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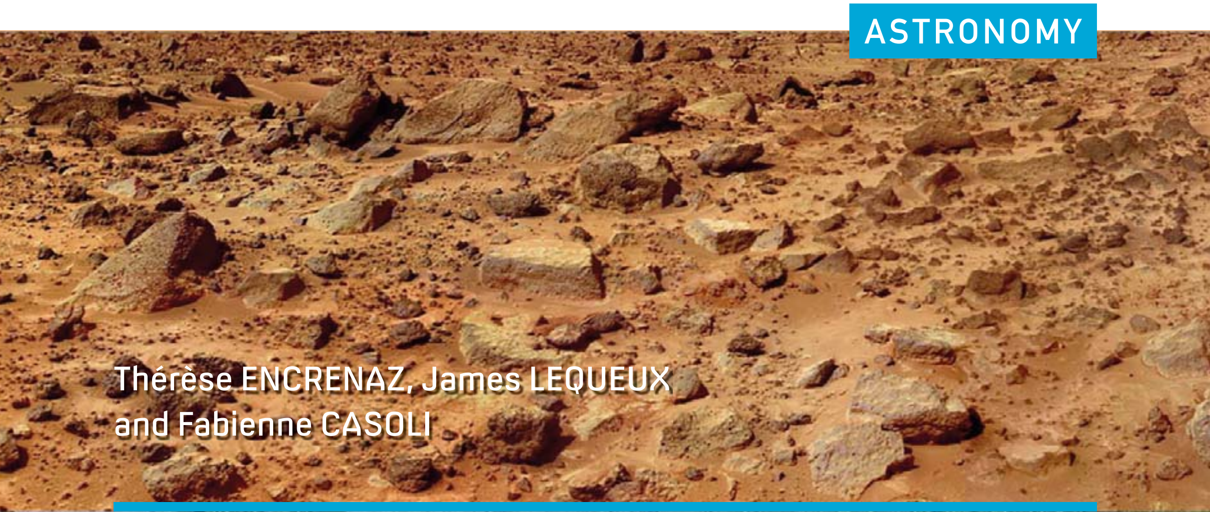
ASTRONOMY



Thérèse ENCRENAZ, James LEQUEUX
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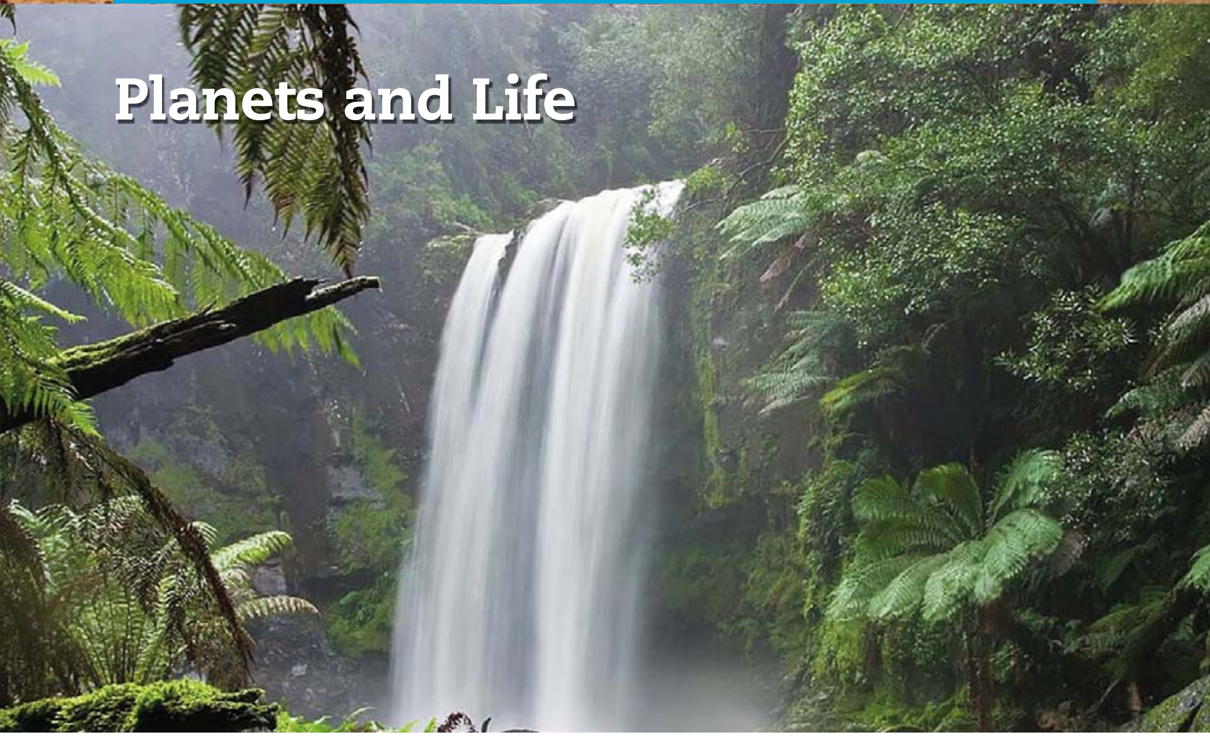

