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Astrobiology and Life

Learning Outcomes

- ➤ Understand that astrobiology is concerned with the origin, evolution and distribution of life in the Universe. It investigates life in its cosmic context.
- ➤ Know about some aspects of the history of astrobiology and how it emerged as a field.
- ➤ Understand some of the detailed scientific questions that underpin its main lines of enquiry.
- ➤ Understand some of the complexities in the definition of life and how we can construct useful operational definitions of life.

1.1 About this Textbook

It is not a straightforward task to decide how to structure a book whose objective is to describe life in its cosmic environment – **astrobiology**. This is a formidable task and the fields that must be covered to do justice to this subject, even at an introductory level such as this, include astronomy, biology, chemistry, geosciences, planetary sciences, physics, social sciences and others. I read many books to see how others had approached this problem. One logical way is to start at the beginning. From the Big Bang we arrive at the first generation of stars and then as they die and explode they sow the Universe with the elements needed for life (Figure 1.1). Planets form around new stars. Some are habitable and on at least one of them the origin of life occurs. Life proliferates, transitions from single-celled organisms to animals, all the while being harassed by extinctions. Ultimately an intelligence develops that sets about detecting planets around distant stars and it puts together a programme to attempt to find other civilisations.

This fine narrative is a logical backdrop to organise the chapters of a textbook. The chronological story has a certain rhythm and emerging complexity about it. It is the approach taken by many astrobiology texts.

However, I decided not to take this approach. This textbook begins with a study of the one data point of life that we know – life on Earth. If we want to investigate how the elements required for life were produced after the Big Bang or why a habitable environment needs certain characteristics, or why certain molecules might have been needed for life to emerge, we need to know about biology first. We need to understand its structure, its requirements and what conditions it can subsist under in order to question how those characteristics were made possible.

We start by looking at the fundamental properties of matter and how those properties underpin the structure of the molecules of life. We then consider how these molecules are assembled into the major components of living cells. With a sound knowledge of the structure of life we then move on to think about how these cells can get the energy they need to grow and reproduce, all the time being mindful of those factors that might be specific to terrestrial life or from which we could learn something about life anywhere.

Supported by our knowledge of living things, we then explore how all life on Earth is related or linked into a tree of life. We investigate what the physical and chemical

Astrobiology: Understanding Life in the Universe, First Edition. Charles S. Cockell.

Companion Website : www.wiley.com/go/cockell/astrobiology.

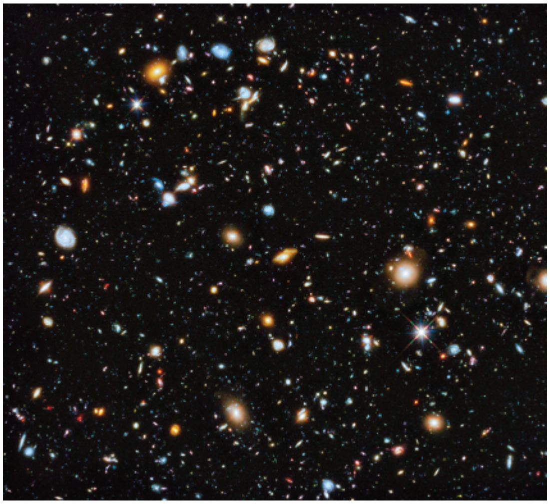

Figure 1.1 *Astrobiology seeks to understand the phenomenon of life in its cosmic context. This 'ultra deep field' view imaged by the Hubble Space Telescope includes nearly 10 000 galaxies across the observable Universe in both visible and near infra-red light. The smallest, reddest galaxies are among the youngest, in existence when the Universe was just 800 million years old.* [Source: NASA, ESA, H. Teplitz and M. Rafelski (IPAC/Caltech), A. Koekemoer (STScI), R. Windhorst (Arizona State University), and Z. Levay (STScI)].

limits are to life that might define how diverse or extensive this tree can become in extreme environments at the limits of planetary habitability.

At this point we are now equipped with a solid understanding of the structure, interrelationships and capabilities of the life that we know on the Earth. It's time to put this into its cosmic context.

We will turn to look at how this life might have come about. To start with we return to the beginning of the Universe and investigate how stars and planets form. This distinctly astronomical turn of events in the book is a necessary way to address the question: how did the elements required for life form and where did they form? In particular, we will examine the conditions for the formation of carbon compounds in the Universe.

To begin to understand how the formation of the elements of life, especially carbon, could have led to the origin of life we need to know something about the conditions on the early Earth (we'll be assuming in this book that life originated here, for reasons that will be discussed). We will investigate the environmental characteristics of our planet during the first billion years to understand what sort of environments and habitats could have existed on the Earth at that time.

