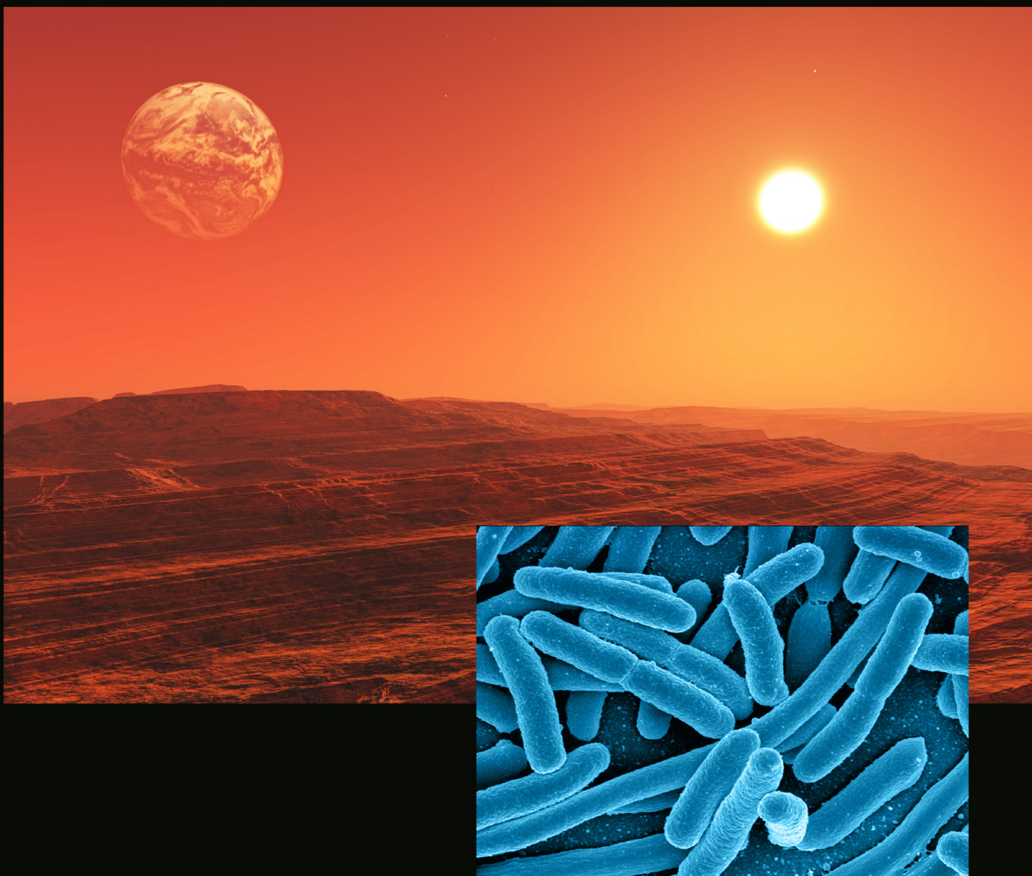
# Astrobiology for a General Reader

## *A Questions and Answers Approach*



Vera M. Kolb and Benton C. Clark III

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V. M. K. dedicates this book to the memory of her dear brother, Vladimir Kolb.

B. C. C. dedicates this book to the memory of his beloved wife, Johanna.

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# PREFACE

**VMK:**

Much has been written about astrobiology, for all readership levels, from popular books to highly advanced treatises on one or more topics in the field. This book is geared for the general reader who has some science background or a strong interest in science. A unique aspect of this book is that it utilizes a Q&A (Question and Answer) approach to aid the thought process and hold the interest of the reader.

The knowledge base of general readers is typically quite broad. I felt that the content of this book should not be oversimplified, but I also avoided highly detailed or overly speculative analyses. It remains for each reader to decide if this approach is successful.

The questions in this book are inspired by those that have been asked of me from beginning students and from the general audience at public presentations and various science conferences. In formulating the answers, I am drawing upon my astrobiology research, experience in teaching, and the current developments of pedagogical approaches suitable for science fields.

The strings of the related questions and answers are organized into chapters of various topics. Chapters are not equal in length, which reflects the topic of the chapter. Some topics require a more technical approach and longer explanations, while some others allow for a less extensive coverage of the main ideas.

There may be some slight overlap in the material, to enable readers to understand a chapter in which they are interested, and who may have skipped a previous chapter(s) that provided a foundation. In such cases, I have given minimum background without extensive repetition.

I have utilized many resources, such as various astrobiology references at different levels. Also, I have relied on some advanced material from two recent books for which I was the Editor and also contributed chapters:

"Astrobiology: An Evolutionary Approach" (2015), and the "Handbook of Astrobiology" (2019), as well as many different research journal articles to assure the answers are up to date.

Carefully chosen literature resources are given in the section "Further Readings." This section starts with the general information on how to find references, followed by an abbreviated version of selected references for each chapter, arranged sequentially for each Question/Answer number. Following the abbreviated versions are the full References, arranged alphabetically. They include books, book chapters, and journal and magazine articles. These literature references acknowledge the authors of the ideas and accomplishments this book utilizes and enable the reader to further explore topics of their own interest. Selected web resources, including Wikipedia, are also given. At the end is an Index, keyed to the Answers to the Questions.

After I had finished writing about one half of this book, I was fortunate to recruit a co-author, Dr. Benton C. Clark III (Ben Clark), to contribute mostly to the chapters which deal with space missions. Ben has participated in Viking and numerous other missions and is now involved in the Mars 2020 rover mission, among others. His background in biophysics and first-hand knowledge of such missions made him an ideal co-author of this book. He also complements my own expertise, which is in the chemical aspects of astrobiology.

**BCC:**

The invitation by VMK to join this book adventure as a co-author reflects the development of astrobiology as a science. At the time VMK was receiving her astrobiology training in San Diego (1992-1994), the post-Viking missions were only in the planning or preparatory stages. Now, however, the astrobiologist's dream to search for life elsewhere in our Solar System has come to fruition via significant and extremely productive new missions to Mars and other objects in our Solar System.

Thus, any astrobiology book for a general reader needs significant coverage of these endeavors. The cooperation with VMK on this book and my part to cover the space missions is truly a marriage made in heaven, since most of my life's work was and is dedicated to such missions.

# ACKNOWLEDGMENTS

The authors are thankful to Prof. Richard H. Judge for reading the manuscript and making useful comments. Vladimir Kolb provided numerous wonderful tips and suggestions for the Q&A approach.

# CHAPTER 1

# WHAT IS ASTROBIOLOGY?

*Q 1.1 What is astrobiology?*
*A 1.1* Astrobiology is a field of science which studies the origin, evolution, distribution, and future of life in the universe.

*Q 1.2 What are the key questions astrobiology seeks to answer?*
*A 1.2* Astrobiology seeks to answer questions about the origin and evolution of life on Earth, the possibility of extraterrestrial life, and the future of life on Earth and in the universe in general.

*Q 1.3 What are the specific goals of astrobiology?*
*A 1.3* Specific goals include understanding the origin of life on Earth; study of the early life on Earth and how it interacted and evolved with the changing environment; study of the evolution of the early life on Earth to more advanced life; investigation of the environmental limits of life; exploration of the habitable environments on Earth and in our Solar System and beyond; the search for extraterrestrial life; and recognition of the signatures of life ("biosignatures") on early Earth and on other worlds. These goals are delineated also in the NASA's astrobiology roadmap.

*Q 1.4 Is NASA's astrobiology roadmap the only one?*
*A 1.4* No. For example, a similar roadmap has been developed for astrobiology research in Europe. It just focuses more on European research and space missions.

*Q 1.5 How old is the science of astrobiology?*
*A 1.5* "Astrobiology" became a designated scientific field in 1995, thus rather recently (it was founded by Wes Huntress at NASA). Astrobiology evolved from its predecessor, "Exobiology" (named by Joshua Lederberg in 1960), which studied the origin of life and possibility of extraterrestrial life.

*Q 1.6 What are some examples of recent advances in astrobiology?*
*A 1.6* The examples are summarized below.

New developments in genetics and studies towards synthetic life help us understand the basic requirements for life on Earth. Improved identification of the fossils of early microbes on Earth help us nail down the beginning of life on early Earth. The search for potential biosignatures on Mars informs us about the possibility of extraterrestrial (ET) life. Advances in planetary geology, especially those resulting from space missions, point out the planetary bodies in our Solar System which may be habitable for life, based on the presence of water, energy sources, and the availability of organic materials (chemical compounds that contain carbon). Improved analysis of organic materials from space, notably in meteorites and micrometeorites, helps us understand chemistry in space. Worlds, like Mars, are promising because they provide water and all the key elements necessary for life as we know it (CHNOPS = carbon, hydrogen, nitrogen, oxygen, phosphorus, and sulfur). Discovery of numerous exoplanets (those that are outside our Solar System), some of which may be habitable, extends our search for ET life to more distant worlds.

*Q 1.7 But surely people explored the idea of extraterrestrial (ET) life much earlier than 1960s?*
*A 1.7* Yes, this is correct. Although astrobiology is a new science, it has a long history of ideas which originated in the antiquity. Thus, the debate about the possibility of ET life was carried out by the ancient Greeks and has continued up to and including modern times. However, only recently have science and technology developments enabled search for ET life via space missions, and for the ET intelligent life (ETI) through radio-astronomy to search for the signals emanating from the extraterrestrial intelligent civilizations.

*Q 1.8 These scientific efforts have been so far unsuccessful in confirming either the ET life or ETI. Is this correct?*
*A 1.8* Yes, this is correct. The space missions, notably the Viking missions on Mars in 1976, searched for microbial life on Mars, but did not confirm its existence. The same is the case for the later missions. Likewise, the analysis of a meteorite ALH 84001 which originated from Mars and was found in Antarctica revealed interesting morphology reminiscent of the fossils of bacterial life, but the results were not convincing enough to indicate remnants of life on Mars. The search for ETI via SETI (Search for Extraterrestrial Intelligence) did not yield positive results so far, although efforts continue.

*Q 1.9 Astrobiology is referred to as a "field of study" or "science", rather than a discipline. Isn't astrobiology a discipline, like chemistry or physics?*
*A 1.9* The question if astrobiology should be treated as a separate scientific discipline is still open to discussion, but the prevailing view is that astrobiology is a field of study rather than a discipline. The reason is that astrobiology is multidisciplinary in its contents and interdisciplinary in its execution. Although not a discipline itself, astrobiology draws upon other disciplines, subdisciplines, and specialized areas of research such as physics, chemistry, biochemistry, biology, molecular biology, microbiology, ecology, evolutionary science, geology, planetary science, astronomy, cosmology, atmospheric science, oceanography, evolutionary science, and paleontology. Furthermore, astrobiology also seeks insights from the history of science and philosophy.

*Q 1.10 Is being multidisciplinary/interdisciplinary a disadvantage?*
*A 1.10* No, it is not a disadvantage. It is a necessity. Multidisciplinary and interdisciplinary approaches are needed to investigate complex problems which are beyond the reach of any single discipline.

*Q 1.11 It seems that astrobiology covers lots of ground. What is its all-encompassing goal?*
*A 1.11* According to NASA, an all-encompassing goal of astrobiology is to understand cosmic evolution. Such evolution includes the following sequence: Big Bang; formation of galaxies, stars, planets, and elements including the biogenic ones; chemical evolution which led to life; pre-Cambrian biology; complex life; intelligent life; cultural evolution; civilization; science and technology; and the search for life in the universe.

*Q 1.12 Who are astrobiologists, and where do they work?*
*A 1.12* Astrobiologists are typically trained in one of the scientific disciplines, and later they learn other disciplines which equip them to work on complex astrobiology problems. Astrobiology training is offered by selected universities, at the advanced undergraduate, graduate, or postgraduate levels. Astrobiologists often work for NASA, ESA (European Space Agency), or other space agencies, or at the universities which have astrobiology programs. They also work in industries which are involved in space missions.

*Q 1.13 If I would want to become an astrobiologist, how do I do it?*
*A 1.13* First, one needs training in one of the scientific disciplines, such as chemistry, physics, biology, or geology, as some examples. Another

example is planetary science, which would typically require some geology background. Another example is study of the chemical composition of meteorites, which will require an analytical chemistry background. If one is interested in survival of microbes in space, one would need a microbiology background. Virtually every astrobiology problem requires a solid scientific background. Then one needs additional training on the specific astrobiology topics. This is just general guidance.

Much can be learned from specific examples, such as those described in a book "Talking About Life" by Chris Imprey, in which he presents interviews with 37 leading astrobiologists, who share how they got into the astrobiology field. For example, we find that Iris Fry was originally trained in chemistry, biochemistry, philosophy, and history of science, to become a leading philosopher on the subject of the origin and emergence of life. Steven Benner was first trained in biophysics, biochemistry, and chemistry, before he became one of the leading experts in so-called prebiotic chemistry (chemistry before life existed on Earth, and from which life emerged). Guy Consolmagno is the curator of the large meteorite collection in the Vatican. He is a Jesuit religious brother who has a strong interest in the possibility of life elsewhere in the Universe and is known for his popular astronomy books, among other contributions. Each one of the 37 interviews by Imprey are highly inspiring and will resonate with readers of various backgrounds.

# CHAPTER 2

# UNDERSTANDING THE CONCEPT OF LIFE WITHIN THE ASTROBIOLOGY FRAMEWORK: WHAT IS LIFE?

*Q 2.1 Don't we all know what life is?*
*A 2.1* Not really. At some levels we do, at some other levels we do not. For example, life which is visible to the naked eye, such as plants and animals, is easily recognizable by its familiar features, such as shape, behavior, and reaction to stimulus. Microscopic and submicroscopic life forms and structures are by now familiar to most people and can be described by images of cells and their components, for example. However, life can be also described by molecular means, namely by the chemical composition of biological monomeric (monomer = single unit) building blocks, such as amino acids, sugars, and nucleic acids, and also their respective polymers (many units hooked together), such as proteins, polysaccharides, and polynucleic acids (such as RNA or DNA). Further, life can be characterized by its inner workings, such as metabolism, information and energy flow, growth, and reproduction. Life requires a high level of organization to ensure that all of the contributing parts are working together properly. Such organizational features reflect life's complexity. But all these different descriptions of characteristics of life are still not adequate for astrobiology, which requires its own definition of life.

Q *2.2 What is wrong with the already existing descriptions of life?*
*A 2.2* They are Earth-centric, namely they are focused on life on Earth as we know it. While this is understandable, since this is the only life we know, it is not sufficient for astrobiology, which is concerned with the search for extraterrestrial life. While such life may or may not be the same as ours, scientists believe that the ET life should share at least some of its essential characteristics with Earthly life. Thus, astrobiologists wish to extract from the description of life on Earth its essential features, devoid as much as possible of Earth-centric specifics, and hopefully define universal life. The latter would then be appropriate also for recognizing ET life if we find it.

*Q 2.3 What are the essential characteristics of the earthly life?*
*A 2.3* Examples include metabolism (the set of chemical processes that occur within a living organism to maintain life), presence of a boundary (such as a membrane), growth, and reproduction. Life must also have capacity for mutations (changes of the structure of the genes) which will enable its evolution via natural selection. This means the following: mutations generate modified forms of life, some of which are better able to adapt to environmental changes. Better-adapted life is naturally selected over life which cannot adapt as well. Also, life differs from inorganic objects and dead matter. These essential properties are likely shared with ET life.

*Q 2.4 This seems relatively straightforward. Is there a problem?*
*A 2.4* Yes. One problem is the existence of various exceptions and borderline cases. One example is reproduction as the requirement for life. Some life forms, such as viruses, are not able to independently reproduce, but use the cellular machinery of their host for this purpose. This poses the question if viruses are alive. However, most recent findings show viral cooperation which in some cases verges on altruism. Such sophisticated behavior is typically attributed to life forms. Some organisms, such as mules and worker bees cannot reproduce, but are obviously alive. Some other organisms cannot reproduce on their own since they require a partner, as in the case of sexual reproduction. Even for organisms which normally can reproduce, they may be in part of a life cycle in which reproduction is not possible, such as for the babies or quite old people. Still, they are alive.

Another problem is that when essential life properties are considered, they are usually chosen such as to describe life via its lowest common denominator. Only properties which are in common to all life, from the lowest organisms, such as bacteria, to the most developed organisms, such as intelligent humans, are taken into account. Thus, if intelligence of the type humans have is included as a critical property of life, then bacteria and plants would not be alive (along with many other organisms). On the other hand, if we decide to use the entire set of characteristics of an organism as a basis of defining life, we run into a problem, since characteristics for one life form may not be applicable to another.

For example, if one describes the properties of a flower in exquisite detail, many such details are not in common with a bacterium or a bird. Thus, using phenotype (the set of observable characteristics of an organism, such as morphology or physical structure) for the purpose of defining life does not appear to be practical. This difficulty is further complicated by the influence that environment exerts on phenotype. Namely, phenotypes are determined not only by genotype (the genetic constitution of an organism, which provides the hereditary information) but also by the environmental factors. Due to such problems, although numerous attempts have been made to define life, no definition is universally accepted.

*Q 2.5 Is it perhaps easier to define life by the specific chemical and physical properties of its machinery at the molecular level?*
*A 2.5* Not really. The problem is that specific details about the machinery of life on Earth, which uses either DNA or RNA as its genetic material, may not be the same as for the putative ET life, although they are probably related at a general level.

*Q 2.6 Can you clarify this with an example?*
*A 2.6* Yes. As one example, Steven Benner posed a question if life could be based on chemicals which are similar but not the same (so-called “analogs”) as those that life on Earth utilizes. To answer this question, he synthetized in the laboratory various analogs of important chemical compounds which are components of nucleic acids (such as DNA). The latter are critical for transfer of information and replication (the process of making a copy) at the molecular level. He has found that some laboratory-made analogs can function as the naturally occurring ones, albeit less efficiently in some cases. He hypothesized that the ET life could be based on such analogs.

*Q 2.7 Could the ET life be based on silicon instead on carbon?*
*A 2.7* Not likely! (One should not take as truth the famous Star Trek episode “The Devil in the Dark”, about the Hortas silicon-based life forms from the caves of planet Janus VI). Chemical properties and reactivities of individual atoms put a constraint upon what any type of life may or may not be based. Because of such constraints, life based on silicon is considered to not be feasible, because of unfavorable and limited reactivity of silicon as compared to carbon, which is the basis of our life on Earth. Similarly, an old argument that everything reacts with everything else, and thus we get an unlimited and unconstrained number of chemicals just by mixing them, is not correct. Some chemicals do react with each other, but many others do not due to their lack of reactivity or unfavorable thermodynamic factors. Thus, while we can only hypothesize about the characteristics of the ET life, we do know for sure that some possibilities for such a life are precluded, simply based on the laws of chemistry. This would be the case for the silicon-based life.

*Q 2.8 In light of all these difficulties, how do astrobiologists define life?*
*A 2.8* Examples of definitions as proposed by different authors are shown below, selected from about 100 definitions of life compiled and fully referenced by Radu Popa in 2004 and expanded in 2015. In general, these definitions were constructed by first observing and analyzing properties of life on Earth, and then choosing a minimum number of critical features of life. Specifics were removed as much as possible. This makes such definitions suitable for the ET life, for which we do not know the specifics, but expect their general features to be like those on Earth. Since the definitions of life are stripped of the specifics, they may sound quite theoretical and abstract. Further, these definitions would be applicable to the life of e.g. a butterfly, but we cannot reconstruct the butterfly from the definitions alone. Our comments are shown in the parentheses after the definitions.

a) Arrhenius 2002: Life is a system capable of 1. Self-organization. 2. Self-replication; 3. Evolution through mutation; 4. Metabolism and 5. Concentrative encapsulation.
b) Baltscheffsky 1997: Life may be described as a "flow of energy, matter and information." (A very abstract definition).
c) Joyce 1994: NASA's working definition of life: Life is a self-sustained chemical system capable of undergoing Darwinian evolution. (This definition extends Darwinian evolution from organisms to chemical systems).
d) Oparin 1961: Any system capable of replication and mutation is alive.
e) Trifonov 2011: Life is self-reproduction with variations. (Similar to d).
f) Brack 2002: Life is a chemical system capable of transferring its molecular information independently (self-reproduction) and also capable of making some accidental errors to allow the system to evolve (evolution).
g) Horowitz 2002: Life is synonymous with the possession of genetic properties, i.e. the capacities for self-replication and mutation.
h) Kolb and Liesch 2008: Life is a chemical phenomenon which occurs in space and time as a succession of life forms which when combined have a potential to metabolize, reproduce, interact with the environment, including other life forms, and are subject to natural selection.
i) Kolb 2010: We propose that the life of an organism is the sum of its life forms over a period of time. We set the integral of time from the birth of the organism to its death (this would include babies to old age in case of humans).
j) Lauterbur 2002: It's alive if it can die. (The problem with this definition is that defining death is as difficult as defining life).

k) Horowitz 1986: Life is synonymous with the possession of genetic properties. Any system with the capacity to mutate freely and to reproduce its mutations must almost inevitably evolve in directions that will ensure its preservation. Given sufficient time, the system will acquire the complexity, variety and purposefulness that we recognize as alive.
l) Vilee and co-authors 1989: The characteristics that distinguish most living things from nonliving things include a precise kind of organization, a variety of chemical reactions we term metabolism, the ability to maintain an appropriate internal environment even when the external environment changes (a process referred to as homeostasis), movement, responsiveness, growth, reproduction and adaptation to environmental change.
m) Nealson 2002: Any definition of life that is useful must be measurable. We must define life in terms that can be turned into measurables, and then turn these into a strategy that can be used to search for life. So, what are these? a. structures; b. chemistry; c. replication with fidelity and d. evolution. (There is a problem in measuring evolution, as in the NASA's definition above, definition c).

*Q 2.9 How are these definitions useful when we search for ET life?*
*A 2.9* They delineate certain essential characteristics of life on Earth which should apply also to the ET life in principle, if not in all the details.

*Q 2.10 What is meant by "in principle, if not in all the details"?*
*A 2.10* "In principle" means that all life, including the ET life, should be able to metabolize, reproduce, extract energy from the environment, adapt to both physical and biological environments, mutate and evolve according to natural selection, and to be sequestered in some sort of a compartment. "Not in all the details" means that the chemistry does not need to be the same for the life on Earth and the ET life. For example, chemically speaking, one would need some sort of genetic system, like a DNA, which would keep and transmit the information, plus some sort of enzymatic system which would catalyze the reactions, and some sort of cell membrane. However, chemistries may differ, as long as the function stays the same. Thus, a genetic system may vary chemically, but it must be able to keep and transmit the information.

*Q 2.11 This still appears quite abstract. Is there a practical guidance on how to recognize and detect the ET life?*

*A 2.11* Yes. Practical guidelines have been developed for the space missions in our Solar System, which seek to detect the ET life or remnants thereof. Recently, comprehensive guidelines have been formulated, which focus on detection of life by various criteria which are specific and mostly Earth-centric and are described as a "ladder of life detection". This ladder summarizes measurements seeking to find life, including searching for biosignatures. The latter are substances, phenomena, and patterns whose origin specifically requires a biological agent. Examples include complex organic matter characteristic for life; polymers with repeating charge, which could be indicative of genetic material; co-location of reductant and oxidant, which could be related to metabolism; organic materials not found in abiotic milieu; bacterial microfossils; cell-like structures in multiple stages of development, indicating reproduction; etc. Further, guidelines for detecting life on exoplanets (planets outside our Solar System) have also been developed based on what we know about life on Earth, and what can be detected via remote sensing. Examples include biosignatures that are gaseous, such as oxygen, ozone, and methane, and surface biosignatures, such as pigments that indicate photosynthesis.

In conclusion, there is a difference between *definitions* of life, which are by necessity abstract to be applicable also to the ET life, and guidelines for *detecting* the ET life, which are practical and include many specifics. There is a need for both approaches. The practical, specific guidelines are useful for detecting life that is expected to be quite similar to ours, while the abstract definitions prepare us to look for life that may be substantially different than ours.

# Chapter 3

# Philosophically speaking: Can something be both alive and not-alive?

*Q 3.1 Isn't "not-alive" the same as dead?*
*A 3.1* Not necessarily. "Dead" customarily refers to something which was alive but is not alive anymore. "Not-alive" makes the distinction from dead. In the context of this chapter, it is something which has some but not all the features of a living system.

*Q 3.2 What is an example of this?*
*A 3.2* One such example is the viruses. Viruses have some, but not all the essential properties of life, according to some schools of thought. Virologist Luis Villarreal classifies viruses as belonging to a "twilight zone of life". For example, viruses have genes and evolve via natural selection, which are critical features of life, but they lack some essential characteristics of life, notably that they do not have metabolism and cannot reproduce on their own. However, viruses in their non-reproductive form (virions), thus not-alive according to the reproduction criterion, can penetrate cells of their hosts. They then become capable of reproduction with the *assistance* of their hosts, and thus they act as alive. This is only if we accept the assisted reproduction as a *bona fide* mode of reproduction, since there are precedents in other species which use it and are recognized as alive (e.g. species that use sexual reproduction and thus cannot reproduce on their own but need "assistance" of the sex partner). Thus, viruses could be classified as alive, with respect to the crucial reproduction requirement. Therefore, one could state that viruses are both alive and not-alive.

*Q 3.3 The statement that viruses are both alive and not-alive is contradictory and defies common logic. Isn't is so?*
*A 3.3* Yes. Indeed, according to the traditional logic, which comes from Aristotle, it is impossible to *be* and *not to be* at the same time, or for both *p* and *not-p* to be true, namely that both the statement and its negations are

true. However, Aristotelian logic has been challenged with a view that there are some contradictions that are true. This is the subject of a branch of logic named dialetheism (Greek: *aletheia* = truth; *di-aletheia* = a two-way truth), proposed by Graham Priest. Classification of viruses as both alive and not-alive is possible within the dialetheism.

*Q 3.4 What are some important features of dialetheism?*
*A 3.4* Dialetheism examines the limits such as those of the mind, thought, concepts, expressions, descriptions, and knowing. Transcendence beyond these limits may create contradictions. One of the strengths of dialetheism is that it can account for transitional phenomena in general, and the contradictions they create. A simple example that Priest gives is a case of a person leaving the room, thus transitioning between the inside and outside of the room. At some point of this process, the person will be both inside and outside the room. While the statement "a person is both inside and outside the room" appears contradictory based on Aristotelian logic, it is clearly true for this transition process, which dialetheism can treat.

*Q 3.5 What are some examples of applications of dialetheism to astrobiology, other than the case of viruses?*
*A 3.5* There are two additional significant examples: that of the emergence of life on Earth from abiotic (not-alive) matter, and the concept of extraterrestrial life.

The example of the emergence of life on Earth: Astrobiologists believe that life on Earth has emerged from the not-alive chemical systems, which are termed abiotic (not-biotic; biotic = living) or prebiotic (before living). However, details of how the transition between abiotic and biotic occurred are not clear but include a "transition zone" in which complex abiotic systems gradually acquired some, but not all properties of life. This would be to some extent analogous to the case of viruses, which exhibit some, but not all properties of life. Just like viruses can be considered both not-alive and alive, the chemical systems in the transition zone can be looked at as both abiotic and biotic.

Dialethism also provides a fruitful approach to extraterrestrial life. We do not know if extraterrestrial life exists or not, since we have not found it yet. Thus, we do not know its properties, if it exists. In contrast, we know volumes about terrestrial life and its properties. When we envision extraterrestrial life, we cross the conceptual boundary of terrestrial life and transcend beyond it to the putative extraterrestrial life. Priest examined the limits of concepts and knowing, among other limits, and has found that these limits are boundaries which cannot be crossed, and yet we do cross them.

By conceptualizing extraterrestrial life, we cross one such boundary. If we are not aware of this problem, we may believe that our conceptualization of extraterrestrials as modeled by the earthly life is correct. Problems with the conception of alien life have been recognized by means other than dialetheism, but the latter helps us to see clearly the intrinsic problems in our thinking about this issue.

*Q 3.6 What is the most important thing that we have learned from applications of dialetheism to astrobiology?*
*A 3.6* The most important thing is the improvement in our own way of thinking. Astrobiologists often get bogged down in an endless debate whether (1) viruses are alive or not, or (2) what is the nature of the transition from abiotic to biotic, or (3) what is the nature of extraterrestrial life. Based on dialetheism, we simply acknowledge that viruses can be considered as both alive and not alive, that the transition zone has properties of both alive and not-alive, and that in conceptualizing the extraterrestrial life we are going beyond our limits of knowledge. Dialetheism takes the mystery out of our thinking processes.

# Chapter 4

# What is synthetic life?

*Q 4.1 What is synthetic life? How is it important to astrobiology?*
*A 4.1* Synthetic life, just as the term implies, is life made artificially in the laboratory, by unnatural means. There are various levels of accomplishing this, as discussed below. The importance for astrobiology is that if we are successful in making life synthetically, then we could understand the origin of life more fully.

*Q 4.2 If we make life synthetically, does it have to be like our familiar life, or could it be different?*
*A 4.2* In principle, it could be either. If the same, it will tell us more about our own life. If different, it would point out to variations of life, some of which may be relevant to the extraterrestrial life.

*Q 4.3 Is the idea of making synthetic life new?*
*A 4.3* No. The ideas on how to make synthetic life span the period from antiquity to the present. The history of these ideas and various attempts to create synthetic life are critically reviewed by Phillip Ball. Selected material is presented here for illustration.

The early ideas reflected a widespread belief in the spontaneous generation of life from decaying matter, such as Aristotle's recipe on how to make vermin (insects and mice), as described in his book "On the Generation of Animals", and Virgil's method for making synthetic bees from a carcass of a dead cow which was left on a bed of thyme and cinnamon sticks. It was later shown by Louis Pasteur that life is not generated by these methods, but is instead a product of life forms already present in the decaying matter, or which infiltrated it from outside (e.g., maggots).

More ideas came about, notably by the early chemists who believed that life is the result of a particular chemical composition, and that generating life is just an exercise in getting the right mixture of ingredients. Later ideas focused on the organization of matter, since it does not suffice to get just the right mixture of ingredients; they need to be configured such to interact with each other in specific ways.

