4 Searching for habitable sites in the outer Solar System

Looking for habitable conditions in the outer Solar System leads us to the natural satellites rather than the planets themselves. Although the theoretical conditions under which life might be sustained on natural satellites are similar to those of planets, there are key environmental differences which can make moons of particular interest in the search for extraterrestrial life. The gaseous giant planets cannot provide even the minimal conditions of a surface or interior with suitable pressures and temperatures to sustain life. But the moons around these planets offer a great range of possibilities for exploring habitability conditions and furthermore studying the question of the emergence and evolution of habitable worlds in our Solar System, in some cases more so than any other object closer to the Sun. Scientists generally consider the probability of life on natural satellites within the Solar System to be remote, though the possibility has not been ruled out.

Within the Solar System's traditional habitable zone, the only candidate satellites are the Moon, Phobos and Deimos, and none of these has an atmosphere or water in liquid form. But, as discussed in Chapter 2, the habitable zone may be larger than originally conceived. The strong gravitational pull caused by the giant planets may produce enough energy to sufficiently heat the cores of orbiting icy moons. This could mean that some of the strongest candidates for harbouring extraterrestrial life are located outside the solar habitable zone, on satellites of Jupiter and Saturn. The outer Solar System satellites then provide a conceptual basis within which new theories for understanding habitability can be constructed. Measurements from the ground and also from the Voyager, Galileo and Cassini spacecraft have revealed the potential of these satellites in this context, and our understanding of habitability in the Solar System and beyond can be greatly enhanced by investigating several of these bodies together.

Objects with oceans in our Solar System may belong to one of two families: 'terrestrial' planets, or icy satellites of giant planets. The question is whether the liquid water therein has existed for periods of time long enough to have been biologically useful, because a frozen surface may not necessarily have inhibited life. If liquid layers exist below ice layers and these water-reservoirs are in contact with heat sources from the interior of the planet (from radioactive decay, volcanic interactions or hydrothermal activity) the planet may be considered as a potential habitat.

In particular, the satellites around Jupiter and Saturn, closer to the Sun than those of the ice giants, have been revealed as extremely interesting active bodies from the viewpoint of astrobiology. Indeed, several of them show promising conditions for habitability and the development and/or maintenance of life. Europa, the smallest of Jupiter's four Galilean satellites, may be hiding, under its icy crust, a putative undersurface liquid water ocean which may be in direct contact with a silicate mantle floor and kept warm through time by tidally generated heat. If its mantle is geologically active like that on Earth, giving rise to the equivalent of hydrothermal systems, the simultaneous presence of water, geodynamic interactions, chemical energy sources and a diversity of key chemical elements may fulfil the basic conditions for habitability.

Further out, around Saturn, Titan constitutes another such example. The largest Kronian moon (Kronos being the Greek name for Saturn), Titan is the only other body in the Solar System besides Earth to possess a dense atmosphere composed essentially of nitrogen (~98 per cent), which combines with methane (~1.5 per cent in the stratosphere) to give rise to a host of organic compounds. The presence of seasonal effects manifesting themselves in the atmosphere, geomorphological features similar to our planet's, and a more and more probable internal liquid water ocean make Titan one of the most astrobiologically interesting bodies, as revealed by the ongoing Cassini–Huygens mission.

Future extensive and *in situ* exploration concepts could help us improve our understanding of Titan and Europa, and some of their siblings such as Ganymede or Enceladus. For all these reasons, these moons have often been proposed as the main targets for future missions.

In the outskirts of our Solar System we find Uranus and Neptune surrounded by moons which are also unique in many aspects, such as Triton and its geysers. Hereafter we investigate the astrobiological prospects of this extended habitable zone, focusing on the smaller bodies which are being more and more revealed as exciting objects in the search for habitable conditions.

Although some 50 or so extrasolar moons have recently been announced, there is still no firm confirmation or perception of how common they may be, what their characteristics are and how many could be considered habitable. Some studies do, however, consider exomoons as among the most likely habitable environments, as we will see in Chapter 5.

Furthermore, natural satellites have been considered by some astrobiologists as potential candidates for space colonization if the right artificial environment could be created. As Coustenis and Taylor argue, ‘the most Earth-like moon in the Solar System is Titan’, with a nitrogen atmosphere, organic chemistry and extents of liquid hydrocarbons on its surface, but its surface nevertheless remains a hostile place for life (Coustenis and Taylor, 2008). Terraforming of moons might be considered but is outside the limits of current technology, as we shall discuss in Chapter 6.

Further out in the Solar System we find more objects of interest, such as the comets and the trans-Neptunian objects. Cometary atmospheres incorporate prebiotic molecules and pristine material that help us to understand how the Earth’s atmosphere came to be, and also how the Sun’s neighbourhood formed and evolved. Furthermore, comets are filled with water. . .

Triton (orbiting around Neptune) and objects beyond Neptune’s orbit have been hypothesized to harbour subsurface liquid water oceans (even today, and even at the very low temperatures of their environments). Thus, following the water is not a wild goose chase in the outermost regions of the Solar System and even beyond, as we shall see in the next chapter.

4.1 THE OUTER SOLAR SYSTEM: A HUGE RESERVOIR OF FROZEN WATER

Even if they are located beyond the so-called snow line (or ice line; the distance from the Sun beyond which water cannot be liquid on the surface), large satellites of gas giants are known to include substantial quantities of water. Indeed, with an average density around 1.8 g cm^{-3}, the largest moon is composed of almost 45 per cent by weight of water. Among these satellites, some have a silicate-rich core and may contain underground liquid water oceans deposits in contact with it (as for Europa) and therefore harbour heat and chemical sources below their ice crust. This is important as on Earth in such a context we find life (in hydrothermal vents at the bottom of oceans). Other satellites may have liquid water layers encapsulated between two ice layers, or liquids above ice. In the study of the emergence of life elements on such satellites, the timescale is of the essence. If this liquid environment persists for long enough, it might see the emergence of life; but, on the other hand, this could be inhibited if the ocean is so isolated from the surrounding environment that it is impossible to assemble the concentration of ingredients necessary for life or the proper chemical inventory for the relevant biochemical reactions.

Icy layers on the outer moons can be very thick (Figure 4.1). One can assume their thickness to be of the order of a few hundred km for Ganymede, Callisto and Titan. As Galileo data indicate, unlike Ganymede, Callisto is probably not fully differentiated, which means that the icy layer might be thicker, but mixed with silicates. For Europa, a thinner icy layer (possibly 100 km) is hypothesized, because its proportion of water is 'only' 10 weight per cent. For Titan, an icy crust some hundred kilometres in depth is expected. Understanding the internal structure of the water layer requires knowledge of the water phase diagram under certain pressure and temperature conditions.

