1

Astrobiology

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.
- ➤ Understand some of the detailed scientific questions that underpin astrobiology's main lines of enquiry.
- ➤ Know about some aspects of the history of astrobiology and how it emerged as a field.

1.1 Introductory Remarks

If you've ever wondered about some of the most fascinating questions in science, such as how life originated, whether it could exist elsewhere, and how life has managed to evolve and persist on our **planet** for over three and a half billion years, then you've opened the right book.

Astrobiology is a remarkably diverse subject whose main objective is to investigate and understand the phenomenon of life in its cosmic context (Figure 1.1). Astrobiology might be said to address at least four large-scale questions:

1. How did life originate and diversify on Earth?
2. How does life co-evolve with a planet?
3. Does life exist beyond Earth?
4. What is the future of life on Earth and its capacity to move beyond the home planet?

Astrobiology covers and integrates a wide diversity of subjects including astronomy, biology, chemistry, geosciences, planetary sciences, physics, and social sciences. In that sense, to the newcomer it may even look intimidating in its scope. However, as I hope you'll discover in this book, it is an enormously rewarding area of study and whether you come at this subject as an astronomer, biologist, or chemist, or from another discipline, the subject will encourage you to cross seamlessly into other areas of science.

Who is this booked aimed at? Its core audience is students taking astrobiology courses or lectures, but it can be read by anyone with an interest in the subject. The book might be useful for scientists in specific disciplines keen to see where their subject area intersects with other fields of science. For policy makers or others with a social sciences or humanities background, the book will provide a scientific backdrop to astrobiology and its links to space exploration. I would hope, given its structure and layout, that interested laypersons might find this a useful reference source to learn about astrobiology and get to grips with some of its key concepts.

You might ask: But why would we want to study biology from a cosmic perspective in the first place? And in answer: Even the most limited view of life on Earth forces us to consider the cosmic view. Our planet seems like a tranquil place. However, it is subjected to the vagaries of its astronomical environment. For example, a key hypothesis for the mechanism of the extinction of the dinosaurs is an asteroid impact

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

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

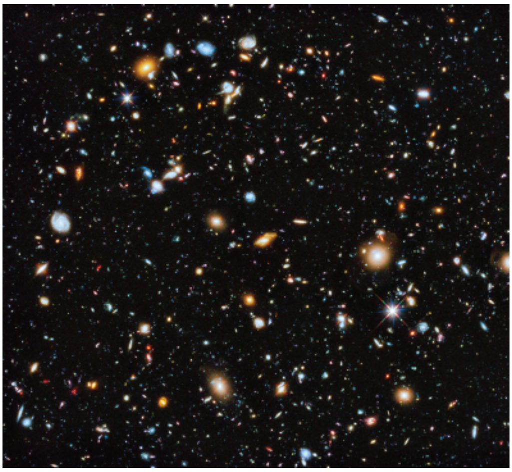

Figure 1.1 *Astrobiology seeks to understand the phenomenon of life in its cosmic context. This "ultra-deep field" view imaged by the Hubble Space Telescope includes nearly 10 000 galaxies across the observable Universe in both visible and near infrared light. The smallest, reddest galaxies are among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

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

66 million years ago (Figure 1.2). This hypothesis underscores the fact that to understand past life on Earth, we need to understand how the astronomical environment may have influenced life. To know how the dinosaurs and about 75% of all animal life went extinct at the end of the Cretaceous geological period, you have to know how frequently asteroid impacts occur. That means knowing something about how many asteroids are in space, where they come from, and why they exist in the first place, a question itself linked to the formation of the Solar System. The death of the dinosaurs takes you into astronomy, and that means into the purview of astrobiology.

Instead of looking back in time, we could look into the future. 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 1.3). This will probably occur in approximately 1.5 billion years. 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 and what the fate of planets is during this stellar evolution.

In summary, investigating the past and future of life on Earth means that we need to look beyond Earth to get answers. Astrobiology is about taking that journey and linking the diverse scientific fields needed to understand life on our own planet and, potentially, life beyond.

Let me address an interesting question that I often get asked: What's the use of astrobiology and how is it different from biology? Can it really claim to be a field in its own right? I hope that you've already got some understanding of why it is a useful area of science. Without a long digression into the philosophy of science, it is worth remembering that scientific fields are human constructions. It is true to say that the existing field of "biology" covers investigations into all the living things that we know, which might make you wonder why we need astrobiology at all. However, astrobiology is merely a way to think about living things in their astronomical or cosmic context, to address questions such as the origin of life or the existence of life elsewhere that requires

