Chapter 6
Pioneering Concepts of Planetary Habitability

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Abstract Famous astronomers such as Richard A. Proctor (1837–1888), Jules Janssen (1824–1907), and Camille Flammarion (1842–1925) studied the concept of planetary habitability a century before this concept was updated in the context of the recent discoveries of exoplanets and the development of planetary exploration in the solar system. They independently studied the conditions required for other planets to be inhabited, and these considerations led them to specify the term "habitability." Naturally, the planet Mars was at the heart of the discussion. Our neighboring planet, regarded as a sister planet of Earth, looked like a remarkable abode for life. During the second part of the nineteenth century, the possibility of Martian intelligent life was intensively debated, and hopes were still ardent to identify a kind of vegetation specific to the red planet. In such a context, the question of Mars' habitability seemed to be very valuable, especially when studying hypothetical Martian vegetation. At the dawn of the Space Age, German-born physician and pioneer of space medicine Hubertus Strughold (1898–1987) proposed in the book *The Green and Red Planet*: *A Physiological Study of the Possibility of Life on Mars* (1954) to examine the planets of the solar system through a "planetary ecology." This innovative notion, which led to a fresh view of the concept of habitability, was supposed to designate a new field involving biology: "the science of planets as an environment for life" (Strughold 1954). This notion was very close to the concept of habitability earlier designated by our nineteenth-century pioneers. Strughold also coined the term "ecosphere" to name the region surrounding a star where conditions allowed life-bearing planets to exist. We highlight in this chapter the historical aspects of the emergence of the (modern) concept of habitability. We will consider the different formulations proposed by the pioneers, and we will see in what way it can be similar to our contemporary notion of planetary habitability. This study also shows the convergence of the methodological aspects used to examine the concept of habitability, mainly based on analogy.

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6.1 Introduction

The question of planetary habitability is nowadays a topical subject thanks to the continuous discoveries of exoplanets. Exo-Earths, in particular, are the center of interest of astrobiologists. Exoplanets' habitability is estimated according to the specific characteristics of each exoplanet and the precise habitable zone of each newly detected planetary system. As underlined by Impey in this volume (Impey 2013), it remains however unclear if our solar system is "typical" or not. The detection of more and more numerous multiple planetary systems and the presumption that in the Galaxy every star could have at least one planet, have enlarged our understanding of planetary systems. We have nowadays to contemplate studying an "exoplanet zoo" (Impey 2013). Perhaps are we surrounded with millions of habitable Earth-like planets.

However, habitability is not a new concept. It has been defined in scientific terms and widely discussed among the astronomical community during the second part of the nineteenth century—even if this notion was already present during previous centuries (e.g., Fontenelle 1686; Huygens 1698). Some personalities of astronomy of that time have examined in detail what could be, in our solar system, habitability for every planet. In this chapter, we will successively present the pioneering viewpoints of Richard A. Proctor, Jules Janssen, and Camille Flammarion. The planet Mars will be one of the main objects of this study, within a context devoted to the investigation of the puzzling Martian surface.

Besides this, the second part of the nineteenth century was rich in new methods and theories. Biological evolution and spectroscopy represented, respectively, breakthroughs in theory and technique (Dick 1996). On one hand, spectroscopy confirmed the unity of nature by observational methods, leading to the detection of similar molecules in different planetary or stellar environments. This new science strengthened the idea that the buildings blocks of life were common in the universe. On the other hand, Darwin's theory of evolution provided a scientific background in which physical evolution of the universe became conceivable, along with mechanisms of evolution from inorganic matter to life (Dick 1996).

At the dawn of the Space Age, nearly one century later, the question of habitability reappeared in a completely different context. While the first programs for the launch of artificial satellites were starting, the problem of life in space (human life in outer space) and the question of other life elsewhere, began to be examined in concrete terms. We will present in this chapter Hubertus Strughold's viewpoint—as a pioneer in space medicine—about planetary ecology, a concept similar to habitability.

Finally, this chapter will highlight how close the early concepts of habitability could be to the contemporary ones, when one considers the recent discoveries about exoplanets and the exploration of satellites of giant planets in our solar system.

6.2 The Question of the Plurality of Worlds Through the Ages

The historical question of the plurality of worlds has been studied in detail in reference books, such as those of Michael J. Crowe (1986) and Steven J. Dick (1982, 1996). An overview of this debate in the Western intellectual context prior to 1900 is presented in this volume by Michael J. Crowe and Matthew F. Dowd (Crowe and Dowd 2013). This question is entirely linked to the cosmological models that were accepted during each historical period. It is particularly clear that the heliocentric view of the universe has offered new possibilities leading to the admission that other worlds could be inhabited in the universe. Of course, this last idea is older than that. The question of the plurality of worlds goes back to antiquity and was supported by the atomistic philosophers, such as Leucippus, Democritus, Epicurus, and Lucretius. According to their philosophy, there are innumerable worlds that follow one another in an infinite universe. However, these assumptions remained essentially a philosophical school of thought, without calling into question the central place of the Earth in the universe.

