Vandenberg and Clem, 2003, ApJ, 136, 778.

Figure 13-8. Two colour-magnitude diagrams for the cluster NGC 7790. The left-hand panel shows early data and the Cepheid CF Cas with its changing position as it brightens and changes colour. In both diagrams the empty space between the Cepheid(s) and the main sequence indicates that evolution is rapid across this region. There are two additional Cepheids in the cluster data shown in the right-hand panel along with two sets of evolutionary tracks differing only in the assumed abundances used for the calculations. From this fit, the age of the cluster can be derived from these calculations. Note that, because of interstellar reddening. the colours in each panel do not align. Because of this, there is no temperature scale in the left-hand panel. Credit: Left panel. Sandage, 1958, ApJ, 128.150. Right panel, Gupta et al., 2000, A&AS, 145,369.

Figure 13-9. Both panels show a series of evolutionary track for masses ranging from 5 to 12 $M_{\odot}$. Note the “Cepheid loops“ to the right in each image. The tracks move from left to right (higher to lower temperature) up the red giant branch and down to form a loop before the stars migrate back up the red giant branch. The left panel shows the boundaries of the calculated instability strip. In the right panel, the observations are plotted on these tracks. Note that these data fall directly into the region where we see the loops and within the instability strip. The difference between tracks in each image, notably the size of the loops, result from adopting different physics. Credit: Left panel. Valle et al., 2009, A&A, 507, 1541. Right panel. Halab et al., 2012, ApJ, 761, 1.

Figure 13-10. Left panel shows the effects of rotation on evolution through the Cepheid loops. Notice how the rotational tracks (yellow-black lines) sits above the non rotating results (green line). Right panel. Cepheids with determined masses plotted as cyan open circles onto the blue loop portions of evolutionary tracks. Tracks corresponding to models rotating at about 200 km/s are shown in red to the right. Non-rotating tracks are shown in blue. The stars and the instability strip (shaded area) are nicely encompassed by the loops. Because the full evolutionary tracks are not shown it is difficult to tell just how closely the two sets of masses agree but it is very close. Credit: Left panel. Anderson et al., 2017, Proceedings of the 22nd Los Alamos Stellar Pulsation Conference "Wide-field variability surveys: a 21st-century perspective". Right panel. Anderson et al., 2014, A&A, 564, 100.

Figure 13-11. The light curve of a Cepheid (OGLE-LMC-CEP-0227) that is also an eclipsing binary. The Cepheid cycles are shown along with two obvious eclipses. A

Cepheid light curve is derived from the non-eclipsed data and subtracted from it to show the eclipses. Credit: Pilecki et al., 2013, MNRAS, 436, 953. Modified by the author.

Figure 13-12. Left panel showing a Cepheid light curve extracted from observations of OGLE-LMC-CEP1812. The right panel shows the eclipses (primary on left and secondary on right) that are solved to yield the relative sizes of each star in terms of the separation between them and, critically, the inclination of this system to us. Credit: Pietrzynski et al., 2010, ApJ, 742, L20. Modified by the author.

Figure 13-13. The left panel shows the RV pulsations of OGLE-1812 and the right panel the orbital motion of the primary star (filled circles) and the secondary less massive star (open circles). Credit: As in Figure 13-12.

Figure 13-14. Evolutionary results for OGLE-LMC-CEP-0227 plotted in the "loop region" of Cepheid evolution. The Cepheid is plotted in blue and the red giant, which is not pulsating, is in red. Clearly, the loop with maximum mass loss produces a loop that does not encompass the data. All other models are possibilities. Credit: Moroni et al., 2012, ApJ, 749, 108.

Figure 13-15. Two types of light curves shown for RR Lyrae stars. RRab stars are more common than the RRc. Credit: Left panel. Unknown source. Right panel. Hartwick et al., 1972, ApJ, 174, 537.

Figure 13-16. Left panel. An annotated H-R diagram of the globular cluster M3 showing the location of the RR Lyrae (RRL) stars on the horizontal branch (BHB, RHB—blue and red horizontal branches respectively).and the blue straggler stars (BSS). Right panel. Shows the evolutionary track of a 0.8 $M_\odot$ star on its way to the horizontal branch to become an RR Lyrae star. Follow its evolution upward on the right-hand side to the helium flash where it swoops down quickly to the left and the horizontal branch and a life as an RR Lyrae star. From there, evolution takes the star upward to the right to the red giant tip (RGT) and then has a long march to the left as a slowly exposed hot core imbedded in a planetary nebula. Note that in the process the star the 0.7 $M_\odot$ star has lost 0.175 $M_\odot$ of its mass. Credit: Left panel. Buonnano et al., 1994, A&A, 290, 69. Right panel. Iben, 1991, ApJS, 76, 55.