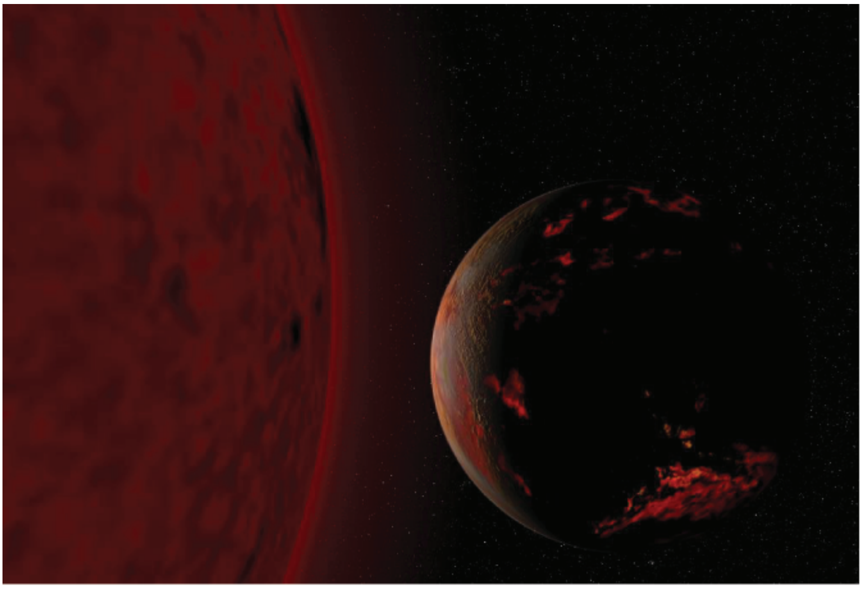

Figure 1.3 *The future of the Earth is a topic in astrobiology. When the Sun turns into a Red Giant star in several billion years from now, the Earth will be a dead planet. However, the increasing luminosity of the Sun over the next one to two billion years will ensure that life on Earth will already have long since been extinguished and the oceans boiled away when the planet enters a greenhouse state. 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: Reproduced with permission of Fsgregs, https://upload.wikimedia.org/wikipedia/commons/6/60/Red_Giant_Earth.jpg.

linking biology with other fields such as planetary sciences or astronomy. Does that make astrobiology a subfield of biology or something wider? You decide! I don't think it really matters. What is important is that it is a useful term to encompass a set of scientific questions. It brings together a wide range of scientists, in textbooks like this or at scientific conferences, and of course in scientific papers. If a scientific word achieves nothing more than the advance of collaboration between thinking human beings, then it is an outstanding thing.

1.2 The Major Questions of Astrobiology and the Content of the Textbook

Astrobiology is a very broad field, and it can be difficult to grasp all the topics and fascinating questions that it addresses. This textbook is focused on providing a comprehensive overview of some of the major strands of science that underpin the study of life in its cosmic context, while hopefully achieving an appropriate depth of understanding in key subjects such as physics, biology, chemistry, and geosciences. The textbook is based on six years of teaching an astrobiology course at undergraduate level at the University of Edinburgh. During that time, I have been able to observe what undergraduates find interesting and the things for which they have less enthusiasm. The content of the chapters is based around these experiences. In particular, concepts that are important and sometimes more tricky to grasp have more pages devoted on them. The textbook should by no means be regarded as exhaustive, and there are many other texts that can provide ancillary information and deeper discussion on particular subjects.

There is a point I would like to make right away. If you bought this textbook to read all about aliens, you are going to be disappointed. The matter of whether life exists elsewhere in the Universe is certainly one of astrobiology's major questions. "Does life exist beyond Earth?" sometimes expressed as "Are we alone in the Universe?" or similar formulations of the question of whether we are the only type of life in the Universe grips the public as well as the scientific imagination. It justifiably finds itself center stage whenever the word "astrobiology" comes into view. In fact, one of the challenges of being an astrobiologist is to explain to people that the subject is not just about searching for alien life! Perhaps one reason why the question of whether alien life exists is so pervasive is that it is a statistically reasonable question to ask. Earth is one planet in a galaxy which might have about 200 billion stars (the exact number is not known) in a Universe with possibly something like 150 billion galaxies (the exact number is also not known). These numbers tell us that there are about 10^{22} stars in the Universe (give or take orders of magnitude), which we could explore for the presence of habitable worlds. There is no shortage of planetary bodies for the attention of astrobiologists. It's quite reasonable that anyone who looks into the night sky should wonder whether we are alone. As soon as you start to talk about life in its cosmic context, the question of alien life therefore comes into full view.

However, astrobiology is concerned with many other fascinating questions that relate to life on our own planet and its future. In Table 1.1, you can see a summary of the textbook, its chapters, their content, and the fields they cover. This will give you an instant glimpse of what those topics are.

A great deal of this book is unapologetically focused on a basic understanding of biology. Indeed, even if alien life is your focus, you still need to know about the one type of life we currently know – life on Earth – before you can embark on any discussion about the conditions and possibilities for life elsewhere.

The textbook therefore begins with a study of life on Earth (Figure 1.4). There is another reason for starting with biology. If we want to investigate how the elements required for life were produced during and after the Big Bang or why a habitable environment needs certain characteristics, or why certain molecules and environments 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. In that sense, the first part of this book looks very much like standard biology textbook material and, at its core, it is. However, I have written it specifically to provide you with the necessary understanding of biology to enable you to think about the major questions of astrobiology. Throughout these chapters, I address some of the topics in biology that relate to questions about the conditions and possibilities for life elsewhere. These chapters are biology with an astrobiology flavor.

We start this tour of life 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 knowledge of the structure of life, we can 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.

Once life did become established on Earth, what were its limits? We will investigate the physical and chemical boundaries of life that might define how diverse or extensive this life can become in extreme environments at the limits of planetary habitability. If we can find out what the physical and chemical extremes of life are, i.e. the most extreme conditions it can tolerate, we can begin to assess the habitability of other planetary bodies as locations for life. This knowledge even helps us to assess what the impact of human activity and industry might be on the biosphere. Questions that fascinate astrobiologists in this area of research 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 in unusual environments, from the deep oceans to the freezing wastes of Antarctica.