The problem of the plurality of worlds reappeared once the Copernican theory (stated by Nicholas Copernicus in *De revolutionibus orbium coelestium*, 1543) had dethroned the central place of the Earth in the universe, in spite of many difficulties this new paradigm has had to face. In this model of the universe, every planet of the solar system turned round the Sun. Hence, the Earth became no more than one planet among others, and one of the main conclusions was that our planet was no more the center of the universe. It turned out to be a planet "like the other ones" in the solar system. It became therefore quite conceivable that other planets could be inhabited. The ideological consequences of that new paradigm were significant.

One of the most famous authors of that time to have defended the idea of the plurality of worlds was Giordano Bruno (1548–1600), an Italian Dominican friar. He published in 1584 a work of great consequence enclosed in his "Italian Dialogues," entitled *The Infinity, the Universe and Its Worlds*. In this writing Bruno defended the idea of infinite inhabited worlds going round innumerable suns located in an infinite universe. His system of thought could be considered as a materialistic pantheism in which God and the world were one. This idea was very disturbing for the Catholic Church, considering that it left no room for a greater infinite conception named God. Bruno was burned at the stake at Rome in 1600 after the Roman Inquisition had accused him of heresy. The question of the plurality of worlds was just one accusation among many pronounced against Bruno (Raulin Cerceau and Bilodeau 2011).

At the same time, astronomical observations strengthened the new paradigm of heliocentrism. In 1610, Galileo Galilei (1564–1642) discovered the four largest moons of Jupiter with his astronomical telescope. If the planet Jupiter was surrounded by moons, it became difficult to maintain that the Earth was the center of the universe. In spite of strong confrontations with the Catholic Church, Galileo largely contributed to promote the heliocentric view of the universe. In the meantime, heliocentrism was demonstrated by Johannes Kepler's works about the planetary motions in the solar system. However, during the first part of the seventeenth century, the idea that other worlds similar to ours could exist was still supported by very few people. Kepler himself was interested in Moon's habitability (*Somnium*, 1634), but he perceived that strong difficulties remained to assert that our planet was like any other bodies of the solar system.

This idea was more openly tackled at the end of the seventeenth century, as curiosity in planetary studies was increasing. Bernard le Bovier de Fontenelle (1657–1757), a French philosopher and writer, published in 1686 his *Entretiens sur la Pluralité des Mondes* (*Conversations on the Plurality of Worlds*). This influential piece of scientific popularization was presented in the form of a pleasant and elegant dialogue between a philosopher and a Marquise (*la Marquise de la Mésengère*). It expounded the Copernican world system and speculated about the inhabitants of other planets in the solar system.

During the same century, Christiaan Huygens (1629–1695), a Dutch astronomer and mathematician, wrote a treatise entitled *Cosmotheoros*: *or, Conjectures Concerning The Inhabitants of The Planets*, posthumously published in 1698 by his brother (Huygens 1698). This book presented Huygens' speculations on the construction of the universe and on the question of planetary habitability, as deduced from his own astronomical observations and those of other astronomers. However Huygens' viewpoint could be considered as anthropocentric, since he proposed that "men" (and animals too) living on other planets were very similar to the terrestrial ones (same mind, same body, same senses).

Our study will be focused on the second part of the nineteenth century, marked by many developments in astronomy and an explosion of interest in the plurality of worlds, especially through specific attention paid to the planet Mars.

6.3 The Nineteenth-Century Pioneers of Planetary Habitability

During the second part of the nineteenth century, astronomical research was stimulated by the increasing observations of the planet Mars. Distinguished astronomers attempted to penetrate the secrets of its surface. The canals controversy, introduced in 1877 by Giovanni Schiaparelli (1835–1910) and considerably developed by Percival Lowell (1855–1916) from the very end of that century to the beginning of the twentieth century (see Lowell 1909) intensified the importance attached to the study of the red planet. In such a context of high hypotheses, a few assumptions were however commonly accepted:

- Mars has great similarities with our planet.
- The red planet could present seas, continents, and seasons, like the Earth.
- Mars would be a planet older than ours.
- This planet could be then inhabited by living beings superior to humans.
- The Martian world seemed to be very exciting and represented a fantastic ground for speculative studies about the possibility of life elsewhere.