The modern era of attempts to make synthetic life are based on the discovery of the double helical structure of DNA in 1953, and the mechanism by which DNA encodes genetic information and passes it from one generation to the next. The information is encoded in a DNA molecule as a sequence of molecular building blocks (nucleotides) along the helix. The mechanism by which the information is copied during replication involves the complementary match of the basic components of nucleotides and their interaction via hydrogen bonding. This gave chemists a long awaited “instructions for life”.

*Q 4.4 How is the knowledge on instructions for life translated to the recipe to make synthetic life?*
*A 4.4* The process was gradual. It involved development of new laboratory tools and methods for modifying “the instructions for life”, namely DNA. First, scientists discovered how to use natural enzymes to edit (insert, delete, or replace) one or more of a DNA’s nucleotides. This discovery was the foundation of the field of genetic engineering, which started in the 1970s, and the ability to create the *recombinant* DNA. These new developments also fed directly into the flourishing field of biotechnology, with many practical applications, e.g. medical, agricultural, industrial, and environmental. The focus here is only on what is most directly relevant to the recipe for life, namely genetic engineering and recombinant DNA. These terms are briefly defined, and then the recipe for life is addressed.

Genetic engineering is a method for manipulation of an organism’s genes coded in its DNA. Genes may be inserted or removed. This method can transfer the genes within and across species, thus producing new organisms.

Recombinant DNA is DNA that has been formed artificially by bringing together genetic material from various sources, including different species. This creates nucleotide sequences that are not found in the original DNA. Furthermore, DNA sequences that do not exist in nature may be created by chemical synthesis, and then incorporated into the DNA molecule.
However, the recipe for life for the new organisms produced by these techniques may not be a *legitimate* recipe.

*Q 4.5 What is meant by a legitimate recipe? What is the problem? Are these new species alive or not? Or, is there another problem with them?*
*A 4.5* The problem, in general, is not with the new species, many of which satisfy the requirements for life. The problem lies in the process (procedures and ingredients) for producing such a life.

*Q 4.6 Is the problem that the processes involved are not natural?*
*A 4.6* This is only a part of the problem. The antipathy and distrust towards artificial/unnatural life started in antiquity and persists to the present time. Metaphors for synthetic life that are used in the media coverage are often religiously, culturally, and emotionally charged. Scientists are said to be "playing God", or are "creators of life", or are producing "Frankenstein" organisms, which are dangerous and might escape to the environment.

Another part of the problem is deciding which processes, with their associated procedures and ingredients that are involved in the recipe for synthetic life are considered legitimate. If one starts with an alive system, and genetically engineers it into a different alive system, does it mean that life has been formed? The answer to this question is not straightforward. One possible answer could be yes since a new life has been created. Another possible answer could be that the original life has been only modified. Finally, the answer could be no, since life has not been created starting from the abiotic ingredients, such as prebiotic chemicals, which are not alive. In the latter scenario, the recipe would include various prebiotic chemicals, reactions that lead to the formation of biochemicals, and the processes which lead to the proper organization of life from these biochemicals. This is beyond reach at the present time. One of the grand challenges of synthetic life, "cooking from scratch" (a bottom-up approach), still remains.

*Q 4.7 Is this then the end of the story of formulation of the recipe for life?*
*A 4.7* No. There is a way to break down the process for formulating the recipe, by conquering the individual steps that could eventually lead to the solution.

*Q 4.8 Is there a good example for this?*
*A 4.8* Yes! Work by J. Craig Venter and his research group is an excellent example. These researchers aimed to reduce life to its bare essentials, which would constitute a milestone in the process of designing life from scratch. In 2016, they designed and created a synthetic cell which contained only 473 genes, which is the smallest genome of any known, independent organism. These researchers utilized techniques by which a whole genome can be built, starting from chemically synthesized nucleotides, and then transplanted it into a receptive cellular environment, resulting in a brand-new, viable, but artificial species.

*Q 4.9 What is the current trend in this area?*
*A 4.9* It is difficult to decide since the field is rapidly evolving. Still, the goal of synthesizing the human genome from scratch seems to be the current

focus of many research groups. Such a goal, which is otherwise worthwhile, is less related to the origins of life, and thus astrobiology, than the above-described project by Venter and coworkers, in which a minimal genome cell was created.

*Q 4.10 Is research related to producing synthetic life ethical? Is it regulated?*

*A 4.10* Such research has significant ethical issues, ranging from creation of "Frankencells" to the danger of synthetic life to natural life, from rights of humans to create synthetic life to the "rights" of such synthetic life. Following publication of Venter's work, the ethics of synthetic biology in general have been examined by The Presidential Commission for the Study of Bioethical Issues, and guidelines about such types of research have been published. It was concluded that new regulations, oversight bodies, or a moratorium on pursuing this type of research were not needed at that time. However, it was recommended that society must be vigilant about potential harms of such research and be prepared to revise the policies as needed. The moral significance of the creation of artificial life, such as concerns about playing God, and potentially undermining the special status granted to life, is also examined, with a conclusion that the creation of artificial life is not morally insignificant, but that more work needs to be done to support the view of its significance. Thus, at this time, both ethical and moral issues associated with the creation of artificial life are still in the examination phase.

# CHAPTER 5

# ORIGIN OF LIFE ON EARTH: WHAT IS CHEMICAL EVOLUTION, PREBIOTIC CHEMISTRY, AND THE RNA WORLD?

*Q 5.1 What is the current understanding of the origin of life on Earth?*
*A 5.1* The major hypothesis about the origin of life on Earth, which is accepted by astrobiologists, is the so-called Oparin-Haldane hypothesis. It was proposed independently by Alexander I. Oparin in 1924 and J. B. S. Haldane in 1929. This hypothesis states that the origin of life on Earth can be understood based only on the laws of chemistry and physics. Importantly, life arose on the early Earth by a series of chemical reactions and physical processes over a *long* period of time, and under the specific conditions in the early Earth's distant past. Thus, life is a product of the chemical evolution of matter.

*Q 5.2 Does this hypothesis have any experimental support?*
*A 5.2* Yes. Since the original proposal of the Oparin-Haldane hypothesis, experiments were performed which supported it, such as the synthesis of amino acids and other key biological precursor molecules under conditions that simulated those on the early Earth. The most famous such experiment was Stanley Miller's, in 1953. Miller, in association with Harold Urey, built a glass apparatus which consisted of a series of connected flasks and tubing, designed such as to simulate the primitive Earth's environment. Thus, one flask was filled with water, simulating the early ocean. The water could be heated for evaporation to add water vapor. Another flask contained the water vapor and the gases of methane, hydrogen, and ammonia to simulate the early Earth's atmosphere, which was believed at that time to be chemically reducing**.** In such an atmosphere oxygen is absent. The energy source was an electric spark, generated by a Tesla coil which was sparking in the "atmosphere" flask to simulate lightning as the natural energy source. Various amino acids were formed, such as glycine and alanine. Miller's experiment demonstrated that organic compounds which are central to life

can indeed be formed under simulated prebiotic conditions (prebiotic = before life existed).

Miller later synthesized amino acids under more mildly reducing or non-reducing conditions, to address the possibility that those atmospheric conditions existed on the early Earth. These syntheses were not as successful as those in the reducing atmosphere but were judged adequate.

*Q 5.3 What are the "simulated prebiotic conditions"?*
*A 5.3* These conditions mimic the presumed early Earth's environment, such as the chemical make-up of the atmosphere, the geological availability of organic and inorganic chemicals and minerals, and chemical reactions which are feasible to occur on their own and which yield compounds that are important for life, or are precursors of the latter. The environmental conditions chosen among the available ones are those that are compatible with the stability of the organic materials. Many minerals exhibit catalytic properties, but they are not always used in the experiments, since this makes the overall experimental design overly complicated.

*Q 5.4 What is meant by "occurring on their own"?*
*A 5.4* This means that once the chemicals are assembled and mixed by the investigators, no further intervention is allowed. Chemical compounds then react without outside interference (external heating or cooling, isolation and purification of reaction intermediates, sequential addition of chemicals after the initial ones react, etc.), following chemical principles of reactivity (not all chemicals are reactive with each other), and thermodynamic requirements, such as the availability of energy that can be utilized by the chemical system. Typically, mixtures of new compounds are produced. Investigators then isolate and purify compounds out of the mixtures to prove that they indeed are present. Sophisticated analytical procedures and instruments are often used for this purpose. Although chemical reactions occur on their own in nature, reproducing the process in the laboratory is often an imperfect simulation of what might have happened on the early Earth.

*Q 5.5 Were the Miller experiments the only prebiotic syntheses?*
*A 5.5* No. Many more experiments have been performed since then, targeting other biologically relevant organic compounds. Based on these experiments, new proposals emerged on the chemical origins of life. A brief historical summary follows.

As early as the 1970s, prebiotic syntheses of urea, fatty acids, porphyrins, vitamins, purines, pyrimidines, sugars, and nucleosides had been attempted, with varying degrees of success. Much progress had been made by the 1990s and early 2000s and continues to this day. Notable early researchers dedicated to the field of prebiotic synthesis included Leslie Orgel, James Ferris, Juan Oró, Gustaf Arrhenius, Sidney Fox, Cyril Ponnamperuma, Manfred Eigen, Albert Eschenmoser, and Jeffrey Bada. Prebiotic syntheses of life's building blocks, such as amino acids and peptides; sugars such as ribose; lipids; and components of nucleic acids such as nucleobases, nucleosides, and nucleotides, have been improved. Most recently, progress has been made with new, innovative prebiotic syntheses of nucleosides and nucleotides, which previously gave only marginal results. Prebiotic chemistry is now looked at in a geochemical context, in which geological components and conditions facilitate the occurrence of prebiotic chemistry.

New chemistries were explored to deal with the origins of life problem. The role of sulfur in life's beginning was brought up. Thus, Günter Wächtershäuser proposed that life originated in an "iron-sulfur world". He believed that the prebiotic organic material formed under deep sea vents conditions by reduction of carbon dioxide with hydrogen sulfide over ferrous sulfide as the reducing agents. Christian de Duve proposed a "thioester world." In thioesters, the ester's singly-bonded oxygen (-O-) is substituted with sulfur (-S-). According to de Duve, thioesters had a role in primitive (proto) metabolism. He based this proposal on the present-day biochemistry, in which thioesters are common intermediates in metabolism.

The leading breakthrough hypothesis for the origins of life based on RNA emerged in the 1960's, quasi-independently from the separate conceptualizations of several highly-regarded scientists: Alexander Rich, Leslie Orgel, Francis Crick, and Carl Woese. RNA (ribonucleic acid) is a molecule similar to DNA, but more versatile. This hypothesis, named later "The RNA World" by Walter Gilbert, postulates that the RNA molecule is the original self-replicator and had not only a capability to carry the genetic information, but also to act as a catalyst for its own replication and other reactions. In current-day biology, proteins are the typical catalysts ("enzymes"), while nucleic acids such as DNA carry genetic information. With this concept, there was no need for protein enzymes at the beginning of evolution, since one molecule, RNA, carries both functions. An RNA molecule that can catalyze one or more reactions is termed a ribozyme.

Work on developing ribozymes to demonstrate they could have fulfilled this function has been explored in the laboratories of Gerald Joyce, Jack Szostak, and others. The RNA world hypothesis is also strongly supported by advancements in prebiotic chemistry.

Recent research by John Sutherland and colleagues has demonstrated that it is possible to synthesize the building block molecules for the three most fundamental components of primitive life (RNA, proteins, and lipids) from the same simple set of starting materials. The starting organic source is HCN (hydrogen cyanide), a compound found in comets, meteorites, the interstellar medium, the Titan atmosphere, and also produced by lightning in early atmospheres of Earth and Mars. Combining HCN with volcanic $H_2S$ gas (hydrogen sulfide) under the UV from sunlight, plus some catalytic agents based on copper (Cu) can, in various ways, produce all the molecules needed for the three fundamental components. The John Sutherland group call this the "cyanosulfidic pathway" to the origin of life.

Stabilization and protection of the RNA molecule during polymerization is aided by certain boron (B) minerals, which has been studied by the Steven Benner group. Follow-on research by Thomas Carell and colleagues has shown a "one-pot" system of simple starting ingredients which can produce all four bases needed by RNA to encode the genetic information and provide the spatial configurations that enable RNA to function as an enzyme. They use zinc (Zn) based catalyst and also invoke boron, as well as wet/dry cycling to drive key polymerization reactions.

*Q 5.6 Is there some way to check if prebiotic syntheses are reasonable?*
*A 5.6* Yes. One way is for scientists to experimentally investigate if the compounds which result from their simulated prebiotic syntheses have been found in the meteorites which are rich in organic compounds ("organics"). The most famous such meteorite, Murchison, a carbonaceous chondrite type, contains a huge number of extraterrestrial organic compounds, including many which are biologically relevant for life on Earth. A match between the structure or type of a compound which resulted from the simulated prebiotic synthesis and the list of compounds from Murchison indicates that such synthesis is feasible under abiotic conditions elsewhere in space, and thus, by analogy, on the prebiotic Earth.

Details on formation of complex organic compounds in space are becoming available. Organic compounds found in the meteorites were made in space but are sometimes altered while present on meteorite's parent bodies, such as asteroids. Alteration may be aqueous and is the result of a transient availability of water. As scientists apply modern analytical methods to the analysis of biologically relevant organic materials from meteorites, such as amino acids and nucleobases, they understand more about prebiotic chemistry -- what is reasonable and what may not be. This is only one check, however, because synthesis of organics on a planet can be different from that in space and asteroids.

*Q 5.7 Are there any differences between the compounds found in meteorites and those in living systems?*
*A 5.7* Yes. The most important one is in the property of homochirality, which is uniformity of chirality (handedness). This is further described below, after a brief explanation of chirality and homochirality.

Chirality (from Greek "kheir" = hand) is a type of asymmetry in which an object is not superimposable with its mirror image (such as your left and right hand). When molecules are not superimposable with their mirror images, they also exhibit chirality. When all the molecules are of the same chiral form (thus exhibit either left-handedness or right-handedness), homochirality results. A term "enantiomer" (from Greek "enatios" = opposite and "meros" = part) denotes each of a pair of molecules that are mirror images of each other. While homochirality means an exclusive existence of a single enantiomer, in some cases one enantiomer prevails while the other is found in a lesser amount. Such cases are referred to as "enantiomeric excess".

In general, organic compounds characteristic for life, such as amino acids and sugars, among many others, exhibit homochirality. Life on our planet always uses sugars that are right-handed, and amino acids are always left-handed. However, organic compounds made in the laboratory by simulated prebiotic syntheses, or in space, as found in meteorites, are equal mixtures of both right and left-handed versions. Life on another planet conceivably could be based upon the opposite enantiomers, but otherwise could use the same molecules. If so, we would not be able to live off their food, and they would not be able to live off ours.

A very small enantiomeric excess has been observed in the amino acids in some meteorites, with no satisfactorily explanation so far. Likewise, the origin of homochirality is not known, especially if it occurred prebiotically or during biotic evolution. The evolution of chirality is proposed to occur in three steps (mirror-symmetry breaking, chiral amplification, and chiral transmission), which are the subject of promising studies in the laboratory.

*Q 5.8 What is meant by chemical evolution?*
*A 5.8* Chemical evolution is a hypothesis in which abiotic (thus, not-alive) matter evolves over a sufficient period of time to give matter which is alive (thus, life). Chemical evolution occurs in the universe, starting from the Big Bang to nucleosynthesis in the stars to formation of inorganic and organic compounds on the objects in space, which are then organized into abiotic systems which in some cases transform to life. Reconstruction of the history of prebiotic chemical evolution that has led to life is difficult for many reasons, one of them being that some chemical species may have been

destroyed because of changes, such as dynamic geological processes on the early Earth, while others, which are more resistant to such changes, may survive.

*Q 5.9 Has life been continuously created on Earth from the abiotic chemical matter, including the present time?*
*A 5.9* No. It is believed that once life has evolved and established on the Earth, any other advanced abiotic chemical matter that may have been created by chemical evolution, would simply be eaten by the established life. This view is supported by the fact that all life on Earth has the same biochemical foundation in terms of its genetic apparatus and many metabolic constituents and pathways.

*Q 5.10 So, how do we reconstruct the origin of life if it happened so long ago and is not occurring today?*
*A 5.10* To reconstruct the origin of life, scientists typically use two general approaches: bottom-to-top and top-to-bottom; and three specific hypotheses: metabolism-first, genetics-first, and membrane- or coacervate-first.

The bottom-to-top approach involves studying prebiotic chemistry under simulated prebiotic conditions, starting from the simple compounds, all the way up towards molecular complexity from which life emerges. In the top-to-bottom approach, investigations start from existing, more developed life forms and continues to the most primitive ones, with the objective to discover the simplest design of present life. Based on the latter, scientists then hypothesize about the characteristics of LUCA (the Last Common Universal Ancestor), a presumed DNA-based organism which emerged from the RNA world and became the progenitor of the three domains of life

The metabolism-first approach starts from the premise that the development of the primitive metabolism was the starting step to life. Metabolism is the set of chemical processes that occur within a living organism to maintain life. This can be envisioned as a proteins-first scenario, in which amino acids became polymerized to primitive peptides which then catalyze key reactions. The difficulty of this approach is that it does not have a clear way to include a genetic component to preserve information about chemical syntheses of individual metabolic components and their assembly into the functioning metabolism. These would have to be constantly reinvented, and progress would be mostly by chance.

The membrane-first approach emphasizes the importance of prebiotic compartmentalization, in which primitive membranes enclose and concentrate organic materials, and thus separate it from the aqueous environments in which they are diluted. Concentrating chemicals within the compartments speeds up the rates of chemical reactions and protects them from the outside environment.

Membranes can be formed from a class of molecules called amphiphiles. Extracts of Murchison meteorite have included amphiphilic molecules.

The coacervates-first approach was proposed by Oparin in 1929, in which coacervates provide compartmentalization, in addition to acting as prebiotic chemical reactors which are also able to reproduce. Coacervates are organic rich droplets that are formed by liquid-liquid separation. Their reproduction is achieved by splitting, which occurs when coacervates grow so much as to become thermodynamically unstable or are impacted by another body. Like membranes, they contain no genetic information, so that their organization and functioning stays at a primitive level since it is mostly reinvented rather than being preserved via genetics.

In the genetics-first approach, formation of self-replicating molecules, such as RNA, is the essential start towards life. This case is supported by the fact that all life on Earth has a common genetic basis, and that the RNA, in addition of being an informational molecule capable of self-reproduction, can also act as a catalyst for its own replication, as well as for other reactions. The instructions for development and organization of these early RNA systems is preserved in their genetic material, so that the system does not need to be constantly reinvented.

*Q 5.11 What is the actual process in which the transition to life occurs from non-living matter?*

*A 5.11* We do not know. Even if we were able to make life in the laboratory, which we have not accomplished yet, it would not guarantee that the process would be the same as it occurred on the early Earth in the distant past (4.3 to 3.8 billion years ago). However, various hypotheses about so-called "abiotic-to-biotic" transitions have been proposed. They are briefly presented here.

The abiotic systems which have transitioned to life probably had many life features, such as self-organization, self-assembly from parts, formation of autocatalytic networks (in which products catalyze their own formation), metabolic cycles, establishment of self-replicating systems, use of energy, etc., but at a primitive level (e.g. proto-metabolism).

Some prominent hypotheses are those of Stuart Kauffman, who proposed a mechanism by which order emerges out of chaos; and theoretical and computational approaches by Sara Walker who examines if there is an algorithm for an abiotic-to-biotic transition, and addresses the nature of biological information and informational limits of evolution. Some hypotheses break down the problem of emergence of life into sub-stages, such as prebiotic, protobiological, and biological stages. Each stage is proposed to be comprised of additional sub-stages. The transition from prebiotic chemistry to protobiology has been addressed by analysis of a diverse pool of prebiotic building blocks, to see how it could lead to a self-assembling system which is capable of chemical evolution. Classes of bio-organic compounds capable of building worlds based on proteins, lipids, thioesters, and the RNA, have been considered.

# CHAPTER 6

# WHAT ARE THE STAGES OF CHEMICAL EVOLUTION THAT LEADS TO LIFE? IS THE EMERGENCE OF LIFE IN THE UNIVERSE INEVITABLE?

*Q 6.1 What are the stages of chemical evolution which leads to life?*
*A 6.1* Stages of chemical evolution are best understood within the context of cosmic evolution starting from Big Bang all the way to life. They are then followed by the biological Darwinian evolution. Chemical evolution may be conveniently presented in 10 consecutive stages. They are: Stage 1: The Big Bang yields hydrogen and helium; Stage 2: Other elements are formed by nucleosynthesis in the Stars; Stage 3: Simple inorganic and organic compounds are produced in interstellar space or on the bodies in space; Stage 4: Complex organic molecules are formed; Stage 5: Macromolecular aggregates are produced; Stage 6: Complex systems that are rich in diverse chemicals and catalysts are generated; Stage 7: Abiotic transitional systems are produced, which have a potential to lead to life; Stage 8: Primitive proto-life is brought about; Stage 9: Simple life is generated; Stage 10: Biological evolution occurs that leads to complex life.

*Q 6.2 Is this sequence of events, which Stages are the least understood in regard to the emergence of life?*
*A 6.2* They are Stages 8 and 9, which are also the most directly involved in the emergence of life.

*Q 6.3 Would Stages 8 and 9 be viable for chemical evolution that occurs elsewhere in the Universe?*
*A 6.3* We hypothesize that they would, if life evolved elsewhere. These steps may be qualitatively and quantitatively different than those on the primordial Earth, for the reasons that the geochemical environment on another planet may be different.

*Q 6.4 But these steps would occur?*
*A 6.4* Not necessarily. Chemical evolution of complex chemical systems may or may not proceed further to give life.

*Q 6.5 Why would evolution to life not happen?*
*A 6.5* A specific and detailed answer is not possible at this time, primarily since the Stages 8 and 9 are still poorly understood. However, progress towards life may not occur due to the geological and geochemical conditions on another planet, which would not be compatible with life. There are also many complex and critical steps which would need to occur, such that the probability of achieving a form of life that could survive for a significant time may be exceedingly low.

*Q 6.6 Does this mean that life would always emerge if the geochemical conditions are favorable to life?*
*A 6.6* Not always. Some investigators believe that life would emerge by a "path towards certain outcome", which is predetermined and guaranteed, while some others believe in the significant role of chance in this process.

*Q 6.7 So what is it? A guaranteed outcome or outcome by chance? Is there a solution to this dilemma?*
*A 6.7* Not yet. Arguments for both views have been analyzed recently by Iris Fry, from a philosophical point of view.

*Q 6.8 Is the scenario in which complex organic chemicals do not evolve to life important to astrobiology?*
*A 6.8* Yes. If we find the evidence of the complex organic chemicals on other planets, but not the evidence of present or past life, this would indicate that there was a time in the past of such a planet that life could have evolved but simply did not do so. This could indicate that the origin of life has a quite low intrinsic probability of success. Alternatively, the life may have been too highly dependent on a particular environment, and hence not capable of surviving when that environment changed.

*Q 6.9 Does it mean that chemical evolution to pre-life was "wasted" on such planets, as far as generation of life?*
*A 6.9* Not necessarily. Highly developed organic materials from the planet where the further evolution towards life was arrested may be transported to another planet where such materials may be able to continue evolution to life due to different and more favorable environmental conditions.

*Q 6.10 How can transport of such material from one planet to another occur?*
*A 6.10* Such an interplanetary transport can occur when a large object (such as an asteroid) impacts the planetary surface and ejects surface material into space. The material then travels thorough space and after a period of time lands on a new planet, where chemical evolution to life can continue due to the favorable geochemical conditions. This would be considered a case of interplanetary "panspermia," which is further described in Chapter 10.

*Q 6.11 What is the difference between chemical evolution and Darwinian evolution?*
*A 6.11* Darwinian evolution applies to evolution of life through changes in its progeny, while chemical evolution applies to pre-life only.

*Q 6.12 Are these two types of evolution clearly distinct, or do they share some common aspects?*
*A 6.12* They are clearly distinct in the sense that one system is alive, while the other is not, but some aspects of Darwinian evolution can be modified to apply also to chemical evolution. Let us consider the aspect of *natural selection* in Darwinian evolution. In this context natural selection is a process such that the organisms, as individuals or groups, which are better adapted to their environment tend to survive and produce more or better offspring than those which are not as well adapted. When considering chemical evolution, which is pre-life, one could also introduce natural selection by which chemical reactions and processes are favored if they can occur in an environment which has a particular set of chemical precursors, including metal ions and clay catalysts, and energy sources, which may be limited or change over time. Thus, chemical reactions will occur preferentially if they are more suitable for the environmental circumstances.

*Q 6.13 Why is it important to extend the concept of natural selection to prebiotic chemistry?*
*A 6.13* Without it, we would be tempted to believe that chemicals react by chance and in a random, uncontrolled manner which is not connected to the natural environment in any way.

*Q 6.14 What would be so bad about such a belief?*
*A 6.14* Our design of prebiotic chemical experiments, aimed to elucidating the origin of life, would be very poor. One would just mix chemicals at random and sit and wait until something interesting comes up. Instead, a better design would be based on our understanding that some chemical

reactions would be favored by some specific mineral catalysts that come from the environment, or by the presence of some specific energy sources. We would then match the chemicals with the catalysts and energy sources in an informed way, rather than at random.

# CHAPTER 7

# HOW ARE CHEMICAL DIVERSITY AND COMPLEXITY DEVELOPED?

*Q 7.1 Why is this topic important to astrobiology?*
*A 7.1* Availability of a complex and diverse pool of chemicals is necessary for life to emerge. Complex chemical systems which are rich in diverse chemicals and catalysts give rise to abiotic pre-life systems which then lead to proto-life and finally complex, full-featured life.

*Q 7.2 How are prebiotic chemical diversity and complexity developed?*
*A 7.2* We do not know the details of these processes, which are historical and thus unknown. Chemical species that were instrumental for building precursors for chemically diverse and complex systems are presumably the ones that were available on the early Earth. We can then construct hypotheses about the specific steps by which diverse and complex systems evolved from these chemical precursors. However, we can consider some general hypotheses about these processes without involving the specific chemicals.

*Q 7.3 What are some examples of such hypotheses?*
*A 7.3* Some selected examples are “messy chemistry” and “adjacent possible.” Messy chemistry is chemistry that results in a high diversity of products, intermediates, and reaction pathways, which are typically challenging to identify. This type of chemistry in the field of synthetic organic chemistry is known as “chemistry which gives intractable mixtures” and is normally considered a huge negative result when one runs chemical reactions in the laboratory. “Messy chemistry” is a relatively new term which has been used in conjunction with prebiotic chemistry. In this context, “messy chemistry” is an important concept for elucidating chemical evolution which could lead to life.

*Q 7.4 Why is this concept important for prebiotic chemistry?*
*A 7.4* Firstly, this concept brings up the possibility that complex chemical systems, including chemical reactions and their networks which led to a primitive metabolism, may have started messy and then later became streamlined and less messy. Traditionally, prebiotic chemists design experiments in which they choose reactions which give as products those that resemble biological systems or their precursors in the cleanest possible way (thus, a minimum number of products, and very few by-products). Messy chemistry, in contrast, suggests that we should perform simulated prebiotic experiments without much prejudice as per prebiotic utility of the produced compounds or number of products and by-products, but instead should study messy mixtures and try to figure out only the types of the compounds that are produced, rather than exactly identifying each individual compound of the mixture (e.g., sugars, rather than glucose). This may be a more adequate model of the prebiotic chemistry than the one which is limited prematurely in its design (namely, to choose chemicals that we believe would give the pre-biologically relevant compounds). A strong point of "messy chemistry" is that it takes an *observational* approach, which has a potential for discoveries of new reactions and their products which otherwise would have been missed by not being included in the prebiotic reaction design.

*Q 7.5 What are disadvantages, if any, of the "messy chemistry" approach?*
*A 7.5* There is an intrinsic problem in studying any system which is too complicated to begin with. While such a study may be more holistic and thus more accurate than that of a simplified system, it is quite difficult to study experimentally. At the end of the day, one needs to identify chemical components so that one can understand the chemical processes. Likewise, a discovery of new chemicals can be confirmed only via chemical identification. This is also extremely difficult to do in a chemical mixture.

*Q 7.6 So, should "messy chemistry" be pursued?*
*A 7.6* Yes, but with an understanding of its weaknesses.

*Q 7.7 Can this weakness be remedied?*
*A 7.7* Yes, but in the future. As the analytical tools for identifying chemical compounds advance, it is possible that in the future we shall be able to easily and more accurately analyze chemical mixtures which at this point of time we are not able to and thus consider them "messy".

*Q 7.8 What is "adjacent possible", and how is it related to generation of complex prebiotic chemical systems?*

*A 7.8* The concept of "adjacent possible" was proposed by Stuart Kauffman. This is a general concept, but we shall focus here on its applications to prebiotic chemical systems. A set of organic molecules in a particular setting, such as a prebiotic one, is termed "actual". The "adjacent possible" is comprised of all organic molecules that are not members of the "actual" but are one reaction step away from the "actual". In biochemistry, the reaction substrates are in the "actual," and the products are in the "adjacent possible". One element of this concept is of a critical importance for prebiotic chemistry: the "adjacent possible" is essentially the total environment, which typically contains not only key chemicals, but also metal catalysts, clays, and energy sources which will help drive chemical reactions of the "actual". The "adjacent possible" is essentially the environment. Although the detailed features of "adjacent possible" cannot be predicted, we may have a reasonably good idea about their general character (such as within a specific planetary geochemical situation).

# CHAPTER 8

# WHAT IS OUR CURRENT UNDERSTANDING ABOUT THE CRADLE OF LIFE?

*Q 8.1 What is meant by the cradle of life? Why is this concept important?*
*A 8.1* So far we have talked mostly about different concepts and proposed happenings in regard to the chemical evolution that leads to life. Thus, we talked about chemicals from space which served as an initial stock of prebiotic chemicals. We considered RNA-first, metabolism-first, and membranes-first proposals. We also discussed the transition between not-alive and alive matter. However, we have not put everything together to be able to answer the question: Where, in which location and under which geochemical setting did all these steps come together?

Here, we use the term "cradle", in analogy with an infant's bed or crib. This signifies that life is started in the cradle, but such life is not fully developed yet and is not self-sufficient in the outside world.