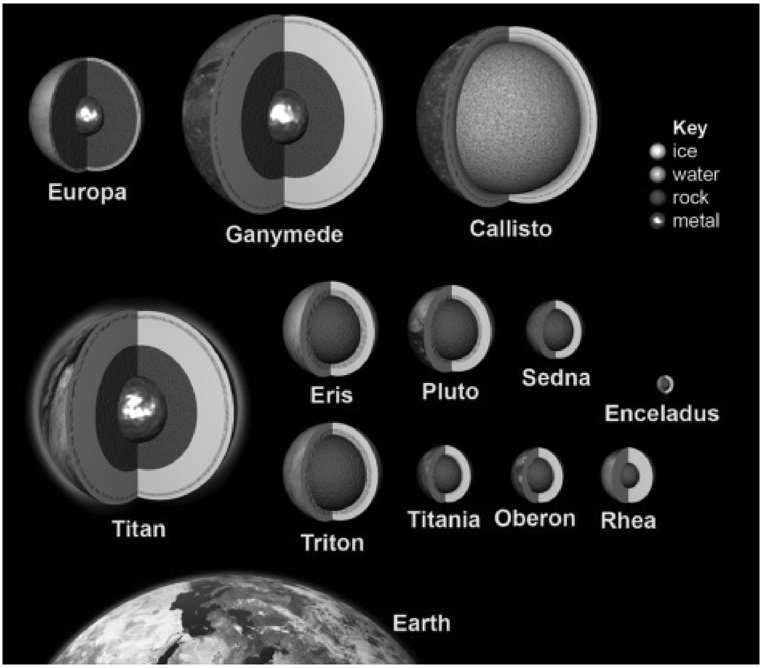

FIGURE 4.1 Liquid water is thought to be present under the surface of many bodies in our Solar System, particularly the Galilean moons of Jupiter, such as Europa, Callisto and Ganymede, and Saturn's Titan and Enceladus. In addition, models of heat retention and heating via radioactive decay in smaller icy bodies suggest that Saturn's Rhea, Uranus' Titania and Oberon, Neptune's Triton, trans-Neptunian objects and dwarf planets Pluto, Eris, Sedna and Orcus may also have oceans underneath solid icy crusts approximately 100 km thick. The models vary and in some cases predict that the liquid layers are in direct contact with the rocky core, which allows efficient mixing of minerals and salts into the water, while in others layers of high-pressure phases of ice are thought to underlie the liquid water layer. For colour version, see plates section. (Image credit: Doug Ellison, for the Planetary Society.)

On Earth, almost all of the ice present in the biosphere is in the form of a hexagonal crystal constituting what we are used to calling frozen water, but whose scientific term is 'ice Ih' (pronounced 'ice one aitch'). Ice Ih is stable down to –200 °C (73 K; –328 °F) and can exist at pressures up to 0.2 GPa. It exhibits many peculiar properties which are relevant to the existence of life and regulation of global climate. If the temperature is between 250 and 273 K, it is possible for a liquid layer to be located below an ice Ih layer, because ice Ih is less dense than the liquid. This situation is compatible with large icy moons and indicates that many ice polymorphs can exist in the pressure range 0–2 GPa, relevant to icy satellites. As noted in recent thermodynamical studies, the icy moons of Jupiter and Saturn can benefit from the fact that the melting curve of the low-pressure ice Ih decreases with pressure. Like the recently discovered exoplanets, they could, according to some studies, in the case of a coupled sea/ice system provide the necessary conditions for life emergence as on the primitive Earth.

As explained in Subsection 2.3.2 and following the suggested classification of habitable worlds proposed in Lammer *et al.* (2009), Class I habitats are similar to the Earth and generally represent bodies whose stellar and geophysical conditions allow them to evolve so that complex multicellular lifeforms may emerge. Class II habitats are planets or satellites on which life may indeed emerge and develop, but owing to different stellar and geophysical conditions they evolve toward Venus- or Mars-type hostile environments where complex lifeforms may not develop. Class III habitats are planetary bodies where subsurface water oceans exist, like on Europa, but where they also interact directly with a silicate-rich core, while class IV habitats have liquid water layers sandwiched between two ice layers, or liquid extents above ice (Figure 4.2).

In this chapter we concern ourselves more with the two latter types of habitats. In the Lammer *et al.* (2009) classification, ‘Class III habitats where subsurface oceans are in contact with silicates on the sea-floor open the question of where the building blocks for life could come from.’ If the organic material necessary to start life is supplied by exogenous sources such as meteoritic and cometary impacts and by precipitation of interplanetary dust, it still has to find its way into the subsurface oceans. As Lammer and colleagues point out, in addition:

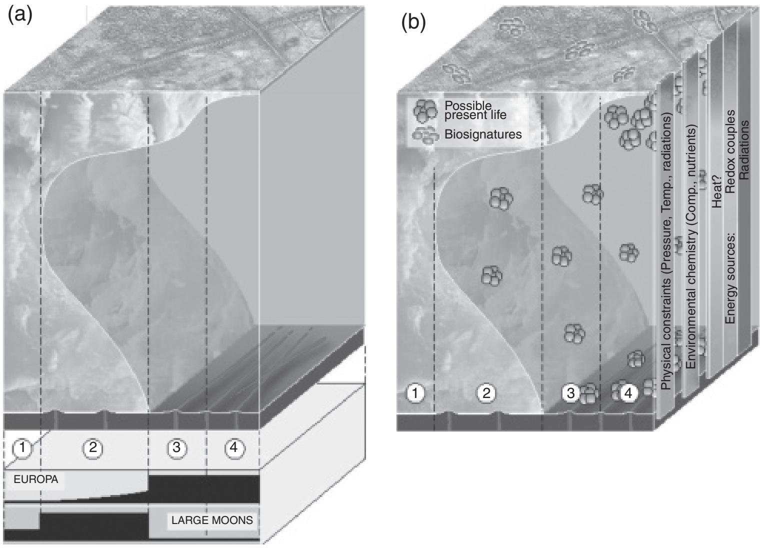

FIGURE 4.2 (a) Possible locations of liquid layers in the icy moons of Jupiter are plotted here as a function of depth: (1) completely frozen; (2) three-layered structures impeding any contact between the liquid layer and the silicate floor; (3) thick upper icy layer (>10 km) and a thick ocean; (4) very thin upper icy layer (3–4 km). (The four different sections apply to different structures for the moons, and are joined here only for the purposes of the illustration.) The black shading at the base indicates probability of finding the structure above. Structures 3–4 are the most probable for Europa. The larger moons Ganymede and Callisto are located in the left region (1 or 2) where internal pressures are sufficient to allow for the formation of high-pressure ice phases. Oceans in Ganymede and Callisto – if they exist – should be enclosed between thick ice layers. For colour version, see plates section. (Redrawn from Lammer *et al.*, 2009.) (b) Current habitability of Europa. Possible locations of present life and biosignatures have been plotted as a function of depth. Habitability depends on physical and chemical constraints which are indicated on the right using colour scales (green: highly favourable; red: hostile). Numbers refer to possible interior structures described in (a). For colour version, see plates section. (Redrawn from Blanc *et al.*, 2009.)

this material has to reach meaningful concentrations in some (small) compartment of the ocean, which is hard to imagine in a connected body of water as large as a planet-wide subsurface ocean. However, one should keep in mind that synthesis of organic material by

> either Fischer–Tropsch reactions (which convert carbon monoxide and hydrogen into hydrocarbons) or catalytic cycles are possible under the high pressure/high temperature conditions occurring at deep-sea vents.