Could Mars be an abode for life? Lowell's book title about Mars (*Mars, as The Abode of Life*, 1909) is representative of the speculations of that time on Martian life. Lowell, convinced of the presence of complex life on the red planet, formulated pertinent comparisons between Mars and the Earth. He examined what could be a "Martian ecology," and as such, was perhaps the first "exoecologist," as assumed by Markley (2005). Lowell imagined, indeed, a kind of model of "sustainable development."

If the possibility of another intelligent life was a great subject of discussion among the astronomical community, especially during the canals controversy, the hypothesis of Martian vegetation was largely accepted. Since the middle of the nineteenth century, variations of color were observed on the Martian surface. They were interpreted as evidence of seasons correlated with the presence of some kind of vegetation. It should be noted that at the end of the nineteenth century, while the Martian canals controversy was fading (except, perhaps, in Lowell's works), the vegetation hypothesis was at its height.

It became then significant to determine the parameters required *at a minimum* to allow the presence of some simple forms of life on the Martian surface. Planetary habitability began to be a scientific field worth studying in detail, especially thanks to pioneers, namely the astronomers Richard A. Proctor, Jules Janssen, and Camille Flammarion.

6.3.1 Richard A. Proctor (1837–1888)

The British astronomer Richard Anthony Proctor, famous for his first detailed map of the planet Mars (1867) and his talent in astronomy popularization, stated that habitability was a determining factor to answer the question of a potential existence of other life forms in the universe.

In his famous book *Other Worlds Than Ours* (1870) he examined systematically the planets of our solar system. He studied their criteria of habitability, depending on physical and environmental parameters such as climate, seasons, atmosphere, geology, and gravity. According to Proctor, defining planetary habitability was a very difficult task, but this difficulty could be overcome in considering *analogy* with our planet. Proctor's methodology was based on comparison between the terrestrial environmental parameters and all the environmental parameters characterizing every planet. However, a planet could not be necessarily inhabited, at any time. The example of the Moon showed that the question of habitability was not valid for any celestial body. Basically, in Proctor's opinion, the existence and diversity of life forms should depend on the *specific* conditions prevailing on the surface of each planet.

One important point concerning Proctor's study of habitability is that he took into account Darwin's theory (*The Origin of Species*, 1859). The question of adaptation is tackled all throughout the book, especially in the chapter entitled "What Our Earth Teaches Us." This point—considered here by Proctor while evolutionary ideas were developing—has been re-discussed after the reformulation of

Darwin's theory by synthetic evolutionists in the early 1960s, as established by Vakoch (2013). These ideas, indeed, influenced those who speculated on the possibility of extraterrestrial life.

According to Proctor, Darwin's works have demonstrated that a correlation existed between the environmental changes (along with their rhythm and intensity) occurring in a specific habitat and the survival (or not) of the living species in this habitat (Proctor 1870). One conclusion of this observation is that specific conditions of environment could be appropriate only to specific species. Considering analogies with the terrestrial model, Proctor thought that if many other worlds could exist, they should be very different from ours (the title of his book is very explicit). Creatures on their surfaces could be very unusual, and could delight in being in environments inhospitable for terrestrial living beings. To summarize, according to Proctor, these other worlds shelter life in other ways (Proctor 1870).

Proctor examined the celestial bodies of our solar system: Mercury, Venus, Mars, Jupiter, Saturn, Uranus and Neptune, the Moon and other satellites, meteors, and comets. A special attention was given to the planet Mars, "the miniature of our Earth," in Proctor's terms (Proctor 1870, 90). Many physical analogies with our planet could be found on Mars: continents, seas, straits, water, which would be largely present on the surface. The atmosphere would contain water vapor with a water cycle equivalent to the terrestrial one. The Martian world described by Proctor would allow any form of life, from the simplest forms of vegetation to life forms much more complex.

Even Mercury and Venus, which would present very different conditions than ours, could have life on their surfaces. However, since the environmental parameters would be quite dissimilar from those known on our planet, these planets could shelter unfamiliar forms of life—some *microscopic creatures* on Mercury, for instance. Proctor thought that the other planets of the solar system offered their own conditions of habitability.

The same argument was applied to the giant outer planets, especially Jupiter. Proctor assumed that Jupiter was not at present a fit abode for living creatures. However, he suggested that one day Jupiter would be a living world that must be very differently constituted from those we are familiar with. The living creatures, if any existed, would be built on a much smaller scale than the inhabitants of the Earth. According to Proctor, Jupiter could probably be inhabited by "the most favored races existing throughout the whole range of the solar system" (Proctor 1870, 115). However, Proctor expressed some doubts about intelligent life in the solar system. In his book *Our Place among Infinities* published in 1875 (in a chapter entitled "A New Theory of Life in Other Worlds"), Proctor withdrew intelligent extraterrestrials not only from most planets of our solar system but also from other stellar systems (Crowe and Dowd 2013).