*Q 8.2 Are there different ideas about the cradle of life?*
*A 8.2* Yes. However, some of these ideas are either overlapping or are depending on each other. It boils down to the question which hypothesis includes *more of the steps* of the chemical evolution that lead to life in *one location*, and thus is *more comprehensive*.

*Q 8.3 Why is it good to have more steps of chemical evolution in one location?*
*A 8.3* If we have a scenario which requires that the individual steps occur at different locations, then we have an additional problem, i.e., how to get the products of these steps together later in a single location. For example, if we have a primitive proto-metabolism developing in one location, and the RNA genetic component in another, and the membrane component in yet another one, then we must determine how these are getting together.

*Q 8.4 But, couldn't the scenario of developing at different locations and then coming together still be valid?*
*A 8.4* Yes. The simplest scenario, all steps in one location, would be a case supported by the principle of Occam's Razor, which favors the case with the fewest assumptions. This does not make it true, however. Still, the simplest scenario is more probable in the examples that we gave.

*Q 8.5 What are some hypotheses for location of the cradle of life?*
*A 8.5* There are several, and someday there may be more. One of the leading candidates came about in a most unexpected way. Here is how it began.

Just as the Viking-mission biologists were finishing up their experiments searching for life on Mars, in 1977, a separate group of scientists was exploring the ocean bottom near the Galapagos Islands in search of hot water where sub-surface volcanic activity was expected to occur. The team of marine geologists did not include any biologists, but their deep undersea robot named ANGUS (**A**coustically **N**avigated **G**eophysical **U**nderwater **S**ystem) discovered and photographed a small area of the seafloor with not only warm water but abundant white clams where no bottom life was normally to be seen. They circled back, dove in the Alvin submersible research vessel, and made a sensational discovery of life flourishing where there is no sunlight for photosynthesis.

Ironically, while biologists were searching for life on Mars but apparently finding only geochemical novelties, a group of geochemists exploring the ocean bottom with a robot was stumbling upon bizarre new forms of life on Earth in a location least expected for it. This inspired scientists to start thinking that life may have originated in these newly discovered locations.

Subsequent explorations have found hundreds of individual locations where hot water is coming out of seafloor volcanic areas, often forming spectacular pipes that have been called "chimneys." Ocean water that seeps down into the subsurface elsewhere gets heated to temperatures far above the normal boiling point but does not boil because of the high pressures deep in the ocean. Instead, it forms underground channels that then pop to the surface and form chimneys that can be meters tall. Some chimneys produce black clouds of particles, and are called "black smokers", and others produce white clouds.

*Q 8.6 What is the difference between these types of "smokers"?*
*A 8.6* The black smokers emit water at a higher temperature (up to 400° C) and contain dissolved sulfides which precipitate as black particles when they hit the cold ocean water on the seafloor (2° C). The white smokers are cooler (typically less than 300° C).

*Q 8.7 What else besides sulfide is in the plumes from the smokers?*
*A 8.7* The smoker plumes, and other emissions from the sea floor in these areas, are loaded with important chemicals. They include methane and carbon monoxide, both of which are ideal for synthesis of the organic biochemicals needed for life. They also produce hydrogen and have dissolved out of the basaltic rock numerous metals and sulfur compounds. The clams and other organisms, such as colonies of bizarre red tube worms, are higher levels of life that are possible because of the food chain arising from the abundant bacteria at the lowest level. The bacteria themselves are various chemotrophs (organisms which obtain energy from chemical reactions) by obtaining their energy from oxidation of the sulfur, methane, or hydrogen being vented, taking advantage of oxygen and other oxidants dissolved in the seawater.

*Q 8.8 Aren't these some of the chemicals needed for the origin of life?*
*A 8.8* Yes indeed, and the dissolved metal ions include those of iron (Fe), copper (Cu), manganese (Mn), and zinc (Zn), which are often found to be useful as catalysts in different prebiotic reactions leading to life. It has long been known that hot water can dissolve or corrode rock minerals efficiently, and geologists often discover areas that have been modified by these "hydrothermal" conditions. Many ore deposits have hydrothermal origins.

*Q 8.9 So, these submarine hydrothermal vents are not only a place for life today, but could have been where life began?*
*A 8.9* Possibly. There are strong proponents for and against this hypothesis as being where it all began.

*Q 8.10 What are the arguments in favor of submarine hydrothermal vents as the location for the origin of life?*
*A 8.10* The abundant life seen at these vents is a testament that all the key ingredients for an ecosystem are available. And, as we just mentioned, many important ingredients for an origin of life happen to be present also. This includes nitrogen compounds – the black smokers contain nitrates and the white smokers include ammonia ions. Not only are the key elements present, but an abundance of redox couples can provide the energy to drive metabolic activity and reproduction.

*Q 8.11 How can organisms live in such hot water?*
*A 8.11* At first it seemed that they were very unusual and special. Although plants and animals cannot tolerate hot water, many microbes can. Some species of archaea actually thrive in very hot water and are therefore called

"thermophiles" (heat-loving). And a few of them can even survive water at its boiling point. These are the "hyperthermophiles." Fortunately, very few of the archaea organisms can cause disease in us humans, so boiling infected water is still a reasonably effective way to sterilize it, as is a flash heating of milk to pasteurize it.

When scientists include microbes to construct a Universal Tree of Life, they find that the organisms with the oldest known genes are thermophiles. This, say the proponents of a hydrothermal setting for the origin of life, is evidence that earliest life came from scalding environments. Furthermore, their genes seem ancient and specialized for proteins which are fully functional at very hot temperatures, whereas many proteins in organisms that live at lower temperatures are destroyed by mild heating.

*Q 8.12 How is a Universal Tree of Life constructed?*
*A 8.12* Originally, the Tree of Life was a diagram of the evolutionary relationships among various species, as deduced from the fossil record and anatomical characteristics of organisms. Thus, for example, fish gave rise to amphibians (e.g., frogs), with the fins becoming legs. Then reptiles (e.g., turtles, snakes and dinosaurs) arose, leading to the eventual appearance of the flying dinosaurs (the birds!). Arising as an offshoot were the first mammals, the predecessors of everything from dogs and cats, to mice and monkeys.

There also is a Tree of Life for the microscopic forms of life, to determine which species of organisms have existed longer than others. Scientists have examined specific RNA sequences in the ribosomes of various species and found patterns that indicate the successive history of mutations, showing thermophilic species at the very root of the universal tree. They have also used this molecular technique to make a few corrections of the original Tree of Life.

*Q 8.13 What, then, are any arguments against the submarine hydrothermal vents hypothesis?*
*A 8.13* Perhaps the most obvious one is that when these chemical-rich waters spill out into the cold ocean water, it causes precipitations and then quickly dilutes any of the chemicals which are not precipitated to very low concentrations. The oceans are so vast, and the waters disperse quickly, that their usefulness is quickly lost. As a result, the communities of organisms are only located very close to the vents themselves. A counter-argument is that the chimney's walls are somewhat porous, and prebiotic chemical evolution could occur within pores while still hot.

Besides dilution, there is the problem that if organic compounds are expected to be formed within the hot water from the chimneys, there is a two-edged sword effect. The high temperatures and high concentrations of reactants favor many chemical reactions. However, certain of the most important organic compounds formed, including amino acids, are destroyed by high temperatures.

In the deep ocean, there is no access to sunlight, including its ultraviolet radiation. And, any organics from meteorites or comets will be dispersed throughout the vast ocean and not be available at any reasonable concentration for prebiotic syntheses leading to life.

Most importantly, the benefits of wet/dry or freeze/thaw cycling are not available to drive the formation of essential polymers, such as RNA and polypeptides (the forerunners of proteins). Moreover, synthesis of many key biomolecules has not yet been demonstrated under the conditions expected in these vents.

Detractors of this theory also point out that the existence of thermophilic organisms with an ancient pedigree do not *prove* that life *began* in a hot environment, but rather that early organisms may have been selected for adaptation to a relatively higher temperature environment that became more common at one time in history.

*Q 8.14 At what other locations could life have first begun?*
*A 8.14* There are three general possibilities for the locations where the key ingredients for life originated. These are *from below*, *from above*, or just *at the surface* of the Earth itself.

We have just described some of the characteristics of the ocean floor hydrothermal vents, which is the *from below* hypothesis. Possible contributions *from above* are via organic-rich meteorites or comets. These sources would contribute organic materials for development of life *on the surface*.

*Q 8.15 What are some specifics of these scenarios?*
*A 8.15* Obtaining substantial organics from meteorites or comets for prebiotic evolution is tricky, although researchers often cite this source favorably without further analysis. The problem is that these objects invariably encounter the Earth at extremely high relative speeds (much higher than the speed of sound, or "hypervelocity"). Part of the reason for the high speeds is that these bodies are in quite different orbits around the Sun than we are, and the relative crossing velocities are large, similar to the devastation wreaked by head-on collisions of automobiles. The other reason is that the Earth's gravity accelerates them even faster towards us. The

velocities are so high that the objects often break apart and burn up in the atmosphere, destroying much of the organics in the process. Some do not, and although those get extremely hot on the outside, the inside can remain cool and not destroy their organic compounds. The very largest ones are not slowed enough by our atmosphere, however, and strike the surface so hard that they explode and disperse their contents over a huge area, while leaving a deep crater in the ground.

But there is another, more practical problem. It is difficult to accumulate a large amount of organics in the soil because even though at the early time of the origin of life there were far, far more impacts per year than today, the impacts were spread out over a major fraction of geologic time. The time interval between successive impacts in any one location was quite long, thousands of years, during which time the most recent set of organics delivered may already have been widely dispersed, or mixed into the soil, or covered by lava, or washed to the ocean by rainfall and rivers, or otherwise diluted or destroyed..

For this reason, one hypothesis for the origin of life postulates a very unusual event: that a portion of a comet somehow survives the passage through the atmosphere and is slowed enough to not explode when it hits the ground, but creates a depression and then melts to make its own local environment. This "comet pond" scenario has a quite low probability of happening but has the advantage of preserving the concentrated and extremely organic-rich and perhaps unique components in a comet.

A "meteorite pond" hypothesis has the advantage that meteorites are stronger and more likely to survive to the surface. But they do not have their own water and only a few of them will land in ponds. Furthermore, even though we do have many meteorites of this type in our laboratories and museums, their mixture of organics is complex and may not be the best starting material for conversion into the chemicals needed for the first life compared to comets.

The original idea has been that life arose somehow at the surface of the Earth, without help from below or above. In 1871, Charles Darwin famously wrote --- not in a book, but in a letter to a friend – "But if (and oh what a big if) we could conceive in some warm little pond with all sorts of ammonia and phosphoric salts, light, heat, electricity etcetera present, that a protein compound was chemically formed, ready to undergo still more complex changes."

*Q 8.16 Why did Darwin parenthetically say, "oh what a big if"?*
*A 8.16* Most likely, he was speculating because only relatively little was known at that time about the biochemistry of life and how it works.

It was more than 50 years later that Oparin and Haldane independently hypothesized that the organic molecules needed for life could have been produced in an ancient reducing atmosphere much different than we have today. Without organic molecules, Darwin's little pond would have had no chance to succeed. It was the Urey-Miller experiment another 30 years later which showed that lightning bolt discharges in a mixture of gases thought to be a likely ancient atmospheric composition could produce reactions that resulted in the synthesis of amino acids.

*Q 8.17 So, what do we know about an origin of life that was at the surface of Earth, independent of the "above" and the "below"?*
*A 8.17* This is the classic hypothesis. We just pointed out that lightning discharges can produce key organics from simpler atmospheric gases, such as $CO_2$ (carbon dioxide), $H_2O$ (water vapor), and simple nitrogen-containing molecules. Other methods for forming these products include solar UV (which can also destroy organics, if intense enough) and the shock waves when meteorites hit the Earth's atmosphere.

The reality is that we have only limited knowledge about the ancient atmosphere. Clearly, it once had much more $CO_2$ than today because the vast majority of it was converted to carbonate rock, as observed in widespread limestone, marble, and coral reefs. And our ancient atmosphere had almost no oxygen gas. Scientists do have reason to believe, however, that it may have had a significant amount of hydrogen gas, and from that, perhaps some methane, ammonia, and even HCN.

*Q 8.18 Any major advantages for "what happens at the surface of the Earth"?*
*A 8.18* Yes. With sunshine, the primordial soup has access to energetic ultraviolet light, which can catalyze or enable certain prebiotic reactions.

Furthermore, if events occur in a small pond, the concentrations of important ingredients can be high, and remain high. For example, assuming the depth of a body of water is proportional to the diameter of the lake or pond, then the ratio of the area of the ground that is covered to the volume of water is higher for smaller diameters, as can be shown mathematically. This means key nutrients leached out of the ground or dissolved from the atmosphere will be in higher concentrations for smaller ponds. For this factor, a smaller pond is better than a larger pond.

Even higher concentrations could be achieved in an underground porous aquifer. This would avoid the deleterious aspect of extreme UV light. A pond could be connected to, and even fed by a shallow aquifer, and hence combine the attributes of both types of environments.

*Q 8.19 How is a "warm little pond" formed in the first place?*
*A 8.19* Ponds can be created by many different processes. Rainwater filling natural depressions, or meandering rivers, or ephemeral streams can form and feed ponds. The braided streams at a river delta can be quite dynamic, with changing patterns of successive ponds having interconnecting rivulets. Tidal flats that are subject to repeated flooding with ocean water between high and low tides also provide opportunities for wet/dry cycling. Springs can pop up anywhere the groundwater has access to the surface.

Large impacting bolides from outer space not only create craters when they hit, but some of their kinetic energy turns into heat and if there is ice or ground water in the terrain, they can create hydrothermal conditions just at that location alone. The bowl shape of a crater is ideal for a pond or lake. Although this would be only a one-time injection of heat energy, analyses have shown that for large impact craters, the high temperatures could persist for tens of thousands, and perhaps even a million years. This is yet another hypothesis that has been examined and proposed as an ideal setting for a hydrothermal-related origin of life.

*Q 8.20 Could there be other hydrothermal activity at the surface of the Earth, where it would be possible to avoid some of the disadvantages of the vents deep in the ocean?*
*A 8.20* Yes, from volcanic activity. Yellowstone National Park in the United States is an outstanding example of hydrothermal activity. This wonderland has hundreds of geysers as well as hot springs which support a wide variety of microbial organisms. Bands and streams of spectacular colors give testament to communities of thermophilic archaea and, in cooler locations, bacterial communities taking advantage of sunlight and the chemicals leached out of the rock over which the hot water has flowed.

*Q 8.21 Besides Yellowstone National Park in the United States, where else are there examples of hydrothermal activity at the surface of the Earth?*
*A 8.21* They can be found in many place all over the world, including Iceland, New Zealand, Greece, Turkey, Japan, and China. However, the combination of all the hydrothermal locations in Yellowstone is as much or more than almost all the others put together. Overall, the percentage of land area today which is populated by hydrothermal springs is extremely small. In earlier times, volcanic activity was much more pronounced during certain periods of geologic time than it is today. Hot springs can combine the advantages of both the warm little pond and hydrothermal chemicals.

Back in 1912, in a remote part of Alaska, a large volcanic eruption created the "Valley of the 10,000 Smokes." At the time, it was a major wonder of the world, partly because it accompanied the largest natural eruption of lava for what turned out to be the entire 20th Century. The "smoke" was from an uncountable number of locations where hydrothermal conditions were causing the release of steam.

*Q 8.22 What are you thinking of in terms of a "pond?" How big is it?*
*A 8.22* Not necessarily very large. If it is less than a one or two meters in diameter, it would rightly be called a puddle, and would be easily and quickly erased by the vicissitudes of weather. But if it is quite large, say a hundred meters in diameter, then only the shoreline might be an area where concentrations of important chemicals might be high enough to be useful. Therefore, it seems likely that the most favorable size would be of the order of a few meters to perhaps tens of meters in diameter. The reasons favoring a small size is that, as noted before, it could have higher concentrations of nutrients from the air and ground. Also, chemicals formed in the shoreline area where some of the key reactions occur would not be over-diluted when they reentered the main body of water.

Another scenario might be a shallow depth pond, so that the energy-supplying UV radiation could penetrate down to where heavier, less soluble organic material might have sunk. Alternatively, the energetic UV needed might be absorbed well by dissolved organics so that molecules needing protection could be shielded and protected in the lower levels of the pond. Molecules in a surface scum could be transformed by the UV, but also provide shielding.

*Q 8.23 Are there other factors that might favor smaller and more shallow ponds?*
*A 8.23* Yes. Even if the energetic UV at the surface is not needed, another key factor is available. That factor is the access to wet/dry cycling in order to facilitate the polymerization reactions that are energetically unfavorable but are needed in order to form RNA and proteins from their subunits. A shallow pond dries out faster during drought and is also more easily flooded to the brim by rainwater. Too small a pond under conditions of too much rain will, as expected, cause overflow. This overflow may be bad (if the contents are washed downstream and lost) or good (if some contents are transported to a nearby, but deeper pond with different ingredients).

For various reasons, the smaller pond may often have a greater ratio for the shoreline area compared to its volume than a geometrically larger pond. This shore is where so many important processes can occur, including not only wet/dry but also freeze/thaw cycling. It is where gels can form, through partial dehydration of organic solutions. Salts will precipitate. Although UV is at its maximum, the salts and other organics can shield chemicals just below the surface.

A shallower pond has the advantage that the depth of penetration of the UV can be more significant compared to its volume. The same relationship is true for a surface scum, dissolved constituents to a certain depth, or perhaps even a bottom sludge.

There are also negative attributes for smaller size. Too small of pond could have too short of lifetime against evaporation or overflow flooding. Convection may not be possible, but wind currents may cause mixing too often without time for semi-compartmentalization to be in effect. Larger ponds can have different chemical processes in different portions (shoreline; surface; bottom; bulk solution) that are somewhat isolated from one another. Diffusion of their products is a slow process that permits this semi-isolation to persist. Smaller ponds have less opportunity for quasi-compartmentalization.

*Q 8.24 What do you mean by semi-compartmentalization?*
*A 8.24* This is part of what we call the "Macrobiont" concept. The idea of the macrobiont (MB) is that it is a pond large enough and normally sufficiently quiescent that the time for molecules to mix by the slow process of diffusion is long compared to the time-scale of chemical reactions of different types in different locations in the pond. This allows a build-up of different desirable reaction products before some event, such as a windstorm or rainstorm, comes and causes mechanical stirring to more thoroughly mix these products together.

Alternatively, the interaction could occur at mutually colliding diffusion fronts. Mixing of multiple reaction "pots" has been assumed by various researchers, analogous to different laboratory experiments which are routinely conducted in independent test tubes before mixing together.

*Q 8.25 What does "Macrobiont" mean?*
*A 8.25* This is the concept that the first life could occur in something that is "macro" in scale, i.e., something we see with our eyes and not something that is microscopic like a bacterial cell. But as an entity it is a "biont" which signifies life because there are within it primitive life forms. These can be the RNA molecules which have the characteristics of both genetics and of catalytic activity for their reproduction, the basis of the widely held concept of an RNA World.

*Q 8.26 Can RNA be considered alive without being inside a cell?*
*A 8.26* Some scientists think so, because in an RNA World, the RNA molecules can reproduce, evolve, and catalyze their own reproduction,

perhaps the most fundamental characteristics of living organisms. The key "living" molecule is a version of a class of molecules called ribozymes (an RNA molecule with enzymatic properties). In the macrobiont, different locations act as different chemical reactors (places where specific chemical reactions occur). The system of these chemical reactors gives rise to primitive metabolism. And its physical boundaries are at the macro-scale limit of this system of life form entities. Not just millions but a gazillion number of RNA molecules can be in a small little pond, each evolving, some or many of which may eventually co-opt a mineral grain on which to adhere, or inhabit a primitive membrane envelope in which to reside.

*Q 8.27 Why do only some scientists think this RNA could be considered to be "alive", and others do not?*
*A 8.27* Biologists are usually taught, from the very first sentence in their very first biology textbook, that "the Cell is the unit of all life." Many scientists casually talk about the "free-living cell" as the fundamental biological unit, yet do not care to define it and simply ignore the fact that so many cells actually have a great dependence on the existence of other cells. The reality is that the only cells which can be truly independent are the chemolithoautotrophs and the photoautotrophs. Consider, for example, that typically all the cells in multicellular organisms are each so specialized that they cannot exist as single cells in any known natural environment on Earth. Thus, the chicken egg provides the environment of nutrients which allows the fertilized cell to grow and split into millions of specialized cells that give rise to the chick which pecks its way out of its protective shell. Culturing single cells from plants or animals is now technologically possible, but in highly artificial laboratory-based environments.

Yet, in spite of their absolute dependence on other cells, the cells from these advanced organisms are clearly recognized by any scientist as being "alive." Likewise, some scientists argue, anything that can reproduce itself and achieve evolution in its progeny is clearly not an inanimate object. Ergo, it must be an instance of life.

Some scientists are unsure whether viruses are examples of life, as discussed earlier (answer 2.7). Yet, when the influenza virus H1N1 (Swine Flu) or the COVID-19 virus wreak havoc on the human population, it is the biologists who we turn to, not the ivory tower astrophysicists and their telescopes, or the inorganic chemists in their labs in academia. Viruses, say some scientists, are simply an extreme form of parasitic life, because they leave the tasks of metabolism, harnessing of energy, and even reproduction itself to the cellular victims they infect. All a virus does is to provide genetic instructions to the involuntary host cell and divert its normal processes of protein and RNA production to be specific for the protein(s) and the RNA sequence of the virus. An analogy would be when one corporation forces an involuntary merger with another corporation and diverts its factories into the manufacture of its favorite products rather than their original products.

*Q 8.28 What happens when an RNA molecule exits the macrobiont?*
*A 8.28* Just like a baby in its cradle, if RNA leaves its cradle of life, it will not survive because it is not protected and is not self-sufficient.

This is why more evolution must occur within the macrobiont, and a cell must eventually be formed that is capable of existing in the outside world. Untold numbers of RNA ribozyme replications and evolution in the macrobiont can, however, eventually result in the formation of the first protocell.

*Q 8.29 What do you mean by protocell?*
*A 8.29* It is a popular term, but different authors use "protocell" differently. Here, we interpret it as the early precursor to the eventual highly developed "cell" which is capable of leaving the macrobiont and surviving and prospering in some typical external environment at large. There does seem to be consensus that in order for such an entity to be called a protocell, it must achieve the combination of three critical ingredients: a genetic storage system, a means to convert these gene instructions into products and actions, and being inside a semi-isolated compartment, such as a membrane enveloping its contents.

*Q 8.30 Why do you say "semi-isolated"? Doesn't a protocell cell's membrane isolate it from its environment?*
*A 8.30* No, not completely. True, it isolates the contents from undesirable chemicals and from some harmful agents. But there must be a way for nutrients to cross the membrane into the protocell, and likewise the waste products that the protocell creates during its proto-metabolic functions must have a way to be shunted out across that barrier. The membrane also prevents large macromolecules such like RNA and proteins from leaking out.

*Q 8.31 What are some other concepts of protocell?*
*A 8.31* Some scientists equate it with a cell so highly sophisticated that it is the jumping-off point for the three main domains of life: Bacteria, Archaea, and Eukaryotes. This is a whole separate research topic in its own right. A common terminology used for the type of cell which preceded these three divisions is the LUCA (**L**ast **U**niversal **C**ommon **A**ncestor). Sometimes "protocell" is taken to have the same qualification as the LUCA, but this

seems to ignore the likely reality that whatever the first protocell was, it needed to become a fully free-living cell in the wide world and probably then later significantly evolved with many innovations before achieving a version that is rightfully the LUCA.

*Q 8.32 Do these locales have an unlimited amount of time to invent life?*
*A 8.32* For most envisioned environments for a macrobiont, there is only a limited time available. In the case of a pond environment, excessive rainfall might wash out all the ingredients and erase all evidence of an aborted journey toward life. Or drought may cause it to dry up, leaving behind an organic-rich deposit of uncertain success towards evolving to life.

The enemy of the macrobiont is the extremes in weather.

In the case of a submarine hydrothermal setting, many of these smoker vents have disappeared over the course of a couple decades of exploration, as subsequent ocean-bottom eruptions destroy them with lava. For hydrothermal locales such as Yellowstone, the underlying volcano itself has been active for at least a few million years, but the actual surface pools wax and wane with time, sometimes in just a period of days. And some geysers cease activity for years or decades, only to resume later with little or no warning.

*Q 8.33 What happens if life did not have time to fully develop in these locales? What happens to all these chemicals that were made, but did not have time to emerge to life?*
*A 8.33* They could be mechanically (wind, water overflow, etc.) transported to a new locale, in which chemical evolution to life can continue.

*Q 8.34 Did life evolve on Earth only once, or could it emerge many times?*
*A 8.34* We do not know, but hypothesize that it could have emerged many times, but prior to the widespread establishment of life, since once organisms came into existence they would "eat" the chemical mixtures that are still evolving.

*Q 8.35 If life could have originated many times on Earth, shouldn't life be everywhere, on any planets in a habitable zone?*
*A 8.35* Be careful with this conclusion. The evolution from a macrobiont stage of life to a protocell stage may require many changes and adaptations. And then, from a protocell in the favorable environment of the macrobiont to evolve to a fully capable cell that can migrate successfully out into the external environment is also likely to invoke a daunting series of genetic inventions. From the "top-down" approach to the origin of life, researchers are finding that a minimum free-living cell seems to need several *hundred* different genes and an extremely complex metabolism.

Therefore, the rise of *cellular* life may be, as often presumed, a low-likelihood event. Such a cell must: cope with adversities in its environment; harness external energy sources; copy its key ingredients; divide to become separate physical entities; and dispose of toxic waste products. For a life form to persist for billions of years, as our biosphere has, it must mutate at reasonable rates and walk the fine line of balance between too accurate copying of its genetic information versus too sloppy copying.

*Q 8.36 Isn't it good to have diversity in the descendants?*
*A 8.36* Yes. If copying is too accurate, the rate of evolution may be inadequate for diversification of the descendants to cope with the ever-changing nature of environments. This is akin to a company which produces the same product that is no longer appropriate for the consumer market (example: film-based cameras replaced by digital cameras).

If not sufficiently accurate, the large number of disadvantageous mutations that accumulate could lead to extinction. This is like a company which cheats on quality control and goes out of business because of products with random defects, leading to a destroyed reputation or fatal lawsuits. Somewhat analogous is a corporation which insists on "improving" a product that is already highly successful (examples: Boeing 737 Max; New Coke; Sony AIBO; Windows Vista; Smell-o-Vision movies; Ford Edsel).

Many dominant companies have become extinct or miniscule because of not walking that fine line (examples: Compaq, Schwinn, Pan Am, Kodak, Polaroid, Netscape, Woolworths, Enron, Blockbuster, Napster, Westinghouse, Toys R Us, Howard Johnson's). Likewise, the number of species that have become extinct over the eons of life on Earth is in the millions, perhaps even billions (examples: dinosaurs, trilobites, pterodactyls, sabre-tooth tigers). These were not sufficiently diverse to have at least some members able to survive a change in environment, whatever the cause.

*Q 8.37 What type of life was the LUCA?*
*A 8.37* There is some evidence from ancient genes but mostly speculation about what the Last Universal Common Ancestor actually was. Life is so versatile that it has been very difficult to determine, for example, whether the first successful cells were living off energy from chemical reactions involving minerals and/or atmospheric gases (chemotrophs), or organics in the environment (organotrophs), or the light from the Sun (phototrophs). With all the diversity of life on Earth, and with much yet to be discovered, it would not be surprising if life on another planet would have taken a rather different course early on, even if it first arose in a similar way as here.

# Chapter 9

# Which type of life is feasible in our Solar System?

*Q 9.1 Which type of life do we expect to find in our Solar System?*
*A 9.1* Life elsewhere in our Solar System is believed to be microbial (visible only with a microscope, such as bacteria) in its nature. In some cases, it may have existed in the past, but not anymore. Instead, its remnants may be present.

*Q 9.2 Why would life not exist anymore?*
*A 9.2* One of the main causes would be that the habitability conditions on the celestial bodies may have changed over time, making it impossible for life to continue.

*Q 9.3 What types of habitability conditions?*
*A 9.3* Common examples include temperature conditions, which may become very low, or very high, and thus not conducive to the biological processes; lack of water, which is deemed necessary for life; extreme acidity or basicity which causes degradation of biosystems and their bio-molecules; and extremes in salinity, pressure, and radiation.

*Q 9.4 Do we have guidance for the types of microbes which would be good candidates for life in our Solar System?*
*A 9.4* Yes. These would be microbes similar to those which can live also on Earth under harsh conditions, which most other life on Earth cannot survive.

*Q 9.5 Where do such harsh conditions exist on Earth?*
*A 9.5* They exist in deserts, such as Sahara desert in North Africa and Atacama desert in Chile; in hot springs, such as Yellowstone National Park in USA; in hypersaline environments, such as the Dead Sea in Israel; in alkaline or acidic lakes; in hydrothermal vents, such as black smokers and carbonate chimney vents in the deep sea; and in permafrost. These are just some examples.

*Q 9.6 What are some examples of microbes which inhabit these places?*
*A 9.6* There are numerous examples, which are categorized as extremophiles and polyextremophiles. Extremophiles live and thrive under a single extreme environment, while polyextremophiles are adapted to several such environments. These microbe categories are named based on the type of the extreme environment. Selected examples are:
- Psychrophiles (psychro = cold; phile = love for), which thrive in cold environments, at temperatures less than 15 °C
- Thermophiles, which love warm environments; their optimal growth is above 60 °C, and for "hyperthermophiles" up to 113 °C
- Acidophiles, which love acidic environments; their optimal growth is below pH 3
- Alkaliphiles, which love basic environments, pH more than 9
- Halophiles, which love hypersaline environments, and grow optimally in NaCl concentrations higher than 5%
- Piezophiles (piezo = pressure, in Greek), which survive high hydrostatic pressures
- Xerophiles (xeros = dry, in Greek), which survive and flourish in very dry environments
- Radioresistant, which resist high radiation.