Planets and Life

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Thérèse ENCRENAZ, James LEQUEUX and Fabienne CASOLI

The Earth is the only planet in the Solar System where liquid water is present on the surface, a condition that seems necessary for the development of life. Its sisters Venus and Mars are extremely different. Why did these three planets, born under fairly comparable conditions, evolve to the conditions we observe today? Understanding the physical or chemical factors that are at the origin of such divergent evolutions is a first step in an approach to the problem of the origin of life on Earth.

This question takes on a new dimension with the discovery of thousands of planets around the stars of our Galaxy, some of which could resemble the Earth. Could they be home to life? With their discovery, the question "Are we alone in the Universe?" is no longer limited to our Solar System, and the field of possibilities opens up to infinity. It is now possible to approach the problem from a scientific perspective and not only from a philosophical one, as was the case in the past.

The enthusiasm of the public for the subject sometimes results in sensational and premature announcements. This book reminds us that there is still a long way to go before we can detect life outside the Earth.

Thérèse ENCRENAZ is an expert in planetary atmospheres. She has directed the Department of Space Research of the Paris Observatory and was the vice-president of the Scientific Council of this observatory. She has written several textbooks and popular books.

James LEQUEUX has directed the Nançay radioastronomy station of the Paris Observatory and the Marseilles observatory. He has been for fifteen years editor-in-chief of the European journal Astronomy & Astrophysics. He has published several textbooks and popular books, in particular on the history of science.

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Foreword

With a surface pressure of 1 bar and an average temperature of 15°C, the Earth is the only planet in the Solar System with liquid water on its surface. The surface conditions of Venus and Mars are extremely different, with a pressure close to one hundred times the Earth's value on Venus and less than one hundredth on Mars, and a temperature ranging from more than 460°C on Venus to about –50°C on Mars. How could these three planets, starting from relatively comparable initial conditions, have evolved to the extreme diversity we observe today? Understanding the origin and evolution of the atmospheres of the three terrestrial planets – Venus, Earth and Mars – is a major challenge for planetology. Highlighting the physical or chemical factors that were and are still at play appears as a first step to better understand the context in which life appeared and developed on the Earth.

This question takes a new dimension with the discovery, since a quarter of century, of thousands of extrasolar planets, among which are many "rocky" ones, *i.e.*, with a surface like the terrestrial planets of the Solar System. They are called, according to their mass, "exo-Earths" or "super-Earths". Could some of these exoplanets harbor life? With their discovery, the question "Are we alone in the Universe?", which is as old as humanity itself, is no longer confined to our Solar System, and the field of possibilities opens up to infinity. In this new context, it is more than ever necessary to understand the evolution of the rocky planets and to identify the factors that determine their habitability, *i.e.*, their capacity to allow the emergence and development of life. These factors can be multiple. Some are of physico-chemical nature (pressure and temperature, atmospheric composition); others are related to the planet's environment (nature of the star, presence of a magnetosphere) or some of its parameters (ellipticity of the orbit, obliquity of the planet axis, rotation period).

For more than two millennia, the quest for extraterrestrial life, present from the earliest ages of mankind, has been based on philosophical considerations. It is only since the end of the 19th century that astronomers were able to begin to approach the question in a scientific manner, first with the observation of the planets that surround us, and then, half a century later, with the search for exoplanets around other stars. The end of the 20th century witnessed an avalanche of discoveries that continued and amplified until now. Increasingly complex planetary space missions explore the soil and subsoil of Mars for possible traces of fossil life; others, in the coming decades, will explore the satellites of the giant planets of the outer Solar

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System, some of which may harbor an ocean of liquid water beneath their icy surfaces. In parallel, we now have the possibility to determine the nature of the exoplanets and, in some cases, their atmospheric composition. Among the rocky exoplanets known today, several tens could have a temperature compatible with the presence of liquid water. In one or two decades, this research will be refined to allow, perhaps, to discover on one or more of them oxygen or its derivative, ozone, a possible signature of the presence of life.

