1 Introduction

The search for life in the Universe, from theoretical concept to actual exploration, has never ceased to interest and amaze humanity. After the first ideas had arisen on cosmology (the structure of the cosmos) and cosmogony (its creation), early civilizations and philosophers turned their minds towards living beings and how they came to be. Once some basic principles had been set – for instance in the biblical book of Genesis or in Hesiodos' *Theogony*, which both basically define the creation of Earth and Heavens from nothing (or Chaos) – the first 'scientific' minds set to work all over the world, and new ideas were sparked in Egypt, in the Indies, in the Americas, in China and in Europe. Thus, in Greece for instance, Aristarchus conceived the idea of the heliocentric Solar System; Eratosthenes proved that the Earth was spherical and determined the distance to the Moon; and Anaximander had a structure worked out for the whole Universe.

Some of the early thinkers had already advocated a Universe consisting of 'many worlds'. Thales, from Miletus, and his students in the seventh century BCE argued for a Universe full of other planets, teeming with extraterrestrial life. They also proposed the idea with which we are all familiar today (through Drake's equation, Carl Sagan's musings, and the contributions of many other scientists): that a Universe so full of stars must also have a large number of populated worlds. This proposal was defended by Epicurus and other Greek atomists who countered the geocentric models put forward later by Aristotle. In the cosmogony developed by Plato's famous disciple, the mythological separation of Earth from the Heavens was put into more modern words and widely promoted, as was his geocentric perception of the cosmos and the limited and well-defined sphere of stars in which matter and space were confined and interconnected. Aristotle's philosophical attempt at modern physics took strong roots, caused the ancient open-minded theories to be forgotten and hindered scientific progress in this domain for quite a long period. The Copernican revolution in the sixteenth century gave a boost to the concept of life's emergence and possible existence elsewhere in the Universe, because Earth was no longer the privileged and unique place where this could occur.

In 1862, the French scientist Camille Flammarion published *La pluralité des mondes habités* ('On the plurality of inhabited worlds'), in which he discussed the conditions of habitability and the possible presence of life on such habitable planets of our Solar System. The public loved the book, but Urbain Le Verrier (then Director of the Paris Observatory) and many of his colleagues utterly rejected Flammarion's arguments, and Flammarion was consequently fired from the Observatory. Open-mindedness was not always accepted at that time, but – thankfully – we have come a long way since then.

1.1 THE QUEST FOR LIFE

One hundred and fifty years later, in the era of planetary exploration, with space missions and large telescopes at our disposal, the quest for life remains just as important to humanity. The discovery in the past 20 years of planets around other stars (exoplanets) has made a difference in our perception of the possibility that other worlds might harbour life or the conditions necessary for life to emerge and survive.

But, as the quest for life-supporting conditions in our Solar System moves onwards, with ever more powerful means, it is essential to know exactly what we are searching for. Such type of investigations have in the past been driven by geocentric considerations. Robotic exploration surveys in the Solar System, and several astronomical surveys from the ground and space targeting 'exoplanets' (planets beyond our Solar System), have been designed to retrieve information on present or past signatures of life or biotic-related elements, but up to now these have always been based on life as we know it on Earth – terrestrial life (Figure 1.1). The modern definition of the main features