*Q 9.7 How is this knowledge relevant to the search for extraterrestrial life in our Solar System?*
*A 9.7* The extreme environments on Earth serve as analogs for such sites in our Solar System. We can study Earthly analogs much easier than the extraterrestrial ones. Both extremophiles and polyextremophiles could, in principle, live in the similar extreme environments elsewhere in our Solar System, providing that liquid water, sources of energy, a supply of carbon or organic compounds, and various bio-essential elements are available.

*Q 9.8 What are the best candidates for the extraterrestrial microbial life in our Solar System?*
*A 9.8* The best candidate is Mars, followed by Europa (moon of Jupiter), Enceladus (satellite of Saturn), and, to a lesser extent, Titan (satellite of Saturn).

# Chapter 10

# Was life brought to the Earth from outer space?

*Q 10.1 Is it possible that life on Earth was delivered from outer space?*
*A 10.1* Yes. This possibility is explored within the so-called *Panspermia* hypothesis.

*Q 10.2 What is the Panspermia hypothesis?*
*A 10.2* The Panspermia hypothesis states that life exists elsewhere in the universe, and could be distributed far and wide. This idea was first introduced by the ancient Greek philosopher Anaxagoras ($5^{th}$ Century BC), who believed that the universe is made of an infinite number of seeds ("spermata" in Greek). Upon reaching the Earth, these seeds gave rise to life. Anaxagoras introduced the term "Panspermia", which in Greek means literally "seeds everywhere".

*Q 10.3 Did the panspermia hypothesis change after it was introduced by Anaxagoras?*
*A 10.3* Yes. This concept was taken up and developed, notably in the $19^{th}$ and early $20^{th}$ Century, and has undergone various changes since. A summary of major developments and proposals by the scientists follows.

In 1871 Sir William Thomson (later Lord Kelvin), a physicist, claimed that "germs" (microorganisms) coming from space via meteorites originated life on Earth. Another physicist, Herman von Helmholtz, adopted this view in 1884. In 1903 Svante Arrhenius, a chemist, proposed that spores can be propagated through space by radiation pressure by a sun, and can seed life on the planet on which they land. The panspermia hypothesis took a new turn with a proposal for "Directed Panspermia", which considered that life on the Earth may have been transported to Earth deliberately by intelligent beings from another planet.

*Q 10.4 Is panspermia still a viable hypothesis?*
*A 10.4* Some aspects of this hypothesis are still viable. Panspermia received support from studies of microbial spores placed on the outside of the International Space Station, which exposed the spores to the harsh space conditions, such as vacuum desiccation, low temperature, and harmful radiation. The spores showed their resilience and survivability under these conditions, which indicated that they could survive travel in space for a limited time. However, when the spores were encased in rocks, which shield them from radiation, they survived much longer. This indicated that spores could be transported in space for longer distances when they are inside the rocks. This version of panspermia is termed "lithopanspermia" (from Greek "lithos" which means stone).

Further, transport of geologic material between the planets by exchange of meteorites is known. As one example, meteorites from Mars are found on Earth. If the rocks which are exchanged between the planets contain bacterial spores, lithopanspermia becomes a possibility. However, the galactic cosmic rays (GCR) will penetrate several meters into rock and can sterilize the spores if the time to transfer from one object to another (e.g., Mars to Earth) is more than a hundred thousand years. So far, the meteorites that are known to be from Mars were in space for much longer times than this. We know this because the GCR radiation also changes some of the elements in the rocks into radioactive isotopes. Specialists know how to date this and determine the "cosmic ray exposure age" of any meteorite.

*Q 10.5 Can Directed Panspermia go the other way, namely can we seed life on the lifeless planets and other bodies in our Solar System?*
*A 10.5* In principle, yes. Our space missions could transfer earthly microbes to the planets or other bodies in our Solar System which we consider lifeless, but which could harbor life. Microbes then could take up residence on these bodies. In the next chapter, on Planetary Protection, this scenario is further considered.

*Q 10.6 Have we done it so far?*
*A 10.6* No, at least not deliberately.

*Q 10.7 Why not?*
*A 10.7* Firstly, we do not know for sure that the planets and other bodies in our Solar Systems are indeed lifeless. Although we have not found life so far, this does not mean that life out there does not exist. If we transfer our Earthly life to such objects, and if life on them already exists, Earthly life could interfere with it. We thus would miss on a chance to identify the

extraterrestrial life. Even if life on these objects does not exist, but if they have substantial amounts of organic materials which are evolving towards life, the introduction of our own life could interfere with such an evolution (our life may “eat up” their organic material, for example). In this case we would miss on an opportunity to learn about chemical evolution which may lead to life.

*Q 10.8 But, wouldn’t be in our own interest to propagate our Earthly life to another planet, to save it from a potential demise on Earth?*
*A 10.8* The answer is yes. However, the scientific and public consensus is that we should not do it at this time. Thus, there are policies, guidelines, and protocols within a program termed “Planetary Protection” to prevent inadvertent spreading of Earthly life to the potentially habitable bodies in our Solar System via space missions which include landing on such bodies. Briefly, such regulations require a rigorous sterilization (more specifically, bioburden reduction) of the spaceships and their payload, such as landers and rovers, which will touch down on the Solar System bodies.

*Q 10.9 How do we make sure that we do not bring harmful life from our Solar System to the Earth inadvertently via returns of spaceships or astronauts?*
*A 10.9* Policies, guidelines and protocols within the “Planetary Protection” program cover these possibilities also. A quarantine, among other measures, may be needed.

# CHAPTER 11

# WHAT IS THE PLANETARY PROTECTION PROGRAM, AND WHY DO WE NEED IT?

*Q 11.1 What is the planetary protection program?*
*A 11.1* The planetary protection program develops policies, guidelines, and protocols for prevention of interplanetary cross-contamination. Such contamination can be forward- or back- contamination. The latter considers contamination of Earth with alien microbes, while the former addresses contamination of other space bodies in our Solar System with microbes from Earth. In the case of back contamination, alien microbes are carried to the Earth by the returning astronauts, space vehicles, and by the returned samples. In forward contamination, Earthly microbes are transported by astronauts, spaceship landers and probes. The underlying assumption of the planetary protection program is that some microbes can survive space travel and take up residence on another space body.

*Q 11.2 When was the planetary protection program developed and by whom?*
*A 11.2* The planetary protection program was initiated in the late 1950s by an international effort of space agencies and non-governmental scientific organizations. It has a rather rich history.

Some significant timeline events follow.

In 1958 the International Council of Scientific Unions (ICSU) introduced the quarantine standards. In 1962 the US National Academy of Sciences recommended non-contaminating spaceflight practices. A consensus has been reached that interplanetary contamination should be regulated, which resulted in the Article IX of the United Nations Outer Space Treaty in 1967. This article placed the following obligations on spacefaring nations: "….parties to the Treaty shall pursue studies of outer space, including the Moon and other celestial bodies, and conduct exploration of them so as to avoid their harmful contamination and also adverse changes in the environment of the Earth resulting from the introduction of extraterrestrial matter and, where necessary, shall adopt appropriate measures for this purpose". Based on this Treaty, the Committee on Space Research (COSPAR), which was established by ICSU in 1958, includes a section which develops recommendations and policies for avoiding interplanetary contamination.

*Q 11.3 This seems like lots of regulations. Aren't these complicating space missions?*
*A 11.3* Not in all cases. Some space missions do not require planetary protection.

COSPAR classifies space missions into 5 categories. This classification is made based on the nature of the space mission and its target body. Mission types such as flyby, orbiter, lander, probe, and return to Earth, are evaluated for the planetary protection needs in conjunction with the nature of the target celestial body, such as its potential to harbor life, to be habitable to life, to have a potential for chemical evolution and origin of life, and/or to have a significant chance of contamination by spacecraft organisms.

*Q 11.4 Which space missions do not require planetary protection?*
*A 11.4* Examples include missions to the Sun, Mercury, Io (one of the Jupiter's moons, having extensive volcanic activity on its surface), and some (but not necessarily all) asteroids. They belong to Category I, which does not require planetary protection. These celestial bodies are not habitable and are not suitable for chemical evolution and the origin of life.

*Q 11.5 Which space missions would require the most stringent planetary protection?*
*A 11.5* Space missions to Mars, but also to Europa and Enceladus, based on the possibility of harboring life or being hospitable to life and for having a significant possibility for chemical evolution and the origin of life. Mars is a strong case, since it has water and possible surface and subsurface habitats for life, it may harbor life or it may be hospitable to life, and it is a site for possible chemical evolution and the origin of life.

The highest planetary protection priority in Mars exploration is safeguarding the Earth from back contamination. Europa, one of the satellites of Jupiter, is less explored, but is promising since it has a subsurface ocean. Enceladus, a moon of Saturn, shows evidence of water plumes, carbon dioxide and organic material such as methane, propane, acetylene and formaldehyde. These celestial bodies are in Category III/IV, based on a significant chance that the forward contamination could compromise future explorations, since niches hospitable to proliferation of terrestrial microorganism are present on these bodies, and spacecraft contaminants are likely to reach these niches.

*Q 11.6 What is a specific description of the 5 categories?*
*A 11.6* This description is available in the COSPAR and NASA's documents, which are available on their web sites.

A somewhat modified version from COSPAR which shows category, mission type, and target body is shown below. A brief summery about celestial bodies in our Solar System which are listed below is available on Wikipedia.

Category I: Flyby, orbiter, lander missions to undifferentiated, metamorphosed asteroids; Io.

Category II: Flyby, orbiter, lander missions to Venus; Moon; Comets; Carbonaceous chondrite asteroids; Jupiter; Saturn; Uranus; Neptune; Ganymede; Callisto; Titan; Triton; Pluto/Charon; Ceres; Kuiper-Belt Objects > 1/2 the size of Pluto; Kuiper-Belt Objects < 1/2 the size of Pluto and others are TBD (To Be Determined).

Category III: Flyby, Orbiters to Mars; Europa; Enceladus; others TBD.

Category IV: Lander Missions to Mars; Europa; Enceladus; others TBD.

Category V: Any Earth-return mission. "Restricted Earth return": Mars; Europa; others TBD; "Unrestricted Earth return": Venus, Moon; others TBD.

Planetary protection recommendations must be developed for each case in each category, for both forward and back contamination, if the latter is applicable.

*Q 11.7 What types of recommendations?*
*A 11.7* The types of planetary protection recommendations include contamination control, spacecraft sterilization, a sample handling protocol, and quarantine. For all these, specific procedures are developed. One example of the latter is the decontamination procedure for spacecraft. The assembly needs to be made in clean rooms (which have a specified maximum number of particles in it). One needs to sterilize components individually before assembly, and clean all surfaces frequently with alcohol wipes during assembly. Engineers wear cleanroom suits. Bioburden reduction can also be accomplished by dry heat, hydrogen peroxide vapor, and other means.

*Q 11.8 Are the planetary protection recommendations permanent, or are they periodically re-evaluated?*

*A 11.8* Planetary protection recommendations are periodically re-evaluated. Very recently, NASA's independent advisory panel reported that some of the planetary protection recommendations are anachronistic and should be *relaxed*. Thus, modern genomic tools could be adopted to characterize the microbes on the spacecraft and cleanrooms. Also, NASA should open up regions on Mars for human exploration with less restrictions and should revisit the biohazard restrictions on samples to be returned from Mars to Earth. The full report and its summaries are available on the web sites. https://planetaryprotection.nasa.gov/documents/ .

# CHAPTER 12

# THE SEARCH FOR LIFE IN OUR SOLAR SYSTEM: WHAT ARE SOME SIGNIFICANT ACHIEVEMENTS?

*Q 12.1 Which space missions have searched for life in our Solar System?*
*A 12.1* The Viking missions to Mars, in 1976. This was the only search for life mission, so far.

*Q 12.2 How did the Viking missions search for life?*
*A 12.2* By performing three biology experiments on each of the two Viking landers. These experiments attempted to detect different types of metabolic activity of the putative Martian microbes. In all of these experiments a robot arm on the Viking landers was used to gather the Martian soil samples and transfer them to the on-board Viking Lander Biology Instrument (VLBI). The experiments were conducted in separate chambers of the VLBI.

*Q 12.3 What were the specific experiments?*
*A 12.3* These were: the "Labeled Release" (LR) experiment, the "Pyrolytic release" (PR) (also known as "Carbon Assimilation") Experiment, and the "Gas Exchange" (GEx) Experiment.

*Q 12.4 Why were there so many different experiments?*
*A 12.4* The reality is that there are millions of different species of life on Earth, and they all have different specialties. Some need solar energy in order to grow, like plants and algae and lichen. Some use chemical energy available from various minerals and atmospheric gases, which includes many different types of bacteria. Others specialize in using organic compounds from the environment for their energy and as a source of carbon atoms to make their molecules --- such as the fermentation process which leads to a product we call beer. Detecting active life on another planet requires us to decide on what types of metabolism should be investigated. The Viking VLBI was carefully designed to test for a variety of well-known metabolisms used by different species of organisms on Earth. If Martian life

were as diverse as life on our own lonely planet, perhaps all the techniques would be successful. If it were not as diverse, at least one of the experiments might come up with positive signs of metabolic activity. Without metabolism, organisms cannot convert external sources of energy to useful biochemical energy, or raw nutrients into the biochemicals of life. Hence, they cannot grow. And, they cannot accomplish the key function that is the hallmark of living organisms: they cannot reproduce and make more copies of themselves.

In fact, there were originally four experiments. However, the VLBI instrument was completely different from most space instruments because it had complex plumbing (for gases and liquids), strict temperature controls (including both coolers and heaters), as well as motors and other mechanisms. There was very little volume available, so the different experiments had to be packaged intermingled with one-another. And it all had to be sterilizable with heat. When all was done, it was the most expensive instrument ever designed for a space mission. During the development, NASA decided that at least one of the four experiments needed to be deleted in order to simplify the complexity and avoid more increases in cost. The experiment not flown was known, colloquially, as the "Wolf Trap."

*Q 12.5 What were the main features of the Wolf Trap experiment?*
*A 12.5* This experiment would have stirred some soil into a clear nutrient solution and shined a thin light beam through the liquid to see if it became cloudy due to the growth of bacteria. This experiment often works well with various soils that were tested here on Earth. Ironically, it may not have worked well at all on Mars because, although unknown at that time, the Martian soil is predominantly made up of miniscule particles (a few microns in diameter), far smaller than typical soil particles on Earth or the Moon -- so tiny that they could have stayed suspended for long times and caused the solution to remain cloudy just from the soil particles alone.

*Q 12.6 What were the main features of the LR experiment?*
*A 12.6* This experiment was elegant, yet very simple. It used a special nutrient liquid that contained five different types of organic compounds that many organisms will metabolically convert to gas. This is analogous to how beverages are carbonated to produce their fizz. A drop of the nutrient liquid was placed on a small pile of soil to make it wet, at least on its top. In a separate part of the chamber, a detector used radioisotope tracer techniques to measure how much gas was released. Right on cue, $CO_2$ gas was indeed released in this experiment. This happened for soils sampled at both Viking

landing sites. To "prove" it was accomplished by life forms, samples were taken and subjected to heat sterilization treatments, and it was indeed shown that the heated samples did not release gas, as if the organisms had been killed by the sterilization treatment.

As we shall see later (in 12.9), this was not the end of this story, especially because the other experiments obtained negative results for detecting life on Mars and the LR experiment also had some unexpected results.

*Q 12.7 What were the main features of the PR experiment?*
*A 12.7* The PR experiment was based on the assumption that organisms on Mars would have the ability to assimilate carbon dioxide ($CO_2$) and/or carbon monoxide (CO) from the Martian atmosphere and convert these into organic compounds, especially if provided with a light source simulating natural sunlight to enable photosynthesis.

The experiment was conducted several times, on different samples, with and without adding water to the soil samples. Only the very first experiment indicated that carbon in the gases might have been converted into some solid organic molecules, but this result could never be reproduced. After null results were obtained on all other samples, the conclusion was that there were no forms of life that could "fix" the carbon in the atmosphere into useful organic compounds. Thus, no evidence of plant life, and no algae, no lichens, no cyanobacteria.

*Q 12.8 What were the main features of the GEx experiment?*
*A 12.8* In this investigation, a generous cocktail of nutrients was added to soil. Included in this solution of nutrients were amino acids of all kinds in both chiral versions; other basic metabolites such as nucleosides; and salts and chemical energy sources. This cocktail was known, affectionately, by the scientists as their "chicken soup."

First, however, the soil chamber was opened to the water vapor from the chicken soup solution. Totally unexpected was a sudden release of oxygen gas from the soil. Then, the "soup" was allowed to wet the soil. Also not expected was that nothing further happened, even after days and weeks of incubation. With typical soils on Earth, various organisms would become very metabolically active, signaling their presence by taking up the $CO_2$, and also releasing other gases, such as methane or $H_2S$, into the chamber. Using a GC (gas chromatograph) to measure the composition of the gas above the soil, the GEx scientists were disappointed to find no discernable changes after the initial release of $O_2$ gas. They concluded there were no viable organisms in the Martian soil.

*Q 12.9 If the LR experiment detected life, what was wrong with the other two experiments?*

*A 12.9* That is the question everyone has been asking ever since the Viking mission completed its year-plus set of experiments attempting to detect life on the Martian surface.

There are many possible answers to this question.

As we mentioned before, the LR experiment did have one very strange and unexpected result. What it did was wait until all the gas had been released, and then squirt a new drop of nutrient onto the soil to watch it release more gas. But it did not. In fact, it seemed to reduce the amount of gas that was in the chamber. There are two possible explanations. One explanation is that the organisms had a brief flurry of activity over several hours to produce the initial results, but by the time the second injection was commanded, they had all "died" or become inactive. Were they killed by too much water?

The other explanation is a purely chemical one. It supposed there is a small amount of a highly oxidizing chemical in the soil, and with the first injection it reacted with the nutrient's organic molecules to create the $CO_2$ gas, but was all used up in the process. Thus, the second injection accomplished nothing, except add more liquid into which a small portion of the $CO_2$ gas previously liberated could now dissolve. But what was this highly oxidizing chemical?

Many experiments were then conducted with minerals and salts and super-oxides and other chemicals to test this latter hypothesis. None seemed to match the results. But decades later, scientists at NASA found that if a perchlorate salt, which was discovered in soils by the Phoenix mission to Mars, is irradiated to simulate the action of cosmic rays, it could acquire the chemical reactivity needed to oxidize certain of the organic molecules in the LR nutrient solution. Perchlorate is exceedingly rare in soils on Earth.

Thus, we are left with intriguing uncertainties whether Martian soil is simply a chemical oddity compared to Earth, or indeed does contain some amount of biochemical activity that signals the presence of living organisms. Hopefully, when samples are returned to Earth in the not too distant future, the far more detailed and today's far more sophisticated methods will help resolve these issues, and perhaps reveal whether life does or ever did exist on the planet Mars.

*Q 12.10. Were there any other ways to detect life by the Viking science instruments?*

*A 12.10* Yes. There was also a very sophisticated instrument designed to search for various molecules of life -- the carbon-containing organic compounds that living organisms produce and are composed of. On Earth, these organics can be found in soils, even if the original microbes are absent or dead. Certain types of organic molecules could be indicators that biological activity had occurred. Two laboratory techniques, gas chromatography (GC) and mass spectrometry (MS) are particularly powerful in analyzing for unknown mixtures of organic compounds, especially when conducted sequentially. Highly miniaturized, the GCMS instrument on Viking took tiny samples of soil and quickly heated them to high temperatures (up to 500 °C) to evaporate the organic molecules and feed them to the GC portion and then into the MS.

*Q 12.11 Did Viking find molecules produced by life?*
*A 12.11* No. In fact, it found essentially no organic compounds at all in the various Martian soil samples. This was very surprising, especially since Mars is closer to the asteroid belt than Earth. The meteorites that bombard the planets, many of which contain significant amounts of organic molecules of great diversity, come primarily from asteroids. Comets occasionally will impact Mars as well, and comets are known to have remarkably high concentrations of organic matter. From the samples analyzed at both Viking landing sites (on opposite sides of the planet), the GCMS scientists concluded that the Martian soil contains less than one part per billion of organic compounds.

*Q 12.12 Have more recent missions found some organic compounds in the Martian soil?*
*A 12.12* Yes, the Mars rover named *Curiosity* has now discovered certain types of organic compounds in some samples. These new results were obtained by an instrument called *SAM* (Sample Analysis on Mars) that includes an advanced GCMS. It is now believed that the perchlorate and perhaps another oxidant in Martian samples has been reacting with organic compounds during the heating process for the GCMS type of analysis. Perchlorate can destroy most organics during heating, but SAM can do the heating more slowly than Viking, which is apparently part of the reason why it has detected some organics.

*Q 12.13 Is there some other way to analyze for organics without heating them?*
*A 12.13* Yes. The European rover in their ExoMars program has an instrument developed jointly between ESA (European Space Agency) and NASA that uses a laser to quickly release the organics without heating the

sample appreciably, and this may reveal even higher amounts and complexity of organics in the samples.

*Q 12.14 Will this experiment be able to detect evidence of life?*
*A 12.14* Possibly, although the life-signaling organics (biosignature) may have been degraded by radiation and oxidizing chemicals in the Martian atmosphere.

*Q 12.15 Where do the oxidizing chemicals in the Martian atmosphere come from? Do we have them in our own Earth's atmosphere?*
*A 12.15* On Mars, the extreme ultraviolet light from the Sun causes chemical reactions in the carbon dioxide and water vapor in the atmosphere that produce strong oxidants which can convert organic compounds back into carbon dioxide. Here on Earth, the extreme UV does not reach the surface because we have a strong layer of ozone molecules high in our atmosphere that are very efficient in absorbing UV but not the visible light needed by our plants on land and the phytoplankton in our seas.

The Martian atmosphere is about 100 times thinner than ours. Also, it contains very little oxygen, from which ozone is produced. Thus, it cannot absorb the UV. We know that long ago, the Martian atmosphere was more dense, and would have shielded the surface more than today. Although UV can kill most organisms, some Martian microbes may have survived by utilizing coatings (including salt) which absorb UV, or simply be lurking just below the surface.

*Q 12.16 How will ExoMars or other missions avoid these problems?*
*A 12.16* In addition to using a laser, the ExoMars rover includes a drill which can go deep into the soil (about 1 meter), where the UV does not penetrate and the oxidant molecules in the atmosphere probably do not either. One of the Viking landers did dig to a depth of over 20 cm, but that was too late to put a sample into the GCMS instrument. However, Viking did take samples from underneath rocks, which could also have protected the soil and any microbes from UV and atmospheric oxidants.

*Q 12.17 Did Viking make any other discoveries that might be related to the question of life?*
*A 12.17* Yes, it was discovered that the Martian soils at both landing sites contain levels of sulfate salts that are one hundred times higher than typical on Earth or the Moon. The sulfur in this sulfate is one of the six most critical elements making up the composition of all known forms of life. Furthermore, some prominent microbes on Earth can gain their energy by

reacting hydrogen gas with sulfate. None of the three life-detection experiments on Viking included hydrogen in what they added to soil. Ironically, the GCMS utilized hydrogen gas to operate the GC part of its instrument, so there was a tank full of hydrogen located just centimeters away from the biology incubation chambers, but because there was no physical connections between the GCMS and the VLBI instruments, there was no possibility of incubating Martian soil with hydrogen to see if metabolic activities would be stimulated.

*Q 12.18 How did Viking get samples for the biology instrument and GCMS into those instruments?*
*A 12.18* Viking had a novel sampling arm made up of sheet metal shaped like a tube but that could be temporarily deformed and rolled up to retract the arm. At the end was a scoop that also had a sieve so that particles of soil could be delivered to the various instruments, without clogging them up with rocks. In addition, there was a hoe blade for digging trenches, and a set of magnets to test whether the dust in the atmosphere and the soil contained magnetic particles (they did!).

*Q 12.19 Didn't the scientists worry that the scoop might have some tiny bacteria or other organisms from Earth on it, and then the biological tests could have given a "false positive" for detecting life on Mars?*
*A 12.19* Yes, the scientists were extremely concerned about this possibility. For this reason, the scoop was cleaned thoroughly, to make sure it did not have organic compounds (like greases) on it, and no living organisms. The arm was rolled up for launch and the scoop had a special can-shaped cover on it, to keep it clean and sterile. After landing on Mars, a command was sent to extend the arm and push off the can, and let it fall onto the ground. With the first Viking lander, a late change in the software for the deployment sequence was made that did not take into account that in order to push off the can, the arm first had to retract a small amount to release a retainer pin that captured the scoop firmly to withstand the extreme vibration during launch of the rocket that sent the Viking on its way to Mars. This small mistake caused the arm to jam, until the engineers determined what the mistake had been, and quickly devised some commands to rectify the situation and eject the pin to free the scoop.

*Q 12.20 Was only the scoop sterilized?*
*A 12.20* No, in fact all the instruments and engineering "black boxes" were individually sterilized, and then the entire lander was put into an oven for final sterilization. Heating the spacecraft to the temperature of boiling water

for about one day was considered sufficient to reduce any residual bioburden and avoid the possibility of accidentally detecting life brought from Earth. This had never been done to a spacecraft before. All the electronic and mechanical parts had to be tested and certified that they could withstand this final heat treatment without making them less reliable, and also that they did not release organic vapors as a result. It may be for this reason that the Viking landers worked so perfectly as they conducted the first successful landed missions on the surface of Mars. The fundamental reason there were two Viking landers in the first place was because of the fear of the engineering community that because so little was known at that time about Mars, and the entry and landing sequence was so complicated (the "seven minutes of fear"), that it was all too likely that the very first attempt to land would be a failure. Hopefully, enough could be learned that a second landing would be successful. Fortunately, both landings were perfect.

*Q 12.21 Were there any other ways Viking might have detected life on Mars?*

*A 12.21* Yes. There were the cameras. These cameras had to be all-electronic and sterilizable. The electronic camera chips we have today, including in our smartphones, did not exist at the time of Viking. Instead, the scenery was scanned through a periscope to bring light to a small array of single-pixel detectors, each equipped with a different filter for color imaging, including infrared wavelengths. This took nearly an hour to create a large image, but the detectors' outputs could be sent back digitally through the communication link. What the scientists hoped to discover was not only the geological environment on Mars but perhaps some hints of life.

For example, there might be coatings like lichens on rocks, or even the Martian equivalent of sagebrush. Perhaps there would be evidence for worm-like creatures, and even movement that hinted of life. No one knew what might be possible, because the best photographs of the planet Mars had only been made from orbit, and even a football stadium would be been barely discernable from the relatively rudimentary camera resolution that was possible at that time.

*Q 12.22 Why did the PR experiment need a special light source, instead of using the natural sunlight of Mars?*

*A 12.22* This was because of the way that Viking was designed. All experiments were inside the body of the spacecraft, which was thermally insulated from the cold external environment and kept warm by the surplus heat from its nuclear batteries.

*Q 12.23 What are "nuclear batteries"? Are they dangerous?*
*A 12.23* These are energy sources, powered by nuclear energy. Engineers call them Radioisotope Thermoelectric Generators (RTG). Viking had two of these RTGs, but they only provided about 60 watts of power to the landers. However, the way the RTGs are constructed is that a special radioactive isotope of plutonium is produced, purified, and concentrated into a compact canister. The alpha particles produced by the plutonium are so energetic that the canister heats up to a very high temperature. A large array of thermocouples is tied to the heat source and also to a cold junction, which converts much of the heat energy into a voltage which supplies electrical power to recharge a conventional battery on the spacecraft. Even though the RTGs supply only a small amount of power, they continue to work day and night, for many years.

A small amount of neutron and gamma radiations are emitted outside the canister, but the radiation level is low enough that it does not affect the spacecraft's electronics. To protect the technicians and engineers while the spacecraft is being assembled, the RTGs are kept in a separate location. Then, they are integrated quickly into the spacecraft a short time before launch.

*Q 12.24 When the Viking landers arrived at Mars, how did they safely land on the surface?*
*A 12.24* Mars is the most difficult place to land in our Solar System. The reason is that multiple systems are required to do it efficiently. To land on the Moon, you simply need a powerful propulsion system to slow down, like the Apollo lunar module used to set down astronauts gently on the Moon. To land a spacecraft coming back from space on Earth, you need a heatshield on the capsule, and some parachutes to slow you down to a splash landing in the ocean.

But the atmosphere on Mars is much thinner than our atmosphere. As a consequence, a Mars lander needs *both* an aeroshell and parachutes, but the parachutes cannot slow it down enough for a safe touchdown. The engineer's solution was that after the aeroshell and then the parachute slowed the Viking lander from supersonic to sub-sonic speed, the aeroshell's forward heat shield was jettisoned and then the lander dropped down out of the backshell so that three custom multi-nozzle engines could fire to slow it down precisely for a "soft landing" without digging a hole in the soil. The Vikings pioneered this complex system, paving the way for future landers and rovers sent to Mars.

*Q 12.25 Was the landing on Mars remotely controlled from Earth?*
*A 12.25* No, because the time between the point when the spacecraft first hit the atmosphere of Mars until touchdown was only about 7 minutes. This time was much too short for engineers on Earth to "remotely fly" the spacecraft to the ground. The reason is that even when the information is communicated by radio waves traveling at the speed of light, the distances between Mars and the Earth are too large for rapid communication. The distance between the two planets continuously changes, depending on where each planet is in its orbit. A roundtrip communication time between Earth and Mars can take more than 40 minutes.

Everything on the Viking landers had to happen under the control of a very early version of a computer which would be considered to be primitive by today's standards. There was not enough time for the spacecraft to be controlled directly from Earth, so that sequences for the next set of operations and observations had to be radioed up to the lander every day.

*Q 12.26 Since Viking results about the possible presence of life were conflicting, did another mission to Mars follow soon after to get more results?*
*A 12.26* No. After the Viking results were digested, and partly because NASA already had underway major new programs that had to be pursued (development of the Shuttle and deployment of the International Space Station), Mars exploration faded into the background. Not until more than twenty years later did a new Mars mission, the Pathfinder spacecraft, touch down as a technology demonstration of airbag-based landing as well as deployment and operation of a mini-rover. The Pathfinder mission included minimal science, but sparked the rejuvenation of a Mars exploration program.

*Q 12.27 What missions did the Pathfinder success foster?*
*A 12.27* Subsequent to Pathfinder, the exploration of the surface of Mars has proceeded by roving vehicles. The two Vikings left the impression that Mars must be boringly similar everywhere, because the two landers were at different latitudes and on almost opposite sides of the planet, yet had almost identical results for the geochemical composition of soils and responses to the biology and GCMS experiments.