6.3.2 Jules Janssen (1824–1907)

Jules Janssen was a French astronomer who contributed to founding the scientific field of planetary spectroscopy during the second part of the nineteenth century. Janssen and Sir William Huggins (1824–1910) were spectroscopic pioneers who carried out the first spectroscopic observations in the hope of detecting oxygen and water in the Martian atmosphere. Janssen strongly supported this new scientific method, which made it possible to question planetary atmospheres and search for water vapor, one of the first conditions required for terrestrial life development (Janssen 1929). Janssen assumed that the detection of water vapor in a planetary atmosphere was a crucial condition to expect the presence of life on its surface. And then, the new methods of physical astronomy (corresponding to the birth of astrophysics including spectroscopy) could perhaps lead to solving the problem of extraterrestrial life. In 1867, Janssen announced to have discovered the presence of water vapor in the Martian atmosphere (Launay 2008). (It was in fact terrestrial signatures.)

According to Janssen, the question of habitability was one of the most interesting queries given to human intelligence (Janssen 1929). Spectroscopy, when giving the chemical constitution of planetary atmospheres, could help to determine very important parameters defining the possible conditions for life. Janssen understood that a strong link existed between the planetary environmental conditions (especially the presence of water vapor in the atmosphere and then, liquid water on the surface) and the possibilities for life to appear and to subsist on a planet.

In the meantime, spectroscopy also gave some limits to the possibility of life on other planets. In identifying the presumed components of planetary atmospheres, it eliminated the planets whose atmospheres did not contain water vapor. However, great doubts subsisted about the detection of water vapor in planetary atmospheres. Therefore, considering the beginnings of planetary spectroscopy, no strong conclusion could have been formulated about the hypothetical habitability of the planets of the solar system. In particular, the problem of the chemical constitution (qualitatively and quantitatively) of the Martian atmosphere remained partly unsolved until the 1940s. However that may be, planetary spectroscopy demonstrated, as stated by Janssen, the material unity of the universe, since molecules analogous to the terrestrial ones were detected elsewhere in the universe (Janssen 1929).

6.3.3 Camille Flammarion (1842–1925)

Camille Flammarion, a very well-known French astronomer, published his first book in 1862 when he was only twenty years old, entitled *La pluralité des mondes habités, étude où l'on expose les conditions d'habitabilité des terres célestes discutées au point de vue de l'astronomie, de la physiologie et de la philosophie naturelle* (*The Plurality of Inhabited Worlds*). In this book, which quickly became famous for its support of the doctrine of the plurality of worlds, Flammarion specified some facts related to the problem of habitability (Flammarion 1862):

- The Earth, as a planet, has nothing remarkable.
- The other planets of the solar system are likely to present other conditions of habitability leading to various life forms, probably very different from the terrestrial ones.

- Living beings present on each world are correlated with the "physiological" state of the planet.
- The degree of habitability could be defined considering the analogies and differences existing between each world.

All these points characterize Flammarion's early ideas about planetary habitability, a concept undoubtedly present in his first book. However, these ideas can also be found in most of his subsequent writings. In *Les Terres du Ciel* (*The Lands of the Sky*) published in 1884, Flammarion advocated the diversity of life forms and various possible adaptations on Earth directly connected to changing environments (as proposed by Proctor, according to Darwin's theory). On Earth, different habitats have led to different forms of life. This observation could be extended to other planets in our solar system and even in the (presumed) numerous inhabited worlds of the galaxy. In *Les Terres du Ciel*, Flammarion stressed the various conditions in which life should exist in each world and the large diversity likely to exist in the universe (Flammarion 1884).

Above all, Flammarion fervently developed the topic of habitability in his two volumes wholly devoted to the planet Mars, entitled *La planète Mars et ses conditions d'habitabilité—Synthèse générale de toutes les observations* (*The Planet Mars and Its Conditions of Habitability—General Synthesis of the Whole Observations about Mars*) (volume 1, 1892—volume 2, 1909). Between the first Flammarion's publication (1862) and that one (1892–1909), the Martian canals controversy has strengthened interest in Martian habitability, even if Flammarion considered the canals above all as natural structures. In these two volumes about Mars, Flammarion offered a synthesis of the Martian observations carried out until then, mainly concerning surface structures, atmosphere, and climate.