The terrestrial hydrothermal vents are environments highly favourable for life, contrary to what might be expected in the absence of sunlight. When in contact with silicates, the hot water from the hydrothermal vent can extract the minerals and hence the C,H,N,O,P,S (CHNOPS) that are necessary and beneficial to the large community of living organisms around them. These species feed on organic material produced by a form of bacteria that use energy obtained by oxidizing reactive chemicals (such as hydrogen). This process, called chemosynthesis, is a substitute for photosynthesis and leads to the assumption that life can indeed exist in subsurface oceans, provided liquid water and some sort of energy are available. Anaerobic chemosynthetic bacteria might then exist on outer Solar System moons. As a consequence, one could imagine that life might exist, as on Earth, in the vicinity of such environments (hydrothermal vent-like formations in subsurface oceans in contact with silicates) in the outer Solar System satellites, if reduced radicals are found in the mineralized water and the environment can also provide the energy to sustain the living organisms, although probably not to power them so they can grow, develop and evolve. This process is more easily envisioned on Enceladus and Europa than on Ganymede and Callisto.

Indeed, the latter two Jovian satellites are considered as Class IV habitats, and such habitats can be found not only in the Solar System but in exoplanets as well. These are environments where a water ocean may be contact with a thick ice layer. In that case, as Lammer and co-authors point out, ‘a much better situation for the influx of organic material from outside the planet’ is afforded for such bodies. The main problem for Class IV habitats, however, is to assemble the necessary ingredients for life in a given location, difficult for a planet whose surface is covered in a deep water ocean with nothing to act as a 'magnetic centre' for organic chemistry, in particular at the right temperature conditions. To better understand this problem and to test the possibilities, we can envisage laboratory experiments and *in situ* studies in cold regions of the Earth such as the deep isolated lakes in Antarctica, as the physical properties there resemble those found on some of these moons.

But all in all, Class III and Class IV waterworlds appear to have considerable astrobiological potential and could be possible habitats if some conditions are combined. Besides the correct pressure and temperature conditions for the presence of liquid water, the planetary object should have adequate energy sources to support metabolic reactions, and chemical elements to provide nutrients for the synthesis of biomolecules. So another very important aspect to consider when looking at the habitability of outer moons is the tidal effect, which can be a significant source of energy on natural satellites and an alternative energy source for sustaining life. Moons orbiting gas giants or brown dwarfs are likely to be tidally locked to their primaries: that is, their day is as long as their orbit. Although tidal locking is expected to affect planets within habitable zones adversely by producing an inhomogeneous distribution of stellar radiation, it may also have favourable effects on satellites by exposing them to powerful tidal forces, inducing plate tectonics through the stresses imposed on the lithosphere and causing higher temperatures. This could bring on volcanic activity, which regulates a moon's temperature, and could even create a geodynamo effect that would provide it with a significant magnetic field.

Monoj Joshi, Robert Haberle and their colleagues modelled the temperature on tide-locked exoplanets in the habitability zone of red dwarfs. They found that an atmosphere with a carbon dioxide pressure of only 1 to 1.5 atmospheres not only allows habitable temperatures but also allows for liquid water to exist on the dark side. If a moon is tidally locked to a gas giant it suffers large temperature variations, but these are less extreme than those for a planet locked to a star. There are ways to bypass the temperature issue, since even small amounts of carbon dioxide could make the thermal properties of a planet suitable for life, as we shall see in Chapter 5.

As a consequence, some of the Saturnian and Jovian satellites, such as Ganymede, Europa, Titan or Enceladus, have been identified as potentially habitable environments and targets for our space-based and ground-based search for life (or at least for habitable conditions). In the Solar System's neighbourhood, such potential habitats can only be properly investigated with appropriately designed space missions; for extrasolar planets we cannot do that, so we must rely on remote sensing, and thus living organisms whose existence does not affect or have signatures in the atmosphere of their host planet will not be detectable. Hereafter we look more closely at these bodies.

4.2 JUPITER'S SATELLITES

The satellites of the Jovian system are unique bodies, each different and precious in its own way. In the case of the Jupiter system, three of the Galilean moons, Ganymede, Europa and Io, are locked in a 1:2:4 orbital Laplace resonance. The Laplace resonance (a resonance is explained in Subsection 1.2.2) involves three or more orbiting bodies; other Laplace resonances exist, as in the Gliese 876 system. The resonance is important because it means that these objects periodically exert a strong gravitational influence on each other.

Ganymede is the biggest moon of the Solar System, even bigger than the planet Mercury. Gravity data point to a fully differentiated structure. It possesses a very tenuous atmosphere, a hydrosphere which may be at least 500 km thick (meaning 50 weight per cent), a silicate mantle and an iron core. A liquid layer up to 100 km thick is trapped between the icy crust on top and a layer composed of high-pressure ices, which do not exist in natural environments on the Earth. It is one of three solid bodies that possess an intrinsic or dynamo magnetic field (the others are Mercury and the Earth), and this Ganymede magnetic field is in turn embedded in the Jovian magnetic field. Finally, it also has an induced magnetic field, generated by currents flowing in a conducting liquid, the best proof of the existence of the deep ocean.

Europa is layered in a similar way. We think that it possesses a similar metallic core and a silicate layer, about the same size as Ganymede's, but a thinner hydrosphere no more than 100 km thick. The big difference here is that the liquid layer is almost certainly in direct contact with the silicate ocean floor.

Callisto is very similar to Ganymede, apart from the fact that it is not fully differentiated and that it does not have an intrinsic field. This lack of differentiation, rather surprising for a body of this size, may be due to the fact that Callisto is decoupled from the Laplace resonance (as defined above), one of the most striking pieces of evidence of the complexity of the coupling processes occurring in the Jovian system. Its surface is very old and heavily cratered, and finally, it probably also possesses a deep ocean similar to Ganymede.