The question of how life might have originated in this early environment is our next task. We will consider the chemical reactions and environments in which life could have originated and discuss some of the ideas for the reactions that allowed simple precursors to come together to make the macromolecules of biology – how chemical reactions led to the formation of the first self-replicating cell.

We follow this up by considering the evidence of early life on Earth, when the first organisms emerged and some of the complexities and controversies of the evidence of preserved life in the rock record. These problems make full use of our acquired knowledge about the structure, energy sources and environments in which life can persist.

It's time to take yet another step back and to think about how this first billion years fits into the whole history of our planet. We begin a chapter where we consider how geologists date rocks, order their understanding of the history of the Earth and we discuss some of the major transitions in life that occurred after the first billion years, including the rise of animals.

With an overarching view of the history of the planet, we might be tempted to think that this has all been rather smooth and structured. Unicellular organisms evolved into animals and then intelligence. However, the next two chapters elaborate why this isn't the case. By investigating rises in atmospheric oxygen that have occurred in our planet's past and the occurrence of mass extinctions, we can see that the emergence of life on a planet, and its success over billion year time scales, is fraught with difficulties, including asteroid impacts (Figure 1.2). We will see that life itself is responsible for some of these changes. Are these challenges universal and were the opportunities that presented themselves during the co-evolution of the planet and life universal? This question will be discussed as we progress, but you might like to keep it in mind at any time you are thinking about the history of life on the Earth.

At this stage, we have a fairly complete understanding of planet Earth, its history, its life, its geology. We have, in essence, got to grips with a detailed understanding of the one planet we know that supports life, its characteristics and how life shaped, and was shaped by, its environment. At this point we take this knowledge and expand further to the cosmic context.

In the following chapters we take what we know about the Earth and consider what might define a habitable planet and where in the Universe such environments might exist. Taking a look closer to home – our own Solar System – we investigate how Mars and icy moons

Figure 1.2 *The dinosaurs, these flying reptiles (pterosaurs) and many other forms of life at the end of the Cretaceous are thought to have been driven to extinction by the effects of a large asteroid impact. Therefore, to understand the past history of life on the Earth, we need to investigate our planet's astronomical environment, a key objective of astrobiology* (Source: NASA).

Figure 1.3 *As this artist impression makes clear, the detection of rocky worlds around other stars offers us the possibility of a statistical assessment of how common Earth-like worlds are in the cosmos, an analysis of their diversity, and determining the abundance of detectable life* [Source: NASA/JPL-Caltech/R. Hurt (SSC-Caltech)].

compare to the Earth. Are other planets in our Solar System habitable? We move on from this position to consider the billions of other planets in our Universe by examining the methods used to search for exoplanets, determine their different characteristics (Figure 1.3) and how we might search for life on them.

In the final chapters of the book we consider extraterrestrial intelligence and whether there are any other intelligences in the Universe with which we can communicate. We contemplate the future and fate of our own civilisation.

Each chapter presents a text on a particular aspect of the link between life and cosmos. I have attempted to elaborate some of the principles of astrobiology with respect to each subject area.

You will also notice that the units I use in the textbook are not consistent throughout. For example, growth temperatures of microorganisms are usually discussed in Celsius. Temperatures of planetary surfaces are often expressed in Kelvin. Different scientific fields tend to use different units and, rather than creating complete consistency (which would result in seemingly odd units being used for phenomena where they are not normally used), I have stuck with the normal conventions. These differences highlight the multidisciplinarity of astrobiology.

The chapters also include some boxes that I thought would be useful. I have written boxes that present some points of debate in astrobiology that are worth discussing with others or contemplating yourself. They are by no means exhaustive and you should use them to encourage other discussions or come up with new questions. Here and there I have written boxes about some of the major facilities that astrobiologists use. There are a vast number of techniques that astrobiologists employ in the laboratory, but some large facilities, coordinated internationally, such as space telescopes, expand the reach of the science significantly. They also give you a flavour of the modern nature of international science.

I often get asked by students, 'What degree do I need to do astrobiology?' Any degree allows a person to explore aspects of astrobiology from different angles. Science should never be closed to inquisitive minds on account of narrow human discipline definitions. So throughout the book I've liberally scattered boxes that contain some personal information about astrobiologists, their original degree areas and what motivates them. There are many fine people in astrobiology and I'd like to emphasise that there is no significance to the astrobiologists not included or included. I chose a selection of colleagues whom I thought would exemplify the variety of disciplines from which astrobiologists come.