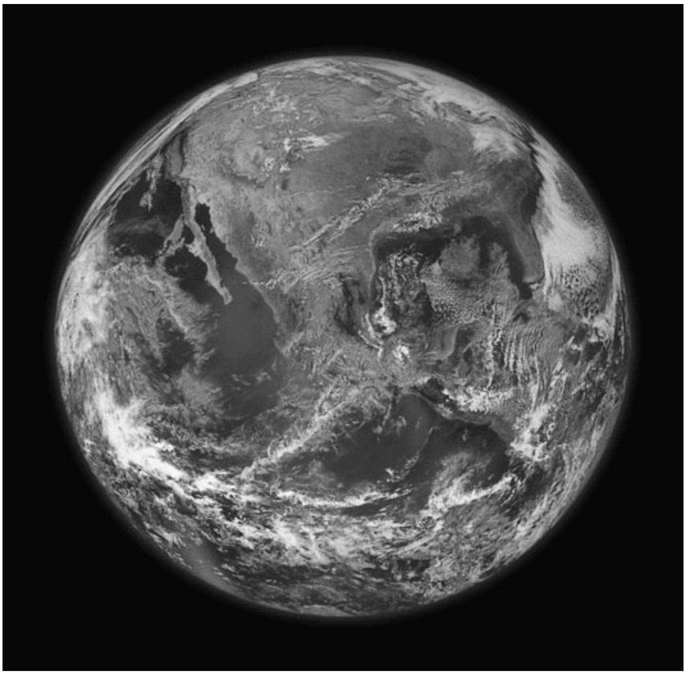

FIGURE 1.1 The Earth from space. The presence of water is detectable remotely from the dark blue colour of the oceans, the water vapour clouds and the northern polar cap. For colour version, see plates section. (Image courtesy of NASA/GSFC/Suomi NPP.)

of life, as found on our planet, includes the presence of liquid water, energy sources, a stable environment and nutrients. We discuss these elements and their relation to life in the next chapter, but there is no doubt that one of the main ingredients, identified as such early on, is liquid water.

It is not surprising, then, that up to now robotic space exploration has been directed to places in the Solar System where liquid water is possible (and more specifically in exposed locations on the surfaces of planetary bodies), and that it emphasizes searches for formations that resemble terrestrial organisms. Even though this approach is understandable, given how little we know about life's origin, biology theories and experiments are now pointing to the fact that living organisms elsewhere may well be quite different from terrestrial life. These new scientific studies seem to indicate that if life appeared elsewhere in our Solar System and beyond, we may need to broaden our exploration designs in order to accommodate the possibility of non-terrestrial-like signatures of current or past biotas. Such organisms may not be using liquid water as a solvent; and simply from a pure physical and not biological point of view, the water may not be located on the surfaces of the planetary bodies but elsewhere. So we may be currently neglecting the exploration of planetary environments which may well be potential hosts for life.

The authors of this book are not biologists, but planetary astrophysicists. Although we do discuss the aspects above, we are mainly concerned with offering the viewpoint of astronomers and observers of our Solar System on where different environments can be found and explored, often in comparison with our own planet, but also as a framework for establishing the conditions that led to the creation of our Solar System. Here we will not deal so much with the search for life itself, although we will necessarily touch on the subject, but rather with the habitability conditions that we can expect to find in the Solar System and beyond, in other stellar systems.

1.2 THE FORMATION OF PLANETS

Before asking whether life might have appeared in other planets of the Solar System, we need to understand how planets formed. Let us start by considering the most recent theories on the formation and evolution of our neighbourhood. In this, we are helped by the observation of other nearby young stars. Over the past decades, observations of star-forming regions have revealed that more than 50 per cent of young stars are surrounded by a protoplanetary accretion disk (Figure 1.2). It is generally accepted that planets outside our Solar System, now discovered in their hundreds, formed within these disks.

A similar story is told by the Solar System itself. A few basic observations, made as early as the eighteenth century by Immanuel Kant (1724–1804) and later by Pierre-Simon de Laplace (1749–1827),

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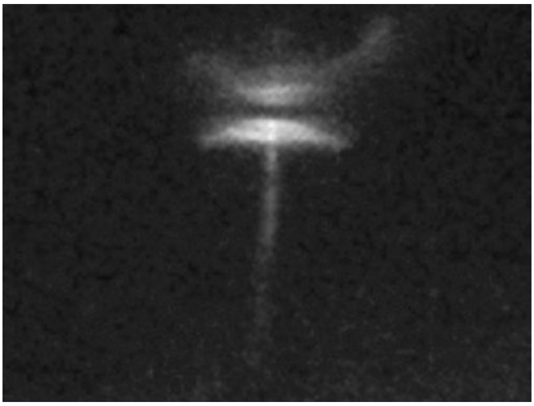