The methodological aspects used to study habitability are clearly expressed in Flammarion's books, particularly in *The Plurality of Inhabited Worlds*. As well as Proctor, Flammarion assumed that reasoning by analogy was necessary to carry studies about habitability through to a successful conclusion. According to Flammarion, the method of analogy was inescapable to proceed from the "known" to the "unknown." Then, he successively considered the planets of the solar system in order to examine the similarities and differences existing between all these worlds. Considering the planet Mars, the conditions of habitability on this planet and on Earth could be very similar. Climatic environment, physical features, and atmospheric conditions would be analogous enough to establish a parallel between each planet. Following such an assumption, the inhabitants of Mars would present many similarities with those of the Earth (Flammarion 1862).

As many of his contemporaries, Flammarion asserted that analogy was a suitable method to extrapolate the life conditions characteristic of each world. However, if Flammarion used the principle of analogy to study habitability on other planets, he did not support the principle of similarity, a quite different principle. According to Flammarion, we would make a big mistake if we would take our world for the unconditional model of the universe. We can't determine the biological organization of other living beings in the universe depending solely on the similarities with our planet (Flammarion 1862). Flammarion admitted that the question of habitability remained then very enigmatic at the present state of knowledge (at the end of the nineteenth century). It mainly consisted in formulating plausible conjectures and even this fact remained a challenge! Eventually, he came to the conclusion that analogy, even if sure and fruitful, presented limits. More specifically, this method could not be applied to the search for the specific characteristics inherent in each world (Flammarion 1862).

One remarkable point is Flammarion's contest with the principle of anthropomorphism, which was, according to him, too much present in many minds. He highlighted that most of the authors who have attempted to define the nature of the inhabitants of other worlds, have represented creatures similar to humans. Flammarion distinguished "habitability" from "habitation," in such a way that (Flammarion 1862):

- *Habitability* concerned the correlations between the presumed physical and environmental conditions of the planets and their physiological conditions (allowing the presence of living forms),
- *Habitation* concerned the mental and physical state of each "mankind" supposed to be present on other planets.

According to Flammarion, the universe would be filled with various "mankinds" in harmony with the characteristics of their planet. It should be noted that this viewpoint contrasts with Huygens's one formulated two centuries earlier (Huygens 1698) and mentioned in this paper. Through his numerous writings, Flammarion exercised considerable influence over the debate on the habitability and plurality of worlds.

6.4 Concept of Planetary Ecology

In the 1950s, the German physiologist Hubertus Strughold (1898–1987) proposed a notion close to the concept of habitability defined by Proctor, Janssen, and Flammarion. Strughold was one of the pioneers of space medicine, while the Space Age was beginning.[1] He coined the term "planetary ecology" to name the study of the planetary conditions necessary for life. He developed his theory in his book entitled *The Green and Red Planet*: *A Physiological Study of the Possibility of Life on Mars* published in 1954. He provided a fresh view on the topic of habitability in confronting physical planetary data with physiological data coming from what was known at that time about terrestrial living beings. His viewpoint was inspired by Percival Lowell's book *Mars as the Abode of Life* published in 1909.

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[1] However, whereas Strughold was considered as "The Father of Space Medicine," he was also unfortunately taken over by Nazis. He emigrated the United States after World War II.

Strughold described Lowell's book as "the most impressive, most original" (Strughold 1954, 6) book about the possibility of life on other planets.

As a physiologist, he defined methods for a biological study of the planets (Strughold 1954). It seemed to him, indeed, that it was necessary to raise the question of life on other planets to the biological plane. It should be underlined that, until then, only astronomers had considered habitability.

In his book, Strughold made a survey of the physiological foundations of *life-as-we-know-it* on Earth. Then, he justified his principles of planetary ecology with some well-established principles of ecology and physiology. Strughold defined planetary ecology "as the science which studies all the planets, including the earth, with regard to their comparative fitness as a biological environment" (Strughold 1954, 2). Strughold's originality was to combine physical or environmental parameters, on one hand, and biological parameters, on the other hand. As did his predecessors, Strughold proceeded by analogy to start his study. Comparisons were made between every biological parameter and between every planetary parameter. Of course, since the first concepts had been formulated by our pioneers at the end of the nineteenth century, many advances have been obtained in planetology and biology. However, in the 1950s, astrobiology [a term coined by L. J. Lafleur in 1941 (Briot et al. 2004)] was a very new field in which biology was still not included.

Strughold's arguments were based on two definitions (Strughold 1954, 2):

- The definition of *physical ecology*: "Ecology is that science which treats of the physical environment of a place or region, with regard to its fitness as a site for the existence and development of living things."
- The definition of *physiological ecology*: "Ecology deals also with the adaptive reactions or responses of living things to their environment, in order to make their existence easier wherever they might be."