This seeming generality was shattered by the two Mars Exploration Rover (MER) missions which followed Pathfinder. Although these rovers, named "Spirit" and "Opportunity," were powered by solar energy, and were not expected to operate for more than a few months because of fallout of airborne dust onto their solar panels, the first was operational for nearly 6 years and the second for over 14 years. This was possible because even though the arrays often became dusty and produced less power, there were occasional “cleaning events” that occurred, presumably due to atmospheric turbulence, perhaps even dust devils, that removed most of the dust.

Opportunity traversed Mars by a distance longer than a Marathon race (42 km), with its final exploration occurring in Perseverance Valley on the flanks of Endeavour Crater before a monstrous planet-wide dust storm on Mars finally shuttered its solar power. The Spirit rover traversed the cratered plains of Gusev Crater, then climbed Husband Hill and descended into Home Plate, before becoming mired in the Martian equivalent of quicksand. Unfortunately, because it became locked into a position that did not illuminate its solar cell array in an optimum manner during the wintertime, it “froze to death” because its electronics were unable to function in the harsh deep-cold environment without heater power.

*Q 12.28 Did the MER Missions make new discoveries compared to Viking?*
*A 12.28* Yes, most emphatically. Unlike Viking, they could move to new terrains and analyze rocks and sediments, as well as soils. And unlike Viking, they discovered an extreme range of diversity in what they encountered. Mars was transformed from the apparently monotonous uniformity that Viking found because of simply analyzing the wind-blown global Martian soil, into a geochemical zoo of rock and sediment compositions, indicating a rich history of diverse volcanism and most importantly, an even richer history of alteration of those rocks by water into minerals such as carbonates, sulfates, and pockets of pure silica.

Mars was dynamic! Hydrothermal events had occurred, transforming their local environment, and sedimentary processes had created coatings as well as deposits of iron-, magnesium-, and calcium-rich sulfates and other salts. The phosphates needed by life were found to be enriched in many rocks and soils containing high concentrations of clays.

*Q 12.29 Was this geologic diversity important to astrobiology?*
*A 12.29* Yes indeed. A key goal of the astrobiological study of Mars has been to determine whether the environment was ever conducive to life as we know it. This meant especially the presence of liquid water, which requires not only the substance of $H_2O$ but also to be in the range of temperatures for which it was liquid. If it is too hot and the pressure is too low, the water will boil away quickly. If the temperatures of the environment are too cold, this will freeze the water, which is especially a problem if the ice remains deeply frozen day and night.

When discoveries are made that the igneous rocks from lavas have been converted into clays, salts, and/or hydrated minerals, it means that liquid water was involved. These sedimentary minerals are therefore an indirect indicator of the warmer, wetter conditions in which microbes can flourish, irrespective of the specifics. Salts can help block the sterilizing UV portion of sunlight, while transmitting the wavelengths that make photosynthesis possible. Clays are useful to organisms because they often trap essential trace elements that are used in many enzymes for metabolism.

These alteration conditions could also help foster the origin of life in the beginning. Mars may have been even more favorable to the prebiotic evolution to form the first organisms than Earth itself, because it avoided the diluting effects of Earth's enormous ocean and provided more opportunity for the cycling between wet and dry conditions that researchers have found to be very important for forming the polypeptides and RNA that are essential for life. Important elements as catalysts, such as copper and boron, have also been found to be enriched in certain of the sediments in Gale Crater.

# CHAPTER 13

# HOW DO WE CONTINUE THE SEARCH FOR LIFE IN OUR SOLAR SYSTEM ON MARS OR ELSEWHERE?

*Q 13.1 Besides Viking's experiments, what other approaches can be used in the search for life?*
*A 13.1* The Viking metabolic experiments were very limited in what could be tested, and based upon very limited knowledge about the composition of the Martian soil. This soil turned out to be unlike any soil on Earth or the Moon, especially with respect to its remarkably high concentrations of sulfates and the presence of perchlorate and perhaps some other highly oxidizing components.

One possibility for the future would be to revise and expand upon these metabolic experiments to search for the presence of active microbes in soils and sediments. It was thought that by simply adding $H_2O$, any dormant microbes could become active and utilize available nutrients. However, the incubation chambers were small, and the mass of Martian gas that was encapsulated when they were sealed was perhaps inadequate. For example, by adding substantial hydrogen and/or methane gas, the soil could be tested for organisms which are sulfate reducers or methane oxidizers.

*Q 13.2 Besides looking for metabolic activity, what other approaches are there for searching for life?*
*A 13.2* Many different methods have been proposed, including everything from miniaturized scanning electron microscopes for directly looking for organized structures at the scale of bacteria-sized organisms, to exquisite chemical analyses for detecting products of metabolism, to placing extracts of Martian soil into a petri dish and trying to grow colonies as we do in the laboratory.

Realizing the challenges of proving whether something is alive, or not, or whether some samples contain something alive, or not, NASA has sponsored a study which has created a hierarchical organization of these various methods for life detection. They call this hierarchy the "Ladder of

Life Detection," organized from the most-convincing down to the least-convincing types of evidence for the existence of life or past life.

At the top of the "ladder" of desired evidence is a demonstration of changes (mutations) that indicate Evolution, according to Darwin's theory. Perhaps this should be broadened to simply Evolution in general, whether it is Lamarckian or Darwinian, since there are an increasing number of examples of organisms changing both themselves and their future progeny in direct response to changing environmental conditions, and not just their progeny being superior in the face of natural selection. Tracking evolution would be a "proof" for the existence of entities which are capable of this most important characteristic of Life. But, at the same time, this can be the most difficult to demonstrate.

Next under Evolution is the demonstration of "Growth and Reproduction." The creation of progeny with inheritance requires the harnessing of energy and the acquisition of nutrients to make possible reproduction and evolution itself. These are the essence, the *sine qua non* properties of life itself.

Although the Viking experiments did not directly prove Reproduction, the very act of demonstrating metabolic activity, especially the syntheses that could have been demonstrated by the PR experiment, would indirectly imply that the entities could have at least the capability of Growth. And the LR and GEx experiments could have inferred reproductive activity if the products of their reactions continued to accelerate on exponential rather than linear curves. Of course, GEx saw no evidence of sustained reactions, and LR had only a one-time response to multiple additions of nutrient.

Reproduction would be essential, of course, for a confirmation of Evolution since it would be necessary to first achieve the creation of progeny in order to test for the acquiring of new traits in subsequent generations. However, there are other ways to infer that the process of Reproduction is occurring or has occurred, if a population of entities shows various morphological forms (shape and structure) that indicate different sequential stages of reproduction, such as: size expansion; division stages; separation. For ancient life, this would involve the study of *micro*fossils, because in the beginning there were only bacteria or bacteria-like microbes.

However, the history of scientists using microscopic pictures of rocks to discover what looks like an assemblage of primitive life forms has been littered with conclusions unaccepted by the scientific community at large. A discovery that garnered attention all the way to the White House of the U.S. was by NASA scientist David McKay and his team in 1996, just months before Pathfinder was launched on its way to Mars. Their announcement was the possible detection of evidence of past life in a meteorite from Mars found in Antarctica and designated ALH 84001. Much of their evidence was based on finding some very unusual mineral forms. In addition, they included an image taken by a scanning electron microscope showing what appeared to be an object in the shape of a bacterium. It was soon pointed out that the object was considerably smaller than the smallest known bacterium at that time. And many other scientists challenged the idea that the unusual mineral forms could only be produced by biological activity.

Over a period of years, the credibility of the discovery was more and more questioned, and it added one more example of where images of what look like microbes in unusual materials has been debunked. For this reason, the current NASA Ladder of Life Detection does not lend much credibility to the use of microscope pictures to claim evidence of life, and places the discovery of "biofabrics" at the bottom of its ladder of decreasing confidence in the detection of life.

*Q 13.3 Where does the Viking approach of searching for metabolism come in?*
*A 13.3* In the official Ladder of Life Detection, it is listed just under searching for growth and reproduction, because it is considered a relatively straight-forward set of tests to perform but subject to false positives due to geochemical reactions that can occur in the natural environment. An example is the uncertainty in what the LR experiment on Viking actually discovered --- was it life, or just some highly reactive but unusual chemical oxidant in the soil?

Life cannot exist without expenditure of energy, and it must find ways to harness available forms of energy from its environment and convert them into the chemical forms of energy that are useful to itself. Generally, cells convert this external energy into energy-rich molecules such as ATP (**a**denosine **t**ri-**p**hosphate), which can be used to enable many of the thousands of chemical reactions that are required to keep a cell functioning. But ATP is not obtained by extracting it from the environment. Rather, it is made by special series of chemical reactions that can synthesize ATP from the sugar glucose and some inorganic phosphate compounds.

The reactions that obtain the energy necessary to produce ATP can be quite different in various species of organisms. For example, not all organisms which can capture the energy in sunlight do it in the same way. Sunlight is harvested in plants when photons are captured by chlorophyll, but in cyanobacteria the photons are captured first by molecules called phycobilins. Other species, such as "purple sulfur bacteria" and the "green sulfur bacteria" have less sophisticated methods of converting the energy of photons into ATP and other energy-dense molecules. The metabolism of these bacteria may have been the basis from which the more sophisticated versions of two separate, but cooperative, photosystems evolved in plants.

Furthermore, not all organisms depend upon sunlight. Some organisms simply eat other organisms, and in effect "burn" their victim's molecules by reacting them with the oxygen in the air, or "ferment" their molecules by turning them into less energetic molecules (e.g., making alcohol or acid).

Many species of bacteria and its cousins, the archaea microbes, do not need to eat other organisms or ferment their carcasses to gain energy. They simply catalyze the reaction of inorganic chemicals, such as minerals in rocks, already in their environment and gain some of that energy for their own use. We call these organisms *chemolithotrophs.*

*Q 13.4 Why is "chemolithotrophs" such a long, complicated name?*
*A 13.4* It is not really that complicated to spell or pronounce, if you break it up into its parts. In this context, chemo refers to use of chemical reactions to obtain energy; litho refers to use of inorganic compounds, rather than organic molecules; troph refers to nourishment. The designation of "chemotrophs" is to contrast it with the "phototrophs" which obtain their energy from sunlight. And "litho" would be replaced by "organo" for those organisms which obtain chemical energy from organic molecules instead of inorganic minerals and gases.

In addition, there is the issue of where the carbon atoms needed for synthesizing all the organic molecules in the organism come from. If the organism gets its carbon from organic matter, it is called a heterotroph; otherwise, if it gets its carbon elsewhere, such as from $CO_2$ in the atmosphere or carbonate dissolved out of rocks, it is called an autotroph.

One of the most amazing forms of life is therefore the *chemolithoautotroph*—that is, an organism which can live off air, rock and water, totally independent of any other organism, organic matter, or even the availability of sunlight. Such organisms could live on Mars in spite of the strong UV irradiation at the surface, and survive deep underground where ice will have become liquid because of the increasing temperatures of planets with depth, in the case of Mars at about 3 to 5 km. On Earth, there is considerable newfound interest in the so-called Deep Biosphere, where organisms are indeed found kilometers deep in gold mines and drill holes.

*Q 13.5 What chemicals in what environments are you referring to?*
*A 13.5* There are many. We have already pointed out that hydrogen gas in the atmosphere can be chemically reacted with sulfate salts in soil to produce the energy needed by the so-called "sulfate reducing microorganisms," such as

the *Desulfovibrio* species, considered to be among the oldest forms of microbes, dating back to the earliest evidence of life on Earth.

Hydrogen can also be reacted with the $CO_2$ in an atmosphere to produce methane, such as by the group of microbes known as the methanogens. And it also could be used by other specialist organisms to react with oxidized iron or perchlorates in the soil to gain the energy they need to live.

Another source of chemical energy is hydrogen sulfide ($H_2S$), which is one of the gasses produced in volcano emissions, or by *Desulfovibrio* as it reduces sulfate. $H_2S$ has the well-known smell often ascribed to rotten eggs (or odoriferous flatulence). When it is reacted with certain oxidizing chemicals in the environment, such as $CO_2$ or $O_2$ gas in the atmosphere, or with nitrate in the soil, specialist organisms can use this energy to grow and reproduce. Iron oxide in volcanic minerals, such as olivine and pyroxene, can be further oxidized by nitrate. There are many other examples of microbes which can take advantage of one or more redox reactions between ingredients already available in the atmosphere and/or soil of a planet such as Earth or Mars.

*Q 13.6 What are "redox reactions"?*
*A 13.6* These are a large group of reactions known in chemistry, many of which proceed spontaneously with the release of energy, most often in the form of heat.

Examples include reactions of anything that can burn in air. If you heat ordinary table sugar in a pan, it will turn into caramel, and if you heat it enough it will smoke and turn black. Marshmallows are mainly made of sugar, with some binders. If you roast a marshmallow over an open flame, it will become caramel colored as the sugar molecules (sucrose) decompose. But if you intensely heat it fast by placing it directly into the flame, it becomes charred black and then catches on fire and burns to a crisp. The chemist's interpretation is that the oxygen in the air is "oxidizing" the sugar in the marshmallow. This is the obvious "ox" part of the "redox" reaction.

The "redox" name is short for the combination of "reduction/oxidation."

The "reduction" part is derived from ancient times. It is unusual to find raw metals in the ground. Gold is an exception, but iron, aluminum, copper, chromium, and many other important metals most commonly exist in their natural ores as compounds, combined with oxygen. Many metals could be made by heating their ores to very high temperatures to release the oxygen, and from this process the weight of the residual metal is, of course, less than that of the original ore. This "reduction" in weight is the origin of the early chemist's terminology that the ore mineral has been "reduced" when the oxygen is driven off. In practice, heating is only a part of the process and other chemicals may be added to aid the reduction process, such as carbon in the form of coal to react with the oxygen in the iron oxide ore and release it as carbon dioxide.

In natural environments, many redox ingredients are present, and living organisms have discovered and made use of them. These organisms are mainly in the form of microbes, invisible to the naked eye. Yet, specialist microbes inhabit virtually every location on Earth where there are "redox couples" available. We cannot see them with the naked eye, yet scientists now have many ways to detect their presence.

*Q 13.7 What are "redox couples"?*
*A 13.7* Various chemicals are now classified as either reductants or oxidants, depending not just on the criteria we explained, but more fundamentally on their tendency to attract or not attract electrons from another chemical. This gets into atomic quantum physics, which we will not discuss here, but suffice it to say that the "couples" refer to one chemical which prefers to gain or attract electrons (the "oxidant") and therefore reacts strongly with another chemical which prefers to lose or share one or more of its electrons (the "reductant").

Thus, chemicals such as $H_2$, CO (carbon monoxide), $CH_4$ (methane), $NH_3$ (ammonia) and some forms of Fe are generally classified as reductants. Whereas chemicals such as $O_2$, $O_3$, $H_2O_2$, $CO_2$, $SO_4$, $ClO_4$, $NO_3$ as well as related ions and other forms of Fe and Mn, are generally classified as oxidants. Many chemicals in the first group will react strongly with many chemicals in the second group. When they do, we call these pairs "redox couples." And there are many cases where one of the reductants can react with one of these oxidants to release sufficient energy to fuel all the metabolic activities of a living cell.

*Q 13.8 If some "redox couple" is naturally present in an environment, why hasn't it already reacted before any organisms can benefit from it?*
*A 13.8* The main reason these redox couples exist in nature is that the reaction between them is difficult to get started or the reaction rate is extremely slow under normal conditions. Again, a simple example is fire. The dried out dead bush, or tree, or bale of hay, is primed for catching on fire because the air around it provides more than enough oxygen. But it doesn't suddenly burst out in flame. The explanation is that this and many other chemical reactions require a trigger, what the chemists call the "activation energy." In this case, a spark or lit match or lightning bolt can heat up a portion of the kindling to start a flame, and once even a small part burns and releases the chemical energy of that reaction, it heats the kindling

even more, sufficiently to overcome the activation energy, and the fire feeds on its own energy, which allows it to spread.

It is important to realize, however, that a fire is not "alive", even though it grows and reproduces itself. Rather, it is a chemical reaction that is nourishing itself, so-to-speak, by heating the next batch of kindling to its combustion temperature. The process that occurs in a typical automobile engine is quite analogous: it is burning gasoline with the oxygen in air, to liberate heat energy which is then transformed into kinetic energy by the auto's motor.

A certain class of living organisms actually harnesses the chemical energy of this combustion reaction to power their own metabolism and livelihood, without burning. That class of organism is the animals, including us. We breathe in oxygen and react it with the food we eat to derive energy, and we then exhale the $CO_2$ produced from that reaction.

*Q 13.9 But animals and we do not have a fire in our belly to get past the activation energy to make the combustion reaction happen – so what is going on?*

*A 13.9* In a few words, "catalysis." And "digestion." And "enzymes."

One way to make a chemical reaction happen is to heat up the two reactants while they are mixed together. But there are other ways. Most commonly, there are what chemists call "catalysts," typically meaning a third chemical added that causes a mixture to more quickly undergo a desired reaction but without itself being changed. A catalyst reduces the activation energy and thus the reaction proceeds faster without added heat. In industrial manufacturing processes, many steps are controlled by special catalysts that chemical engineers have discovered and refined.

Microbes discovered catalysts long before humans walked the Earth. Some natural catalysts include several different metals. In the metabolic activities of all organisms there are many different kinds of proteins, hundreds or thousands of which are specialized catalysts, but for which biologists use the term "enzymes." Each type of enzyme is generally effective for one specific reaction step of the overall complex web of chemical reactions that make life efficient. Many of these enzymes harness metals as part of their structure and make them even more efficient as catalysts than they would be in nature. Others have no metal component but are nonetheless effective as catalysts because they have shapes that help bring together the two reactant molecules in such a way that their key reactive parts are placed in close proximity. In biology, this process of harnessing the chemical energy of the combustion reaction is called "digestion."

*Q 13.10 Are these digestive enzymes in our stomachs?*
*A 13.10* Yes, but not exclusively. When we eat our food, we first chew it up and mix in a lot of saliva. In the saliva are a variety of digestive enzymes that begin the process of breaking down the food into individual and smaller molecules. In the stomach, hydrochloric acid is added as well as more enzymes. As the fluidized food passes into the small intestine, the pancreas injects bicarbonate to neutralize the acid but also additional enzymes that break the food down further, including the digestion of fats and foreign DNA into their fundamental small units from which the body can synthesize its own versions of fats and DNA. Our “microbiome”, the large and diverse group of bacteria that live in our large intestine, also assists in certain aspects of digestion by breaking down residual carbohydrates.

Horses, cattle, sheep and goats are vegetarian (herbivores), and all eat hay without “burning” it. Some animals eat only other animals. As carnivores, they survive by predation or scavenging, but nonetheless at the expense of loss of life of other animals.

Some animals, like us, are omnivores and can eat either plants or animals for food. Unlike plants, we cannot use sunlight energy to grow. In fact, aside from the benefit of stimulating the production of vitamin D, direct sunlight is hazardous to our health because of causing skin cancer. Instead, we must rely on the redox couple of organic matter (food) and the oxygen in the air, to complete the combustion reaction without which we cannot survive. Furthermore, the oxygen concentration in the atmosphere needs to be high in order to support the energy needs of animals as large as we are.

On Mars, the tiny amount of oxygen in the atmosphere is more than ten thousand times less dense than on Earth and could not support the metabolic needs of most of our fauna. On the other hand, the intensity of sunlight on Mars is only about twice as low as on Earth, and in fact much higher than needed for plants which grow in the shade of other plants. Moreover, the carbon dioxide that plants need to grow is at a concentration on Mars more than ten times higher than it is in our own atmosphere. Hence, there would be no problem supporting an extensive plant-based biosphere if Mars were again warm and wet, instead of today’s climate of being too cold and too dry.

Because we have no overt evidence of a plant biosphere on Mars, the more likely possibility of extant life would be microbes. However, there are several species of microbes which are photoautotrophs, i.e., need only sunlight and $CO_2$ (plus water) to grow. Furthermore, what has been discovered from the geological diversity of the red planet is that redox couples also exist on Mars and could support a diverse microbiota. At least from an energy availability standpoint, Mars is ready-to-go for life.

*Q 13.11 What happens if the chemical redox couples are all used up? Won't the organisms all die out and life would come to an end?*

*A 13.11* Not likely, at least until all planet-wide resources were depleted, which we now know is not the case. Organisms which can take advantage of local resources are found all over Earth. How specialist species of organisms find these favorable conditions is essentially by chance, through dispersion by wind and sea currents. But once an organism finds its "niche", it will prosper and reproduce. Many of these organisms are especially hardy to adverse conditions and able to go dormant until they find themselves under better conditions. And if some ecological niche for these organisms is destroyed by flooding or lava, there will be other places on the planet which may have newly formed minerals that can support its kind of life.

Some species of organisms are even able to hibernate by transforming themselves into spores which are extremely tolerant to dryness, to lack of energy sources and nutrients, and to adversities such as UV radiation. Yet, once conditions become favorable again, they can transform themselves back into active, fully functioning cells in just a few hours.

Spores can survive in inert form for centuries. Evidence of even longer survival has come from spores liberated from amber or salt, with the conjecture that they somehow have survived for millennia or even millions of years.

*Q 13.12 How did Viking scientists know what the optimum living conditions would be for Martian organisms?*

*A 13.12* They did not. But the Viking biologists tried different levels of water, different temperatures, as well different nutrients ("chicken soup"). On the other hand, not all the possible redox couples were simulated, on the assumption that the organisms would be adapted to take advantage of the soil composition. Once we bring samples back to Earth-based laboratories, it will be feasible to test for many, many more possibilities.

*Q 13.13 How could you possibly ever detect a Deep Biosphere on Mars? Isn't drilling out of the question?*

*A 13.13* Drilling on Mars has been studied by engineers. Many mission proposals have been rejected by NASA even though the proposed drills were only going to attempt depths of one or two meters. However, the ExoMars rover is now equipped with a system capable of drilling to a depth of two meters.

Studies have also been made of how to drill much deeper on Mars. They indicate that the weight of a drill stem to go kilometers deep, as well as the complexities of robotic operation without human attendance, seem far beyond the practical limitations in coming decades, if not centuries. On the other hand, we have a natural excavator at Mars – impactors.

There are abundant craters that penetrate kilometers into the Martian crust. Perhaps there is evidence within them of microfossils of former life. In addition, new craters are still being formed, by occasional impacts by pieces of asteroids and comets. Some new craters, at mid- to high-latitudes have even unearthed buried ice layers. Perhaps they have brought to the surface subterranean life forms that could be found and investigated. There are also other geologic processes that can provide access to underground materials, such as volcanic activity or strong faulting.

*Q 13.14 How would you detect life or ancient life in such deep material?*
*A 13.14* The same ways you would search for life anywhere. And that brings us back to NASA's Ladder of Life Detection. In addition to testing samples for active metabolism, perhaps with even more sophistication than the complex VLBI on Viking was able to do, it would be possible to search for indirect indications of past metabolism.

*Q 13.15 What are some indirect indicators for past metabolic activity on Earth?*
*A 13.15* For example, scientists look for certain element concentrations. So-called "vanadium reduction spots" have been shown to be microbially formed. Vanadium is normally rare in rocks, but living organisms are able to concentrate elements that are useful to them, which can be part of the evidence that life was present and active at one time.

Manganese is not so rare, but usually is much lower in concentration than iron. "Desert varnish" is a dark coating on desert rocks, often with a glossy appearance and containing a much larger amount of manganese than expected. This coating of iron, manganese, clay and silica on exposed rock surfaces is biologically relevant, because it readily traps wind-borne organisms and because it may also be evidence of microbial-induced oxidation of manganese that would not occur otherwise.

Even more specific and less ambiguous has been isotopic signatures of mineral deposits. Isotopes are different forms of the same element. From nuclear physics, the difference depends on the number of neutrons the isotope contains in its nucleus. In general, for a given element, living organisms incorporate the lightest isotope with higher efficiency than the heavier mass isotopes. Thus, isotopic abundances within carbon, sulfur, nitrogen or even iron and other elements have been used to infer past biological activity in mineral deposits on Earth. This includes ancient mineral deposits that help determine when life started and also when major shifts in activity levels of the biosphere occurred. Although still controversial, some zircon minerals which formed 3.7 or even 4.1 billion years ago have been found to contain graphite with enriched carbon-12 isotope compared to carbon-13 isotope, indicating biological activity that formed carbon-rich molecules long ago. Compared to the time at which the Earth formed, some 4.5 billion years ago, this means life began remarkably early in the history of our planet. Thus, even though life itself had a head start, it took about four billion years to evolve intelligence to our level of human intellect.

*Q 13.16 What about the methane on Mars that has been in the News, off and on, for years?*
*A 13.16* A point has been made that discovery of the co-location of certain redox couples that should have already reacted could also be an indirect indicator of metabolic activity. A classic example has been methane detected in the atmosphere of Mars. According to careful and thorough analyses, atmospheric photochemical models predict that any methane in Mars' UV-rich and oxidizing environment would be destroyed rapidly, compared to geological time. Thus, reports of methane detected on Mars from Earth-based telescopes equipped with spectroscopic analyzers indicated possible biological activity. Subsequently, the ESA's Mars Express orbiter also detected methane at much higher concentrations than expected. This could be due to biological activity by methanogens.

However, much more sensitive instruments on the Curiosity rover and ESA's Trace Gas Orbiter have not detected methane at the levels previously claimed. On the other hand, the rover instrument has detected what seem to be short-lived injections of methane into the Martian atmosphere. Could this be evidence of a deep biosphere? It must be pointed out that methane can also be produced purely chemically, without biological activity, when water reacts with rock containing certain iron- and magnesium-rich minerals that are abundant in the sub-surface or in lavas. This reaction creates the mineral serpentine and releases hydrogen and methane gas.

*Q 13.17 What about fossils?*
*A 13.17* As we already mentioned, the Ladder of Life Detection has images of "biofabrics" at the bottom of its list, for reasons that microscopic images of soils and rocks often reveal mineral grains and textures that mimic the structures of biological life. With painstaking efforts, some evidence of very

ancient fossils of microbes has been discovered, preserved in chert. There are also formations, called stromatolites, made up of "microbial mats" which are layers of sediment and the remains of organisms, that are also in the earliest parts of the geological record.

However, there is a different kind of fossil than those which can be seen in pictures, and that is chemical tracers. When an organism dies, most of its constituent molecules tend to change and decay with time due to slow but persistent reactions with other chemicals in its environment or because they were unstable to begin with. Eventually their remains become unrecognizable, especially when compared to the organic molecules that are found naturally in some meteorites and which for various reasons clearly were not formed by living organisms.

However, a few molecules that are unique to life and not present in meteorites are resistant to change and may be preserved as chemical fossils from past biological activity. These are called chemical "biosignatures." Proteins and DNA are obvious targets, but both are polymers and tend to lose their properties rapidly and eventually break down to their monomer constituents. From proteins, these are the amino acids. Some of the twenty different amino acids used by life on Earth are more stable than others and will persist for millions of years, or longer, especially under dry, cold conditions.

Of special interest for those molecules which can have two possible structural forms, is that living cells produce only one version. Thus, for example, all organisms on Earth exclusively use only the L-forms of amino acids and D-forms of sugars. This is another piece of evidence that all forms of Earth life are related and evolved from the same ancient ancestor. Life elsewhere in the Universe will presumably also have preferences, although they could be different from ours. If certain amino acids were discovered on some other planet, a key measurement would be to determine if that biochemical were homochiral, i.e., existed only in one handed form and not both (as covered in Chapter 5). Many scientists agree this could be a fundamental way to indicate the organized biochemical activity that is a characteristic of life, versus natural chemical processes which typically produce a mixture of left and right-handed products.

*Q 13.18 Are there other chemical "fossils" that could be evidence of life?*
*A 13.18* Yes. Researchers have pointed out that biosignature molecules such as hopanes are particularly resistant to degradation over time, in favorable environments. Also, the family of lipids that make up cell membranes have been equated to a universal biomarker for life. The fatty acid components of lipids typically have an even number of carbon atoms when synthesized

by biological enzymatic processes. In a purely non-life chemical process, lipids can be synthesized from a mixture of carbon monoxide and hydrogen, but that chemical reaction does not produce the same pattern as a typical biological reaction. Thus, the carbon pattern may serve as a biomarker, under suitable conditions.

*Q 13.19 What happens if the place you are exploring simply does not have much, or any organic molecules, like Mars?*
*A 13.19* The Curiosity rover mission has indeed now discovered some organic compounds on Mars. So far, the amounts discovered are extremely small, and are none of the biosignature molecules just mentioned. However, clays and salts are abundant in Gale crater, and both mineral forms can preserve organics well, so there is hope that future exploration by the various Mars rover missions will have the opportunity to discover much higher levels of organics in some samples, and may even be able to test for chirality in the molecules.

NASA's Perseverance rover mission (previously known as M2020) does not have a GCMS but instead uses Raman spectroscopy to search for organic compounds. This rover is tasked with exploring river delta formations and carbonate deposits inside Jezero crater, with a goal of further refining our knowledge of the habitability of Mars as well as searching for evidence of past life.

*Q 13.20 Are there other places in our Solar System that do have abundant organics?*
*A 13.20* Yes, several.

Some are quite small bodies. As we have discussed, there are several classes of meteorites which contain significant amounts and diversity of organic molecules, as do comets. These bodies are so small that they have no atmosphere, which reduces the likelihood of life. Although highly speculative, deep within comets and some asteroids, the primordial heating by radioactive isotopes may have caused melting, and hence liquid water that could have supported life. Because of their great depth, these hypothetical regions are hidden from view and are impractical for exploration at the state of technology now, and in the anticipated future.

Titan, a satellite of Saturn, is the largest moon in the Solar System and has a very thick atmosphere, composed primarily of nitrogen but also abundant methane. This atmosphere creates a thick haze due to solar UV reactions that photochemically convert the methane into particles of a variety of organic molecules. Is Titan a proxy for conditions in the atmospheres of early Earth or Mars? Perhaps. That is one of the important reasons for studying this body and which led to ESA's Huygens probe landing there in 2005 as part of NASA's Cassini mission to explore Saturn and its moons. Some information was obtained about the composition of the haze and surface of Titan, but a more ambitious mission is now planned (see next chapter).