In this context of abundant and constantly evolving research, it seemed useful to try to better define the criteria for habitability of rocky exoplanets, those that could shelter life. This book is to some extent the continuation of the book "The Exoplanet Revolution", by J. Lequeux, T. Encrenaz and F. Casoli, published in the same collection in 2020. Like it, it is addressed to all audiences interested in astronomy, planetology and the search for extraterrestrial life. Here, we start from the planets we know well, the three terrestrial planets of the Solar System possessing an atmosphere, to analyze the various physico-chemical mechanisms that could have been responsible for their divergent evolution. Then we will try to extrapolate these results to the rocky extrasolar planets, in order to understand the possible mechanisms of their evolution and to apprehend what could be their conditions of habitability. Finally, we conclude this work by an analysis of the means that could allow us to discover possible traces of life, or even to communicate with eventual distant civilizations.

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Chapter 1

Introduction

Within the planets of the Solar System, our closest neighbors, Venus and Mars, are undoubtedly those that surprise us the most. While they belong, like the Earth, to the family of rocky or "terrestrial" planets, and are, like the Earth, with an atmosphere, they have radically different surface conditions: on Venus, the pressure is about a hundred times the Earth's atmospheric pressure and the temperature reaches 460°C, while on Mars, the surface pressure is less than a hundredth of a bar, and the average temperature is around −50°C! Between these two extremes, the Earth holds an intermediate position, with a surface pressure of the order of one bar and an average surface temperature of 15°C (figure 1.1). How could these three rocky planets, all formed in the inner Solar System 4.5 billion years ago, from relatively similar initial conditions, have evolved towards such radically divergent fates? This question, one of the most fundamental of today's planetology, is addressed in this book.

Understanding the comparative evolution of the terrestrial planets of the Solar System is very important to decipher the origin and evolution of our own environment. With the discovery, over the last two decades, of thousands of extrasolar planets in orbit around neighboring stars, including a growing number of rocky exoplanets, the debate takes on a new dimension. Indeed, the major question about rocky exoplanets is that of their potential habitability: if there is an extraterrestrial form of life, is not this new class of objects the best place to look for it? The first step in this search is to determine the temperature and pressure of their atmosphere. An astronomer observing the planets of the inner Solar System from the nearest star, Proxima Centauri, would find it hard to imagine the extreme diversity of conditions on the surfaces of the Earth's planets. That is to say that the physical properties of rocky exoplanets undoubtedly hold many surprises in store for us, and if we cannot study them in detail today, we must understand the mechanisms that are responsible, in the Solar System, for the divergent evolution of the terrestrial planets.

Why does the planet Venus have such a high temperature today? We now know the reason, and there is a lot of talk these days about it concerning the global warming of our own planet: it is the greenhouse effect (figure 1.2). What is it all

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FIG. 1.1 – Venus, Earth and Mars: relatively similar initial conditions but divergent fates. The relative dimensions of the three planets are respected. © NASA.