I have included some further reading. This was, perhaps, the most difficult task. It is impossible to do justice to all the literature that exists in every field that comprises astrobiology, let alone list all of the main contributions. Instead

I've suggested two or three popular books that relate to each chapter that might provide some enjoyable additional reading. I have also listed a set of papers. They are papers I thought would give a representative sprinkling of just some of the possible avenues an interested reader might pursue and that relate to the main themes and subjects covered in each chapter. Again, no significance should be placed on the omission of many important papers or the inclusion of the ones I listed.

1.2 Astrobiology and Life

It may seem strange to begin a science text book by launching into a discussion underpinned by some history, but to begin this journey into astrobiology, we need to agree on what it is that we are all talking about.

First, what do we mean by the very term 'astrobiology' and where did it come from? Second, throughout this text book you'll find regular mention of the word 'life': 'Life in the Universe', 'Life in extremes', 'Life on Mars', 'Life beyond Earth', 'Life on the early Earth' and so on. With all this talk of life, we should perhaps try to agree exactly what it is we are talking about when we speak of 'life'. I say 'try', because I'll declare from the beginning that the multi-century endeavour to define 'life' is not going to be solved in this textbook (and there may not even be a solution, as we'll shortly discuss). However, we can at least engage in a useful debate about what we might mean by life – we might agree on a working definition that will serve us during this journey into astrobiology. In the following sections, let's explore what modern astrobiology is, review its history and see if we can come up with a working definition of life useful for the rest of the book.

1.3 What is Astrobiology?

So let's begin with 'astrobiology', the subject matter of this textbook. What is this field of science?

We might summarise by saying that astrobiology is the interdisciplinary science that sits at the interface between biological sciences, earth sciences and space sciences – exploring questions that seek to understand the phenomenon of life in its wide universal environment. Although the term was coined in the 1950s, astrobiology has gained new momentum, spurred on by new efforts in microbiology, chemistry, geosciences, planetary sciences and astronomy.

No science has a fixed, constrained and prescribed set of questions, but most sciences have a general set of questions which can be used to successfully circumscribe what its area of endeavour is, and these can be identified for astrobiology. Astrobiology might be said to address at least four large-scale questions: How did life originate and diversify? How does life co-evolve with a planet? Does life exist beyond the Earth? What is the future of life on the Earth?

Undoubtedly one of the most potent questions in astrobiology is: 'Are we alone in the Universe?' or similar formulations of the question of whether we are the only type of life in the Universe. This is one of the most obvious questions to ask when considering how life fits into its cosmic context. Although this question captures the public imagination, it is just one of many big questions asked by astrobiology. It is, however, reasonable that it is a major question. Discovering whether the Earth is the only planet that harbours an experiment in evolution in a Universe of at least 150 billion galaxies and a galaxy with about 200 billion stars seems like a sensible line of enquiry. These numbers tell us that there are about 10^{22} stars in the Universe, give or take the odd order of magnitude, which we could explore for the presence of habitable worlds. There is no shortage of planetary bodies for the attention of astrobiologists.

Astrobiology recognises that it is difficult to develop a full understanding of life on Earth without understanding its links to the cosmic environment. The Earth seems like a tranquil place (Figure 1.4). However, it is subjected to the vagaries of its astronomical environment. For example, a leading hypothesis for the extinction of the dinosaurs is an asteroid or comet impact about 65 million years ago. This hypothesis underscores the fact that to understand past life on Earth we need to understand how the astronomical environment may have influenced life. Eventually, when the Sun's luminosity increases to a sufficiently high value, the Earth's oceans will boil away and the planet will suffer a runaway greenhouse effect, eventually turning into a Venus-like world (Figure 1.5). Thus, to understand the future of life on Earth, we must also understand our astronomical environment. We need to know how stars are born and die. Investigating the past and future of life on Earth means that we need to look beyond the Earth to get answers.

Figure 1.4 *The one data point we have of a planet that harbours life – the Earth. Astrobiology seeks to understand how the phenomenon of life came about and whether it is unique in the Universe. Here the Earth rises over the lunar landscape in this iconic image taken by Apollo 8 in 1968. The image is sometimes called, 'Earthrise'* (Source: NASA).

We've identified some of the major questions in astrobiology. Let's survey some of the other questions of which these large-scale enquiries are comprised.

First, we start with how life began. Astrobiology is concerned with the origin of life. Questions such as: How did life originate? where did life originate? Was it inevitable? When did it happen? What is the evidence for early life? all encompass this area of research.