According to Strughold, the astronomical discoveries made during the first part of the twentieth century in the field of planetary atmospheres, provided a lot of data, which can be used by biologists. In that way, frontiers between astronomy and biology could be removed, allowing biologists to enter into the discussion about life elsewhere in the universe. One of his arguments was to delineate the limits accepted by living organisms. His study showed that on Earth only specific organisms could survive in extreme environments, in particular characterized by extreme temperatures. This conclusion could be extrapolated to other planets and led to specify the parameters dealing with planetary ecology. He applied this principle to the bodies of the solar system and came to the conclusion, considering temperature parameters, that most of the planets should be excluded except Mars and Venus:

> From the standpoint of temperature alone Mars and perhaps Venus are the only planets, aside from the Earth, which at present possess the prerequisites for living matter as we know it. All the other planets are excluded, for their temperatures lie far outside the range of active life (Strughold 1954, 31).

As did many of his contemporaries and predecessors, he conferred special attention to the planet Mars, which he considered as *a biological environment*. However, in Strughold's opinion, since molecular oxygen (O_2) had still not been detected in its atmosphere, the habitability of this planet could be very restricted. According to Strughold, the presence of molecular oxygen was crucial for the subsistence of living organisms. In spite of this, he considered that the absence of molecular oxygen did not exclude some possible forms of primitive life, like lichens or bacterial life (Strughold 1954).

It must be pointed out that Strughold underlined that the distance to the Sun was a decisive factor to determine the possibilities of life on the planets of the solar system, through the study of the solar constants of each planet. He proposed the pioneering concept of "thermal ecosphere of the sun," including planets capable of supporting life similar to ours (Strughold 1954, 36). This definition given by Strughold, which has been used again by Dole (1964—see following section), was comparable to that of habitable zone defined more than two decades later by Hart (1979).

6.5 Dole's Habitability

In the 1960s, Stephen H. Dole examined the concept of habitability in his book *Habitable Planets for Men* (Dole 1964):

> The use of the term "habitable planet" is meant to imply a planet with surface conditions naturally suitable for human beings, that is, one that does not require extensive feats of engineering to remodel its atmosphere or its surface so that people in large numbers can live there (Dole 1964, 4).

In this case, habitability concerned above all the planetary conditions suitable for human life, even if these conditions could be also convenient to other forms of (terrestrial) life. Dole attempted to delineate the astronomical circumstances (i.e., mass of the planet, period of rotation, age, axial inclination, level of illumination, orbital eccentricity, mass of the star) that produce these requisite environmental conditions. Then he made an estimate of the probabilities of finding these conditions elsewhere in the galaxy. From the probabilities of occurrence of those habitable planets in the galaxy, he deduced the number of habitable planets in the galaxy, which can be expressed as the following product (Dole 1964, 82):

$$N_{HP} = N_s P_p P_i P_D P_M P_e P_B P_R P_A P_L$$

with:

N_s, prevalence of stars in the suitable mass range, 0.35–1.43 solar masses;
P_p, probability that a given star has planets in orbit about it;
P_i, probability that the inclination of the planet's equator is correct for its orbital distance;
P_D, probability that at least one planet orbits within an ecosphere;
P_M, probability that the planet has a suitable mass, 0.4–2.35 Earth masses;

P_e, probability that the planet's orbital eccentricity is sufficiently low;
P_B, probability that the presence of a second star has not rendered the planet uninhabitable;
P_R, probability that the planet's rate of rotation is neither too fast nor too slow;
P_A, probability that the planet is of the proper age;
P_L, probability that, all astronomical conditions being suitable, life has developed on the planet.

From Dole's probability theory and considering the product quoted above, the estimation of the number of habitable planets *for humans* in the galaxy proposed by Dole was 645 million (Dole 1964, 104). Dole himself underlined that any number of the equation was bound to be highly imprecise, since not all factors were known with accuracy. The result of the equation was then to be considered as merely an attempt to formulate an estimation and not a final assessment.

Dole's concept of habitability—for humans—has been proposed while he was carrying out studies on the physical and physiological requirements of human beings in the spacecraft environment. Dole underlined many problems of astronomical interest that are revived today with the study of exoplanets, such as the definition of an "ecosphere" around a star, a definition comparable to the habitable zone (see Dole 1964, chapter entitled "Properties of the Primary"). Considering the question of habitability for humans, Dole redefined the term "ecosphere" (previously proposed by Strughold):

> Ecosphere will be used to mean a region in space, in the vicinity of a star, in which suitable planets can have surface conditions compatible with the origin, evolution to complex forms, and continuous existence of land life and surface conditions suitable for human beings, along with the ecological complex on which they depend. The ecosphere lies between two spherical shells centered on the star. Inside the inner shell, illuminance levels are too high; outside the outer shell, they are two low (Dole 1964, 64).