These icy Galilean satellites, Callisto, Ganymede and Europa, thus present a great diversity of surface features probably caused by their different evolution, despite the fact that they are located in the same 'neighbourhood'. The unique features of their geology are a testimony to their formation parameters, such as composition, density and temperature, as well as evolutionary factors such as geophysical processes and the stage of differentiation. In addition, space weather – for instance interactions with the Jovian magnetosphere and stellar wind – and tidal effects have left their marks on the landscapes we see today (Figure 4.3). Thus, by observing the surface features, one finds evidence for the actual or past presence of aeolian (wind-driven) processes, cryovolcanism, impact cratering and other activity. The Galilean satellites show signs of an increase in geological activity with decreasing distance to Jupiter. Io, nearest to Jupiter, is obviously volcanically active. Europa could still be tectonically and volcanically active today, whereas Callisto, the outermost Galilean satellite, may be geologically 'dead'. Understanding the gravitational interactions between Jupiter and the Galilean satellites is essential for many aspects of Jupiter system science, including habitability, through their influence on the evolution of a satellite's interior and surface. In particular, the evolution of the Laplace resonance may be important

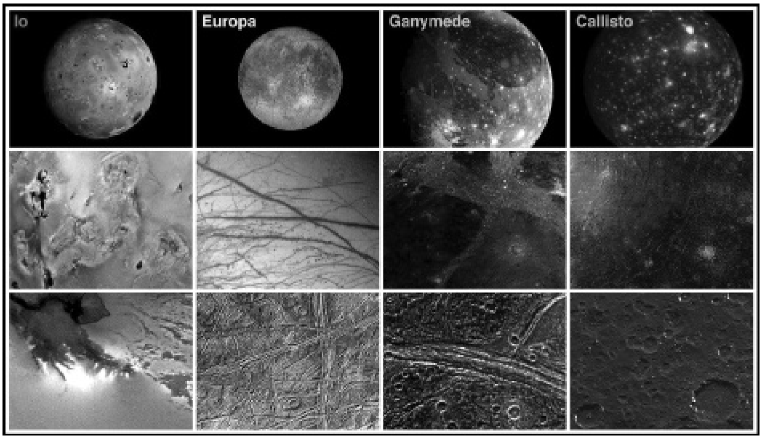

FIGURE 4.3 The surfaces of the Galilean satellites. The image for Europa shows a region of its crust made up of blocks which are thought to have broken apart and 'rafted' into new positions. These features are the best geological evidence so far that Europa may have had a subsurface ocean at some time in its past. Combined with the geological data, the presence of a magnetic field leads scientists to believe an ocean is most likely present at Europa today. In this false colour image, reddish-brown areas represent non-ice material resulting from geological activity. White areas are rays of material ejected during the formation of the 25-km diameter impact crater Pwyll (see global view). Icy plains are shown in blue tones to distinguish possibly coarse-grained ice (dark blue) from fine-grained ice (light blue). Long, dark lines are ridges and fractures in the crust, some of which are more than 3000 km long. These images were obtained by NASA's Galileo spacecraft during September 1996, December 1996 and February 1997 at a distance of 677 000 kilometres. For colour version, see plates section. (Image courtesy of NASA/JPL/DLR.)

for the subsurface oceans of Europa and Ganymede, and for the future of volcanism on Io, on which tidal dissipation can be an important heat source, as it can for some of the other satellites.

Voyager and Galileo data indicate that Europa and Ganymede, and possibly Callisto, possess important prerequisites to be considered habitable. Galileo's detection of induced magnetic fields, combined with imaged surface characteristics and thermal modelling of the moons' evolution, advocates the presence of liquid water oceans below the icy crusts of Ganymede, Europa and Callisto. These three satellites are the targets of the first large mission being developed by ESA in the framework of the Cosmic Vision 2015–2025 framework, and their properties as known today and as will be studied in the future are described in the report of the European JUICE (Jupiter Icy Moons Explorer) space mission (see Subsection 4.2.3) (JUICE, 2011, p. 29). According to that report:

> the depth and composition of the oceans, as well as the dynamics and exchange processes between the oceans and the deep interiors or the upper ice shells, remain unclear. Furthermore, it is unknown whether liquid water reservoirs or compositional boundaries exist in the shallow subsurface ice and how the dynamics of the outermost ice shell is related to geologic features and surface composition.

There is ample evidence that ice and liquid layers both exist on these moons, but there is no certainty as to their exact composition. Observations indicate that the water in the subsurface is most probably mixed with other components such as the salt hydrates or carbon dioxide that we find on the surfaces of most of the Galilean satellites. Besides the basic biochemical components that are required for life (CHONPS; see Chapter 2), other species, such as sodium, magnesium, calcium, iron and potassium, also play an important role. However, if these constituents are found on a surface, the conditions for their survival on Europa will not be the same as on Ganymede, as the distance to the planet and the received radiation doses are very different. Close to Jupiter, as in the case of Europa, this radiation is extremely harmful and probably fatal to any organics or any other biota present there. At the very least, the surface organics and minerals on Europa's surface would suffer from large alteration processes. This is a pity, because radiation also helps to produce oxidants on the surface (molecules with elements in a high oxidation state) through redox reactions (see Chapters 1 and 2), which are essential in life, although harmful to our bodies in high quantities. The composition of the surface is largely reflected in the tenuous atmospheres (and exospheres) of the Galilean satellites observed essentially in UV measurements from space and from the ground, which are the result of sputtering and sublimation of the surface materials. Conversely, the atmospheric constituents also influence the surface composition. Europa has a dioxygen atmosphere with traces of sodium and potassium. Ganymede also has a thin oxygen atmosphere and a hydrogen exosphere.

The oxidants present on the surface could, in some cases, if the ice layer is permeable or not too thick, penetrate down to the ocean, thus enhancing the habitability potential. Similarly, if an undersurface ocean exists under a significant ice layer (thus protected from the radiation effect), the habitability potential is preserved.

Besides their interiors, the Galilean satellites are interesting objects because of their diverse surface conditions (Figure 4.3). In the case of the large moons Ganymede and Callisto, observations show old, densely cratered terrains with a wide spectrum of sizes and multi-ring structures. The surface morphology on Europa is very different, with few craters, suggesting a relatively young surface. In addition, the surface composition may be reflecting internal and external processes. The presence of an intrinsic magnetic field around Ganymede is valuable for habitability, as (rather like on Earth) it protects the satellite from highly energetic particles near the equator.

The dimensions, composition and habitable potential of the putative subsurface liquid water oceans on any of these satellites depend enormously on their geological activity, global composition and interior layering. The latter is still mostly unknown, as is the global distribution of the icy versus non-icy material, but it has strong bearings on the origin and evolution of these bodies, as well as on their astrobiology. As mentioned in Chapter 2, the essential difference in classes of habitable worlds lies in the way the water content may or may not be in contact with the silicates in the interior (an important aspect when sources of biological material are considered). Whereas Europa's internal water ocean has a good chance of being in contact with the rocky/silicate layer, those of Ganymede and Callisto are probably not (although in the case of Ganymede it has been argued that silicates could be present).

Hereafter we focus on two of the satellites in the Jovian system that have attracted most of the attention of astrobiologists, namely Europa and Ganymede.

4.2.1 Europa

Europa is a Class III habitat unique in the Solar System because of its high rock/ice mass ratio, in that it is the only satellite on which a large ocean might be in contact with the silicate layer. On the other moons, the existence of an ocean implies the occurrence of a very thick high-pressure icy layer at the bottom, which impedes the contact of the liquid with silicates.