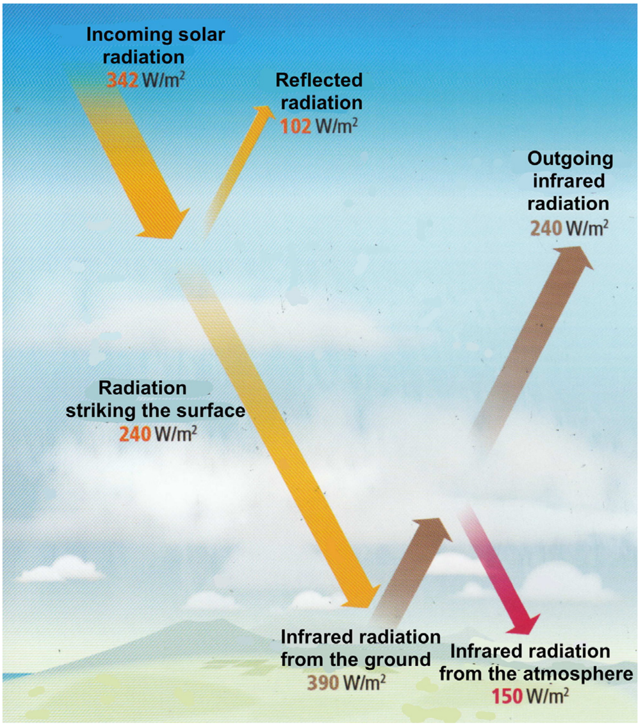

FIG. 1.2 – The greenhouse effect (average figures for the Earth). The atmosphere is transparent in the visible range and solar radiation reaches the surface. When heated, the surface emits infrared radiation which is absorbed by the atmosphere if it contains certain gases with intense infrared vibration modes, such as carbon dioxide CO_2, methane CH_4 or water vapor H_2O. In the case of Venus, CO_2 and H_2O (in the planet's past) have been responsible for the runaway greenhouse effect during its history.

about? The greenhouse effect occurs when an atmosphere is transparent to visible radiation, but opaque to infrared radiation. The glass walls of a greenhouse allow visible solar radiation to pass through, causing the interior of the greenhouse to heat up; as glass absorbs the infrared radiation emitted from the inside, the temperature rises and the effect is amplified. In the case of a global atmosphere, the greenhouse effect occurs if atmospheric gases absorb infrared radiation; this is the case of carbon dioxide CO_2 and also of water vapor H_2O. In the case of the Earth, the main constituents, nitrogen N_2 and oxygen O_2 do not have vibration modes in the infrared, and therefore do not contribute to the greenhouse effect; the increasing emissions of CO_2 are the primary cause of global warming; other gases, such as water H_2O and methane CH_4, also contribute to the greenhouse effect. In the case of Venus, the situation is different. As for Mars, the dominant gas is carbon dioxide, with a small proportion (a few percent) of nitrogen. Since, moreover, the surface pressure of Venus is very large, the very high surface temperature is the result of a strong greenhouse effect due to CO_2.

Why is the Earth's atmospheric composition (about four-fifths molecular nitrogen and one-fifth oxygen) so different from that of Venus and Mars? This is where another key molecule comes into play: water H_2O. It is now established (we will see later how) that the primitive atmospheres of the three planets, Venus, Earth and Mars, were globally similar, with large quantities of carbon dioxide and water and a small proportion of molecular nitrogen. In the case of Venus, closer to the Sun than the Earth, water was, at some point in its history, in the form of vapor, thus contributing to the planet's runaway greenhouse effect. On the other hand, the distance from the Earth to the Sun is such that the Earth's water was found in liquid form in the oceans; carbon dioxide, also very abundant, was trapped at the bottom of the oceans in the form of limestone; thus the two main greenhouse gases disappeared to a large extent from the Earth's atmosphere, allowing the planet to maintain temperate conditions throughout its history.

How can we explain the evolution of Mars? The planet has two notable differences with respect to Venus and Earth: being more distant from the Sun, it is colder (today, water cannot stay on the surface in liquid form) but it is also smaller: its mass is only one tenth of that of the Earth. With a gravity field much lower than that of Venus and the Earth, it could not capture, like its neighbors, a thick atmosphere; it is thought that its primitive atmosphere (today largely disappeared by escape) could not have gone beyond a pressure of a bar. Because of its smaller volume, its internal energy, mainly due to the disintegration of the radioactive elements that the planet contains, was also much less than that of its neighbors, resulting in reduced volcanic and tectonic activity that eventually died out over the course of history.

If the main lines of the evolution of the terrestrial planets seem well defined to us, many open questions remain, starting with that of their habitability. Did Mars and Venus ever shelter a form of life? We are today quite unable to answer. The question becomes even more complicated if we take into account the amount of solar radiation at the beginning of the history of the planets: it is the paradox of the "young Sun". Models of stellar evolution tell us that, about four billion years ago, the Sun's radiation in visible light (which corresponds to the maximum of its energy) was only

70% of its present value. The equilibrium temperatures of the surfaces of our three terrestrial planets were thus lower than what they are today. Hence a major consequence for Venus: the temperature may have been compatible with that of liquid water, and the primitive Venus may have been covered with oceans, and perhaps even, who knows, sheltered life! Unfortunately, if these conditions existed, they did not last: as solar radiation increased, water vaporized (contributing for a time to the greenhouse effect), then was dissociated by solar ultraviolet radiation into hydrogen and oxygen atoms that escaped to the outside. If an ocean (and a fortiori life) ever existed at the beginning of the history of Venus, we will probably never know anything about it, because the traces of it have irremediably disappeared: the surface of Venus is indeed covered with relatively recent volcanoes, less than a billion years old.