Supported by our knowledge of living things, we then explore how all life on Earth is related or linked into a "tree of life." Buried within this tree of life are profound questions. The diversity of life on Earth is extraordinary. But what unites organisms and what is the relationship between them? How has this diversity changed over time? (Figure 1.5). Astrobiologists want to gain a better understanding of the evolutionary links between diverse organisms. We take an introductory look at the tree of life and see how biologists can construct phylogenetic trees to make sense of all the diversity of life on the planet, and to address certain scientific hypotheses.

Table 1.1 *The content of the textbook.*

Chapter number	Subjects covered	Chapter title	Summary of content
1	Introduction	Astrobiology	Summary of the content of the textbook, the field of astrobiology and its history
2	B, H	What Is Life?	Discussion on what life is and the history of attempts to define life
3	B, C	Matter and Life	The basic structure of matter, major bonding types, and relevance to life
4	B, C	The Molecular Structure of Life	How molecules are assembled into the major molecules of life
5	B	The Cellular Structure of Life	The cellular structure of life and the major components and characteristics of cells
6	B	Energy for Life	How life gathers energy from the environment and the major types of metabolism
7	B	The Limits of Life	Life in extremes and its astrobiological significance
8	B, G	The Tree of Life	How phylogenetic trees are used to order biological information and test scientific hypotheses
9	A, B	The Universe, the Solar System, and the Elements of Life	The origin of the Universe, stellar evolution, the formation of planets, and the origin of the elements important for life
10	A, C	Astrochemistry: Carbon in Space	Introduction to chemistry in space and how complex carbon compounds can be formed in space
11	B, G	The Early Earth: The First Billion Years	The environment of the early Earth and the important characteristics for life
12	B, C, G	The Origin of Life	Hypotheses about how and where the first living things may have originated
13	B, G	Early Life on Earth	Evidence for life on the early Earth and the complexities in finding evidence for early life
14	B, G	The Geology of a Habitable World	The long-term geological history of Earth and its relationship to habitability and life
15	B, G	The Co-Evolution of Life and a Planet: The Rise of Oxygen	How life caused the rise of oxygen and the mechanisms and consequences of the rise of oxygen
16	B, G, H	Mass Extinctions	Discussion on the mechanisms and consequences of the major mass extinctions in the Earth's history
17	A, B, G	The Habitability of Planetary Bodies	Discussion on the general factors that determine whether planetary bodies can support life
18	A, B, C, G, H	The Astrobiology of Mars	In-depth discussion on the habitability of Mars, past and present
19	A, B, C, G, H	Ocean Worlds and Icy Moons	In-depth discussion on the habitability of icy moons hosting liquid water oceans
20	A, B, G, H	Exoplanets and the Search for Life	Methods to search for exoplanets, examine their habitability, and search for evidence of life
21	A, G, H	The Search for Extraterrestrial Intelligence	Methods and attempts to search for evidence of extraterrestrial intelligence
22	A, B, G, H	Our Civilization	The history and potential of our civilization beyond Earth

For each chapter, a brief summary of its subject matter is provided. Also shown are the key scientific disciplines covered by the chapters, where A is astronomy/astrophysics, B is biological sciences, C is chemistry, G is geosciences, and H denotes chapters that contain material that intersects with humanities/social sciences.

Figure 1.4 *The one example we have of a planet that harbors life: Earth. Astrobiology seeks to understand how the phenomenon of life came about and whether it is unique in the Universe. Here, Earth rises over the lunar landscape in this iconic image taken by Apollo 8 in 1968. The image is sometimes called "Earthrise".* Source: Reproduced with permission of NASA.

At this point, we will be equipped with a solid understanding of the structure, interrelationships, and capabilities of the life that we know on Earth. It is time to put this into a more cosmic context.

In the next part of the textbook, we rewind and return to the beginning of the Universe and investigate how stars and planets formed. This distinctly astronomical turn of events in the book is a good way to address the question: How did the elements required for life (which we identified in the first part of the textbook) form, and where did they form? In particular, we examine the conditions for the formation of carbon compounds in the Universe, since carbon-containing compounds are the most important class of compounds for life.

I should stress that one could tackle astrobiology in the opposite direction. We could start at the beginning of the Universe and work our way through to the emergence of life. Chronologically, this does make sense. However, to know which elements that were