The putative existence of a subsurface ocean of course depends on the ability to support liquid water (Figure 4.4). In the case of Europa, this possibility has been suggested based on measurements by the Galileo mission of the induced magnetic field and on the interpretation of geological features. If such an ocean exists, we cannot yet precisely determine its depth or its location. The question of whether there is ice convection within the icy crust, leading to the possibility of an exchange of material between the surface and the ocean, remains open in the thin crust model because of the large number of tectonic features such as cracks and faults visible on the surface (Figure 4.5). This is an important issue for habitability, because Europa's surface is subject to heavy bombardment by energetic particles from Jupiter's radiation belts, leading to the breaking of water molecules and to the generation of hydrogen peroxide, H_2O_2, a strong oxidizing component which may be a source of chemical energy. Indeed, H_2O_2 tends to decompose exothermically into water and oxygen gas, and it has been detected on Europa's surface in infrared and ultraviolet wavelength spectra.

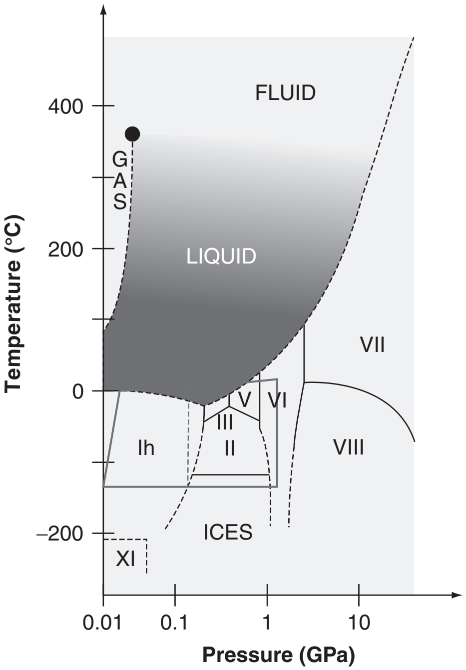

FIGURE 4.4 Phase diagram of the pure water system. Five ice polymorphs can exist in the pressure range relevant to icy moons (box). The dashed line symbolizes the highest pressure that can occur in the water layer of Europa. (From Lammer *et al.*, 2009.)

The determination of the surface topography and the internal structure at the interface between the silicate core and the liquid, together with the detection of any possible mass anomalies there, would allow us to test the hypothesis of whether volcanism and/or hydrothermal activity may exist or have existed, as it does at the Earth's mid-oceanic ridges. Such activity releases into the ocean a variety of organic components that are essential in sustaining possible simple lifeforms on the ocean floor, like those discovered around the Earth's deep-sea hydrothermal vents more than three decades ago.

Given the existence of an ocean, the question of habitability can be summarized by an inspection of the 'triangle of habitability' (Figure 4.6a). In addition to an ocean lasting for a billion years, it involves the presence of the key chemical elements for life (CHNOPS...), and of energy sources. In reviewing the possible

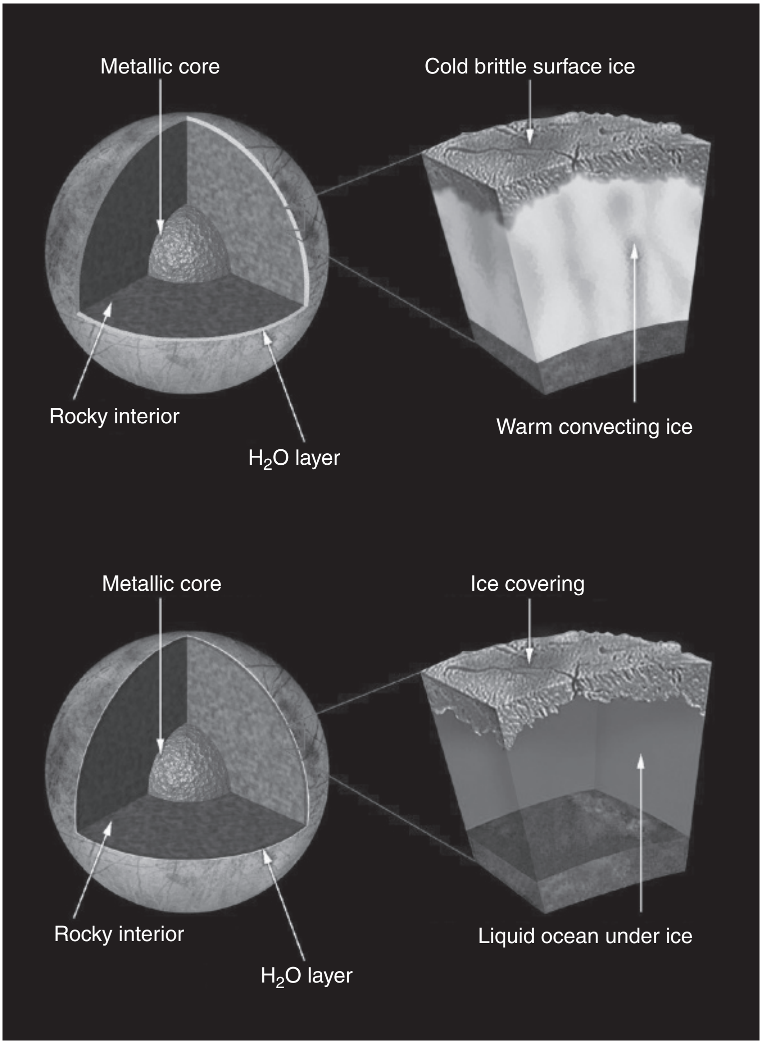

FIGURE 4.5 These artist's drawings depict two proposed models of the subsurface structure of the Jovian moon, Europa. Galileo's observations of surface features can be explained in two ways: either by the existence of a warm, convecting ice layer, located several kilometres below a cold, brittle surface ice crust (top), or by a layer of liquid water with a possible depth of more than 100 km (bottom). For colour version, see plates section. (Image courtesy of NASA/JPL.)

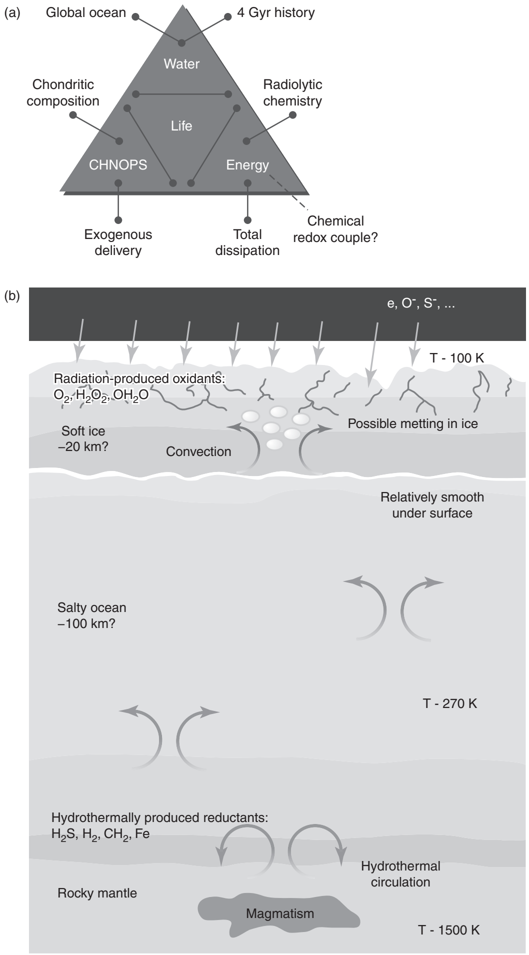

FIGURE 4.6 (a) Illustration of the 'triangle of habitability' for Europa. (Adapted from Hand *et al.*, 2009.) (b) Scheme showing the possible existence of chemical energy sources at Europa. (Adapted from Stevenson, 2000, p. 1823.)