Whether Titan could support life is in question because its surface is quite cold due to its distance from the Sun being so great that the solar illumination is about 100 times less than for Earth. Water is frozen solid at its surface, but methane and ethane condense to form the seas that have been observed. These might support a unique kind of life, as considered by Christopher McKay and co-workers. Whether water-based life could ever exist on Titan is also still a possibility, however, because of new evidence from the Cassini mission which studied it for more than a dozen years. The mission discovered that there is a subsurface layer of salty liquid $H_2O$ which could be brought up to the surface by volcano-like activity.

*Q 13.21 Isn't methane the same thing as what we call "natural gas" for cooking food and heating our houses and buildings, and which is a greenhouse gas?*
*A 13.21* Yes, but methane cannot be a fuel on Titan, because there is no significant amount of oxygen available. One thing it does do, however, is provide Titan with a very strong greenhouse effect, although the surface temperature is still extremely cold because the Sun is so far distant.

*Q 13.22 Are there any bodies in our Solar System where there may be a simultaneous combination of liquid water and organic molecules?*
*A 13.22* Yes. Another especially interesting moon of Saturn is Enceladus. Although much smaller than Titan and therefore without any atmosphere, it does also have an ocean beneath its icy surface. What is so exciting about this moon is that it constantly has plumes of droplets spewing out of this ocean through cracks in the ice. Although not designed for the task, one instrument on Cassini was able to make rough measurements of the composition of these particles as the spacecraft flew several times through these plumes. Among the things it measured was not only the $H_2O$ ice and $H_2O$ vapor, but also a variety of fundamental organic molecules, as well as ammonia and hydrogen. This is all consistent with the expectation that solid matter similar to that found in carbon-rich meteorites and comets may have sunk to the center of the interior ocean and subsequently reacted with the ocean water to produce an organic-rich brine, ideal for life.

*Q 13.23 If Titan is so cold, and Enceladus is covered with ice, what prevents their oceans from freezing?*
*A 13.23* Planetary geologists learned some time ago is that the tides that we have on Earth caused by the gravitational pull of our Moon occur everywhere in the universe and can create considerable energy. Being close to a giant planet like Saturn causes immense tidal forces on a moon as it orbits, and these forces transfer energy that heats its interior. The most dramatic example of this effect is on the nearest large moon of Jupiter, named Io, because its orbit is close enough that this tidal heating actually melts solid rock and results in several hundred volcanoes which are continuously active.

What is so important about this for Enceladus and also Titan is that the interior heating causes reactions in what is known as the hydrothermal regime, which is hot enough to create methane and also leach out many trace elements that could help organisms survive or to provide some of the catalysts needed to start life in the first place.

Enceladus is one of a class of objects in our Solar System now called the “Ocean Worlds.” Earth is a member, of course, but our ocean is on the outside of our planet, whereas all the other examples have solid ice covering their ocean.

*Q 13.24 What other bodies are Ocean Worlds, and do they have organics?*
*A 13.24* Another important Ocean World is a large moon of Jupiter, named Europa. This moon has an icy outer shell, with intriguing surface structures resembling cracks (or faults). There is also some evidence that Europa currently has one or more active plumes. Several other moons of Jupiter are now known to have subsurface oceans of water. These are Ganymede and Callisto.

Although it is known that these oceans have dissolved out some elements to create a salty brine, the details are yet to be learned. In particular, it is not yet known what the organic contents might be, and even for Enceladus it is still unknown how complex is its complement of organic molecules. There are also Icy Worlds which contain organics and may have so-far-undetected subsurface oceans or pockets of liquid water.

*Q 13.25 What are some other examples of Icy Worlds?*
*A 13.25* Pluto has both $H_2O$ ice and other ices, and a tenuous atmosphere containing methane. The New Horizons mission which flew by Pluto in 2015 made several discoveries, among which is indirect evidence that there might be a subsurface liquid ocean.

Ceres is the largest body in the asteroid belt, but too small to have an atmosphere. Spherical in shape, it was discovered by the DAWN mission that in its surface are organics, clay, carbonates and ammonia, as well as abundant water ice. Although it might not have a global ocean, it could have vein-like deposits of brine-rich melted ice. Because of its location, Ceres also is of great interest because it could represent a class of matter with compositions which were added to Earth early in its history and could have initiated the origin of life with a set of ideal ingredients.

*Q 13.26 Are there any future space missions planned for these Ocean and Icy Worlds?*
*A 13.26* Yes. This leads us to our next chapter to discuss some future missions with strong relevance to the science of astrobiology.

# CHAPTER 14

# WHAT ARE SOME NEW SPACE MISSIONS WITH ASTROBIOLOGICAL SIGNIFICANCE, AND WHAT DO WE EXPECT TO LEARN?

*Q 14.1 Space missions are sometimes named in a way that is not easily understandable. How can one figure out from the name of the space mission what they are all about?*
*A 14.1* Space missions are often named with acronyms (acronym = an abbreviation made from the initial letters of other words, and pronounced as a word, e.g. NASA = **N**ational **A**eronautics and **S**pace **A**dministration). Some acronyms for space missions make sense as a normal word and may lead one to an interpretation of the goals of the mission which, however, may be completely wrong.

*Q 14.2 What are some examples of such wrong interpretations?*
*A 14.2* One such example is the MESSENGER mission. One would be tempted to conclude that this mission is about carrying a message to some putative recipients in space (aliens?). However, MESSENGER is an acronym for **Me**rcury **S**urface **S**pace **En**vironment **Ge**ochemistry and **R**anging. Thus, it is a mission to Mercury, which is not easy to guess from the acronym, unless one knows that MESSENGER is actually a backronym with a reference to the Roman mythological messenger Mercury (backronym is a reverse acronym, namely an acronym deliberately formed from a phrase whose initial letters spell out a particular word to create a memorable name).

Another example is the InSight mission, which, based on its name could be interpreted as a mission to gain insight into a space target, but it is not clear what the target is. Actually, "InSight" is an acronym for **In**terior Exploration using **S**eismic **i**nvestigations, **g**eodesy, and **h**eat **t**ransport, but it still does not include information about the space target (which is Mars).

*Q 14.3 What is then the purpose of such acronyms?*
*A 14.3* For people to remember the name of the space mission, by associating it with some word which makes sense and is easy to remember, and which is constructed from the actual words describing the missions. It also provides a unique identifier for each specific mission. The exact meaning and implications of these acronyms and identifiers are obvious only to the specialists who work on them or are deeply involved in the overall programs of these agencies.

*Q 14.4 How does one find out what the acronyms for space missions stand for? Please include in your answer examples of missions which are of importance to astrobiology.*
*A 14.4* One can find this information on the NASA website or Google. Especially helpful are the websites: www.ninfinger.org/karld/My Space Museum/acronyms.htm and https://www.nasa.gov/pdf/632702main_NASA_FY13_Budget-Reference-508.pdf.

The reality is, however, that new acronyms are being invented every day. Furthermore, the same acronym is sometimes used more than once, for describing completely different missions or things. This is part of the jargon of science, and especially space exploration. Sometimes it can be taken to an extreme. For example, "Stardust" is the name of the first mission by NASA to autonomously (no astronauts) bringing back samples from space for scientists to analyze in their laboratories. This mission was completed in 2006 when samples of comet Wild 2 were returned to Earth after a 7-year mission that traveled three billion miles in space (the "long way" from Florida, where it was launched, to Utah, where it was landed). Yet, because they were in vogue at the time, the acronym STARDUST was given a complex breakdown of words for each letter, which everyone promptly forgot.

The Stardust mission was quite relevant to astrobiology because it was the first (and so far, the only) mission to a comet which brought back to Earth samples of cometary matter. Comets have often been cited as possibly relevant to what enabled the origin of life on Earth because they are well known to contain both high levels of key organic compounds and also water (as ice). Comets may have provided many of the key starting ingredients from which life first arose.

*Q 14.5 Do all space missions use acronyms for their names? An example, which is significant for astrobiology, would be welcome in your answer.*
*A 14.5* Not all missions use acronyms. For example, the "Genesis mission" had no acronym when it flew. However, the concept for this mission was

originally designated by the acronym SWSR (pronounced "Swiss-Er"), which stood for **S**olar **W**ind **S**ample **R**eturn. Its goal was to bring back to Earth samples of the atoms in space in the "wind" that passes by Earth as matter evaporates from the surface of the Sun. Even before it was selected for flight, and was still being proposed to NASA, the acronym was dropped and the mission was christened "Suess-Urey" in honor of two great scientists, Hans Suess and Harold Urey, who accomplished some of the first compilations of data on early evidence for the relative abundances of elements in the outer portion of the Sun. Unfortunately, this name was sometimes misspelled or mis-interpreted (as the Dr. Seuss of childhood fame), and only to hard core scientists was it evident in its meaning or intent. Subsequently, the name was changed to Genesis, to signify the fundamental abundances of elements in our Solar System, as preserved in our own Sun. This is important to Astrobiology because it provides a basis of not only the original abundances of key elements, such as CHNOPS and transition metal elements, but also their isotopes. In comparing the compositions of comets, asteroids and the surfaces of planets to these data, scientists gain insights into how the evolution of planets and small bodies occurred during their formation and maturation.

The Genesis mission turned out to be a poster-child for what was wrong with a concept known as "Faster-Better-Cheaper" and by its acronym, FBC. This idea, which came into vogue in the 1990's, was to arbitrarily force new space missions to be smaller and less ambitious, in order to proceed under lower funding than traditionally applied for such missions and take more risk of success than NASA would normally accept. Although this led to lower costs for missions like Stardust, the idea was pushed to a further extreme with Genesis, which led to less testing and double-checking. Genesis functioned amazingly well while collecting solar wind, moving its collecting arrays hundreds of times without any getting stuck, and folding the arrays back into the sample return capsule so it could return them to Earth. But when the capsule entered the atmosphere, its parachute failed to deploy and the capsule hit the ground very hard, breaking apart and contaminating most of its ultrapure silicon wafers that were collecting the solar wind. However, the science team was later successful in cleaning and analyzing the samples to meet all its four primary science objectives, with publications in the leading scientific journals, as well as meeting most of the optional secondary science objectives, leading to more publications. Genesis did help NASA gauge, however, how hard they could push down costs before affecting reliability of the missions they were sponsoring.

*Q 14.6 Where did the Genesis capsule land?*
*A 14.6* It performed its reentry over the state of Washington, as planned, and came down well within its targeted location at the Utah Test and Training Range (UTTR). The UTTR is a facility used by the U.S. Air Force and other agencies primarily for tests in the Great Salt Lake desert, a large plain west of Salt Lake City. This is an ideal location for recovering samples from comets, solar wind, Mars, Ocean Worlds, etc., because it has excellent radar tracking capabilities, a restricted air space, and very few obstacles on the ground. And because it is also adjacent to the Dugway Test and Proving Grounds, which is equipped to safely handle biological and chemical agents, the entire area is secured with fencing, monitoring, and special guarding.

*Q 14.7 Interesting. So, have newer missions avoided acronyms? In your answer, please give examples of astrobiologically-relevant missions.*
*A 14.7* No, not necessarily. A more recent acronym for a mission, which also forms a pair of legitimate words, is OSIRIS-REx. "Osiris" was one of the most important gods of ancient Egypt, while "Rex" evokes regal qualities. But the full acronym is derived from "**O**rigins, **S**pectral **I**nterpretation, **R**esource **I**dentification, and **S**ecurity - **R**egolith **Ex**plorer." Not many lay people will know that "Regolith" is the geologist's jargon for what the public calls rocks and soil. The mission is to the asteroid "Bennu," which itself is named after the ancient Egyptian deity in the form of a mythological bird, similar to what we would call a heron. The third-grade winner of a contest to name this asteroid saw a similarity between the image of the spacecraft and the Bennu bird. More officially, Bennu is scientifically known as asteroid 101955, and was earlier-on designated 1999 RQ36. Until the ORISIR-REx spacecraft arrived at Bennu, the asteroid was only described as a nearly-spherical object about 0.5 km in diameter, with one or two large, house-sized boulders on it. But once the spacecraft arrived and began a systematic mapping of its surface, the expected soil-like surface of small grains was not to be seen. Rather, the surface is littered with cobble-sized, irregular large rocks and huge boulders.

The OSIRIS-REx mission is important to Astrobiology because Bennu is a Class B asteroid, expected to contain significant amounts of organic compounds. Like comets, the so-called carbonaceous meteorites that come from asteroids such as Bennu may have seeded Earth with the organic compounds which kick-started the prebiotic chemical evolution that led to the first life forms on Earth. When samples of Bennu are returned to Earth they will be investigated, like the Stardust and Genesis samples, in state-of-the-art analytical laboratories all over the world to learn how likely it might be that life was made possible by such materials. Unfortunately, the hoped-for sample size of at least 90 grams of material may not be possible because the spacecraft's sampling system (which uses bottled nitrogen gas to facilitate the action of a vacuum cleaner) is designed for sweeping up soil and not for collecting large rocks. However, on Bennu there are a few places where rocks are much less abundant and collection of smaller material may be possible.

When OSIRIS-REx reaches Earth in 2023 it will be aimed at Utah, but after its Sample Return Capsule (SRC) is separated from the main spacecraft, it will then be diverted to flyby Earth because if it did not, the spacecraft would burn up in our atmosphere because it does not have an aeroshield (aerodynamic heatshield) around it like the SRC does. Landing just as the Stardust SRC did, the valuable samples will be flown to NASA's Johnson Space Center in Houston, where they will be curated for scientists to analyze for decades to come.

Another space mission, Hayabusa2, by the Japanese Space Agency (JAXA) has visited asteroid Ryugu, a C-type asteroid that has also been expected to contain large quantities of diverse organic compounds. This spacecraft fired a small projectile (bullet) downward at high speed after landing and collected a small amount of material that was ejected as the projectile penetrated the surface. Hayabusa2 will return to Earth in late 2020 and land its sample at the Woomera Test Range in Australia, after a six-year mission in space.

*Q 14.8 The knowledge of the meaning of acronyms is not necessarily illuminating to the average reader. How can one find out what a mission with a strange acronym is all about?*

*A 14.8* One needs to research the goals of the mission by looking on Google for the acronym *and* NASA (thus MESSENGER *and* NASA, as one example). Or, if it is a mission by ESA or some other space agency, then simply substitute ESA for NASA. At these websites you will often find a rather detailed description of a mission, its objectives, and the scientific instruments it is carrying. One of the best resources for a concise, but insightful description of the goals and engineering achievements of any particular mission is the on-line encyclopedia known as Wikipedia. Simply type in the name or acronym of the mission and the word "Wiki" and you will usually get the answers you were looking for.

*Q 14.9 It would be nice if some missions honored deserving people from the past. Has this been done?*

*A 14.9* Yes, several missions of astrobiological interest are named after deceased persons who excelled during their lives. Thus, ESA's pioneering first mission to any comet was named "Giotto" to honor the works of the renowned Italian artist, who observed the comet in 1301, and has depicted it as the Star of Bethlehem in his famous painting, "Adoration of the Magi." That comet in question is popularly known as Halley's Comet, in recognition of the astronomical analyses by English astronomer Edmond Halley.

The first NASA Mars rover was named "Sojourner Truth" in honor of the former American slave who became a famous outspoken abolitionist and champion of women's rights. And the ExoMars program's rover is now known as "Rosalind Franklin" in honor of the woman scientist who directed the pioneering x-ray diffraction imaging of the DNA molecule which revealed its helical structure and phosphate backbone, but was not included in the Nobel prize awarded to Watson-Crick-Wilkins.

*Q 14.10 What other missions to Mars will conduct astrobiological exploration?*

*A 14.10* The China National Space Administration (CNSA) has a multi-pronged mission to Mars. Provisionally named Huoxing-1 (Mars-1), the mission includes an orbiter, lander, and rover. In addition to the typical set of instruments there will be compositional analysis capabilities and collection of samples for a future sample return mission. The plan is to land somewhere on the Utopia Planitia region, an area on Mars at which the Viking-2 landed and where an extensive underground deposit of ice equivalent to the water in Lake Superior has now been discovered by a ground penetrating radar onboard NASA's Mars Reconnaissance Orbiter (MRO).

The United Arab Emirates (UAE) has developed the Mars orbiter "Hope." Celebrating the $50^{th}$ anniversary of the young Arab nation, Hope will study the atmosphere of Mars, complementing NASA's orbiter MAVEN (**M**ars **A**tmosphere and **V**olatile **E**volutio**n**) that has been operational at Mars since 2014. These missions allow investigation of the most probable history of the Martian atmosphere, from its originally more dense phase that enabled higher temperatures which made possible melting and the widespread occurrences of liquid water, to the thin atmosphere and frigid, icy desert plains we see today.

*Q 14.11 What about the Russian program for Mars exploration, and other countries?*

*A 14.11* The Russian space agency, Roscosmos, is providing the lander for the ESA ExoMars program, as well as the Proton launch vehicle. On the Kazachok lander is a wide array of instruments to study the Martian environment.

The space agency of India, ISRO, sent an orbiter to Mars in 2013.

The space agency of Japan, JAXA, is planning a mission that will explore the two moons of Mars, named Phobos and Deimos, and attempt to obtain samples of Phobos and return them to Earth. Although these moons are apparently objects similar to certain asteroids, made of matter different from Mars itself, they may also contain small amounts of Martian material because these miniature moons sweep up debris that was injected into Mars orbit, especially by the giant impacts that occurred early in Martian history.

*Q 14.12 Will samples from Mars be potentially dangerous to Earth?*
*A 14.12* Extremely unlikely, say the experts. Even if Martian organisms do exist, several NASA and National Science Foundation (NSF) studies by independent scientists and disease specialists have judged the likelihood of them to be able to infect our animals, plants or human beings to be extremely low. This is because infectious organisms are typically well-matched but specific to one or a narrow range of target species.

On the other hand, say the experts, although the risk is evaluated to be exceedingly small, "one cannot assume the risk is zero." Something that is a low risk but could have major consequences must be treated with caution. For this reason, it has always been planned that the Martian samples will be examined in a special facility that has all the precautionary features that are used in the highest-security laboratories for studying dangerous infectious diseases.

Such a laboratory would be even more complex than a Biosafety Level 4 laboratory on Earth. Why? Because not only would it be necessary to protect the humans from the samples, for example with full-body pressurized suits, but also to protect the samples from becoming contaminated with organisms or organic molecules from the humans and all their equipment. In a BSL-4 lab for a highly dangerous virus, such as Ebola, there is a positive pressure gradient such that the flow of viral particles is always away from the humans. But the opposite is needed for protecting the samples of Mars. Thus, the receiving laboratory may require a pressurized volume within another pressurized volume which, when combined, protect both the investigators from the samples, and the samples from the investigators.

*Q 14.13 Wouldn't that result in one small, highly secure laboratory without taking advantage of specialized laboratories around the world that have unique, state-of-the-art instruments and highly-experienced personnel?*
*A 14.13* Yes, and it also means that only a handful of the hundreds of scientists who will want to be involved in analyzing the first samples to come back from Mars would be able to do so. However, if a portion of each

different sample could be somehow sterilized to be sure it is safe yet without disrupting the chemical and physical properties that need to be studied, then these sterile samples could be distributed to the most advanced laboratories in the world. The Planetary Protection Offices at NASA, ESA, and other space agencies are evaluating the use of heat and/or ionizing radiation as methods of killing any possible microbes, with minimal damage to the minerals and molecules in the samples.

*Q 14.14 Will such a laboratory be only useful for samples from Mars?*
*A 14.14* Actually, it is hoped that someday there will be samples coming back from other locations in the Solar System where it is conceivable that life may exist. These locations include Europa (moon of Jupiter), Enceladus (moon of Saturn), Ceres (minor planet) and other Ocean Worlds and Icy Worlds.

*Q 14.15 Would astronauts be allowed to go to Mars if they potentially might get infected?*
*A 14.15* Yes, but not yet. Most scientists believe it is essential to return to Earth a variety of Martian soils, rocks and sediments, if for no other reason than to determine whether there is any evidence of life and/or there is any chance that the Martian soil might be hazardous.

For example, the particles of dust in the Martian atmosphere are extremely fine-grained (about ten times smaller than lunar soil) and could cause respiratory damage similar to silicosis or black lung disease. The soil also contains small amounts of perchlorate, which is a hazard to thyroid health. And Mars has high chromium levels that could include a chemical version which is known to be carcinogenic.

*Q 14.16 What will happen to the Mars explorers when they return to Earth?*
*A 14.16* Most likely, they will be put into quarantine, much like the Apollo astronauts were when they returned from the Moon. How long they will be forced to quarantine is not yet determined, but the Apollo astronauts had to remain isolated for 21 days. However, missions after Apollo 14 no longer required astronauts to be quarantined because the returned samples verified the lunar soil is extremely dry and contains only trace amounts of critical elements such as carbon and nitrogen. These factors, combined with the fact that the high vacuum environment is also inimical to life, convinced scientists and regulators that the Moon was not a source of hazards to the Earth.

*Q 14.17 When will humans go to Mars?*

*A 14.17* In spite of various studies, intermittent programs and even national initiatives for a human mission to Mars, there has never been adequate funding for such an adventure in the foreseeable future. Sending astronauts on a roundtrip to Mars is roughly 100 times as ambitious as sending humans to our Moon. The roundtrip to Mars requires about 1,000 days and nights, because Mars is much further away and the two planets are in optimum alignment only on specific dates for the outbound and return trips. The Mars mission requires a huge amount of food (15,000 meals for a crew of five), whereas a trip to our Moon and back can be completed in just one week, as if one were going on a long picnic. Mars travelers would also need to recycle their water and chemically extract oxygen back out of the $CO_2$ they exhale.

Most importantly, the rocket propulsion needed is much, much higher for going to Mars, including fueling the new rocket for the high energy needed to get off the Martian surface and on the way back to Earth. Many other factors of danger come into play, such as far longer and greater exposure of the crew to cosmic ray damage once outside of Earth's protective geomagnetic shield, as well as the adverse psychological factors of being so far from Earth that it appears in the night sky as if it were simply another star.

*Q 14.18 What would astronauts do at Mars once they are there?*

*A 14.18* They will be able to conduct exploration of the area they operate in much faster and probably with more scientific insight than is possible with our rover missions to the red planet. No longer would scientists be handicapped by the limited number of close-up pictures and locations that could not be explored in depth. Many highly experienced field geologists have expressed the conviction that the search for direct evidence of previous life, as is found in fossils of early organisms, can only be conducted through the efforts of seasoned experts and their helpers. Rovers operated from Earth, with all their limitations on data bandwidth and agility, are simply not as likely to make the eureka discoveries that typically accompany new findings of great biological significance.

Furthermore, not only would such a mission be a great event for the public, it would inspire its schoolchildren to higher goals in their education. The pedagogical and aspirational value of such an undertaking, especially if conducted in the spirit of international cooperation, could be sufficient justification for its costs.

*Q 14.19 Even if Mars is safe for humans, will humans be safe for Mars? Won't astronauts contaminate the environment with all the microbes in and on their bodies, as well as with organics, such as the lubricants and oils for their equipment?*
*A 14.19* Not necessarily will they contaminate all of Mars. After all, the land area of Mars is about equal to the land area of Earth (not counting our oceans). That is enormous, compared to the small size of a region that a Mars base would operate within. If some areas of Mars are more critical than others, and the human base is far away from those areas, the human exploration may be accommodated within Planetary Protection guidelines. It turns out that some areas of Mars are considered possibly more hospitable to life, such as the RSL's (Recurrent Slope Lineae) that have been identified as potential Special Regions on Mars, where Viking-class sterilization may be a requirement for exploration. Also, higher latitudes are colder and hence less likely to have even transient temperatures approaching the freezing point of water except on time scales of many thousands or millions of years, due to obliquity cycling.

*Q 14.20 What do you mean by "obliquity cycling"?*
*A 14.20* Unlike the Earth, which is always tipped 23.5° on its rotation axis as it goes around the Sun, it has been determined that the "obliquity" (tip angle) of Mars can vary from about 15° to 45° over very long periods of time. Currently, it is coincidentally close to Earth's tip angle, at 24°. When Mars is at smaller values, the polar regions get colder, but when is it at the larger values, the higher latitudes get much warmer. If a Martian organism had the capability to withstand very long time periods in a frozen state, it could then rejuvenate when ice melts. This is one scenario for how life might survive the current adverse climate on Mars, if it can be dormant long enough.

*Q 14.21 What are the other various scenarios for how life could survive on Mars?*
*A 14.21* Living organisms ("extant life") may be found: in the near surface of Mars, close enough to take advantage of the atmospheric constituents but beneath some soil to shield them from the damaging UV; deeper in the subsurface, perhaps in or near permafrost ice; at the interface between ice and rock, where nutrients would be available; in salt deposits, which will be in places where the water last existed before everything dried up; or very deep underground where the temperatures are always warm enough for liquid water to be constantly available.

Local warm spots may exist on Mars, although searches from orbit have not detected them, to date. Warm spots could be caused by volcanic activity, or hot springs such as are found in Yellowstone National Park and elsewhere, from Iceland to New Zealand.

*Q 14.22 How can we keep up with the plans and new missions for Mars exploration?*

*A 14.22* An organization for the Mars science community named the **M**ars **E**xploration **P**rogram **A**nalysis **G**roup, better known by its acronym MEPAG, was established decades ago to provide input for prioritizing Mars exploration in the future. At the time, the goal of Mars exploration had become "Follow the Water." In the intervening years, all the rover missions and new orbiter missions have greatly explored the past and present occurrences of water on Mars, both liquid and ice.

The MEPAG organization has a rotating leadership and generally meets twice a year for briefings on present and especially upcoming Mars missions. The group provides a community-based, interdisciplinary forum for Mars scientists. Anyone may attend meetings, some of which are conducted virtually, and anyone may access their documents, at https://mepag.jpl.nasa.gov/.

A fundamental task of MEPAG is to periodically update their goals, objectives, investigations and required measurements for robotic and human exploration of Mars. The current version emphasizes four overarching goals: Determine if Mars ever supported life; Understand the processes and history of climate on Mars; Understand the origin and evolution of Mars as a geological system; and Prepare for human exploration. Within each of these four goals are a set of specific Objectives and the Investigations (measurements and analyses) that support them. The value of MEPAG is that it provides a systematic overview and justification of various investigations. However, it cannot set NASA priorities, which arise instead from organizational needs and additional recommendations from other advisory committees, special study groups, and NASA's Decadal Studies, in this case the Planetary Science and Astrobiology Decadal Survey.

*Q 14.23 What plans are there to explore other locations, besides Mars, where there might be life?*

*A 14.23* As we discussed in the previous chapter, scientists are excited about several large moons of the giant planets which have planet-wide water layers beneath surfaces of ice. As a result, there are several planned missions to these Ocean Worlds.

NASA's Europa Clipper mission will orbit Jupiter and conduct a series of close flyby's to Europa to analyze its surface and any gases or particles which it may emit into space. The spacecraft will include a number of imaging systems and spectrometers of various types to perform the analyses to assess its habitability and to seek biosignatures of simple extraterrestrial life. Such a mission has the challenge of surviving the dangerous environment of Jupiter's radiation belt, but previous missions such as Galileo and Juno have demonstrated that engineers can design the electronics and shielding systems that make this possible.

In addition, the ESA is developing its JUICE mission (**Ju**piter **Ic**y Moons **E**xplorer), which will also orbit Jupiter. Although it will conduct additional explorations of Europa, as well as Callisto, its most important target will be the moon Ganymede, around which it will eventually go into orbit. Ganymede is the only moon which has its own magnetic field and furthermore appears to have a very thick ocean between two layers of ice, overlying a mantle layer of silicate rocks, and an iron-rich innermost core.

At Titan, the Dragonfly mission will land a vehicle based on a quad-copter design and operate by flying in repeated hops as it makes its way across the terrain. With each landing, it can measure bulk composition of the surface and drill to create powdered samples which can be analyzed by the advanced GCMS it will carry. Because Titan has an atmosphere which is more dense than our own, and a force of gravity even less than our own Moon, this electrically-operated 'copter will be able to fly with much greater efficiency than on Earth.

# Chapter 15

# How do we search for life outside our Solar System? What type of biosignature could we use?

*Q 15.1 To search for life outside our Solar System, shouldn't we be looking first for planets which are similar to Earth?*
*A 15.1* Yes. However, first we need to find a number of planets outside our Solar System – they are termed "exoplanets" – and then search among them for the Earth-like ones.

*Q 15.2 How many exoplanets have been found?*
*A 15.2* To date, there are more than 4,000 exoplanets discovered, and the number is growing daily. These are the confirmed cases. However, there are thousands of apparent exoplanet detections that are not confirmed yet, since further verification of their exoplanet status is required. In the meantime, they are classified as "candidate" exoplanets (see NASA's web site on exoplanets https://exoplanets.nasa.gov/what-is-an-exoplanet/about-exoplanets/ ) .

*Q 15.3 When were the first exoplanets discovered?*
*A 15.3* In the early 1990's, after many previous attempts had failed.

*Q 15.4 How are exoplanets discovered?*
*A 15.4* They are discovered by using instruments such as space telescopes and applying different methods, such as *transit, radial velocity, direct imaging,* and *gravitational microlensing*.

*Q 15.5 What are some specifics about these methods?*
*A 15.5 The transit method* is based on the dimming of the star's light that is caused by a direct passage of the planet between its star and an observer on Earth. This is similar to a solar eclipse, which occurs when our Moon passes directly in front of the Sun, blocking its light. However, the image of most

exoplanets is much smaller than its central star, and the dimming is by an exceedingly small amount, which makes the detections challenging. The transit method has resulted in the discovery of over 3,000 exoplanets.

*The radial velocity method* is based on the phenomenon of a star's wobbling, which is caused by the gravity of its orbiting planet. Star's wobble results in a change of color of the light which astronomers observe. This is due to the Doppler effect, which occurs when a wave such as light is emitted from a moving source. A more familiar example from everyday experience is the sound of an ambulance siren when passing a person on the street. When such a source is moving toward an observer, the wavelength of light is perceived as shorter, and the light color shifts towards the blue end of the spectrum (while the sound would give a higher pitch). Conversely, if the source is moving away from the observer, the light color shifts towards the red (and sound gives a lower pitch). This method has been used for discovery of over 800 exoplanets.