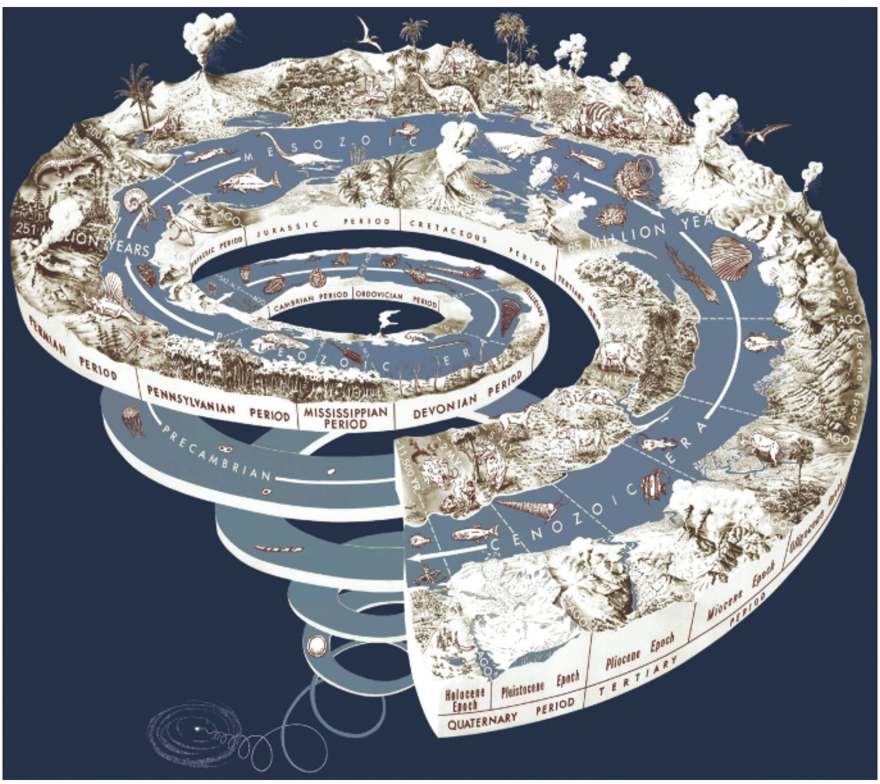

Figure 1.5 *A schematic of the history of Earth. Understanding this history and the co-evolution of life and the planet constitutes a key objective in astrobiology.* Source: Reproduced with permission of William Crochot.

formed in the early Universe are relevant for life, it's important to know something about biology in the first place, which is why I have started the textbook with biology. However, I have attempted to write each chapter as a stand-alone text. If you want to select chapters and work through them in a different order, such as from the beginning of the Universe in a more astronomically focused class, you can do that.

Once we have investigated the history of the Universe, the formation of the elements of life and the important role of carbon, the textbook then returns to Earth to examine the emergence of life on this habitable planet. We investigate the environmental characteristics of our planet during its first billion years to understand what sort of environments and habitats could have existed on Earth at that time.

The question of how life might have originated in this early environment is our next task. We consider the chemical reactions and environments in which life could have originated and discuss some of the ideas for the reactions that allowed simple precursor molecules to come together to make the macromolecules of biology – how chemical reactions led to the formation of the first self-replicating cell. This leads to questions such as: How did life originate? Where did life originate? Was it inevitable? When did it happen? All of these questions encompass the question of the origin of life on Earth and might tell us something about whether an origin of life could happen somewhere else.

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

It's then time to take yet another step back and to think about how this early period fits into the whole history of our planet. We begin a chapter where we consider how geologists date rocks and order their understanding of the history of Earth, and we discuss some of the major transitions in life during the history of the planet, including the rise of multicellular animals. In a similar way to the first chapters, which may seem quite basic to a biologist, the geologists among you may feel that these chapters are very much in the tone of a standard geology textbook, and you'd be right. But remember, we are bringing scientists from many disciplines on this astrobiology journey, so for a biologist or chemist, for instance, this material may be new. However, as with the chapters on biology, I have written these chapters with an astrobiological flavor, so even if the core material is familiar to you, I hope you will consider it from a new angle.

With this overarching view of the history of our planet, we might be tempted to think that all this geological and biological evolution has been smooth and orderly. Unicellular organisms evolved into animals, and then intelligence emerged. However, the next two chapters elaborate on why this isn't the case. By investigating rises in atmospheric oxygen that have occurred in our planet's past and the role of mass extinctions in changing biological diversity, we can see that the emergence of life on a planet, and its success over billion-year timescales, is fraught with difficulties, including astronomical perturbations such as asteroid and comet impacts.

We will see that life itself is responsible for some of these changes, such as the rise of oxygen, but in other cases, such as the effects of an asteroid impact, it has been a hapless passenger. Are these challenges universal and were the opportunities that presented themselves during the co-evolution of the planet and life ones that we would expect to occur on any planet that has life? This question is 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 Earth. If there is life on other planets, is our own planet a universal template for how it too would evolve? What features of this planet's biological evolution are an idiosyncratic result of particular conditions here?

At this stage, we have a more complete understanding of planet Earth, its history, its life, its geology. We have 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. So now we take this knowledge and expand further to the cosmic context: We leave Earth and head outwards.

In the following chapters, we take what we know about Earth and consider what might make a planet habitable for life and where else in the Universe such environments might exist. Taking a look close to home – our own Solar System – we investigate how Mars compares to Earth. We examine the icy moons of Jupiter and Saturn that host oceans beneath their surfaces. Are other planetary bodies in our

Solar System habitable? We move on from this position to consider the billions of other planets in our Universe, looking at the methods used to search for planets around other stars, so-called exoplanets, how we determine their different physical characteristics (Figure 1.6), 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. Is intelligence inevitable and has it arisen elsewhere? If it has evolved elsewhere, can we communicate with it? What happens if we do?