presence and likely abundances of these key elements in Europa's ocean and sea floor, recent studies reached a rather positive conclusion. Concerning the energy sources, the presence of a H_2O_2 oxidizing chemistry at the surface, owing to the radiolysis of ice by radiation belt particles, and of a reducing chemistry at the ocean floor if hydrothermal activity exists, opens up the possibility of a redox couple acting at the scale of the ocean (Figure 4.6b). But this only works if oxidants from the surface can feed into the ocean via a (hypothesized) partly permeable icy crust. Further exploration of Europa *in situ* by an orbiter and, better still (when the technology becomes available) by a lander, appears mandatory, as we shall see in Subsection 4.2.3).

4.2.2 Ganymede

Ganymede is in many aspects recognized as a unique satellite in the Solar system because of its size, intrinsic magnetic field and geological features. It is believed to be composed of approximately equal amounts of silicate rock and water-ice. Investigations show it to be a fully differentiated body with an iron core (Figure 4.7). Its surface has two

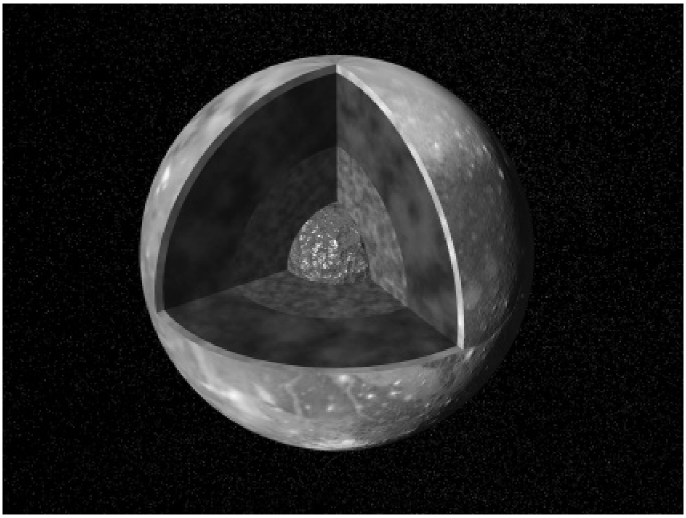

FIGURE 4.7 Voyager images are used to create a global view of Ganymede. The section shown here reveals the interior structure of this icy moon. This structure consists of four layers based on measurements of Ganymede's gravity field and theoretical analyses using Ganymede's known mass, size and density. Ganymede's surface is rich in water-ice, and Voyager and Galileo images show features evidencing geological and tectonic disruption of the surface in the past. As with the Earth, these geological features reflect forces and processes deep within Ganymede's interior which has a differentiated structure with a large lunar-sized 'core' of rock and possibly iron overlain by a deep layer of warm, soft ice capped by a thin, cold, rigid ice crust. (Image courtesy of NASA/JPL.)

main types of terrain. A third of the surface is made up of dark old regions, exposing a high impact crater record and dating back to four billion years ago. The other two-thirds of the geological regions are bright terrains, probably more recent ones indicating resurfacing processes, forming a network and crosscut by extensive grooves and ridges. The cause of the light terrain's special discontinuous geology is not fully understood, but it could be the result of tectonic activity due to tidal heating. As the JUICE Yellow Book report (JUICE, 2011) indicates, we do not currently know if exchange processes are possible between the silicates and the liquid layer in the saltwater ocean

> believed to exist nearly 200 km below Ganymede's surface, sandwiched between layers of ice. [Nevertheless] in the Jovian satellite system Ganymede holds a key position in terms of geologic evolution because it features old, densely-cratered terrain, like most of Callisto, but also widespread tectonically resurfaced regions, similar to most of the surface of Europa.

Unique in some ways but far from rare in others, Ganymede is, indeed, one among many other bodies of its type, both in the Solar System and probably beyond. Ganymede-like objects are expected to be more common in the Galaxy than Earth-like planets since they occupy the giant stellar zone beyond the snow line. Depending on how many such objects we find in the Universe, the probability of having habitable worlds in the Universe (one of the key parameters of the Drake formula for astrobiologists) could be significantly changed.

With the different processes that have marked its atmosphere (which includes O, O_2 and possibly ozone) and its surface (such as tectonics, cratering and cryovolcanism), Ganymede is an archetype for understanding many of the icy satellite processes throughout the outer Solar System and beyond, the class of the so-called 'waterworlds', with properties very different from terrestrial planets but still eligible for habitability.

Hydrated minerals have been detected on Ganymede's trailing hemisphere (that is, the side of the moon that faces the direction of the motion as it orbits Jupiter, centred at 270° W, while the leading side is the opposite). In addition, various non-water-ice materials have also been identified on Ganymede's surface from Galileo data and ground-based observations: carbon dioxide, sulfur dioxide, molecular oxygen, ozone and various organic compounds probably formed locally thanks to the radiolytic processes we mentioned above. And since O_2 gas is also formed during this process, its detection near the equator is a proof of the existence on the surface of organic material.

As mentioned above, Ganymede is the only satellite in the Solar System known to possess a magnetosphere, thought to be the result of convection within its liquid iron core. This magnetosphere lies in a complicated context: it is embedded in Jupiter's enormous magnetic field and appears as local perturbations of the field lines, interacting with the plasma flow and electromagnetic fields of the Jovian magnetosphere.

4.2.3 *Future exploration of Jovian satellites*

From what has been discussed above, we have established the interest in the exploration of habitats in the satellites of the giant planets. One of the major issues of future missions would be to determine how much water exists in the Jovian system, how it is distributed and what is its content in biological material on and underneath the surfaces of the icy moons, and how the material is transported among the moons by volcanism, sputtering and impacts. As the JUICE report (2011) points out, 'adequate experimentation might also allow us to infer environmental properties such as the pH, salinity, and water activity of the oceans and will investigate the effects of radiation on the detectability of surface organics'.