Once life did spread across the Earth we wonder what its limits are. If we can find out what the physical and chemical boundaries of life are – the most extreme conditions it can tolerate – we can begin to assess the habitability of other planetary bodies as locations for life. This knowledge also helps us to assess what the impact of human activity and industry might be on the biosphere. Questions that fascinate astrobiologists include: What are the limits of life? How does life survive at physical and chemical extremes? Are these limits universal? What do these limits tell us about habitable conditions or the possible presence of life elsewhere? These probing lines of thought drive us to study life

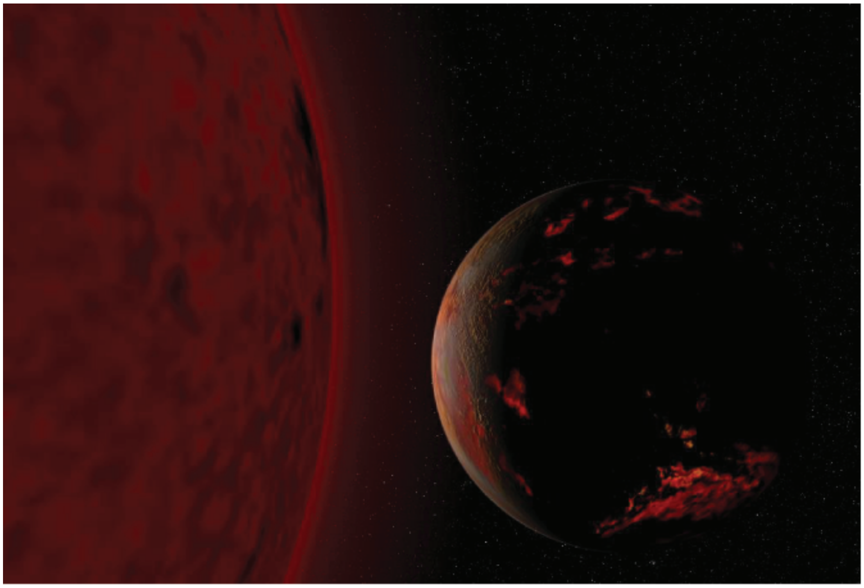

Figure 1.5 *When the Sun turns into a Red Giant star in several billions years from now, all life on Earth will already have been extinguished and the oceans boiled away. Therefore, to understand the future of life on our planet, we need to know about the evolution of stars. Biology and astronomy are inextricably linked in astrobiology* (Source: wikicommons via Fsgregs).

in extreme environments, from the deep oceans to the freezing wastes of Antarctica.

It is one thing to know about how life originated and what its abilities to live in extreme planetary conditions might be, but how are all the organisms on the Earth related? The diversity of life on the Earth is extraordinary. What unites organisms and what is the relationship between them? Astrobiologists want to better understand the evolutionary links between diverse organisms with questions such as: How is life related? What triggered the appearance of multicellular life? What have been the major catastrophes for life and the effects of mass extinctions?

We are then faced with the profound question of whether this vast evolutionary experiment is unique and whether other planets in the cosmos harbour life. This central question in astrobiology can be summarised with the sub-questions: Is there life elsewhere? If there is, what is it like? If there isn't life elsewhere, why not and what is missing elsewhere that was present on the Earth when life emerged? A rather more specific, but nevertheless very interesting, set of questions can also be identified: Is intelligence inevitable and has it arisen elsewhere? If it has evolved elsewhere, can we communicate with it? What happens if we do?

Finally, of course, we should not forget our own civilisation. Our future is as much part of the evolution of life as any other organisms and this future impels us to ask many questions such as: Will humans leave the Earth permanently? How do we settle other planets? How do we preserve Earth whilst settling space? How will we adapt to space – can society be successfully extended to this environment? These are not so much scientific questions, more technical questions, but they very much bear on the applications of astrobiology to human society. These questions generate direct links between astrobiology and humanities and social sciences as they force us to confront our own place in the cosmos and the story of life.

1.4 History of Astrobiology

Having explored the main questions in astrobiology and summarised them, we might ask ourselves when all this enquiring began. Astrobiology is, from a philosophical standpoint, an ancient science. Greek philosopher, Metrodorus of Chios (fourth century BC; Figure 1.6), a student of Democritus (c. 460–370 BC) (one of the first people to propose the atomic theory of matter) stated: 'It would be strange if a single ear of wheat grew in a large plain, or there were only one world in the infinite'. The Greeks had a very different view of the Universe than the one we have today. They had no real conception of the planets as rocky bodies or the vast distances to the stars. Indeed, they thought that all the stars were held in the surface of a huge sphere. Metrodorus's statement was, nevertheless, a remarkable perspective on the potential plurality of Earth-like worlds. Metrodorus's view of the world was very different from Plato's (c. 428–348 BC) and Aristotle's (384–322 BC) who asserted the uniqueness of the Earth in the cosmos. Indeed, the idea that the Earth was the centre of the Universe was based on the observation that the stars never moved with respect to one another, which the Greeks incorrectly interpreted to be a result of the fixed position of the Earth rather than the great distances to the stars. Aristotle's view would dominate for many centuries. Until the Enlightenment, the idea that the Earth was a sole inhabited world in the cosmos held its grip on the public view, bolstered by religious doctrine.