However, the concept of habitability introduced by Dole was not exactly analogous to the one previously proposed by the pioneers, and the one studied today. Nowadays, the concept of habitability is closer to the proposals coming from the nineteenth-century pioneers than to the belated definition provided by Dole.

6.6 Conclusion

The concept of planetary habitability is today in the heart of discussions dealing with the search for life elsewhere in the universe, especially when considering the increasing detection of exoplanets. Most of the astronomers adhere to a conventional and conservative definition of habitability which corresponds to the zone around a star within which water can be in stable liquid form on the surface of a rocky planet (Impey 2013). Born—with scientific arguments—at the end of the nineteenth century in the astronomical community, while the studies of the Martian surface were intensifying, the notion of habitability has been supported by important personalities of astronomy. It is noteworthy that the principles formulated about habitability by these pioneers are so close to our current concept.

One century ago, habitability dealt with the physical and environmental conditions necessary to make life possible on other planets (Proctor, Janssen, Flammarion). As today, the definition was globally the aptitude of a planet to develop life, from its origin to its diversification. As today the study of habitability required various parameters of astronomical, geophysical, and geochemical interest, which had connections with the nature of the planetary surface, and the atmosphere. Nowadays, criteria of habitability also integrate biological parameters, as it was attempted by Strughold. Above all, the biological parameters are supposed to identify limits in which the (terrestrial) living forms could persist. Extreme environments on Earth are in that case very significant, since they could provide information that could be extrapolated to other celestial bodies.

Habitability is strongly correlated with the presence of permanent liquid water on a planetary surface. This fact was already clear in the minds of our pioneers, at the end of the nineteenth century. However, the exploration of the solar system has recently shown that the satellites of giant planets could also be relevant targets for the search for life elsewhere. If these celestial bodies do not present liquid water on the surface, they could however contain liquid water ocean under their surface (Titan, Europe, Callisto and Ganymede). This example was not conceivable at the time of our nineteenth-century pioneers. It remains today a problematic case because it is not in accord with the usual definition of the habitable zone. This concept is nowadays questioned again within the astronomical community, following the continual discoveries of planetary systems in the galaxy. For instance recently, Barnes et al. (2010) have suggested that the concept of habitable zone should be modified to include the effects of tides. If planets form around low-mass stars, then the terrestrial ones, which are in the circumstellar habitable zone, will be close enough to their host stars to experience strong tidal forces. According to such models, a *tidal habitable zone* can be delimited. For example, if heating rates on an exoplanet are near or greater than that on Io[2] and produce similar surface conditions, then the development of life seems unlikely. On the other hand, if the tidal heating rate is less than the minimum to initiate plate tectonics, then CO_2 may not be recycled through subduction, leading to a runaway greenhouse that sterilizes the planet. These two cases represent potential boundaries to habitability (Barnes et al. 2009). This could change the usual definition of habitable zone and subsequently planetary habitability, if we assume that orbital evolution due to tides has to be considered for any potentially habitable world.

Eventually, it must be pointed out that the methodological choice of analogy, chosen in order to study habitability, is a convergent approach used by the scientists mentioned in this chapter throughout the centuries. The method of analogy has been used for a long time in the debate about pluralism: the logic of the argument “The Earth is inhabited; therefore the planets are,” has been widely discussed (see Crowe 1986), and also criticized. In the case of habitability, some questions

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[2] Where tides drive volcanism that resurfaces the planet at least every million years; tidal heating can drive plate tectonics, including subduction.

could be raised about the parallel established between our planet and the other planetary environments supposed to be suitable for life. Habitability depends on complex criteria, such as those required *at a minimum* for the presence of life, and on the definition of life itself. Then, analogy—as noted by Flammarion in 1862—has limits, even if it remains (up to now) the unique and tangible way to estimate the possibilities of life on other planets.

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References

Barnes, Rory, Brian Jackson, Richard Greenberg, and Sean N. Raymond. 2009. “Tidal Limits to Planetary Habitability.” *The Astrophysical Journal Letters* 700 (1): L30–L33.

Barnes, Rory, Brian Jackson, Richard Greenberg, Sean N. Raymond, and Rene Heller. 2010. “Tidal Constraints on Planetary Habitability.” In *Pathways Towards Habitable Planets, ASP Conference Series* 430: 133–138.