In the *direct imaging method* astronomers take pictures of exoplanets. To find exoplanets, astronomers look for faint companions of nearby stars. Observations are typically taken at different times to establish if the potential planet is orbiting the star, and if the star and its potential planet are moving together. It has been possible to detect only about fifty exoplanets by this technique.

The *gravitational microlensing method,* which was utilized in discovery of over ninety exoplanets, is founded on Einstein's theory of general relativity, according to which spacetime curves in the presence of mass, such as galaxies, stars, and planets (spacetime = a four-dimensional continuum which has three coordinates of space and one coordinate of time). A consequence of the spacetime curvature is that light is bent when it passes near massive bodies. The bending of light may cause a change in the brightness of the star, as shown in the following scenario: If two stars line up with respect to the Earth, the nearer star can act as a gravitational lens and focus the light from the further star, making it appear to be brighter. If the lens star has an orbiting planet, and if this planet happens to be in the right place at the right time, it can also act as an additional gravitational lens and can further increase the brightness. This can be used to infer the exoplanet's presence and some of its properties, such as its mass and orbital distance.

*Q 15.6 What are some examples of space telescopes that are used for finding exoplanets?*

*A 15.6* The most significant one is the Kepler space telescope, which was launched in 2009 and operated for almost a decade. Kepler used the transit method to discover exoplanets. While most of the exoplanets previously detected by other projects were giant planets, the size of Jupiter and larger, Kepler was designed to search for planets closer to the Earth's mass. Kepler was put in an Earth-trailing orbit around the Sun. A continuation of the Kepler mission is TESS (**T**ransiting **E**xoplanet **S**urvey **S**atellite), launched in 2018, which is able to survey a space area much larger than that of Kepler and is expected to find perhaps 300 Earth-sized exoplanets.

*Q 15.7 It appears that a large number of exoplanets have been discovered, and more are being discovered daily. Are these discovered planets similar to the planets in our Solar System?*
*A 15.7* Some of exoplanets are similar to the planets in our own Solar System, like Venus or Neptune, but others are radically different, such as the so-called hot Jupiters, carbon planets, and super Earths. One general similarity is that, just like planets in our Solar System, the smaller exoplanets are rocky, big ones are gassy, and the ones in between these sizes may have water as well as land and atmosphere.

*Q 15.8 Is there some classification system for exoplanets, since there are so many and they appear to be quite different?*
*A 15.8 Yes.* There are about fifteen criteria for exoplanets, but some planets may be described by more than one type. Five of the exoplanet types use the exoplanet's size as the classification tool. The size is given as mass and diameter. In the increasing order of size, we have rocky planets, super-Earths, mini-Neptunes, ice giants, and gas giants. Several classification types are based on both size and location of a planet within its stellar system. The examples include hot Jupiters and hot Neptunes. There are more types and more examples, but we focus on Earth-like planets since they are the best candidates for finding life.

*Q 15.9 Which features of the Earth-like planets are critical for finding life?*
*A 15.9* The existence of liquid water on the surface is most important since it is necessary for life as far as we know from our Earth-based experience. For this condition to be fulfilled, the exoplanet must be in the so-called "habitable zone" around its star. In such a zone it is not too cold or too hot, but just right for the liquid water to exist on the surface of the planet without being all frozen or boiled away.

*Q 15.10 Have Earth-like planets been found in the habitable zones around the stars?*
*A 15.10* Yes. There are numerous examples, and the list is growing fast. We give one example, that of the TRAPPIST-1 planetary system. This star was

discovered in 1999 and was officially named "2MASS J23062928-0502285". It is an ultra-cool dwarf star located 39.6 light years from our Sun, in the constellation Aquarius. A study of its planetary system in 2015 resulted in discovery of three exoplanets, and in 2017 four more were added. The star was unofficially named as TRAPPIST-1, which is an interesting story by itself. TRAPPIST is an acronym for **Tra**nsiting **P**lanets and **P**lanetes**i**mals **S**mall **T**elescope, which was used for studying this star's planetary system. Since the first exoplanets of this star were discovered by this telescope, the star was designated as TRAPPIST-1 by the discoverers.

But this is not the end of the story of the TRAPPIST name. TRAPPIST is also a backronym which refers to the Catholic religious order of Trappists, and to the Trappist beer they produce, primarily in Belgium. Since the discovery of these exoplanets was made in Belgium, the discoverers drank this beer to toast their success.

The TRAPPIST-1 planetary system consists of seven terrestrial-like exoplanets, labeled as *b-h.* The planets are assigned letters in order of their discovery, beginning with letter b for the first planet that was discovered. Five of these exoplanets - *b, c, e, f, g* – are similar in size to Earth, while two - *d, h* – are intermediate in size between Mars and Earth. Three planets - *e, f, g* – are in the habitable zone. In 2017 astronomers using the Hubble Space Telescope found indications of water on these exoplanets. In 2018, further studies using e.g. the Hubble-, the Spitzer-, and the Kepler space telescopes provided more precise information about these exoplanets. Thus, the exoplanets *c, e* are almost entirely rocky; *b, d, f, g, h* have a layer which could be a water shell, an ice shell, or a thick atmosphere; and *d* may have a liquid water ocean.

TRAPPIST-1 is a unique planetary system, since it has the greatest number of exoplanets in the habitable zone around a single star. All seven exoplanets could have liquid water under the right atmospheric conditions, but the chances are the best with exoplanets, *e*, *f*, and *g*, that are in the habitable zone. The atmospheres of TRAPPIST-1 planets are amenable to studies using spectroscopy.

*Q 15.11 If life exists on an exoplanet, how would we detect it from Earth?*
*A 15.11* We would detect it via various biosignatures which we can observe from Earth.

*Q 15.12 What types of biosignatures would these be?*
*A 15.12* They would be similar to the biosignatures that are applicable to the search of life in our Solar System, but much more limited. The limitations are due to the difficulty in observing details of distant exoplanets as

compared to the objects in our Solar System, which are much closer. In addition, we cannot send robotic missions to these exoplanets at this time, if ever, while the converse is true for the objects in our Solar System.

*Q 15.13 What are the specific biosignatures applicable to the exoplanets?*
*A 15.13* There are several different types of biosignatures that may be possible. One is to simply observe the surface and look for changes that could be a result of the increase and decrease of plant life during the changing seasons. Caution needs to be exercised, however, not to over-interpret the data. We give here a related example from our own Solar System, the case of Mars.

In addition to the supposed “canals” on Mars, which some of the early astronomers thought they were seeing through their telescopes, there was also a phenomenon which was called “the Wave of Darkening” that progressed from the pole toward the equator, and was interpreted by some as the indication of seasonal changes in vegetation. With the advent of Mars orbiter missions, this was shown to be incorrect, partly due to spotty observations and partly due to the waxing and waning of seasonal dust storm activity. Thus, the object lesson is that it sometimes is all too easy to attach a “life” explanation to a purely physical phenomenon, especially if the observing conditions are marginal.

*Q 15.14 Could we take pictures of some exoplanets by using our telescopes?*
*A 15.14* Yes, but the problem is the resolution of such pictures for observing exoplanets because they are so far away. Space is mostly empty. The nearest stars and their exoplanets are roughly a million times farther from us than Earth is from Mars. The TRAPPIST-1 system is ten times farther away than that.

With current and foreseeable technology, it is not possible to observe the details of the terrain of any of the known exoplanets. Even with the Hubble Space Telescope, only the coarsest aspects of the geological formations on nearby Mars can be discerned. Although oceans might be inferred to be present by other means, exoplanets cannot be imaged in any detail.

*Q 15.15 Could we send spacecraft to an exoplanet to send back close-up images?*
*A 15.15* In principle, yes. In all likelihood, not in our lifetime. The reason is that to send a typical spacecraft to another star in a reasonable period of time would require such an enormous input of energy, that it is far, far beyond the capability of all the rockets that have so far launched into space. The problem is that the kinetic energy needed to accelerate something to a

velocity depends on the square of that velocity, so that to propel something to go 100 times faster requires 10,000 times as much rocket energy.

One private project called Starshot, however, seeks to do this very thing with a multitude of very tiny spacecraft each having a sail panel and camera. In this concept, an extraordinarily powerful laser on Earth would shine its beam on each spacecraft already in nearby space and accelerate it to a significant fraction of the speed of light, so that the spacecraft might fly past our nearest exoplanet, Proxima b, in two or three decades after launch. Currently under study and development of key technologies, such a project is an example of "outside the box thinking" for the future exploration of space.

*Q 15.16 In what other ways, then, could we look for life on some far-away exoplanet?*
*A 15.16* With measurements by spectrometers.

For example, when sunlight strikes a simple prism, or a well-cut diamond, or is being refracted from rain drops, the sunlight will break up what we perceive as white light into a spectrum of colors. Although we normally would say a rainbow has the colors red, orange, yellow, green, blue and violet, in fact it has far more colors as these main colors transition from one to another. Each color is caused by a different wavelength of light. Even with our bare eyes, we can perceive thousands, perhaps a million different colors from one another. A "spectrometer" does the same thing, but also measures the intensity of the light at each wavelength.

Probably the most scientifically powerful way to observe an exoplanet in order to look for evidence of life is through the use of spectrometer instruments, which can be applied for the nearer exoplanets where there is direct observation of the starlight reflected from them. Like sunlight from our star, their reflected light from their central star contains a wide range of wavelengths. Advanced spectrometers can make measurements not only for visible light, but also for infrared and ultraviolet light that we cannot even see with our own eyes.

One reason this can be powerful in the search for evidence of life is that the $H_2O$ molecule can be detected in an atmosphere of another planet through its absorptions in certain portions of the infrared spectrum. Having significant levels of water vapor in an atmosphere implies the presence of liquid water on the surface, which also indicates that temperature conditions are suitable for life as we know it.

Another reason this can be powerful is that vegetation exhibits a strong absorption that corresponds to the wavelength for maximum efficiency for converting solar energy into chemical energy by the chlorophyll molecule.

Consequently, the existence of plant life on Earth can be determined just by examining the spectrum of our reflected sunlight. Martian aliens, if they existed and were technologically advanced, could conclude that Earth has life even without coming here. And they would conclude it is photosynthetic life, such as plants. For exoplanets, we would be looking for a similar absorption phenomenon.

*Q 15.17 What other uses would there be from spectrometers to search for life?*
*A 15.17* One way galactic aliens or a techno-civilization on Mars could know if there is life on Earth is by observing certain other parts of our reflectance spectrum to infer that Earth's obvious atmosphere (from its clouds) contains a high concentration of oxygen gas. The reason that oxygen also is an indication of life is because of the generality that when Earth-sized planets first form, their atmospheres consist mainly of carbon dioxide and nitrogen but not oxygen. Our abundant oxygen gas is rather a byproduct of photosynthesis, which uses light energy to convert $H_2O$ plus $CO_2$ into the organic molecules that grass, flowers, ferns, trees, phytoplankton and certain microbes need to grow and prosper. The byproduct of this fundamental chemical reaction is the release of oxygen from the $H_2O$, and it is this oxygen that enables advanced animals to exist with their extremely high energy needs to achieve active mobility and support complex brainpower.

*Q 15.18 Are there other gases that could be indicative of life?*
*A 15.18* Yes. One is methane, produced by the methanogenic bacteria we discussed before in conjunction with methane on Mars. Normally, on Earth the methane would react with oxygen so well that it should disappear with time. And in fact, it does react, but our methanogenic bacteria keep supplying more methane back to the atmosphere. Because atmospheric scientists know the details about these reactions, they are able to infer not only the existence of this type of life, but how active the bacteria are and hence the vigor of this part of our biosphere. Unfortunately, there could be a false positive result for life since methane can be produced by the chemical reaction of water and $CO_2$ with certain types of rocks. Still, observation of methane in the atmosphere of an exoplanet would be a significant potential indicator of life, although not conclusive without other corroboration.

*Q 15.19 Are there other, more rare gases that are produced by biology?*
*A 15.19* Yes. Certain molecules from biology containing nitrogen, or sulfur, or chlorine are volatile enough to be in an atmosphere and can be detected

by their tell-tale spectral signatures when viewed by a spectrometer attached to a telescope.

*Q 15.20 What is the future of searching for life outside our Solar System?*
*A 15.20* Scientists who combine astronomy with spectrometers and a knowledge of biochemistry continue to examine various exoplanets and study other chemicals which could be biosignatures. New discoveries are being made every day. A seminal event someday, perhaps in not the so-far-distant future, will be evidence that garners the approval of the scientific community at large that a convincing discovery on some exoplanet seems to be conclusive for the discovery of life outside our own Solar System. Such an exoplanet would then become a prime target for astronomers to concentrate their SETI investigations.

# CHAPTER 16

# WHAT ARE THE WAYS OF SEARCHING FOR EXTRATERRESTRIAL INTELLIGENCE (ETI)? WHAT IS THE OUTCOME OF THE SEARCHES PERFORMED SO FAR?

*Q 16.1 What is SETI? How do we search for extraterrestrial intelligence?*
*A 16.1* SETI stands for the **S**earch for **E**xtra**t**errestrial **I**ntelligence. Traditionally, SETI searches for radio signals coming from alien civilizations outside our Solar System. Thus, SETI is a scientific discipline which is observational. In a broader sense, SETI also looks for any artifacts that could be generated by extraterrestrial intelligent beings from technologically advanced societies, the so-called Technosignatures. Such artifacts could be signals encoded in electromagnetic or other radiation, but could also be physical objects like spaceships, launched by ETI beings. Further, since intelligence is not easily defined, and our understanding of civilizations and biological organisms often appears to be anthropocentric, it is good to have an open mind on what such societies could use as a communication method.

SETI started in the early 1960s and continues to this day, under various sponsorships. The early forms of SETI searched for the radio-frequency transmissions by using existing radio telescopes. Such telescopes have a specialized antenna and radio receiver and have been used earlier by astronomers to analyze radio-frequency waves emitted by astronomical objects. Since radio technology has already been developed by human intelligence, it was assumed that intelligent extraterrestrials would also be familiar with this technology. One advantage of such a communication is that it is relatively easy to create radio signals that are straightforward to distinguish from natural sources. The natural signals are typically broadband (from tens of kilohertz to gigahertz), while radio signals by civilizations are extremely narrow bands (less than 1 Hz). If such a narrow band signal is detected, it can be presumed to be artificial.

*Q 16.2 Which radio frequencies are typically chosen for the searches for ETI?*
*A 16.2* A narrow band radio signal at the wavelength of 21-cm (frequency of 1420 MHz) is chosen most often. It corresponds to the natural emission from neutral atomic hydrogen gas, and is also referred to as the H-line. This line was first detected in the interstellar regions in 1951, and has become an important tool for radio astronomers. It was assumed that the 21-cm line would also be known to ETI, and that they may use it to transmit their messages. Further, this radio frequency is also a part of the "cosmic water hole" frequency range, marked by the emission lines from 1420 to 1664 MHz, associated with H and OH, which are the constituents of water, into which water dissociates. Since water is a basis for life, in our understanding, it is assumed that ETI would also know about it. The H line, however, is used most commonly in the ET searches.

*Q 16.3 What was the first modern SETI search?*
*A 16.3* The first modern SETI search was performed by Frank Drake within Project Ozma in 1960. This project was named after the Princess character from children's books by L. Frank Baum. She ruled the fictional land of Oz, a land "far away, difficult to reach, and populated by exotic beings". Further inspiration came from Baum's supposed communication with Oz by radio to learn of the events taking place in the forthcoming books after his book "The Emerald City of Oz" in 1910. This was publicized in the popular media of the time, such as Time magazine.

The Ozma project searched for the narrow band of the 21-cm H line, and focused on only two nearby stars (Epsilon Eridani and Tau Ceti). Other searches were later designed, and many were performed. The results were negative, namely no signals from ETI were detected. This is true for all the SETI programs.

*Q 16.4 What were/are these SETI programs?*
*A 16.4* Examples include the High Resolution Microwave Survey (HRMS) which was designed for two types of searches. The first one was an all-sky search. Its objectives were to look for extremely strong emissions, in case that there might be civilizations transmitting strong signals, possibly as interstellar beacons. The second one was a high-sensitivity targeted search to look for weaker emissions from nearby star systems at a distance of 100 light years or less. However, the program was cancelled by the U.S. Congress in the early 1990s.

SETI experiments were continued under different sponsorships.

Project Phoenix, which was a successor of the targeted search program was rescued from the cancelled HRMS.

SERENDIP (**S**earch for **E**xtraterrestrial **R**adio **E**mission from **N**earby **D**eveloped **I**ntelligent **P**opulations), is a full sky survey which started in 1979 and has undergone several major updates and improvements in sensitivity and a drastic increase in the number of frequency channels examined. This program is sponsored by the Berkeley SETI Research Center at the University of California, Berkeley. It uses special equipment installed at various radio telescopes and piggy-backs on observations by astronomers.

SETI in Australia and Italy use the technology of the SERENDIP program. Due to the rapid technological advances, the detection equipment has become even broader and more sensitive than the original one.

The Allen Telescope Array (ATA) program is currently being revitalized. Operated by the SETI Institute, the ATA is a 42-dish radiotelescope array, based on a novel concept of building radiotelescopes in which a large number of smaller dishes are used, as compared to the conventional large dish antenna. The signals from all small dishes are combined to achieve sensitivity comparable to the large dish antenna. The ATA design is less expensive than the traditional radiotelescope and will be equivalent to a 100-meter diameter dish.

Despite these advances, no signals from ETI have been detected so far, after nearly six decades of attempts. In a recent assessment of this lack of positive results, recommendations were made to increase the chances of future success. They include continuation of the increase in the speed of search and the sensitivity of the observations, but also the number and types of targeted star systems, and the use of different search strategies. One such strategy is optical SETI.

*Q 16.5 What is optical SETI?*
*A 16.5* Optical SETI looks for pulsed and continuous laser emissions at visible or infrared wavelengths coming from ETI civilizations which could be deliberately signaling in the direction of our Solar System. The idea of optical SETI was suggested at the very beginning of SETI, but it was not favored early on because the radio technology was more mature than the laser technology. However, this has changed with the rapid advancements in the laser field, and the realization that communication via lasers has some advantages over that via radio waves. Some of the advantages are that lasers are distinctive. They can be chosen by the ETI to contrast with the natural milieu and they can be aimed much more accurately at the target. Optical SETI programs have been under development especially since 1998 and

include the optical SETI at Berkeley and the optical SETI at Harvard/Smithsonian.

*Q 16.6 Do we know the number of extraterrestrial civilizations which are capable of communication?*
*A 16.6* We do not know this number but can estimate it by using the Drake equation. The latter was formulated in 1961 by Frank Drake. His equation gives an estimate of the present number of extraterrestrial civilizations in our galaxy (Milky Way) which are capable of interstellar communication. It includes parameters which, when multiplied with each other, give this estimate (N in the equation). The Drake equation is typically formulated as:

$$N = R_{*} \cdot f_p \cdot n_e \cdot f_l \cdot f_i \cdot f_c \cdot L$$

N is the estimate described above (the current number of extraterrestrial civilizations in our galaxy which are capable of communication); $R_{*}$ is the average rate of star formation in our galaxy; $f_p$ is the fraction of those stars that have planets; $n_e$ is the average number of planets in a planetary system that could support life; $f_l$ is the fraction of such planets that actually develop life; $f_i$ is the fraction of planets with life where intelligent civilizations arise; $f_c$ is the fraction of those civilizations that develop technology for interstellar communication; L is the length of time during which such civilizations emit detectable signals into space. These parameters are constantly evaluated and updated as we learn more about the subject, and their ranges of values change based on the newest findings. Some parameters are becoming more certain, such as $R_{*}$, (the average rate of star formation in our galaxy); but some others remain highly uncertain, e.g. $f_i$ (the fraction of planets with life where intelligent civilizations arise). This simply means that the estimate N is not very accurate. However, just by having an equation and the parameters formulated gives us a way to think about the problem in a systematic way and to make progress in the estimate.

*Q 16.7 Is SETI strictly an observational science? Is its scope only to observe signals from space coming from ETI?*
*A 16.7* No. SETI also has a branch named Active SETI, which is concerned with sending messages to the putative intelligent ETs, and is, therefore, trying to contact them. This complements the original ("passive") SETI which is strictly observational, since it is focuses only on the search for the signals coming from the intelligent ETs.

Active SETI is more recently also known as METI (Messaging Extraterrestrial Intelligence) and the latter term is now used more often than the original term. METI is focused on the messages that we have already sent or will send to space deliberately. This is different than the unintentional leakage of electromagnetic radiation from Earth due to the radio and TV transmissions as well as signals we beam into space to communicate with spacecraft, which also constitute a message sent to the universe.

METI is concerned with the design of the messages to the ETI aliens, but also with the societal impact of the discovery of ETI, even before its detection. METI fosters approaches from the natural and social sciences, humanities, and arts.

*Q 16.8 What types of messages have we sent to the intelligent ETs?*
*A 16.8* One type is a radio transmission which generates a picture. It utilizes a pictographic communication system. The message is sent as a string of binary digits, which, when placed into a two-dimensional grid, with a blank space for 0 and a filled space for 1, generates a picture. The Arecibo message is one example.

Another type is sending physical objects that contain messages into the space. The examples are Pioneer 10 and 11 plaques, and Voyager 1 and 2 Golden Records.

*Q 16.9 What are the details of Arecibo message?*
*A 16.9* The Arecibo radio message was sent in 1974 by the enormous Arecibo radio telescope in Puerto Rico. The message consisted of a string of 1679 binary digits (bits). (a bit has a single binary value, either 0 or 1). It was assumed that the ETIs would have a basic understanding of mathematics. Thus, they would hopefully recognize that the number 1679 is a multiple of two prime numbers, 23 and 73. Then, an arrangement into 73 rows of 23 characters each, with 0 represented as a blank space and 1 as a filled space, would give a picture. The Arecibo message consists of the following parts: the numbers from 1 to 10 shown in binary format; atomic numbers of the key biological elements (carbon, hydrogen, oxygen, nitrogen, and phosphorus), formulas for biochemicals (sugars and bases in DNA nucleotides), the number of nucleotides in DNA and picture of the structure of the DNA double helix, a stick figure of a human, the human population on the Earth, our Solar system in which Earth is shown as the planet from which the message is coming from, and the Arecibo telescope itself.

*Q 16.10 What were the messages sent on the Pioneer 10 and 11 plaques?*
*A 16.10* The Pioneer 10 and 11 plaques contain messages for ETI in a pictorial form. The messages are engraved on the plaques that were made of gold-anodized aluminum and attached to the Pioneer spacecrafts 10 and 11. These were launched in 1972 and 1973, respectively, but carry with them identical plaques. The pictorial messages include the following.

a) The scheme representing a change of states in a neutral hydrogen atom. This transition results in the radio wave at 21 cm. The scheme also equates this unit of length as the binary digit 1.

b) The figure of a man and a woman, with height indicators.

c) The silhouette of the spacecraft behind the man and the woman, shown on the same scale since the ETIs could determine the size of the spacecraft, they could deduce from it the size of a human (168 cm for a woman).

d) A radial pattern showing our location in the galaxy via the distances from our Sun to the neighboring pulsars. The distance of the Sun to the center of the galaxy at the time of Pioneer's launch is also shown.

e) The drawing representing our Solar System, with the picture of the spacecraft and its trajectory past Jupiter and out of the Solar System.

Both Pioneer spacecrafts carried identical plaques. However, after its launch, Pioneer 11 was redirected toward Saturn, and from there it exited the Solar System. This change in the direction is not reflected in the plaque.

Currently, Pioneer 10 is heading toward the star Aldebaran in the Taurus constellation. Travel to this destination is expected to take more than two million years. Pioneer 11 is traveling towards the constellation of Aquilla and is expected to pass near one of the stars in this constellation in approximately four million years. Therefore, if our message to ETI civilizations is delivered at all, it will be only in the distant future.

*Q 16.11 What were the messages sent on the Voyager 1 and 2 "Golden Records"?*
*A 16.11* The messages on Voyagers 1 and 2 Golden Records were attached to these spacecrafts, when they were launched in 1977. The records on each of these spacecrafts are identical. They are gold-coated phonograph records. The records, together with a cartridge and a needle, were enclosed in a protective aluminum jacket. Instructions are given, in symbolic language, on how to play the record. The messages on the record include 115 images, encoded in analog form. The first images are science-oriented. They show the hydrogen atom diagram and the radial pattern of our location in the galaxy, the same as on the Pioneer plaques. Additional images show mathematical and physical quantities, the Solar System, DNA, human anatomy and reproduction. Further images illustrate life on the Earth. They

include humans and their activities, some animals, insects, plants and landscapes.

Many pictures give scales of time, size, or mass, and some give chemical composition. In addition to the pictures, messages are also given in audio form. They comprise of a variety of samples of music, including classical and ethnic; sounds of the Earth, including wind, rain, birds, elephants, and many more; and greetings from Earth to the Universe in 55 languages. These messages are quite extensive and comprehensive. Their content is described in detail in various sources, notably in the 1978 book by Carl Sagan and co-authors, "Murmurs of Earth", and NASA-sponsored web sites.

In 2012 Voyager 1 entered interstellar space. In about 40,000 years Voyager 1 will come within 1.8 light years from star Gliese 445, located in the constellation Camelopardalis. During this time Voyager 2 will approach within a distance of 1.7 light years of star Ross 248, located in the constellation of Andromeda. Thus, our message to ETI, if delivered at all, will not be delivered quickly.

*Q 16.12 Are there any unintentional messages that we might have sent to space?*

*A 16.12* Yes. Currently, there is no on-going purposeful METI, but we do still create messages which go into outer space. They comprise both radio wave and physical objects, which may reach the ETI, but which we did not send intentionally for the purpose of communication. Examples include omnidirectional signals which we use in local communication such as radio and television broadcasts; the transmissions with satellites (especially communication satellites) and various spacecrafts, especially those which are on escape trajectories from the Solar System.

# Chapter 17

# Since ET intelligent aliens presumably exist somewhere in the universe, why haven't we heard from them?

*Q 17.1 From the Drake equation we have learned that the existence of ETI aliens with developed technology is probable, or even highly probable, based on some estimates. However, we have not identified or heard from these aliens. This appears contradictory. Is this indeed the case?*
(In this section, for brevity, we use the word "alien" to denote ETI communicating civilizations, including those who are also capable of space travel).
*A 17.1* Yes. This contradiction is referred to as Fermi paradox. Enrico Fermi, a famous nuclear physicist (1901-1954), asked this very question, but in a short form "Where is everybody?". The longer form of this question is: If the universe is indeed populated with aliens, why have we not seen them, heard from them, or identified them? This paradox is explained as follows. According to the original Drake equation estimate, the number of communicating civilizations in the Galaxy is $10^3$-$10^8$. However, after more than five decades of SETI searching efforts no ETI signal has been observed. Furthermore, many of the ETI communicating civilizations are speculated to have engaged in interstellar travel, and thus could have visited us in the past. Still, no compelling evidence exists for such visits, either in person or via robotic space probes.

Therefore, a contradiction in terms exists between the prediction of the existence of communicating ETI civilizations and a lack of evidence for them. This inconsistency is known as Fermi paradox.

*Q 17.2 What are some of the proposed solutions to the Fermi paradox?*
*A 17.2* Alan Longstaff lists some possible solutions to the Fermi paradox: SETI searches may have failed because they were relatively short term, and the survey of the sky was limited; the SETI search strategy may be flawed, since we may be looking at the wrong part of the electromagnetic spectrum; the reason why we have not been visited by aliens or detected their artefacts

may be due to their large separation in time and space; energy resources for interstellar travel are too large and this may be an unsurmountable problem for any civilization; extraterrestrial civilizations may be intrinsically rare.

Many other solutions have been proposed. Stephen Webb provides seventy-five solutions to the Fermi paradox. Not all of them are independent. These solutions fall into three categories: extraterrestrials are (or have been) here; extraterrestrial civilizations exist, but we have not yet found evidence of their existence; there is no extraterrestrial intelligence.
Some solutions may be questioned since they assume that *all* aliens would behave in the same manner. Examples of such solutions are: "Earth is deliberately not contacted by aliens"; "It is the nature of intelligent alien species to destroy themselves"; and "Aliens feel that it is too dangerous to communicate with other civilizations".

Some reasonable solutions, such as periodic extinction of alien civilizations by natural catastrophic events, still suffer from the assumption that *all* civilizations will experience them. The suggested solution that aliens are signalling but that we do not know how to listen to them, is reasonable, and while not proven, it holds open the door to further exploration of new types of searches for ET civilizations.

One proposed solution is that since we have not seen aliens, or heard from them, or found any indications of their activities, they simply do not exist. This is the view of Frank Tipler. Opposed to this view are Carl Sagan and William Newman who pointed out that absence of evidence is not evidence of absence.

# CHAPTER 18

# WHAT IS THE NATURE OF ALIENS, FRIENDLY TO US OR NOT? WHAT PROBLEMS DO WE ANTICIPATE FOR OUR POTENTIAL INTERACTION WITH THEM?

*Q 18.1 Are aliens benign, or malevolent?*
*A 18.1* We do not know. Our predictions of the nature of aliens are based mostly on our Earthly experiences. One of our observations is that developments in science and moral behavior do not necessarily parallel each other. Thus, advanced science does not guarantee advanced morals. This could apply also to aliens. Although they may be scientifically and technologically advanced, their morals may not be as advanced. In our case, climbing the evolutionary ladder was often at the expense of less developed animals and other species. Perhaps this would be the way that aliens, if more advanced than we are, would treat us also. If they would visit us, they may harm us or even annihilate us, perhaps out of fear that we would harm them, or infect them with our diseases. If so, we could consider them dangerous to us.

On the other hand, perhaps they are just curious to find out about us and would not harm us but would be happy to find another intelligent life. We cannot tell at this time. While this section is obviously speculative, it is the best the astrobiology community can come up with for now.

*Q 18.2 Is sending messages to the aliens safe?*
*A 18.2* We have already sent messages, as shown in Chapter 16, so this question is really about future messages. The answer depends on our perception of aliens, whether we consider them benign or malevolent. In the latter case, contacting aliens may not be in our best interest, although the communication would take an extraordinary amount of time. Thus, there is no immediate danger to METI communication.