Figure 13-17. Comparison between observation and theory for six stars in a plot of gravity against mass (log g or surface gravity vs log mass). The primary components are denoted as squares and the secondaries as triangles. If they are at the same age, both components should line up along the same isochrone. Except for V3903 Sgr this requirement is largely met. In this case, the reason for the failure is because there has been evolution and interaction between the components (see next chapter). The ages of the stars range from 1.5 to 6.0 Myr. Credit: Hilditch et al., 1996, A&A, 314, 165. Modified by the author.

Figure 13-18. A plot like the previous figure except it is gravity plotted against temperature (log g against temperature). Everything is the same except for the small

Chandra, NASA, edited by Heinke. Right panel. Freire et al., 2017, MNRAS, 471,857. Modified by the author.

Figure 13-25. An artist's impression of Cygnus X-1 comprising a bloated star that is losing mass through L1 to a black hole as it evolves. We are familiar with this scene, as most stars grow in size as they evolve. It you look carefully you will see a beam coming from the black hole. Credit: NASA/ESA illustration. Notation by the author.

Figure 14-1. A schematic illustrating the Roche-lobe geometry. Shown is a cross section of the unique surface that shows the realm where each star's gravity holds sway. These realms form lobes which make contact at a junction (L1, see Figure 1-4) along the line joining the centres of the two binary components. Credit: By the author.

Figure 14-2. The three situations involving Roche geometry that are used to describe the many types of binaries we observe. Increasing interaction with the gravitational balance point between two stars (L1), brings more complex light curves and spectra. Credit: Wikimedia Creative Commons/Hall. Modified by the author.

Figure 14-3. Left panel shows the relationship between radius and age for an evolving 5 $M_{\odot}$ star. Also displayed are the timelines governing the definitions of mass transfer for Cases A, B and C. The right panel shows these cases in terms of the H-R diagram. Notice how big the star is when carbon ignites. One thousand solar radii is the distance from the Sun to Jupiter. Credit: Left panel. Paczynski and Podsiadlowski, 1969, A&SS, 3, 14. Right panel. Wikimedia Commons Contributors/Lithopsian. Annotated by the author.

Figure 14-4. An impression of a contact system where stars have evolved into contact at L1. Continued evolution produces a common envelope of gas which is lost to the system because of its rapid rotation. Credit: Image created with Mathematica—Wolfram Demonstrations Project/Dutton, Penn. State. Annotated by the author.

Figure 14-5. Left panel showing X-ray pulses from a source thought to be two white dwarfs in orbit (right panel). Because of their incredible density they will radiate gravitational waves as they orbit. Credit: Left panel. Light curve: Strohmayer, 2005, AAS, 37, 792. Right panel. NASA/CXC/GSFC/Illustration: GSFC/Berry. Annotations by the author.

Figure 14-6. Left panel show how the time of periastron is advancing. The line is a prediction from the theory of relativity. The match between data and theory is unreal. The right panel shows how a combination of the observed orbit, the advance of periastron and other relativistic constraints predicts the mass of each component with unprecedented accuracy. Credit: Weisberg and Taylor, 2003, ASP Conference Series, 302. 93. Annotations by the author.

individual spectrum of each star) yields a spectrum for each star based on an analysis of all the spectra for each system, finally ending up with the velocities at each phase. These velocities give a spectroscopic orbit, which, when combined with the light curve solution, yields the masses and radii needed for the evolutionary discussion. Credit: Harries et al., 2003, MNRAS, 339, 157.

Figure 15-4. The spaceborne observatory Gaia, tasked with measuring the position, brightness, colours, spectra and velocities of a billion stars. Credit: ESA/ATG Medialab; background image: ESO/Brunier.

Figure 15-5. The LSST focal plane detector array with a diameter of 64 cm. This mosaic will provide over 3 gigapixels per image. The image of the moon (30 arcminutes) is present to show the scale of the field of view. Credit: LSST Project/NSF/AURA.

Figure 15-6. The Extremely Large Telescope (ELT) as it will appear "in situ" on Cerro Armazones in the Atacama desert in northern Chile. The automobile in the parking lot gives us an idea of the scale of this telescope. Credit: Swinburne Astronomy Productions/ESO.

Figure 15-7. An illustration of the Great Magellan Telescope (GMT) in situ on Cerro Las Campanas. There are two things to note. The seven mirrors that make up the primary and the vast area of desert surrounding this observatory that provides perfect viewing for the GMT and the others in Chile. Credit: Great Magellan Telescope Organisation.

Figure 15-8. Summarizes the current crop of telescopes built or planned. Judge their size against the tennis court to the lower left or the basketball court in the lower right. The existing 4-m telescopes that appeared enormous to me don't even show up! The circles around some of the mirror pairs and the GMT represent the equivalent aperture of the combined telescope. Credit: Wikimedia Creative Common/Cmglee.

Figure 15-9. An artist's impression of the Overwhelming Large Telescope (OWL). The enclosure to the right will house the telescope and provide access to the secondary mirror which is visible. The lattice is described as an adaptronic structure designed to save cost and weight. It looks like the telescope sits in a cradle that rotates and tips. Pretty neat all around I'd say! Credit: ESO Telescope Systems Division.