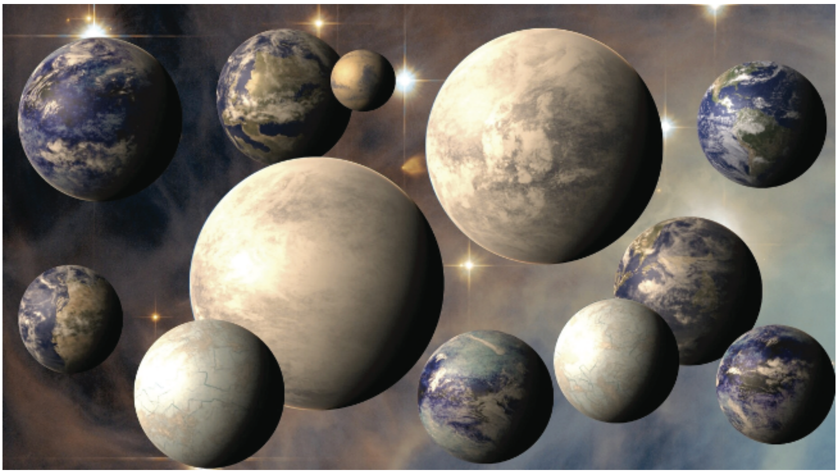

Figure 1.6 *Habitable worlds orbiting other stars. As this artist's impression makes clear, the detection of rocky worlds around other stars offers us the possibility of a statistical assessment of how common Earth-like worlds are in the cosmos, an analysis of their diversity, and the possibility of determining whether they host detectable life.* Source: Reproduced with permission of NASA/JPL-Caltech/R. Hurt (SSC-Caltech).

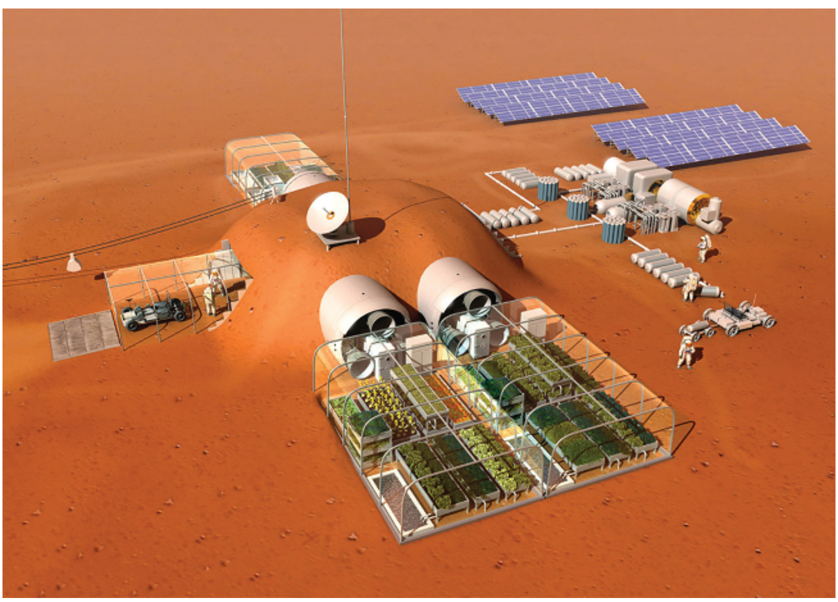

Figure 1.7 *Astrobiology is concerned with the human future beyond the Earth. Can we establish stations on other planetary surfaces and will they eventually become self-sustaining?* Source: Reproduced with permission of NASA.

Astrobiology is not just about non-human life on our planet. As a tool-building civilization that has the capacity to travel beyond Earth and even change the life support system of our own spaceship Earth, our own past and future are part of a complete investigation of the relationship between life and its cosmic environment. In the final chapter, we contemplate the future and fate of our own civilization. We can ask questions about ourselves such as: Will humans leave Earth permanently? How do we settle on other planets? How do we preserve Earth while settling in space? How will we adapt to space? Can society be successfully expanded to these environments? (Figure 1.7). These are not so much scientific questions, more technical questions, but they very much have a bearing 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.

In summary, each chapter in this textbook is designed to present a text on a particular aspect of the link between life and the cosmos. I have attempted to explain some of the principles of astrobiology with respect to each subject area, so that you can read the book in a structured, directional way. Alternatively, you can pick and choose aspects of astrobiology that are of special interest for a whole astrobiology course or parts of a course by reading selected chapters.

1.3 Some Other Features of the Textbook

There are a few other general points I'd like to make about the chapter contents of the textbook. You will notice that the units I use in the textbook are not consistent throughout. For example, growth temperatures of microorganisms are usually shown 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 multidisciplinary nature of astrobiology.

In all the chapters, I have included some other information shown in boxes. Some of the boxes present points of debate in astrobiology that are worth discussing with others or contemplating yourself. These "Discussion Points" are an opportunity to get you to think about ideas in different fields that link to astrobiological questions. I have also written them in places where the material might seem very conventional. I hope they will stimulate you to think about the material being described in new ways. For example, is the biochemical structure of life on Earth something universal or a very particular outcome of Earth's experiment in biological evolution? Such a question should encourage you to think about what the basics of biology might, or might not, tell us about life elsewhere, if it exists. I have attempted to provide some similar thoughts and questions in all the chapters. The content and questions in these boxes are by no means exhaustive, and you should use them to encourage other discussions or come up with new questions. In particular, try to think about questions that bridge different chapters and the different fields in the book.

Here and there I have included some textboxes 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 flavor of the modern nature of international science.

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 the main contributions. Instead, I've suggested two or three popular and/or technical 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 think will 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 listed.