Figure 1.6 *Metrodorus of Chios, ancient Greek philosopher, who wondered about the existence of other worlds* (Source: wikicommons, Keith Schengili-Roberts).

In the sixteenth century, the geocentric view of the Universe, which firmly placed the Earth as the centre of the action, was overturned by Nicolaus Copernicus (1473–1543). The Copernican view was the forerunner of newly emerging ideas that stars may be other suns.

In the seventeenth century, more enquiring and inquisitive minds appeared and, with them, new speculations about the place of the Earth in the larger order of things. One of the most astonishing speculations about worlds beyond the Earth was made by Italian astronomer and philosopher, Giordano Bruno (1548–1600; Figure 1.7), who stated in his book *On the Infinite Universe and Worlds*: 'In space there are countless constellations, suns and planets; we see only the suns because they give light; the planets remain invisible, for they are small and dark. There are also numberless earths circling around their suns, no worse and no less than this globe of ours. For no reasonable mind can assume that heavenly bodies that may be far more magnificent than ours would not bear upon them creatures similar or even superior to those upon our human earth'. This was a prescient statement about the possibility of extrasolar planets and a person couldn't do much better today in writing a clear summary of why Earth-like exoplanets are hard to find. Bruno was eventually burned at the stake for a variety of charges, most of which related to him holding beliefs contrary to the Catholic Church concerning the Trinity, Jesus and indiscretions about his views on church ministers. However, one of these charges was explicitly for claiming the plurality of worlds. It is sobering to remember that it was once possible to be executed for discussing the existence of extrasolar planets.

Figure 1.7 *Giordano Bruno, whose speculations about other worlds (the 'plurality of worlds') contributed to his demise* (Source: wikicommons).

During the Enlightenment, the invention of the telescope allowed scientists to see new moons and planetary bodies. Although one might be forgiven for believing that this would reduce speculation, as more data was available, it had the opposite effect. Armed with new evidence for other worlds, speculation went wild.

Christiaan Huygens (1629–1695), who discovered Saturn's moon, Titan, and invented the pendulum clock, wrote extensively on extraterrestrial life and the habitability of other planets in his book, *Cosmotheoros*, published posthumously in 1698. As well as speculating about astronomers on Venus, he also suggested that other intelligences would understand geometry. About music he said: 'This is a very bold assertion, but it may be true for aught we know, and the inhabitants of the planets may possibly have a greater insight into the theory of music than has yet been discovered among us'.

William Herschel (1738–1822), discoverer of Uranus and infra-red radiation, after observing the strangely circular craters of the Moon speculated about them in preserved manuscripts, in an age when their impact origin was completely unknown: 'By reflecting a little on this subject I am almost convinced that those numberless small Circuses we see on the moon are the works of the Lunarians and may be called their Towns'.

As late as 1909, Percival Lowell (1855–1916), observer of the infamous Martian 'canals' said of Mars in his book, *Mars as the Abode of Life*: 'Every opposition has added to the assurance that the canals are artificial; both by disclosing their peculiarities better and better and by removing generic doubts as to the planet's habitability'.

We could continue with many such quotes (and many other eminent scientists and philosophers were convinced of alien life), but these three are adequate to make two points. First, we would have to wait for the space age and the direct and close-up observation of planetary bodies to truly force astrobiology into an empirical era and, second, these quotes are a warning from the past.