Briot, Danielle, Jean Schneider, and Luc Arnold. 2004. “G.A. Tikhov, and the Beginnings of Astrobiology.” In *Extrasolar Planets: Today and Tomorrow*, *ASP Conference Series* 321: 219–220, ed. Jean-Philippe Beaulieu, Alain Lecavelier des Etangs, and Caroline Terquem.

Crowe, Michael J. 1986. *The Extraterrestrial Life Debate 1750-1900: The Idea of a Plurality of Worlds from Kant to Lowell*. Cambridge: Cambridge University Press.

Crowe, Michael J., and Matthew F. Dowd. 2013. “The Extraterrestrial Life Debate from Antiquity to 1900.” In *Astrobiology, History, and Society: Life Beyond Earth and the Impact of Discovery*, ed. Douglas A. Vakoch. Heidelberg: Springer.

Darwin, Charles M.A. 1859. *On the Origin of Species by Means of Natural Selection*. London: John Murray.

Dick, Steven J. 1982. *Plurality of Worlds: The Origins of the Extraterrestrial Life Debate from Democritus to Kant*. Cambridge: Cambridge University Press.

Dick, Steven J. 1996. *The Biological Universe: The Twentieth-century Extraterrestrial Life Debate and the Limits of Science*. Cambridge: Cambridge University Press.

Dole, Stephen. 1964. *Habitable Planets for Men*. New York: The Rand Corporation, Blaisdell Publishing Company.

Flammarion, Camille. 1862. *La pluralité des mondes habités; étude où l’on expose les conditions d’habitabilité des terres célestes, discutées au point de vue de l’astronomie, de la physiologie et de la philosophie naturelle*. Paris: Mallet-Bachelier.

Flammarion, Camille. 1884. *Les Terres du ciel; Voyage astronomique sur les autres mondes et description des conditions actuelles de la vie sur les diverses planètes du système solaire*. Paris: Marpon & Flammarion.

Flammarion, Camille. 1892. *La planète Mars et ses conditions d’habitabilité—Synthèse générale de toutes les observations*, vol. 1. Paris: Gauthiers-Villars.

Flammarion, Camille. 1909. *La planète Mars et ses conditions d’habitabilité—Synthèse générale de toutes les observations*, vol. 2. Paris: Gauthiers-Villars.

Fontenelle, Bernard (le Bovier de). 1686. *Entretiens sur la pluralité des mondes*. http://abu.cnam.fr/BIB/auteurs/fontenelleb.html.

Hart, Michael H. 1979. “Habitable Zones about Main Sequence Stars.” *Icarus* 37 (1): 351–357.

Huygens, Christiaan. 1698. *Cosmotheoros* (*The Celestial Worlds Discovered: or, Conjectures Concerning the Inhabitants, Plants and Productions of the Worlds in the Planets*). London: Timothy Childe.

Impey, Chris. 2013. “The First Thousand Exoplanets: Twenty Years of Excitement and Discovery.” In *Astrobiology, History, and Society: Life Beyond Earth and the Impact of Discovery*, ed. Douglas A. Vakoch. Heidelberg: Springer.

Janssen, Jules. 1929. *Œuvres Scientifiques, recueillies et publiées par Henri Dehérain*, vol. 1. Paris: Editions de la Société d’éditions géographiques, maritimes et coloniales.

Kepler, Johannes. 1634 (original publication). 2003. *Kepler’s Somnium, The Dream or Posthumous Work on Lunar Astronomy*. Translated by Edward Rosen, New York: Dover Publications.

Launay, Françoise. 2008. *Un Globe-Trotteur de la Physique Céleste, L’astronome Jules Janssen*. Paris: Vuibert and L’Observatoire de Paris.

Lowell, Percival. 1909. *Mars as the Abode of Life*. New York: The MacMillan Company.

Markley, Robert. 2005. *Dying Planet: Mars in Science and the Imagination*. Durham & London: Duke University Press.

Proctor, A. Richard. 1870. *Other Worlds Than Ours: The Plurality of Worlds Studied Under the Light of Recent Scientific Researches*. New York: AL. Burt Publisher.

Raulin Cerceau, Florence, and Bénédicte Bilodeau. 2011. *D’autres planètes habitées dans l’univers*? Paris: Ellipses.

Strughold, Hubertus. 1954. *The Green and Red Planet: A Physiological Study of the Possibility of Life on Mars*. London: Sidgwick and Jackson.

Vakoch, Douglas A. 2013. “Life Beyond Earth and the Evolutionary Synthesis.” In *Astrobiology, History, and Society: Life Beyond Earth and the Impact of Discovery*, ed. Douglas A. Vakoch. Heidelberg: Springer.