FIGURE 1.2 A protoplanetary disk, HH-30 in Taurus, about 450 light years away, observed with the Hubble Space Telescope. The disk emits a stellar jet, aligned with the rotational axis of the disk which appears in black as an absorption in front of the stellar light. For colour version, see plate section. (Image courtesy of STSci/ESA/NASA.)

suggest that Solar System planets formed within a protosolar disk, resulting from the collapse of a protosolar cloud in fast rotation around an axis perpendicular to the disk plane. Indeed, the orbits of the planets show a few remarkable properties: they are almost coplanar, circular and concentric around the Sun, and they all rotate in the same direction, as does the Sun. It is generally accepted that Solar System planets formed by accretion of solid particles, through mutual interactions, collisions and gravity (Figure 1.3). While the first steps of the accretion process can be reproduced in a satisfactory way by models of interactions between gas and dust in the protosolar disk, it is more difficult, at present, to understand how planets crossed the metre-size barrier. For larger sizes, the planet's gravity becomes sufficient to accrete the surrounding material, explaining the runaway growth of the biggest embryos.

Another remarkable property of the Solar System planets is their clear division into two classes: the terrestrial planets, relatively close to the Sun, and the more distant giant planets (Figure 1.4). The terrestrial planets – Mercury, Venus, the Earth and Mars – are characterized

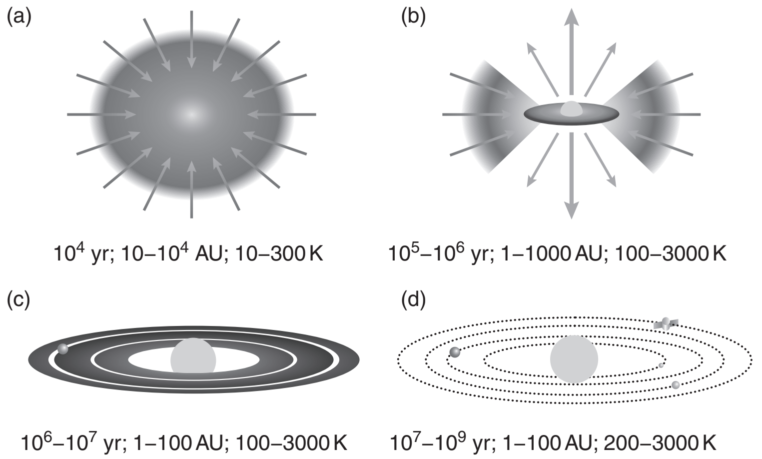

FIGURE 1.3 A schematic view of the formation of planets in the protosolar nebula. (a) A molecular cloud contracts and rotates at an increasing speed. (b) The cloud collapses into a disk perpendicular to the rotation axis of the cloud; the central matter accretes to form the proto-Sun. (c) Planetesimals form within the disk from the accretion of solid particles. (d) After the dissipation of the gaseous disk, a few planets and small bodies are left. (Image adapted from NASA/James Webb Space Telescope.)

by relatively small sizes, high densities (from 3.9 to 5.5 g/cm^3), a solid surface and very few satellites. In contrast, the giant planets, Jupiter, Saturn, Uranus and Neptune, have large radii (from 4 to 11 Earth radii), a low density (from 0.7 to 1.6 g/cm^3), a thick hydrogen-dominated atmosphere and a large number of satellites, with many of these being 'regular' (i.e. in the equatorial plane of the planet). The origin of this dichotomy has to be found in the way these objects formed and evolved.

1.2.1 *Formation of the Solar System*

We have first to remember that the protosolar disk composition must have reflected cosmic abundances: hydrogen was by far the most abundant element. It was formed, together with deuterium, helium, lithium and beryllium, at the time of the Big Bang, by primordial nucleosynthesis. The heavier elements – in particular carbon, oxygen