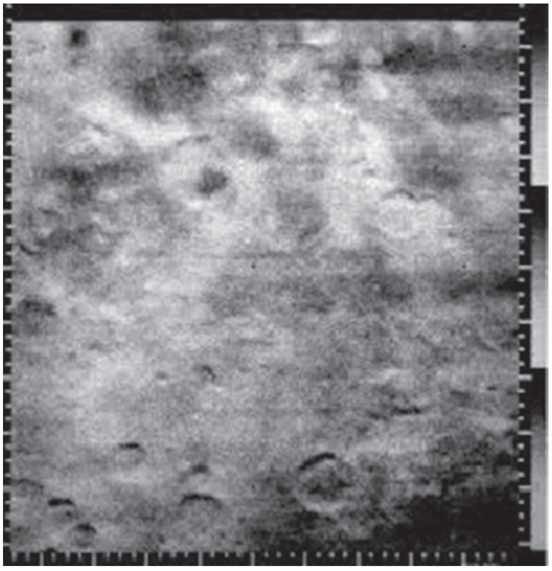

Figure 1.8 *One of the first orbital photographs of Mars, taken by the Mariner 4 craft on 15 July 1965 suggested a dead, desiccated environment unfit for life. The area shown is 262 × 310 km and is a heavily cratered region south of Amazonis Planitia, Mars* (Source: NASA).

The desire to believe in alien life should not trump empirical observation. Life should always be the last explanation after all non-biological explanations have been exhausted.

It was only at the beginning of the space age (Figure 1.8) that the photographic study of planetary surfaces yielded new and more empirically constrained views of the surfaces of other planets. In general, they showed other planets to be devoid of life and this led to a strong retreat from previous optimism. Nevertheless, astrobiology entered into the realms of experimental testing with a range of pioneering experiments and discoveries that would take it from its previous philosophical underpinnings to its present day status as a branch of science.

Laboratory experiments from the 1950s and onwards, simulating conditions on the early Earth and showing the production of amino acids and other building blocks of life, brought the study of the origin of life into the laboratory. The publication of evidence, in the 1980s and onwards, of fossil life on the Earth preserved for more than three billion years turned the search for ancient life on Earth and the timing of the emergence of life into a scientific quest.

The first experimental search for life on other worlds, undertaken by the robotic Viking biology experiments, landed on Mars in 1976 and gave ambiguous results, but nevertheless demonstrated that we can go to other planets and implement the scientific method in a search for life. Attempts were made in the 1970s to transmit messages to other civilisations with all of its social and ethical implications. Despite the lack of response, the efforts to search for, and communicate with, extraterrestrial intelligence triggered a vigorous discussion about the intersection of astrobiology with social sciences.

The discovery of liquid water oceans in the planetary bodies orbiting in the frigid wastes beyond Mars, such as the moons of Jupiter (Europa, Ganymede) and Saturn (Enceladus) and the discovery of complex organic carbon chemistry on Saturn's moon, Titan, has showed us that we can learn about the habitability of planetary bodies and organic chemistry in surprising places (Figure 1.9). In recent years, the discovery of planets, particularly rocky planets, around other stars (exoplanets) has led to a flourishing of astrobiology and our ability to assess the statistical chances of habitable worlds elsewhere in the Universe.

These experiments and discoveries, from the mid-twentieth century and onwards, set the stage for

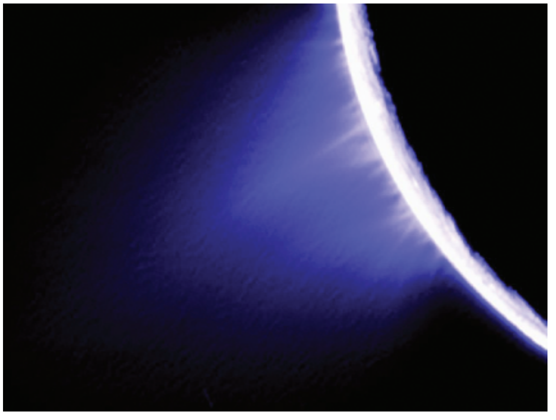

Figure 1.9 *Plumes of water emanating from the south polar region of Saturn's moon, Enceladus, is just one of the many discoveries that have provided an empirical basis with which to test the hypothesis that habitable conditions exist beyond the Earth* (Source: NASA).

Figure 1.10 *Gavriil Tikhov, who wrote an early book called* 'Astrobiology' *and took a great deal of interest in spectroscopy as a means to look for signatures of extraterrestrial life. Here he observes the spectroscopic signatures of vegetation.*

astrobiology as the truly experimental science that we know today.

Throughout this history different terms have been used to describe the science, which can, if you don't take care, cause much confusion. In the mid-twentieth century, although not the first time the word was used, 'astrobiology' was the title of a 1953 book by Gavriil Tikhov (1875–1960; Figure 1.10). His book explored the possibility of life on other worlds. Tikhov was particularly fascinated by the idea of using the spectroscopy of vegetation to seek vegetation on other planets and even founded a Sector of Astrobotany allied to the Science Academy of Kazakhstan. His methods and ideas were forerunners of the use of spectroscopy to search for biosignatures on exoplanets.