The paradox of the "young Sun" also raises questions that are still poorly resolved in the case of other terrestrial planets. How can we explain that the Earth, at the beginning of its history, escaped a "global snowball" episode, its equilibrium temperature being too low to be compatible with the presence of liquid water? One possible hypothesis is that of volcanic eruptions that released into the atmosphere enough greenhouse gases (CO_2 but also CH_4). The same question arises even more acutely in the case of planet Mars. As we will see further on, many clues testify to the presence of liquid water on the surface in the distant past of this planet. How could liquid water have remained on Mars when its equilibrium temperature was incompatible (by several tens of degrees!) with the presence of liquid water? The question is still open.

With the Earth and Mars, we fortunately have an avenue of research: unlike Venus, these two planets keep archives on their surfaces that allow us to trace their history back nearly four billion years. This is why Mars is still the subject of sustained space exploration, with the objective of searching for possible traces of a past – or even present – life. Failing that, research is focused on the characterization of "habitable" sites, *i.e.* sites that meet the physico-chemical criteria compatible with the emergence of life (figure 1.3). These criteria relate in particular to soil acidity (preferably neutral), its salinity (moderate) and its chemical composition (including elements C, H, N, O, P, S). Can we go further? Space exploration of Mars continues and the future will tell us…

From terrestrial planets to rocky exoplanets, it is only a step away. It has been more than twenty years since planets, known as "extrasolar planets" or "exoplanets", were discovered around stars close to the Sun. To everyone's surprise, the first objects discovered (the easiest to detect from an observational point of view), were giant exoplanets very close to their star! This discovery created a real conceptual revolution, challenging our own understanding of the Solar System. Indeed, according to the formation model of the Solar System, widely accepted today in the scientific community, giant planets were formed far from the Sun, by accumulation of gas around an icy core, whereas terrestrial planets were formed from a smaller and denser rocky core. The first discoveries of exoplanets thus showed that the model of the Solar System was not universal… The explanation of this paradox originates in the motion of the planets within the protoplanetary disc: we speak of "migration", a process that, until then, was not much taken into account by planetary scientists.

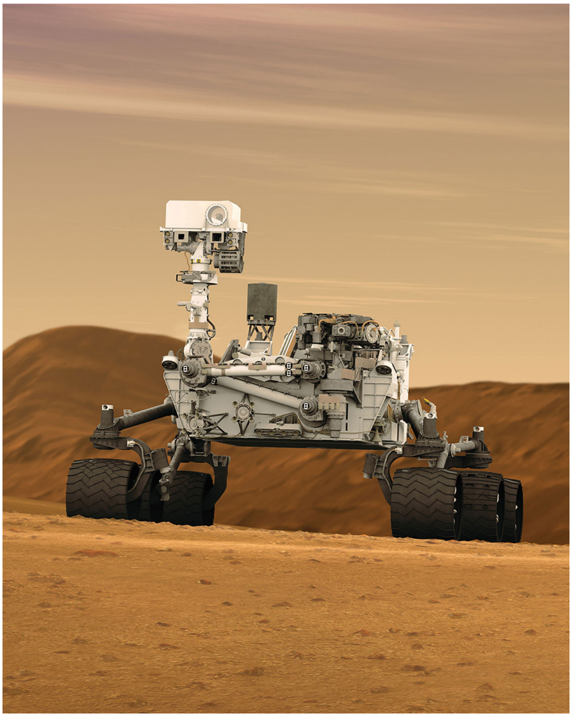

Fig. 1.3 – The Mars Science Laboratory (MSL) space mission, with its rover "Curiosity", launched by NASA in November 2011 and in operation on the surface of Mars since August 2012, has the main objective of determining whether conditions favorable to life may have existed on Mars, in particular through the search for organic molecules. The rover has indeed identified, near Mount Sharp, the remains of an ancient lake that could constitute a "habitable" environment. © NASA.

Very effective within exoplanetary systems, this process has also proved to be important for understanding the dynamic history of our own Solar System.