At the end of each chapter, I have provided some questions for review and reflection. The answers to these questions are within the chapters themselves and do not require new information. Their purpose is to offer a means for some structured review of the chapter content and to help consolidate your knowledge. Even if you choose not to produce written answers, you might like to read them and ponder the answers as a way to ensure you have grasped the main ideas in each chapter.

There is yet another dimension of astrobiology that I have touched on in this book. I often get asked by students, "What degree do I need for astrobiology? What field should I take an interest in to become an astrobiologist?" 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. Throughout the book, I've included sections that contain some personal information about a selection of astrobiologists, particularly colleagues early in their careers. I've shown their original degree areas, what motivates them, and how they got into astrobiology. Their career interests are not necessarily directly aligned to the subject of the chapter in which they appear, but their stories are distributed throughout the book. There are many fine people in astrobiology, and I'd like to emphasize that there is no significance to my selection or omission of these astrobiologists. I chose a selection of outstanding colleagues whom I thought would exemplify the variety of disciplines from which astrobiologists are currently launching their careers.

Figure 1.8 *Metrodorus of Chios, ancient Greek philosopher. He wondered about the existence of other worlds like our own.* Source: Reproduced with permission of Keith Schengili-Roberts, https://commons.wikimedia.org/wiki/File:Metrodorus-PergamonMuseum.png.

1.4 A Brief History of Astrobiology

Having explored the main questions in astrobiology and summarized them, we might ask ourselves when all this scientific interest began. Sometimes a historical perspective on any science can be useful to understand how we got here and why certain questions have become prominent lines of enquiry. A thorough review of the history of space sciences and where astrobiology fits within it could (and indeed does) consume entire books. This textbook is more about the science than the history of astrobiology, but at this point it is worth making some observations about its historical origins to provide some introductory context.

The questions that astrobiology asks are, from a philosophical standpoint, ancient. This is particularly the case for the question of whether we are alone in the Universe. Although this is just one part of astrobiology, let us briefly explore this history. Greek philosopher, Metrodorus of Chios (fourth century BCE; Figure 1.8), a student of Democritus (c. 460–370 BCE) (Democritus proposed an early 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." In other words, if you walk into a field, you rarely see one ear of wheat in a large field that is otherwise completely dead. Where there is one ear of wheat, there are usually lots. Metrodorus was essentially saying: Surely the existence of planet Earth implies many planet Earth's in the Universe? The Greeks had a very different view of the Universe than the one we have today, so we shouldn't draw too many conclusions about what was going through his mind. The Greeks had no real concept of the planets as rocky bodies or the vast distances to the stars. They thought that all the stars were held on the surface of a huge sphere. Metrodorus's statement was, nevertheless, a remarkable line of thought, because even today we still ask the question: Does life on Earth imply life elsewhere? We ask this with the benefit of modern technology and astronomical observations, but the basic conceptual question remains the same: Do the origin and evolution of life on our planet allow us to say anything about the universality of biology?

Metrodorus's view of the world was very different from Aristotle's (384–322 BCE), who asserted the uniqueness of Earth in the cosmos. The idea that Earth was the center of the Universe was based on the observation that the stars never moved with respect to one another, which the ancients interpreted to be a result of the fixed position of Earth rather than the great distances to the stars. Aristotle's view would dominate for many centuries. Until the Enlightenment (during the seventeenth and eighteen centuries), the idea that Earth was the sole inhabited world in the cosmos held its grip on the public view, bolstered by religious doctrine.

In the sixteenth century, the geocentric view of the Universe, which firmly placed Earth as the center of the action, was overturned by Nicolaus Copernicus (1473–1543) (Figure 1.9). He was not the first person to consider that the Sun was at the center of the Solar System and Earth orbited around it. Greek philosopher Aristarchus proposed a heliocentric model, but Copernicus's treatise, *De revolutionibus orbium coelestium* (On the Revolutions of the Heavenly Spheres), caused a landmark shift away from the geocentric view. The Copernican outlook paved the way for a view of the cosmos that would allow for the idea that stars may be other suns.

In the sixteenth century, more enquiring and inquisitive minds appeared and, with them, new speculations about Earth's place in the larger order of things. One of the most astonishing speculations about worlds beyond Earth was made by the Italian Dominican friar, mathematician, and philosopher Giordano Bruno (1548–1600; Figure 1.10), 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."

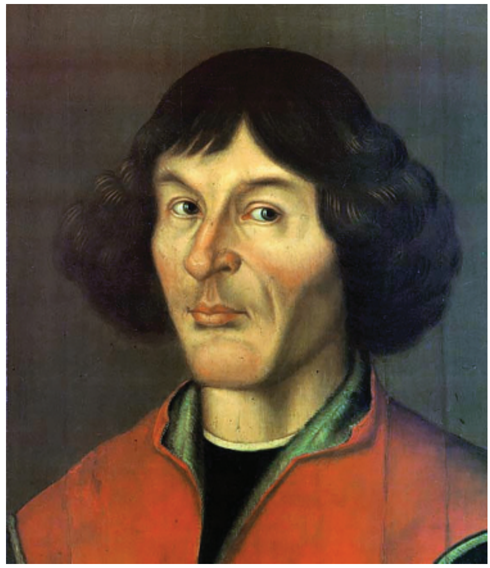

Figure 1.9 *Nicolaus Copernicus, renaissance mathematician and astronomer. He advanced a heliocentric model of the Solar System.* Source: Reproduced from the "Torun portrait," anonymous, c. 1580.