In 1960, Joshua Lederberg (1925–2008; Figure 1.11), a pioneer in bacteriology and molecular biology who won the Nobel Prize for his work on bacterial genetics, used the term **exobiology** to describe the search for life beyond the Earth. Other terms have included cosmobiology, xenobiology and bioastronomy, the latter used by astronomers.

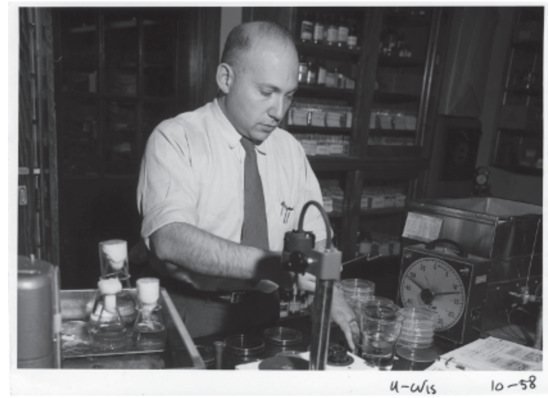

Figure 1.11 *Nobel Laureate, Joshua Lederberg, who was at the forefront of United States efforts in exobiology in the twentieth century, at his laboratory in the University of Wisconsin, October 1958.*

Today, the word astrobiology is used in a wide sense to mean not just the search for life beyond the Earth, but the study of life in its cosmic context in general, including the past history of life on the Earth.

1.5 What is Life?

Attempts to define life are an ancient pursuit. From an astrobiologist's point of view the discussion is rather important since if we want to search for life elsewhere or find it in ancient rocks on Earth, we had better know what we are looking for.

Let's start by saying from the beginning that we probably don't need to accurately define it to progress with our work. We can come up with a working definition of life that encompasses some of its characteristics or its essential processes. For example, life is 'a self-sustained chemical system capable of undergoing Darwinian evolution', is a rather succinct definition by NASA scientist, Gerald Joyce.

Many of these definitions are underpinned by the idea of evolution being a fundamental characteristic of life. Evolution is the process by which variation in a population of organisms, placed under environmental conditions, results in the selection of surviving organisms that pass their traits onto subsequent generations ('natural selection').

There are many other apparent characteristics of life that we could list. For example, life exhibits complex

Figure 1.12 *Life grows, but crystals do as well, such as these salt (NaCl) crystals that could grow if placed in a saturated salt solution* (Source: wikicommons, Mark Schellhase).

behaviour and often unpredictable interactions. Life also grows and reproduces, a point recognised by Joyce's definition that life is a 'self-sustained chemical system'. Life also metabolises, which is a process that involves breaking down compounds or changing their form to generate energy and obtain raw materials.

However, the problem with all these characteristics individually is that many non-biological entities exhibit these behaviours. Salt crystals, when exposed to the appropriate conditions, such as a saturated salt solution, can grow (Figure 1.12).

Computer programs can be made to 'reproduce' in the sense that they can be multiplied and in some cases, even incorporate errors in analogy to biological evolution. Fires, in a rudimentary way, 'metabolise' organic material. They burn organic carbon in oxygen to produce the waste products, carbon dioxide and water. The chemical reaction involved in this process is identical to respiration used to produce energy in animals, the only difference is that the reaction is biochemically controlled in life and uncontrolled in fires (Figure 1.13).

So if we work hard enough, we can find **abiotic** conditions that are similar to biological behaviours. Conversely, we can find biological entities that we might think are alive, but fail to exhibit characteristics that we associate with most life. Viruses, such as influenza viruses, are particles that require a host to replicate, taking over cell machinery to reproduce themselves. As they cannot reproduce on their own, are they alive? In some definitions of life we might include viruses, in some we may not. We can take this argument to extremes. What about a rabbit? Like a virus it too cannot replicate on its own. It requires another rabbit. Is a rabbit dead on its own but a living thing when it is with its mate? Very quickly we arrive at a *reductio ad absurdum* and the discussion goes nowhere.

Figure 1.13 *A wildfire burns organic carbon in oxygen to produce carbon dioxide and water in an identical chemical reaction performed by respiring animals.*

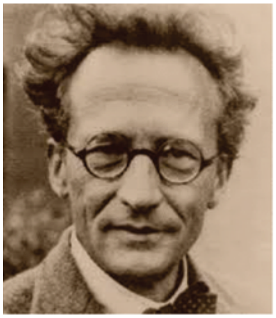

Figure 1.14 *Erwin Schrödinger attempted to define life from a physical perspective.*

Physicist Erwin Schrödinger (1887–1961; Figure 1.14) famously attempted to define life in his seminal book, *What is Life?*, published in 1944 following a series of lectures given at Trinity College, Dublin, in 1943. Quite apart from some fascinating predictions about the nature of the genetic material (that it was an 'aperiodic' crystal – a crystal that lacks long-range order – for which he attempted to estimate the size) he also attempted to get at the nature of life.