The JUICE mission was recently selected by ESA as the first large mission within the Cosmic Vision 2015–2025 plan (Figure 4.8). It is designed as a follow-up to the Galileo mission measurements, aiming to study the Jupiter system and its satellites in depth, with a focus on the largest moon, Ganymede. By thoroughly exploring the system and thereby unravelling its origin, its evolution and the formation of the different components such as the satellites, we will also get a handle on the history of the Solar System and the processes therein. The

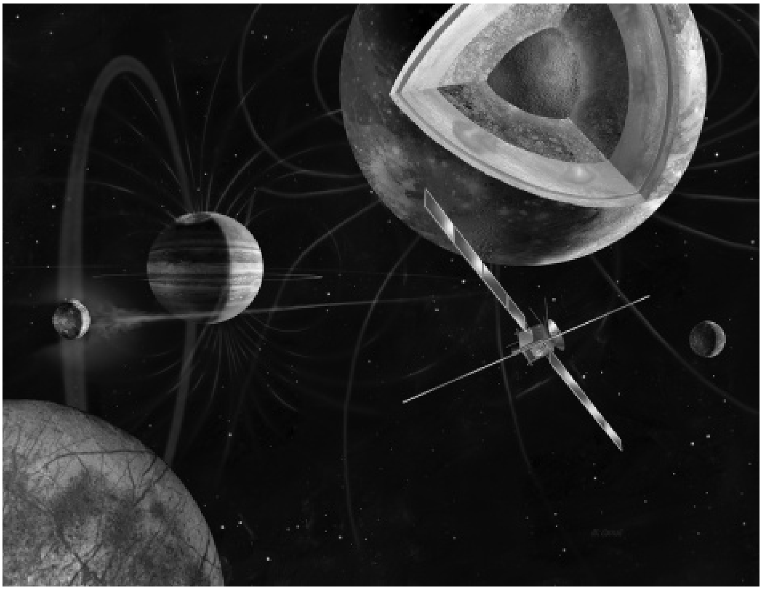

FIGURE 4.8 The JUICE spacecraft exploring the Jupiter system; artist's view. For colour version, see plates section. (Image credit: M. Carroll/ESA.)

overarching theme for JUICE as defined in the Yellow Book report is 'the emergence of habitable worlds around gas giants taking into account the necessary conditions involving the simultaneous presence of organic compounds, trace elements, water, energy sources and a relative stability of the environment over time'. The main questions that concern us in this book – the extent and evolution of habitable zones in the Solar System and the possible existence therein of habitable worlds as defined in Chapter 2 – are at the heart of the JUICE scientific goals for the Jovian system.

Ganymede is the focus of this mission for the reasons evoked above and because the features it shares with other celestial bodies make it the best example we have in our neighbourhood for studying habitable conditions in icy waterworlds in the Solar System and in other stellar systems. For Europa, the JUICE mission has two flybys planned above what are thought to be recently or currently active regions thinly covered with ice layers (regions called 'chaos') aiming to retrieve information on the underlying liquid ocean, its extent and composition, as well as on the morphology and chemical (water and other) composition of the surface. The investigations will focus on organic chemistry, its sources, sinks and evolution, and on identifying the best targets for landing in the future.

JUICE will explore the liquid-water oceans below the icy surfaces of the three moons Ganymede, Callisto and Europa looking for energy sources of chemical, thermal and tidal origin. In addition, the other habitability requirement, the stability of the environment on these moons, will be assessed by evaluating the gravitational coupling between the satellites and the planet. For the purpose of compared planetology and so as to be able to evaluate and appreciate the diversity among the Galilean moons, observations will also be made of Io (although it bears no interest for habitability) and other smaller moons.

The JUICE mission is expected to launch in mid-2022, for arrival at Jupiter in January 2030, after 7.6 years of interplanetary travel using an Earth–Venus–Earth–Earth gravity assist sequence, with a backup window of opportunity to launch in August 2023. The baseline for the mission's design is a spacecraft dry mass of 1900 kg and a propellant mass of 2900 kg, bringing the total launch mass up to 4.8 tonnes to be carried by an Ariane 5 vehicle. The total payload complement selected in 2013 has total mass of about 110 kg, and power requirements of 120–150 W depending on which instrument suites are operating. JUICE is a three-axis stabilized spacecraft whose power will be generated by a solar array of 60–70 square metre capable of producing between 640 and 700 W (Jupiter is probably as far as one can go on solar power with today's technology).

JUICE is foreseen to last a total of about 3.5 years. The current mission scenario is constructed in such a way as to allow JUICE to perform a tour of the Jovian system using gravity assists from the Galilean satellites to shape its trajectory. This tour will include continuous monitoring of Jupiter's magnetosphere and atmosphere, two targeted Europa flybys and a Callisto flyby phase reaching Jupiter latitudes of 30°, culminating with the dedicated Ganymede orbital phase. The current end-of-mission scenario involves spacecraft impact on Ganymede.

Owing to the difficulty of direct access to potential habitats within the Jovian moons, the *in situ* exploration of subsurface oceans is necessarily a long-term scientific endeavour. But on Ganymede and Europa, material (volatiles, minerals and perhaps organic species) rising from the internal ocean to the surface through fractures and cryomagmatic processes could be observed, revealing information on the deep liquid water.

Characterization of the ocean depth on Europa, its thickness and that of the boundary of its interface with the silicate mantle will be a task for a specifically designed Europa orbiter, studied in the framework of future missions to the Jovian system. Clearly, the characterization of the oceanic chemical and possibly prebiotic properties will be a longer-term scientific and technological challenge.

For technical and budgetary reasons, a surface lander or penetrator that could perform some *in situ* characterization of the surface ice of Ganymede and/or Europa is not possible for the moment. However, there are such projects currently being researched. The JUICE mission will nevertheless provide important information by establishing the existence of subsurface oceans under the crust of Ganymede, Europa or Callisto, defining their main characteristics and identifying privileged landing target sites.

4.3 SATURN'S SATELLITES

Further away from the Sun, at a distance of 10 AU, the Saturnian system (Figure 4.9) offers us not only the most popular of the giant planets (the 'Lord of the Rings') but also 62 natural satellites among which are several gems of possible habitats encased in rock, dust, ice and low temperatures. Among them are Titan and Enceladus, two moons of the outer Solar System that also show evidence of a subsurface water ocean from measurements performed by the Cassini–Huygens mission since 2004. Titan, the Earth-like moon with its rich organic chemistry, and Enceladus with its potential cryovolcanism and liquid subsurface water reservoir, are discoveries brought to us by space exploration which have revolutionized our perception of habitability in the Solar System.

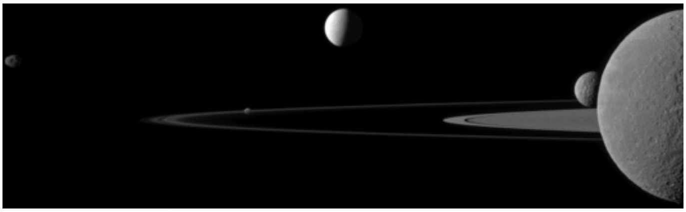

FIGURE 4.9 A quintet of Saturn's moons come together in the Cassini spacecraft's field of view for this portrait. Janus (179 km across) is on the far left. Pandora (81 km across) orbits between the A ring and the thin F ring near the middle of the image. Brightly reflective Enceladus (504 km across) appears above the centre of the image. Saturn's second-largest moon, Rhea (1528 km across), is bisected by the right edge of the image. Rhea is closest to Cassini here. Mimas (396 km across) can be seen beyond Rhea, also on the right side of the image. The rings are beyond Rhea and Mimas, with Enceladus beyond the rings. (Image courtesy of NASA/JPL-Caltech/Space Science Institute.)