While the first exoplanets detected were mostly giant planets, identified from the Earth from the oscillations of their host star with respect to the planet's motion, a new revolution occurred with the launch of the *CoRoT* and, even more, the *Kepler* space missions, dedicated to the detection of exoplanets during their passage (called transit) in front of their host star. *Kepler* has thus detected thousands of new exoplanets, including objects of all sizes, among which are new families of planets: "mini-Neptunes", "super-Earths", even "exo-Earths". Although the physical nature of these planets is not yet known, it is very likely that many rocky exoplanets are among the new discoveries. The first measurements of the atmospheres of the exoplanets show us that water vapor is often present there. Among the rocky exoplanets, some of them, located at the right distance from their host star – in what is called the "habitability zone" – could harbor water in liquid form, and thus perhaps

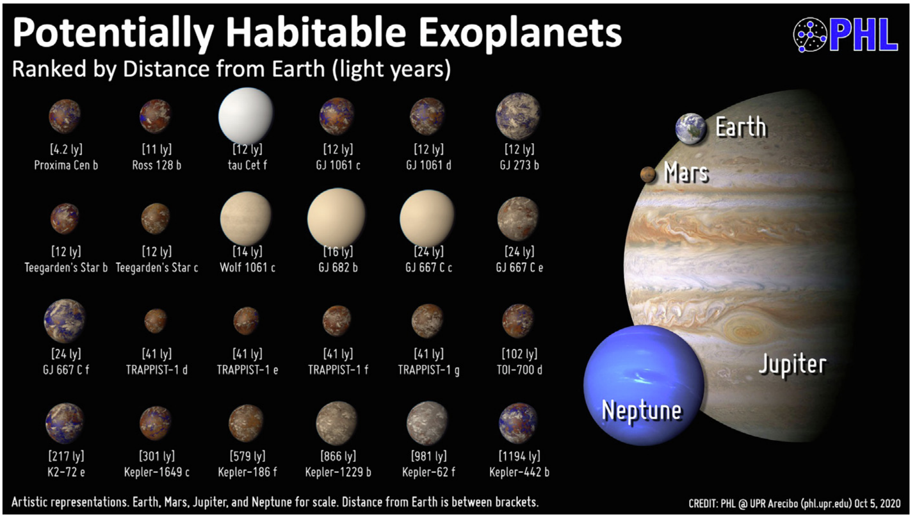

Fig. 1.4 – Among the detected rocky exoplanets, some could experience a temperate environment, given the amount of light they receive from their host star: they are in the "habitable zone" of their star, the one whose temperature is compatible with the presence of liquid water on their surface. However, the composition of their atmospheres remains to be identified, in order to know if water is present, a fortiori in liquid form. This figure represents a sample selected by researchers at Arecibo in 2020. Only the sizes of the exoplanets are meaningful.

constitute potential niches for the emergence and development of life (figure 1.4). The exploration of exoplanets thus opens up immense perspectives in terms of exobiology.

A first question is obvious: if life ever existed on the surface of an exoplanet, how could we identify it? We will come back to this notion in the course of this book. Let us simply say that, according to biologists, living matter can be characterized by the capacity for reproduction, the ability to use the energy of the environment, the separation from this environment, the creation of an organization, and finally the capacity for evolution by mutation. Of course, the forms that life can take can be infinitely diverse, as shown by the only example we know of, that of the Earth. We still do not know how life appeared on Earth. However, as we will see later, chemists and biologists, again based on our experience on Earth, agree to define some essential conditions: the presence of carbon, liquid water, a source of energy, and sustainability. These are the criteria that will be used in the quest for extraterrestrial life, whether within the Solar System or beyond.

How can the presence of life be demonstrated by observing the atmosphere of an exoplanet? Given the immense distances that make illusory the prospect of a space mission, even a robotic one, to approach the object in question, we are limited to remote sensing methods, the most promising of which is spectroscopic characterization. We will have to determine which constituents, in the atmosphere or on the surface of the object, could betray the presence of life. Some tracks are already opening up: in the atmosphere, the presence of molecular oxygen O_2, in substantial quantities, as well as its photochemical derivative, ozone O_3, seem to be a fairly convincing clue, but we will see that the reality is more complex and that the simultaneous presence of other constituents – H_2O, CH_4, CO_2, N_2O… – is probably also necessary for the characterization of life. On the surface, the presence of chlorophyll would be a determining diagnosis, but we will see that its spectroscopic detection is almost impossible. And let us not forget that life on another planet may have taken very different forms from the photosynthesis we know on Earth.