Schrödinger recognised that life made 'order from disorder' and, employing the second law of thermodynamics, according to which entropy (a measure of the homogenisation of energy) increases as energy is dissipated in atoms or molecules, Schrödinger explained that life evades the decay to thermodynamic equilibrium by maintaining what he termed 'negative entropy', for example by gathering energy. The phrase 'negative entropy' is rather unwieldy and counter-intuitive. It should be seen more as a popular statement about his views on life than an attempt to define a real physical process. The notion of negative entropy is not limited to life, however. Chemical reactions such as endothermic reactions (reactions that take up energy) are in some sense extracting energy from the surrounding environment to increase order.

Schrödinger's interpretation has a tendency to give the impression that life is 'struggling' against the laws of physics – attempting to maintain order against the ineluctable forces of the Universe that have a tendency to disperse it into disorder. The problem with this view is that it does not explain why life is so successful. If it was such a struggle, why does life seem to be so tenacious and ubiquitous once it got started on Earth?

Another, related, way to view life is to focus less on the organisms themselves, but instead on the process that life is involved with. We can think of life as a process driving the Universe more efficiently towards disorder than non-biological processes.

To understand this idea, consider my lunch sandwiches. If I place them on a table, and assuming they are not degraded by fungi (which they will be, but this is a thought experiment), it will take a very long time for the energy in their sugar and fat molecules to be released. Indeed, the energy in the sandwich may not be released until it ends up in the Earth's crust from the movements of plate tectonics, heated to great temperatures in the far future when the sugars and fats will be turned into carbon dioxide. However, if I eat the sandwiches, within about an hour or two their contained energy will be released as heat energy in my body, with some portion of it being used to build new molecules. In essence I have accelerated, very greatly, the dissipation of the sandwich into energy. I have enhanced the rate at which the second law of thermodynamics has had its way with the sandwich. Living things represent extraordinary local complexity and organisation, but the process they are engaged in is accelerating the dissipation of energy and the run-down of the Universe. Local complexity in organisms is an inevitable requirement to construct the biological machines necessary for this effect to occur. As the physical universe has a tendency to favour processes that more rapidly dissipate energy, then life is contributing to the processes resulting from the second law of thermodynamics, not fighting it. Seen from this perspective, it is easier to understand why life is successful. It might even be inevitable where organic chemistry allows for it.

But we still haven't *defined* life. One answer to the problem of the definition of life is that life is simply a human word, an artificial definition created by us. It is what philosophers would call 'a non-natural kind', as opposed to a 'natural kind'. The latter term applies to a substance such as gold, whose characteristics can be exactly defined in terms of its physical properties. We can state the molecular mass, melting point and a range of other definitive physical properties of gold that allow for an exact definition of what it is. A good example of a 'non-natural kind' is a 'chair'. If we define it as 'something we can sit on', then does that make my coffee table a chair? And thus we launch into an endless circular discussion about what a chair is. The conversation is rather pointless because ultimately a chair is simply what we define it to be. If that includes coffee tables then so be it. Similarly, maybe life is just a definition that encompasses an interesting segment of all organic chemistry that happens to do certain things, such as reproducing and growing. If we want to include viruses, then so be it; if not, then so be it. Perhaps the crucial point is that we all agree on a definition that we are going to use. Today, astrobiologists tend to think that we can create working definitions that are useful in the search for life elsewhere, such as Joyce's definition quoted earlier.

A working definition of life should not stop us continuing the debate about defining life. Quite apart from refining our understanding of biology, it would be a travesty to destroy some sort of entity elsewhere (if we ever find it) simply because it failed to fit within a narrow definition of life that we have constructed.

1.6 Conclusions

In this introductory chapter we have discussed what astrobiology is. We find it to be an important vehicle to consider life within its cosmic context. It has its own set of scientific questions, such as its most potent: Is there life beyond the Earth? Astrobiology is philosophically an ancient science, but has in recent years gained the empirical knowledge to begin to address questions about life in the Universe, driven in particular by technological advances in space missions. The definition of astrobiology's subject matter, life, has proven to be extremely intractable, but we can produce working definitions of life that allow us to advance our quest to understand the origin, evolution and distribution of life in the Universe.

Further Reading

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