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 – because they are small and dark. 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 so-called "plurality of worlds," the idea that there are other Earth-like planets providing homes for creatures in the Universe.

During the early Enlightenment in the seventeenth century, a major technological step forward was taken with the invention of the telescope. This allowed scientists to see new moons and planetary bodies in our Solar System and to develop a more accurate view of how the Solar System was structured. One might be convinced that this should have reduced speculation, since with much more data available about what was in the Solar System, thoughts about conditions on other worlds could be more constrained. However,

Figure 1.10 *Giordano Bruno, Dominican friar, mathematician, and philosopher. He speculated about other Earth-like worlds (A bronze statue by Ettore Ferrari [1845–1929], Campo de' Fiori, Rome).* Source: Reproduced with permission of Jastrow, https://commons.wikimedia.org/wiki/File:Giordano_Bruno_Campo_dei_Fiori.jpg.

the effect was the opposite. With solid evidence for the presence of other worlds in the Solar System that were planetary bodies like the Earth and Moon, but with little information about their surfaces and whether they were appropriate for life, speculation went wild.

Christiaan Huygens (1629–1695), who discovered Saturn's moon Titan, and who 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."

His book followed on the heels of *Conversations on the Plurality of Worlds*, published by Bernard le Bovier de Fontenelle (1657–1757) in 1686, an enormously popular book at the time about the inhabitants of the Moon and other planetary bodies. The book is set up as a conversation in a moonlit garden with an intrigued marquise keen to know about the Solar System and how the cosmos works. It is a timelessly delightful and short book. These popular works did much to ignite the public imagination.

William Herschel (1738–1822), discoverer of Uranus and infrared radiation, after observing the strangely circular craters of the Moon speculated about them, 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."

Further enthusiasm for the possibility of extraterrestrial life was advanced by Camille Flammarion (1842–1925) in a series of books including *La Pluralité Des Mondes Habités* (The Plurality of Habitable Worlds) in which he emphasized that life elsewhere should adapt to its environment and would be channeled by the environmental characteristics of different planets, although he stressed that we could probably not predict exactly how it might evolve.

As late as 1909, Percival Lowell (1855–1916), observer of the infamous Martian "canals" (Figure 1.11) 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 examples 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. Second, these quotes are a warning from the past. 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.

Herschel's observations on lunar craters being the fortresses of lunar towns are a particularly interesting

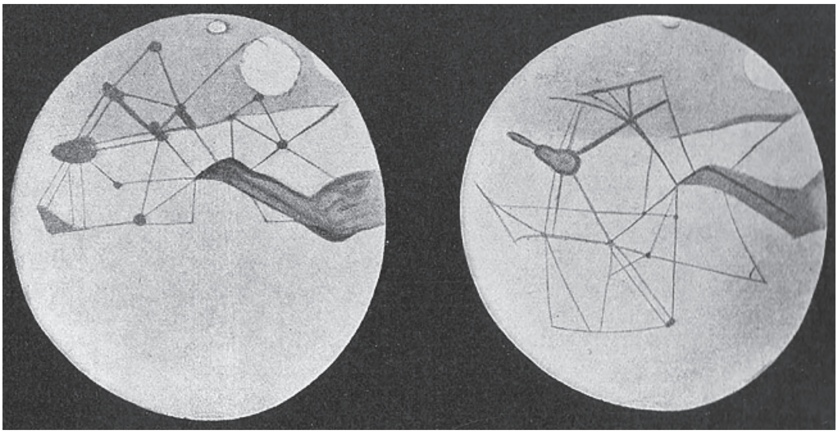

Figure 1.11 *The "canals" of Mars as depicted by astronomer Percival Lowell. He was convinced he could see artificial canals, built by Martians, on the surface of the planet.* Source: Reproduced with permission of Perelman, https://commons.wikimedia.org/wiki/File:Lowell_Mars_channels.jpg.

lesson. At the time when he was writing, asteroid and comet impacts were not understood to be an important geological phenomenon. It would be much later that we would understand that these events do occur and that they make craters. Even more interesting is the knowledge that most impacts, unless they occur at a very oblique angle, tend to create circular craters so that a planetary surface, after being pummeled by impacts for billions of years, will record many of these beautifully round features (Figure 1.12).

In hindsight, the perfectly circular structures Herschel observed on the Moon seemed unnatural, the products of an advanced civilization. However, assuming one's geological knowledge is incomplete is always a safer and more parsimonious way to interpret data than explaining observations using biology. This is an application of Ockham's razor, a philosophical principle that the explanation that requires the fewest assumptions or speculations is the better one. This principle was propounded by William of Ockham, a Franciscan friar who studied logic in the fourteenth century. It's a very useful principle when you are searching for evidence of life anywhere, in ancient Earth rocks or on other planets.

It was only at the beginning of the space age (Figure 1.13) 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.

Figure 1.12 *Lunar craters. In the eighteenth century, the almost perfectly circular craters on the Moon, prior to any understanding of impact processes, looked suspiciously artificial. This view shows the Capuanus crater, which is 60 km in diameter, in the lower left.* Source: Reproduced with permission of NASA.