The main goal of this book is to explore the habitability conditions of rocky exoplanets, starting from what we know: the terrestrial planets of the Solar System with an atmosphere. By observing their divergent evolution, by studying – as far as possible – their past or present habitability conditions, we will try to extrapolate these notions to the rocky exoplanets, of which we know very little at the moment. Among the currently known exoplanets, we will try to identify the most favorable candidates, those which seem to be the best placed in relation to the habitability zone of their star. Finally, we will try to define which observations would allow us to conclude to the possible or probable presence of life. Our first objective is the search for life forms on the surface of an exoplanet, likely to present similarities with the development of life on Earth over the last 600 million years. There are other niches potentially favorable to life: these are the oceans of liquid water that are sheltered under the surface of several of the outer satellites of the Solar System; this is the case, in particular, of Europa, a satellite of Jupiter, and Enceladus, a satellite of Saturn. Such environments could exist around possible satellites in orbit around giant exoplanets; although, with a few exceptions, these have yet to be discovered, their existence is very plausible according to models of planetary formation. However, the detection of life forms within these aqueous media seems *a priori* much more difficult than for those which would have developed on the surface of an exoplanet.

In the first part of this book, we describe the past history of the terrestrial planets, starting from the model of the formation of the Solar System which will make us discover the emergence of two classes of planets, the terrestrial planets near the Sun and the giant planets beyond. This model will allow us to understand the nature of the gases originally present in the atmospheres of these planets. We will also see how the migration of the giant planets during their history has influenced the dynamic history of the whole Solar System. In a second part, we will describe the three terrestrial planets with atmospheres, the history of their exploration, the state of our knowledge about them and finally their different evolution scenarios. Finally, in the third part, we will extrapolate this knowledge to what we know about rocky exoplanets. We will look for targets potentially favorable to the search for life and we will try to define the observations that could allow us, within one or several decades, to finally discover, who knows, the signs of extraterrestrial life. To conclude, we will present some lines of thought to try to define the future stages of exobiology, and we will address the question of a possible communication with extraterrestrial civilizations, if we manage to discover their existence.

Chapter 2

The Formation of Terrestrial Planets

2.1 From Antiquity, the Myth of the Plurality of Worlds

From the eve of civilizations, man has never ceased to question himself about his place in the Universe. Since Antiquity, Greek philosophers have raised this question, with a variety of answers. Plato (428–348 B.C.), a proponent of the uniqueness of the Earth, wrote in *Timæus*:

> In order that this World [the Earth] may be like, in its unity, a perfect creature, its Author did not make two of them, nor an infinite number, but this Heaven was born, remains and will be forever one and unique.

However, Epicurus (ca. 342–270 B.C.), a century later, supported the opposite concept of an infinite number of worlds. Supporter, like Democritus (ca. 460–370 B.C.) before him, of the "atomist" thesis according to which matter consists of invisible atoms that can combine in various forms, he wrote in his *Letter to Herodotus*:

> It is not only the number of atoms, but the number of worlds that is infinite in the Universe. There is an infinite number of worlds similar to ours and an infinite number of different worlds.

At the same time, the astronomer and mathematician Aristarchus of Samos (370–230 B.C.), considering the diameters of the Sun and the Moon, stated for the first time the hypothesis of heliocentrism, which is also mentioned by Archimedes (287–212 B.C.) in the preface to his treatise *Arenarius*; but this hypothesis, in contradiction to the geocentric conception of Aristotle (384–322 B.C.), quickly felt into oblivion.

Three centuries later, the Latin philosopher Lucretius (ca. 98–55 B.C.) took up Epicurus' ideas in his poem *De Rerum Natura*:

> The sky, the Earth, the Sun, the Moon, the sea, all the bodies are not unique, but rather infinite in number.

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Epicurus, like Lucretia and their followers, were fiercely opposed to gods and religion. The development of Christianity plunged their theories into oblivion for nearly a millennium, until Nicolaus Cusanus (1401–1464) and the Copernican revolution. Then, many astronomers and philosophers took up the concept of the plurality of worlds; like their Greek predecessors, they most often associated the notion of habitability with it. The most emblematic among them is undoubtedly Giordano Bruno (1548–1600) who, in his works *La Cena de la Ceneri* (The Ashes Banquet) and *De l'Infinito Universo e Mondi*, published in 1584, postulated that the stars are other suns, no doubt surrounded by planets that could themselves be inhabited. Sentenced to be burned at the stake by the Church, Giordano Bruno paid for his audacity with his life.