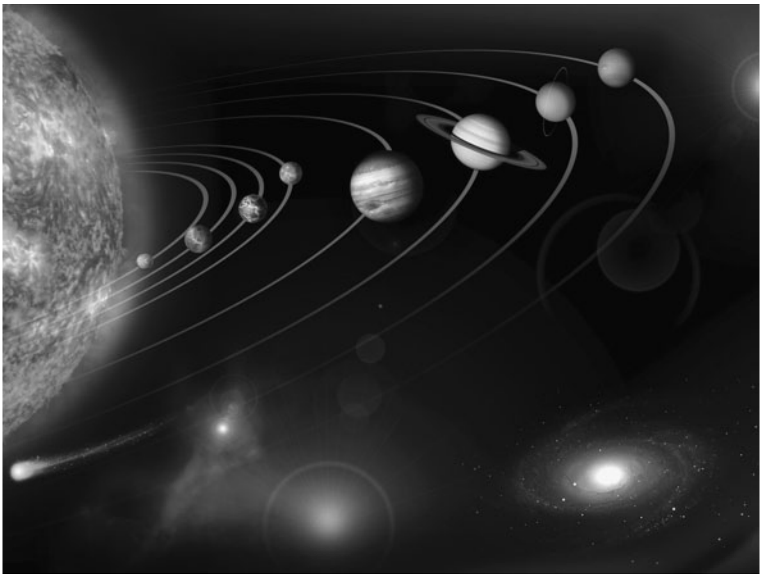

FIGURE 1.4 A schematic view of the Solar System (not to scale), with the terrestrial planets close to the Sun and the giant planets at further distances, beyond the main asteroid belt. A comet is shown near the orbits of Jupiter and Saturn. For colour version, see plates section. (Image courtesy of NASA/JPL.)

and nitrogen – were formed by nuclear reaction within the stars, in abundances which, to first order, decreased as their atomic number increased (Figure 1.5). The heavier elements were thus the less abundant ones.

Within the protosolar disk, the temperature decreased as the distance from the Sun increased. Two cases can be considered: in the vicinity of the Sun, where the temperature was above about 200 K, the only solid material was silicates, oxides and metals. Because these elements are intrinsically rare, the solid mass available for planetary embryos was limited. Only planets of the size of the Earth or less could form, with a relatively high density, typical of silicates or metallic compounds. Their atmosphere represented only a very small fraction of their mass; it was probably accreted in a second step, partly by outgassing (the release of gas from the interior of planetary bodies,

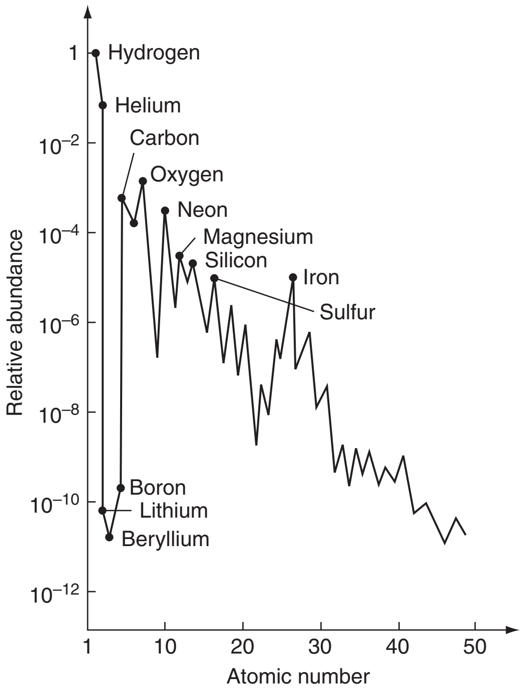

FIGURE 1.5 Cosmic elemental abundances as a function of the atomic mass number of the elements. The abundances are normalized to hydrogen. (Adapted from D. Darling, www.daviddarling.info.)

gas that was perhaps trapped in the primordial material during its formation) and partly from material brought in by meteoritic or cometary impacts.