Laboratory experiments from the 1950s onwards brought studies of the origin of life into mainstream scientific investigations. Scientists simulated conditions on early Earth and demonstrated the production of amino acids and other building blocks of

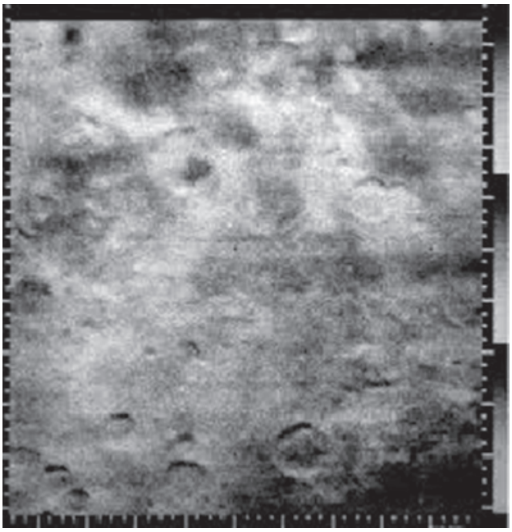

Figure 1.13 *One of the first orbital photographs of Mars, taken by the Mariner 4 craft on July 15, 1965. This and other photographs suggested a dead, desiccated environment unfit for life. The area shown is 262 × 310 km and is a heavily cratered region south of Amazonis Planitia, Mars.* Source: Reproduced with permission of NASA.

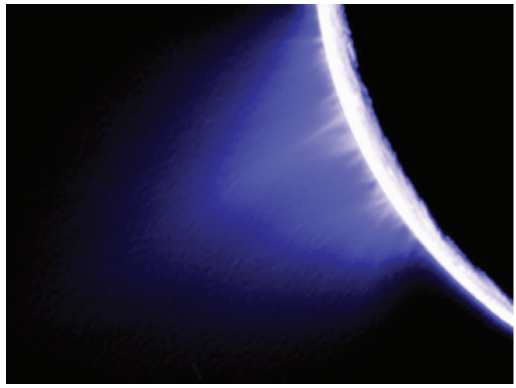

Figure 1.14 *Plumes of water emanating from the south polar region of Saturn's moon Enceladus. These are just one of the many discoveries that have provided an empirical basis with which to test the hypothesis that habitable conditions exist beyond Earth.* Source: Reproduced with permission of NASA.

life from simple gaseous precursors. The publication of evidence, in the 1980s and onwards, of fossil microbial life on 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 another world was undertaken by the robotic Viking biology experiments, which landed on Mars in 1976. The consensus is that their observations are explained by reactive chemical compounds in the Martian soil, not life. However, the landers demonstrated that we can go to other planets and implement the scientific method in the search for life.

Attempts were made in the 1970s to transmit radio messages to other civilizations 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 a complex hydrocarbon cycle on Saturn's moon Titan, has shown us that we can learn about the habitability of planetary bodies and organic chemistry in surprising places (Figure 1.14). 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 astrobiology as the truly experimental science that we know today.

Throughout this history, different terms have been used to describe what we now call astrobiology, 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 1.15). His book explored the possibility of life on other worlds. Tikhov was an interesting and in many ways, a pioneering character. He was particularly fascinated by the idea of using the **absorption spectroscopy** of vegetation to seek vegetation on other planets and even founded a Sector of Astrobotany allied to the Science Academy of Kazakhstan. His notions of using spectroscopy to search for life elsewhere are today at the forefront of methods to search for biosignatures on exoplanets.

Figure 1.15 *Gavriil Tikhov, who wrote an early book called* Astrobiology. *He took a great deal of interest in spectroscopy as a means of looking for signatures of extraterrestrial life. Here he observes the spectroscopic signatures of vegetation.*

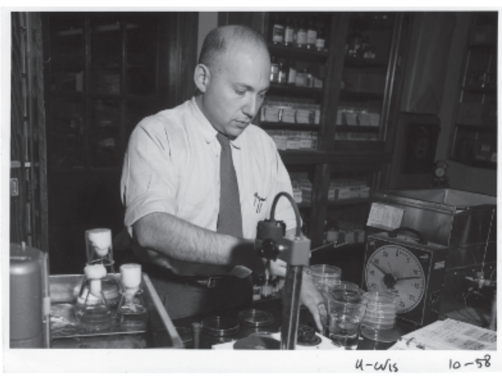

Figure 1.16 *Nobel Laureate Joshua Lederberg. He was at the forefront of the United States' efforts in exobiology in the twentieth century, at his laboratory in the University of Wisconsin, October 1958.*

In 1960, Joshua Lederberg (1925–2008; Figure 1.16), 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 Earth. This term later became associated specifically with the search for life beyond Earth, which now constitutes just one word in the wider term: astrobiology. Other terms that appear in the popular and scientific literature have included cosmobiology, xenobiology, and bioastronomy, the latter used mainly by astronomers.

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

1.5 Conclusions

In this introductory chapter, we discussed what astrobiology is. We found it to be a useful way to consider life in its cosmic context. It addresses a set of scientific questions that include the origin of life, the possibility of life elsewhere, and the past and future of life on Earth. Many of the questions that astrobiology addresses are philosophically ancient, but it has in recent years gained the empirical knowledge to begin to address new questions about life in the Universe. This has been driven in particular by: (i) technological advances in space missions that allow us to directly investigate extraterrestrial environments, and (ii) our growing understanding about the past and future of life on Earth.

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