If Giordano Bruno's convictions were mainly philosophical, his ideas were adopted to various extents by astronomers who, after Galileo, rallied to heliocentrism. Thus Johannes Kepler (1671–1630) published after his death a work of "science fiction", the *Somnium*, in which he envisaged a life on the Moon. The idea was taken up, in a philosophical and literary fashion, by Francis Goldwin (1562–1633) and John Wilkins (1614–1672) in England, then in France by Cyrano de Bergerac (1619–1655) and later by Voltaire (1694–1778). These ideas were also developed by Christiaan Huygens in his *Cosmotheoros* published in 1695, and by Bernard le Bovier de Fontenelle (1657–1757) in his *Entretiens sur la pluralité des mondes* (Conversations on the plurality of worlds) of 1686. In the preface to a reprint of this work, Jérôme de Lalande wrote in 1801:

> The resemblance is so great between the Earth and the other planets, that if one admits that the Earth was made to be inhabited, one cannot refuse to admit that the planets are also inhabited,

and further:

> What I say about the planets that revolve around the Sun will naturally extend to all the planetary systems that surround the stars.

A century later, these ideas were taken up anew and popularized by the astronomer Camille Flammarion (1842–1925) in his work *La pluralité des mondes habités* (The plurality of inhabited worlds) published in 1862, which led to his dismissal from the Paris Observatory by its director at the time, Urbain Le Verrier. In 1892, Flammarion joined the thesis of the "Martian canals" defended by Giovanni Schiaparelli (1835–1910) and Percival Lowell (1855–1916): see chapter 3. The myth of life on Mars continued until the advent of the space age.

But what about life outside the Solar System? The debate has continued among biologists who wonder about the origin of life. Thus Jacques Monod (1910–1976), in *Le Hasard et la Nécessité* (*Chance and Necessity*), published in 1970, expressed the conviction that man is alone in the Universe. But the search for extraterrestrial life went on, nevertheless, in multiple forms, in the Solar System and beyond, and attempts to communicate with possible extraterrestrial civilizations continue through the SETI project (see chapter 9).

Bibliography

Bougher S.W., Hunten D.M., Phillips R.J. (1997) *Venus II: geology, geophysics, atmosphere and solar wind environment.* University of Arizona Press, Tucson.

Catling D.C., Kasting J.F. (2017) *Atmospheric evolution of inhabited and lifeless worlds.* Cambridge University Press, Cambridge.

Connes P. (2020) *History of the plurality of worlds* (J. Lequeux, Ed.). Springer Nature Switzerland AG.

Coustenis A., Encrenaz T. (2013) *Life beyond Earth*. Cambridge University Press, Cambridge.

Coustenis A., Crovisier J., Fulchignoni M., Lamy L., Roques F., Zanda B. (2021) *The solar system, origin and evolution* (T. Encrenaz, J. Lequeux, Eds), 2 vol. ISTE, London.

Encrenaz T. (2013) *Planets, ours and others – from Earth to exoplanets*. EDP Sciences and World Scientific.

Forget F., Costard F., Lognonné F. (2007) *Planet Mars, story of another world*. Springer, New York.

Haldane J.B.S. (1985) *On being the right size and other essays.* Oxford University Press, Oxford.

Kieffer H.H., Jakosky B.M., Snyder C.W., Matthews M.S. (1992) *Mars.* University of Arizona Press, Tucson.

Lequeux J., Encrenaz T., Casoli F. (2020) *The exoplanet revolution*. EDP Sciences, Les Ulis.

Lissauer J.J., de Pater I. (2019) *Fundamental planetary science – physics, chemistry and habitability*, 3rd edn. Cambridge University Press, Cambridge.

McSween H.Y., Jr. (1999) *Meteorites and their parent planets*. Cambridge University Press, Cambridge.

Ollivier M., Encrenaz T., Roques F., Selsis F., Casoli F. (2009) *Planetary systems: detection, formation and habitability of extrasolar planets*. Springer, Berlin.

Perryman M. (2018) *The exoplanet handbook*, 2nd edn. Cambridge University Press, Cambridge.

Rothery D.A., Gilmour I., Sephton M.A. (2018) *An introduction to astrobiology*, 3rd edn. Cambridge University Press, Cambridge.

Schulze-Makuch D., Bains W. (2017) *The cosmic zoo, complex life on many worlds*. Springer, New-York.

Schulze-Makuch D., Irwin L.N. (2018) *Life in the universe*. Springer Praxis Book, Springer Nature Switzerland AG.

Taylor F.W. (2014) *The scientific exploration of Venus*. Cambridge University Press, Cambridge.

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