*Q 18.3 Are there any recommendations regarding the nature of future messages we may send to aliens?*
*A 18.3* Yes. "Declaration of Principles Concerning the Conduct of the Search for Extraterrestrial Intelligence" has been adopted in 2010 by the SETI Permanent Study Group of the International Academy of Astronautics. This declaration contains various statements about the way to conduct SETI searches: the need to be transparent; freedom to report on the search activities and to communicate them to the professional and public media; handling candidate evidence (suspected detection of ETI); the need to verify the evidence, and confirm the evidence (if it happens), among others.

*Q 18.4 Is there any strategy developed on how to inform the public about the discovery of an ETI communication received by us, if it happens?*
*A 18.4* Yes. The "Declaration of Principles Concerning Activities Following the Detection of Extraterrestrial Intelligence" provides guidelines for informing the public in case of confirmed transmission by ETI. This declaration also considers cultural and political responses to such a discovery. The contemporary response would need to consider a rapid transmission of information via social media, some of which may spread panic.

*Q 18.5 What is the public opinion about aliens?*
*A 18.5* In 2018, 41% of Americans believed that aliens have visited Earth in the ancient past, up from 27% two years earlier. Likewise, 57% of Americans believed that Atlantis or other advanced ancient civilizations existed, up from 40% two years earlier.

*Q 18.6 Are these beliefs justified?*
*A 18.6* No. There is no scientific support for these ideas, but they are nevertheless popularized by some books and TV shows. These ideas generally ignore the cultural context of ancient artifacts. As one example, the image of the Mayan King Pakal, which is carved on the lid of his sarcophagus, is interpreted as him taking off in a spaceship, rather than falling into the underworld, which would be a proper archaeological explanation. The misguided, pseudo-archaeological idea was further used to argue that aliens started sophisticated ancient societies like the Mayan.

# CHAPTER 19

# IS THERE A GENERAL METHOD TO ADDRESS COMPLEX ISSUES IN ASTROBIOLOGY?

*Q 19.1 Why do we need a general method to address complex issues in astrobiology?*
*A 19.1* Astrobiology is a multidisciplinary, interdisciplinary and even transdisciplinary science, which draws upon various disciplines, such as chemistry, physics, astronomy, biology, geology, atmospheric science, and engineering. Scientists from these disciplines need to learn from each other to create adequate views and understanding of complex astrobiology topics, such as the origin of life. Thus, they need a general method which is in common to all the participating sciences, rather than depending exclusively on their discipline-specific method.

*Q 19.2 Is there a general method to address complex astrobiology issues?*
*A 19.2* Yes. This method consists in looking at astrobiology as a systems-level science which aims to provide an integrated view across its disciplines. This is achieved by utilizing a method of scientific analysis suitable for the complex systems which abound in the field of astrobiology. Such a method employs "systems thinking", which has been described in detail for some individual disciplines, such as chemistry and engineering.

*Q 19.3* What are some examples of complex systems that are relevant to astrobiology which would require systems thinking?
*A 19.3* Examples include: emergence of life on Earth; formation of early metabolism; origin of primitive membranes; and the nature of the atmosphere on early Earth and Mars.

*Q 19.4 What are the specifics of "systems thinking"?*
*A 19.4* Systems thinking can be presented by the models which have been developed for chemistry, with the modifications that we introduce here to be astrobiology-specific. We focus on two such models: *The Pyramid Model*, and *The Overlapping Circles Model.*

***The Pyramid Model***

The base of the pyramid is the start, and one builds up towards the top of the pyramid in three steps:

*Step 1) Analysis of systems components*

This step requires analysis of systems components relevant to astrobiology, comprising of chemistry, physics, biology, astronomy, geology, atmospheric science, and engineering, among others.

This analysis is done mostly by the specialists in the individual disciplines.

An example: prebiotic reactions (chemistry) are occurring under conditions on the early Earth (geology), are utilizing chemicals which came from comets (astronomy) and are producing chemicals that are related to present-day biochemicals (biology, biochemistry).

*Step 2) Synthesis of systems components*

This step consists of identification of relationships among the systems' components, including dynamic relationships and networks.

An example: Prebiotic chemicals which react among themselves and have a dynamic relationship with the ever-changing environment that supplies metal- and other catalysts; formation of the reaction networks to give rise to a primitive metabolism.

*Step 3. Implementation*

This step represents implementation of what was accomplished in Steps 1 and 2 to formulate generalizations and predictions.

An example: Make generalizations about what life is; predict which types of planetary conditions are suitable for life in our Solar System.

***The Overlapping Circles Model***

In this model one circle represents one complex system that is relevant to astrobiology, e.g. chemistry, and the other one another such system, e.g. geology. These two circles are overlapping to identify complexities between chemistry and geology systems. This overlap would include interactions between chemical and geological systems that are critical for the emergence of life, as one example. More circles can be added, to include additional disciplines that are relevant to the problem. For example, astronomy can be added if one includes source of chemicals that were delivered to the early Earth by the comets.

An advantage of the Overlapping Circles Model is that it points out that we need to focus mainly on the areas of overlap of the circles, rather than on the other areas of the circles. This method of illustrating the common as well as the excluded areas of interest is also known as a Venn Diagram.

# Chapter 20

# What is in the future of Astrobiology?

*Q 20.1 What are the educational requirements in the future for a career in astrobiology?*
*A 20.1* In academia, at selected universities one can find courses in astrobiology. In addition, several universities with strong programs in science now offer not only undergraduate courses, but also advanced courses and degrees.

A prospective astrobiologist may first take a degree in any of the classical fields of science (biology, chemistry, physics, astronomy, geology) and yet specialize in one of the topics with direct relevance to astrobiology. Thus, one may take a general degree in geology, yet take electives in planetary science.

In addition, other fields are open to future astrobiologists. Even mathematicians are needed and may contribute via analytical methods and modeling of complex systems.

Apart from science, there seems to always be a need for those gifted in writing and art who can produce books, articles, social media, videos, films, and other forms of communication as well as artwork. These help convey to the public at large the excitement of answering the questions of where do we come from, how did we get here, and are we alone?

Historically, these fundamental questions date back to the beginnings of civilization.

For scientists with established careers in other areas, there is always the possibility of transitioning into the field of astrobiology. Interestingly, many Nobel Prize winners have done so.

*Q 20.2 How many Nobel Prizes have been awarded for astrobiology?*
*A 20.2* None. The main reason is that the Nobel Prizes which are awarded for science (apart from the awards for Peace, Economics, and Literature) are restricted to only three categories: (1) Physics, (2) Chemistry, and (3) Physiology and Medicine.

There is no award specifically for astronomy or the space sciences, although several astronomers have won the Physics prize. There is no award specifically for Biology, although many biochemists and biologists have won the award for category (3). And there is no award for geology or mathematics. The awards have been given only since 1901, and therefore many of the giants of science, like many great artists, are recognized far more appreciably after their deaths than during their lives.

*Q 20.3 So, is the Nobel Prize then not relevant to astrobiology?*
*A 20.3* To the contrary. Many Nobelists have been fascinated with astrobiology questions and have contributed their expertise and intellect to this field. We have already mentioned (see 5.5) several scientists in astrobiology who have been awarded the Nobel prize for other discoveries (Harold Urey, Christian de Duve, Manfred Eigen, Jack Szostak). And, to name a few, there are physicist Nobel laureates (Walter Gilbert, Max Delbrück, Erwin Schrödinger) and biologist laureates (Joshua Lederberg, Sydney Brenner, Salvador Luria, Baruch Blumberg, Ada Yonath) who have each diverted from their original primary fields to contribute to the field of astrobiology.

Perhaps no area of research has garnered such great interest from such a diverse group of pre-eminent scientists. Only few astronomers have been tagged for the physics award, and only a couple of space scientists have been rewarded by the Nobel selection committee for their outstanding contributions. Yet, many Nobelists find the origin of life to be one of the most important questions a scientist could pursue.

We also must not forget the many outstanding geologists who have contributed to planetary science, but are not eligible for the Nobel Prize. And we should never forget that the success of scientists in their laboratories or on space missions depends not only on dozens or hundreds of other scientists, but also on the dedication, diligence, and inventiveness of an even much larger cohort of hardworking and talented engineers and technicians.

*Q 20.4 Wow, with all that interest from so many of the most outstanding scientists in the world, the field of astrobiology must be well-supported?*
*A 20.4* Not exactly. Most of the funding for astrobiological research in the U.S. comes from NASA, in connection with its space missions, and from the universities themselves. The U.S. National Science Foundation (NSF) supports a wide range of scientific research which sometimes includes topics of relevance to astrobiology. Whereas NASA will spend more than a billion dollars for a single mission to Mars, the NSF only rarely funds awards for over one million dollars for any given laboratory.

Some encouraging signs have emerged that NASA's strong interest and leadership in astrobiology will continue. Their science input document has been renamed to the “Decadal Survey on Planetary Science & Astrobiology”, which elevates astrobiology to a whole new level higher than before.

In 2019, a Congressionally mandated study by the National Academy of Sciences concludes, in their report, “An Astrobiology Strategy for the Search for Life in the Universe,” that to advance the search for life in the universe, NASA should support research on a broader range of biosignatures and environments, and incorporate the field of astrobiology into all stages of future exploratory missions.

In the European Union, each country funds most of its own research. As a result, the European Research Council (ERC) has a much smaller budget than the NSF. Similarly, the budget for ESA is about one-third that of the annual budget for NASA.

The NASA and ESA are the largest funding sources for such research in the world. But many other countries, such as Russia, China, Japan, India, Israel, and Canada also dedicate a portion of their national budgets for supporting space missions, some of which are related to astrobiological goals.

Some expensive projects, such as the upcoming *Mars Sample Return* will be funded through sharing of expenses by ESA and NASA.

*Q 20.5 When will Mars Sample Return happen? Hasn’t it been studied for a long time?*

*A 20.5* This mission has been a long time coming. The mantra for several decades now has been “Mars sample return is always 10 years into the future.” Detailed engineering studies for bringing back samples from the surface of Mars were underway as long ago as the early 1970’s.

Only now, however, is a Mars Sample Return (MSR) mission officially in the planning stages, under a joint agreement by ESA and NASA. This mission, and also potentially a separate sample return by the China National Space Administration (CNSA), are currently envisioning the samples reaching Earth in around 2031. Once we have a suite of representative Mars samples available for study by the multitude of extremely diverse and powerful analytical techniques in laboratories on Earth, the question of putative past life on the red planet may possibly be answered in the affirmative. The very prospect of such an eventuality should provide a strong positive impact upon the general perception of the importance of the field of astrobiology.

*Q 20.6 In the meantime, are there other signs that astrobiology will continue to rise in importance?*
*A 20.6* Yes, very much so. The Mars exploration program is more vigorous than ever before, involving several different nations, and in recent years there has been expression of interest by non-governmental groups as well. Relevant scientific publications have soared, especially with respect to topics such as habitability on Mars, Ocean Worlds, and exoplanets.

*Q 20.7 How important are these publications?*
*A 20.7* Many new astrobiology science papers are being published in the highest-importance scientific journals in the world: *Science* and *Nature*. Space missions with new discoveries receive special attention, but the recent results on prebiotic chemistry by the research groups of John Sutherland, Steven Benner, and Thomas Carrel have been published in these leading journals as well.

*Q 20.8 But these are general-purpose science journals. Where else do astrobiology results get published?*
*A 20.8* Just a few decades ago, there was only one dedicated journal, Origins of Life and Evolution of Biospheres (OLEB). This journal is sponsored by ISSOL, the **I**nternational **S**ociety for the **S**tudy of the **O**rigin of **L**ife. ISSOL currently has over 500 members representing over 20 countries in disciplines as varied as astronomy and molecular biology. The society meets every three years. Ironically, the meeting planned for 2020 in Quito, Ecuador, had to be postponed to 2021 because of the effects of a new, unexpected form of life, namely, the COVID-19 coronavirus.

In the meantime (since 2001), the journal *Astrobiology* has become one of the significant publications for a wide variety of relevant topics, as has the *International Journal of Astrobiology* (since 2002). There is also the web-based *Astrobiology Magazine* (www.astrobio.net), which features synopses of a wide range of interesting new scientific papers related to the field.

*Q 20.9 Besides the ISSOL meetings, what other conferences feature astrobiological research?*
*A 20.9* There is the *AbSciCon* (**A**stro**b**iology **Sci**ence **Con**ference), held every two years. There are innumerable science conferences on topics of interest, but under other auspices. For example, the American Astronomical Society has a branch called Division of Planetary Sciences, which meets once per year. And the American Geophysical Union has a yearly

conference, which also includes planetary exploration, and publishes the *Journal of Geophysical Research - Planets*.

The biennial COSPAR (**Co**nference on **Spa**ce **R**esearch) also sponsors publications of astrobiology and planetary protection, as well as special-topic meetings. There are several relevant Gordon Research Conferences, typically held biennially, including “Origins of Life”, “Systems Chemistry”, and “Geobiology.”

*Q 20.10 But where can the non-professional go to learn about the stunning new discoveries and advances in astrobiology?*

*A 20.10* The professional conferences often have some non-scientist attendees, and also have major discounts and sometimes even travel compensation for students. These typically consist of cursory reports on recent results or research underway which are quite detailed and specialized.

In the popular press, there are several magazines which often cover astrobiological topics, including, but not limited to, *Astronomy, Discover, National Geographic, Popular Science, Scientific American, Sky & Telescope,* and *The Planetary Report* (magazine of the Planetary Society).

Certain radio programs and podcasts often have relevant topics. Seth Shostak’s *Big Picture Science* is produced at the SETI Institute and Ira Flatow’s *Science Friday* is broadcast on NPR. And in addition, there are numerous video programs on television, ranging from science documentaries, such as *NOVA*, to general audience funfests, such as Neil de Grasse Tyson’s radio and TV show *Star Talk*.

*Q 20.11 What will be the next major discovery in astrobiology?*

*A 20.11* No one knows. That is part of what makes it so exciting. We are constantly being surprised, and what we thought we knew is often superseded by a new perspective. Or sometimes, a new result will demolish a long-held idea, and we must toss out an old theory or observation that was either wrong or is now obsolete.

At any time, a new radical discovery forever altering our concepts of “how it all began” could be made in anything from cosmochemistry to geomicrobiology to . . .

Stay tuned.

# Further Readings

## General: How to find references

The books that are cited are a selection of those that we have used to prepare this book. Many are classics. These books can be obtained from the library, or purchased on Amazon.com or other sources.

The journal articles that are cited are those that are most relevant to the material presented in this book. Some journals are Open Access, which means that the articles are free to access and read. Searching the information about the reference (author, title, year, etc.) on Google or Google Scholar (https://scholar.google.com) will link the reader to the web site where the journal and the paper of interest are found. If the journal or the specific article is not available as "open access," one can still find the abstract, which summarizes the work. The abstract is typically linked to the publisher's site, on which one can purchase the article. In general, libraries will provide the articles for free. If one feels that the article is too complicated, a good way to go through it is to read the abstract, inspect figures and tables, and then read the conclusions. This will provide a good overview of the article. If one is interested in the experimental methods and procedures, they are typically listed separately, often under "Methods". If one wishes to pursue the subject of the article in more details, other related articles are listed in its reference section.

For all the journal references, the titles of the papers are given. This will help the reader in deciding if the article appears relevant to the additional questions they might have.

We have provided also the Wikipedia and other web sites. Searching various web sites is a skill that the readers will most certainly have. The sites that we have provided are of a good quality and are updated regularly. Notably, various NASA sites provide an indispensable supplementary material for this book. These sites are generally accurate, up to date, and maintained by experts. These sites typically are linked to the various subsites, which the reader may wish to explore.

# Further Reading by Chapter

The following are sorted by Answer Number (e.g., *A 3.5* is for answer number 5 in Chapter 3). The abbreviated reference is by name and date, which can then be used to look up the full reference to a book or publication in the consolidated list of References provided below this list. A limited number of websites is also included.

**Abbreviated references for Chapter 1:**

*A 1.1* Des Marais *et al.* 2008; Des Marais 2019; Kolb 2019 Ch. 1.1; Domagal-Goldman *et al.* 2016.
*A 1.4* Horneck *et al.* 2016.
*A 1.5* Dick 2007; Dick and Strick 2004; Catling 2015.
*A 1.6* Dudna and Sternerg 2017; Ball 2016; Venter 2007, 2013.
*A 1.7* Crowe 1999; Duhem 1987; Regis Jr 1987; Zuckerman and Hart 1995.
*A 1.8* Kolb 2019 Ch. 1.1; Clark 2019 Ch. 2.2; Ch. 12.4; DiGregorio 1997; Jones 2004; Horowitz 1986; Goldsmith 1997; Tarter 2007.
*A 1.9* Dick 2012; Fry 2000, 2019 Chapter 3.1.
*A 1.10* Repko 2012.
*A 1.11* Dick 2007.
*A 1.13* Imprey 2010.

**Abbreviated references for Chapter 3:**

*A 3.2* Villarreal 2004; Kolb 2008, 2010.
*A 3.3* Gottlieb 2019; Priest 1995, 2006; Priest, Berto, and Weber 2018.
A 3.5 Kolb 2008; Perry and Kolb 2004.

**Abbreviated references for Chapter 4:**

*A 4.3* Ball 2016.
*A 4.6* Braun, Fernau, and Dabrock 2018; Zimmer 2019; Porcar *et al.* 2011.
*A 4.8* Venter 2007, 2013; Gibson *et al.* 2019; Callaway 2016; Hutchinson III *et al.* 2016.
*A 4.9* Bourzac 2017.
*A 4.10* Gutmann 2011; Douglas, Powell, and Savulescu 2013.

**Abbreviated references for Chapter 5:**

*A 5.1* Deamer and Fleischaker 1994; Voet and Voet 2011; Kolb 2019 Ch. 1.1.
*A 5.2* Miller 1953, 2000.
*A 5.5* Miller and Orgel 1974; Mason 1991; Brack 2000; Orgel 2004; Bada 2004; Kitadai and Maruyama 2018; Sutherland 2016; Islam and Powner

2017; Patel *et al.* 2015; Olson and Straub 2016; Becker *et al.* 2019; Hud and Fialho 2019; Cleaves 2013; Benner *et al.* 2019; Hao *et al.* 2019; Wächtershäuser 2000; Orgel 2004; de Duve 2000; Joyce and Orgel 1999; Orgel 2004; Becker *et al.* 2019.

*A 5.6* Schmitt-Kopplin *at al.* 2010; Kwok 2016, 2019; Shaw 2006; Burton *et al*. 2012.

*A 5.7* Soai, Shibata, and Sato 2000; Soai, Matsumoto, and Kaswasaki 2019; Hein and Blackmond 2012; Blackmond 2019; Boerner 2019.

*A 5.8* Mason 1991; Kolb 2012; Krishnamurthy 2018.

*A 5.10* Lahav 1999; Jheta 2017; Smith and Horowitz 2016; Fry 2019 Ch. 6.5; Kolb 2019 Ch. 7.1; Deamer 2017; Dalai and Sahai 2019; Oparin 1965; Smith and Horowitz 2016.

*A 5.11* Kauffman 1995, 2000, 2019; Walker 2014; Peretó 2012; Krishnamurthy 2017.

**Abbreviated references for Chapter 6:**

*A 6.1* Kolb 2012, 2013. *A 6.4* Perry and Kolb 2004. *A 6.6* and 6.7 Fry 2019.

**Abbreviated references for Chapter 7:**

*A 7.3* Guttenberg *et al.* 2017; Kauffman 2000, 2013, 2020.

*A 7.8* Perry and Kolb 2004.

**Abbreviated references for Chapter 8:**

*A 8.4* Fouke *et al.* 2019.

*A 8.8* Lane *et al. 2010;* Cartwright and Russell 2019.

*A 8.11* Di Giulio 2003.

*A 8.12* Fouke *et al.* 2019.

*A 8.13* Deamer 2019; Damer and Deamer 2020.

*A 8.15* Clark and Kolb 2018; Pearce *et al.* 2017.

*A 8.19* Chatterjee 2019.

*A 8.20* Deamer 2019; Damer and Deamer 2020; Colin-Garcia *et al.* 2019; Rimmer and Shorttle 2019.

*A 8.23* Pearce *et al.* 2017.

*A 8.26* Fry Ch. 6.5 2019.

*A 8.29* Dalai and Sahai 2019.

*A 8.31* Weiss *et al.* 2016.

**Abbreviated references for Chapter 9:**

*A 9.5* Seckbach, Oren, and Stan-Lotter 2013; Oren 2019.

**Abbreviated references for Chapter 10:**

*A 10.3* Arrhenius *1908*; Crowe 1999; Dick 1996; Fry 2000; Longstaff 2015; Tirard 2013; Crick and Orgel 1973; Crick 1988.

*A 10.4* Venkateswaran 2019; Melosh 1988; Mileikowsky *et al.* 2000; Clark 1986, 2001, 2002.

**Abbreviated references for Chapter 11:**

*A 11.1* Rummel 2007; Melzer 2010; Conley 2019.

*A 11.2* https://www.nasa.gov/pdf/607072main_WhenBiospheresCollide-ebook.pdf ;
Conley 2019;
https://planetaryprotection.nasa.gov/documents/ .

*A 11.3* https://cosparhq.cnes.fr/sites/default/files/pppolicy.pdf

*A 11.6* https://cosparhq.cnes.fr/sites/default/files/pppolicy.pdf
https://planetaryprotection.nasa.gov/documents/

*A 11.8*
https://www.nasa.gov/sites/default/files/atoms/files/planetary_protection_board_report_20191018.pdf
https://phys.org/news/2019-10-nasa-planetary-reality-space-exploration.html ;
https://spacepolicyonline.com/news/nasa-takes-step-towards-modernizing-planetary-protection-guidelines/ ; Brainard 2019.

**Abbreviated references for Chapter 12:**

*A 12.2* Klein 1999; Horowitz 1986; Levin and Straat 2016.

*A 12.4* Horowitz 1986; Rycroft 1990; Darling and Schulze-Makuch 2016.

*A 12.12* Eigenbrode *et al.* 2018.

*A 12.15* Mahaffy *et al.* 2013.

*A 12.17* Clark *et al.* 1982; Filiberto and Schwenzer 2018.

*A 12.27* Arvidson 2016.

**Abbreviated references for Chapter 13:**

*A 13.2* Neveu *et al.* 2018.

*A 13.5* Price *et al.* 2018.

*A 13.7* Cockell 2015.

*A 13.13* Govil *et al.* 2019; Vago *et al.* 2917.

*A 13.15* Bell *et al.* 2015; Perry and Kolb 2004.

*A 13.17* Sugitani 2019; Schopf *et al.* 2017.

*A 13.18* Dorn *et al.* 2011; Summons *et al.* 2008.

*A 13.19* Williford *et al.* 2018; Salese *et al.* 2019.

*A 13.20* McKay 2016.

*A 13.22* Lunine *et al.* 2018; Deamer and Damer 2017.

**Abbreviated references for Chapter 14:**

*A 14.7* Lauretta *et al.* 2017.
*A 14.12* Netea *et al.* 2019.
*A 14.20* Brack 2018.
*A 14.21* Popa *et al.* 2012

**Abbreviated references for Chapter 15:**

*A 15.1* Summers and Trefil 2017; Rice 2015, 2019
*A 15.4* Rice 2019
*A 15.5* Rice 2015, 2019.
*A 15.16* Schwieterman *et al.* 2018.

**Abbreviated references for Chapter 16:**

*A 16.1* McConnell 2001; Tarter 2007; Korpela 2019.
*A 16.2* Sullivan and Carney 2007; https://www.seti.org/seti-institute/project/details/early-seti-project-ozma-arecibo-message
*A 16.4* Darling and Schulze-Makuch 2016; https://www.seti.org/ata
*A 16.5* Szostak 2015; https://www.seti.org/seti-institute/project/optical-seti
*A 16.8* McConnell 2001
*A 16.10* https://solarsystem.nasa.gov/resources/706/pioneer-plaque/
*A 16.11* Sagan *et al.* 1978.

**Abbreviated references for Chapter 17:**

*A 17.1* Darling and Schulze-Makuch 2016; Longstaff 2015; Webb 2015.
*A 17.2* Regis, J. Ed., 1987; Tipler 1987; Sagan and Newman 1987.

**Abbreviated references for Chapter 18:**

*A 18.1* Darling 2000.
*A 18.4* Tarter and Michaud 1990; Billingham *et al.* 2005).
*A 18.5* Wade 2019.

**Abbreviated references for Chapter 19:**

*A 19.2* National Academy of Sciences, Engineering and Medicine 2019.
*A 19.4* Constable, Jimenez-Gonzales, and Matlin. 2019; Gentili 2019; Orgil, York, and MacKellar 2019.

**Abbreviated references for Chapter 20:**

*A 20.4* National Academy of Sciences, Engineering and Medicine 2019.

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## Websites

The web sites are arranged alphabetically. Look for the ending of the web address, since it provides the key words. All websites were accessed on 6 May 2020.

**Wikipedia websites**
**A**
https://en.wikipedia.org/wiki/Abiogenesis
https://en.wikipedia.org/wiki/Allen_Telescope_Array
https://en.wikipedia.org/wiki/Arecibo_message
https://en.wikipedia.org/wiki/Atlantis

**B**
https://en.wikipedia.org/wiki/Biosafety_level
https://en.wikipedia.org/wiki/Biotechnology

**C**
https://en.wikipedia.org/wiki/Chirality
https://en.wikipedia.org/wiki/Coacervate

**D**
https://en.wikipedia.org/wiki/The_Devil_in_the_Dark
https://en.wikipedia.org/wiki/DNA
https://en.wikipedia.org/wiki/Drake_equation

**E**
https://en.wikipedia.org/wiki/Exoplanet
https://en.wikipedia.org/wiki/Extraterrestrial_life

**F**
https://en.wikipedia.org/wiki/Fermi_paradox

**G**
https://en.wikipedia.org/wiki/Genetic_engineering

https://simple.wikipedia.org/wiki/Genotype
https://en.wikipedia.org/wiki/Genotype-phenotype_distinction
https://en.wikipedia.org/wiki/Gravitational_microlensing

**H**
https://en.wikipedia.org/wiki/Homochirality

**L**
https://en.wikipedia.org/wiki/Last_universal_common_ancestor
https://en.wikipedia.org/wiki/List_of_government_space_agencies

**P**
https://en.wikipedia.org/wiki/Panspermia
https://simple.wikipedia.org/wiki/Phenotype
https://en.wikipedia.org/wiki/Pioneer_plaque
https://en.wikipedia.org/wiki/Planetary_protection
https://www.nasa.gov/sites/default/files/atoms/files/planetary_protection_board_report_20191018.pdf )
https://phys.org/news/2019-10-nasa-planetary-reality-space-exploration.html ; https://spacepolicyonline.com/news/nasa-takes-step-towards-modernizing-planetary-protection-guidelines/ ;
https://en.wikipedia.org/wiki/Planetary_habitability
https://en.wikipedia.org/wiki/Post-detection_policy
https://en.wikipedia.org/wiki/Project_Ozma
https://en.wikipedia.org/wiki/Protocell
https://en.wikipedia.org/wiki/Viking_lander_biological_experiments

**R**
https://en.wikipedia.org/wiki/Radio_telescope
https://en.wikipedia.org/wiki/Recombinant_DNA
https://en.wikipedia.org/wiki/RNA_world

**S**
https://en.wikipedia.org/wiki/Search_for_extraterrestrial_intelligence
https://www.nasa.gov/content/the-search-for-life
https://en.wikipedia.org/wiki/Solar_System

**T**
https://en.wikipedia.org/wiki/Thioester
https://en.wikipedia.org/wiki/TRAPPIST-1

**V**

https://en.wikipedia.org/wiki/Vesicle_(biology_and_chemistry)
https://en.wikipedia.org/wiki/Voyager_Golden_Record

**Other Web Sites**

**A**

Space Exploration Abbreviations, *Acronyms*, and Definitions: www.ninfinger.org/karld/My Space Museum/acronyms.htm
Reference: *Acronyms* and Abbreviations: https://www.nasa.gov/pdf/632702main_NASA_FY13_Budget-Reference-508.pdf
https://www.seti.org/ata

**C**

https://cosparhq.cnes.fr/sites/default/files/pppolicy.pdf

**E**

https://exoplanets.nasa.gov/what-is-an-exoplanet/about-exoplanets/
https://exoplanets.nasa.gov/faq/6/how-many-exoplanets-are-there/
https://www.planetary.org/explore/space-topics/exoplanets/notable-exoplanets.html

**G**

https://voyager.jpl.nasa.gov/golden-record/whats-on-the-record/images/
https://voyager.jpl.nasa.gov/golden-record/
https://voyager.jpl.nasa.gov/golden-record/whats-on-the-record/
https://voyager.jpl.nasa.gov/golden-record/whats-on-the-record/sounds/
https://voyager.jpl.nasa.gov/golden-record/whats-on-the-record/greetings/

**H**

https://exoplanets.nasa.gov/what-is-an-exoplanet/how-do-we-find-habitable-planets/
https://history.nasa.gov/seti.html

**L**

https://www.nps.gov/yell/learn/nature/life-in-extreme-heat.htm

**M**

https://mepag.jpl.nasa.gov/
https://mars.nasa.gov/programmissions/overview/
http://meti.org/mission
https://www.nasa.gov/missions

**O**

http://www.simsoup.info/Origin_Issues_Earth_Or_Space.html
https://www.seti.org/seti-institute/project/optical-seti
https://www.seti.org/seti-institute/project/details/early-seti-project-ozma-arecibo-message

**P**

https://en.wikipedia.org/wiki/K'inich_Janaab'_Pakal
https://www.hq.nasa.gov/office/hqlibrary/pathfinders/intlag.htm
https://solarsystem.nasa.gov/resources/706/pioneer-plaque/
https://planetaryprotection.nasa.gov/documents/

**S**

https://seti.org/

**T**

https://en.wikipedia.org/wiki/Transiting_Exoplanet_Survey_Satellite
https://www.sciencehistory.org/distillations/man-made-a-history-of-synthetic-life

**V**

http://cedmagic.com/featured/voyager/voyager-record.html
https://voyager.jpl.nasa.gov/golden-record/

# INDEX

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