In contrast, at distances more than five times the mean distance from Earth to the Sun (known as an 'astronomical unit' or AU; the AU is the semi-major axis of the Earth's orbit, i.e. 149.6 million km) where the temperature was lower than about 200 K, the most abundant elements apart from hydrogen and helium (i.e. carbon, oxygen and nitrogen) were in the form of ices (H_2O, CO_2, NH_3, CH_4...). These elements were abundant enough to form big solid nuclei. Calculations show that when the mass of such nuclei becomes larger than 10–15 Earth masses, the gravity field is sufficient to pull in or accrete the surrounding nebula, mostly composed of gaseous hydrogen and helium. This is how the giant planets were formed, with very large sizes and relatively low densities. After the collapse phase of the surrounding nebula, regular satellites were formed in the equatorial plane of the planets, and others were captured by the large gravity field of the big planetesimals (small objects formed from dust, rock and other materials, thought to have orbited the Sun at the beginning of Solar System formation, and serving as the building blocks of the planets and satellites by gravitational aggregation), which explains the large number of outer satellites orbiting the giant planets.

1.2.2 *Migration in the Solar System*

Other open questions remain. One of them has to do with the two different classes of giant planets: Jupiter and Saturn on the one hand, and Uranus and Neptune on the other. With masses of 318 and 95 times that of the Earth, Jupiter and Saturn are mostly made up of their protosolar gaseous components, hydrogen and helium (and are thus known as 'gas giants'). In contrast, Uranus and Neptune, located at further distances, with masses of 15 and 17 terrestrial masses respectively, mostly consist of their icy core ('ice giants'). What causes this difference? It has been argued that Uranus and Neptune, located in a less dense region of the disk, needed more time – possibly 10 million years – for their icy core to reach the critical limit of 10 terrestrial masses. After 10 million years, the protosolar disk may have dissipated as a result of the increasing activity of the young Sun (known as the T-Tauri phase), and little gas would have then been available for the accretion phase of Uranus and Neptune. But the true story may have been even more complex.

Indeed, although it was originally believed that planetary orbits had been stable all through the Solar System's history, the consensus today (following the early work of Henri Poincaré and more recent studies) is that unstable and chaotic situations have occurred in the past and may occur in the future. On such occasions, small gravitational perturbations may have induced very strong effects on the motions of planetary bodies. Dynamical simulations support this

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hypothesis and suggest that very early on, at the time of the planetary formation phase or shortly afterwards, gravitational interaction with the gas in the disk may have led to significant changes in the orbital parameters of the planets. Following dynamical numerical simulations performed, in particular, at the Nice Observatory in France (the so-called 'Nice model'), it seems that all giant planets may have migrated somewhat in the early phases of their history (e.g. Walsh and Morbidelli, 2011).

Estimations of the radial migration and mass growth imposed on the giant planets through simulations seem to indicate that a fully formed Jupiter started at 3.5 AU, a location presumably favourable for giant planet formation owing to the presence of the so-called 'snow line', the distance beyond which water can condense. Saturn's core, with a mass of 30 Earth masses (an Earth mass is often given the symbol $M_\oplus$), initially lies at 4.5 AU. It grows to 60 $M_\oplus$ as Jupiter migrates inwards, over 10^5 years. Inward migration is stopped for planetary cores smaller than 50–60 $M_\oplus$, when they attain an equilibrium radius in the disk (where migration forces cancel out mutually), so that Saturn's core remains at 4.5 AU during this phase. Similarly, the cores of Uranus and Neptune begin at 6 and 8 AU and grow from a few $M_\oplus$ without migrating. Once Saturn reaches 60 $M_\oplus$ its inward migration begins, and is much faster than that of the fully grown Jupiter. Then, on catching Jupiter, Saturn is initially trapped in the 3:2 resonance (which means that the revolution periods are in the ratio 3/2, Jupiter revolving precisely three times around the Sun while Saturn manages only two). In the model we are considering, by the time Saturn enters into resonance, Jupiter has migrated inwards as close as 1.5 AU from the Sun, thus stopping the growth of Mars; this scenario therefore explains why the mass of Mars is significantly smaller than expected at this distance from the Sun. The capture in resonance spectacularly changes the migration pattern.

Jupiter and Saturn start migrating outwards together, still staying in their 3:2 resonance. In passing, they capture Uranus and Neptune in resonance (3:2 for Saturn:Uranus and 4:3 for Uranus: Neptune), and these planets are then pushed outwards as well. This