If we follow the water, then the discovery of water vapour plumes, issuing from fractures in the southern hemisphere of Enceladus, suggests the presence of a liquid water ocean (or pockets) in the interior, at distances from the Sun defying all previous notions of the habitable zone. There is ample evidence from Cassini–Huygens measurements that Titan has an internal liquid water ocean, while its rich Earth-like dense atmosphere has attracted interest since its discovery 75 years ago and is probably responsible for the only known case of (hydrocarbon) liquid seas exposed on a planetary surface. The surface of Enceladus is mostly water-ice, with a clear dichotomy between the smooth northern and the rugged southern hemispheres. From the south pole, through canyons known as 'tiger stripes' where the temperatures are warmer than in surrounding areas, strong plumes eject water vapour laden with salts, ammonia and organics out into space. If these geysers reflect the composition of the internal reservoir, then it is mostly composed of water with these compounds also incorporated. Different energy sources have been invoked for this small satellite's activity. The organic chemistry, the energy and the water which is obviously present on the satellite complete three out of the four requirements for habitability, but it is probably not a stable environment. On the other hand, Titan has an organic-rich atmosphere which deposits on its surface, but whether biological species also inhabit the internal water ocean remains unknown. They could hypothetically arise, though, by hydrolysis of organics in the chondritic matter that accreted to form Titan. A combination of Cassini–Huygens measurements with investigations made by future missions to the Kronian system is essential to help us understand the presence of liquid water at locations much more distant from the Sun than previously expected.

4.3.1 Titan: organic factory and habitat

Titan, Saturn's largest satellite, is another unique object in the Solar System (Figure 4.10). Although Titan is much colder than the Earth, as shown in Athena Coustenis and Frederic Taylor's books (*Titan: The Earth-like Moon* and *Titan: Exploring an Earth-like World*; Coustenis and Taylor, 1999 and 2008) the large satellite exhibits many similarities with the Earth and can be considered as a possible Class IV habitat. Recent Cassini–Huygens discoveries reveal that Titan is rich in organics from high atmospheric levels down to the surface, most probably contains a large liquid water ocean beneath its surface and has ample energy sources to allow for chemical evolution. Titan's atmosphere is composed of dinitrogen (N_2), like that of our own planet, with methane and hydrogen as the most abundant trace gases, and has a similar structure from the troposphere to the ionosphere, as well as an equivalent surface pressure of 1.5 bars – the only known extraterrestrial planetary atmospheric pressure close to that of the Earth. It has also been demonstrated that the sources for nitrogen on Earth and Titan are similar. The stratosphere and mesosphere together form what we call the middle atmosphere. The next atmospheric layer, the thermosphere (which on Earth covers the altitudes from 80 to 500 km), together with the exosphere forms the upper atmosphere. The ionized component of the thermosphere is the ionosphere, which is co-localized and interacts with the thermosphere. Titan's upper atmosphere is not protected (as the Earth's is) by an intrinsic magnetic field, and therefore it is subject to a

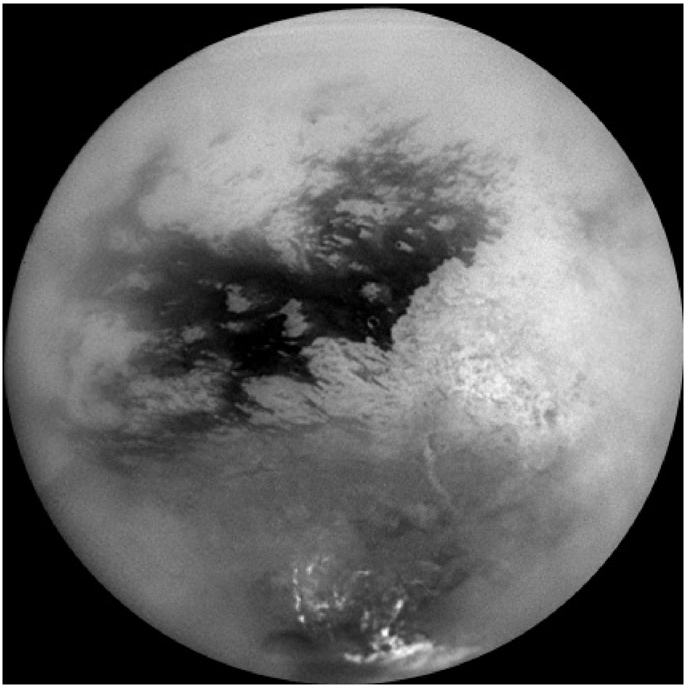

FIGURE 4.10 A mosaic of nine processed images acquired during Cassini's first very close flyby of Saturn's moon Titan on 26 October 2004, giving a detailed full-disk view of the moon. The view is centred on 15° south latitude, and 156° west longitude. Brightness variations across the surface and bright clouds near the south pole are exposed. The images in this mosaic were acquired from distances ranging from 650 000 km to 300 000 km. (Image courtesy of NASA/JPL/Space Science Institute.)

direct bombardment by energetic electrons, protons and oxygen ions. The ionosphere is formed through ionization by the solar radiation and by electron/ion impacts on the neutral atoms and molecules (electron stripping and charge exchange interactions). On Titan it is the place where complex ion–molecule reactions take place leading to the formation of hydrocarbons and nitriles, as studied by the Cassini Ion and Neutral Mass Spectrometer (INMS), and is found to extend up to ~1500 km. Right above this is the exosphere, where collisions between particles are rare and where the dominant force is the gravitational pull, which in the case of

Titan extends its influence (and thus provides an estimate for the limit of its exosphere) to about 50 000 km. The exosphere is thus the region from where atmospheric particles can eventually escape into space. Charged energetic ions from Saturn's magnetosphere can interact with neutral atoms from Titan's exosphere and become energetic neutral atoms (ENAs), as discussed by Iannis Dandouras and colleagues (2009).

Methane on Titan seems to play a role comparable to that of water on the Earth, with a complex cycle that has yet to be fully understood (Figure 4.11). Methane can exist as a gas, liquid and solid, since the mean surface temperature is almost 94 K as measured by the Atmospheric Structure Instrument on board the Huygens probe, approaching the triple point of methane. However, the amount of methane currently found in Titan's atmosphere is a mystery, since methane photolysis and recombination would have reduced these amounts to nothing a long time ago. To explain this paradox, methane reservoirs on or under the surface have been hypothesized. Analogies

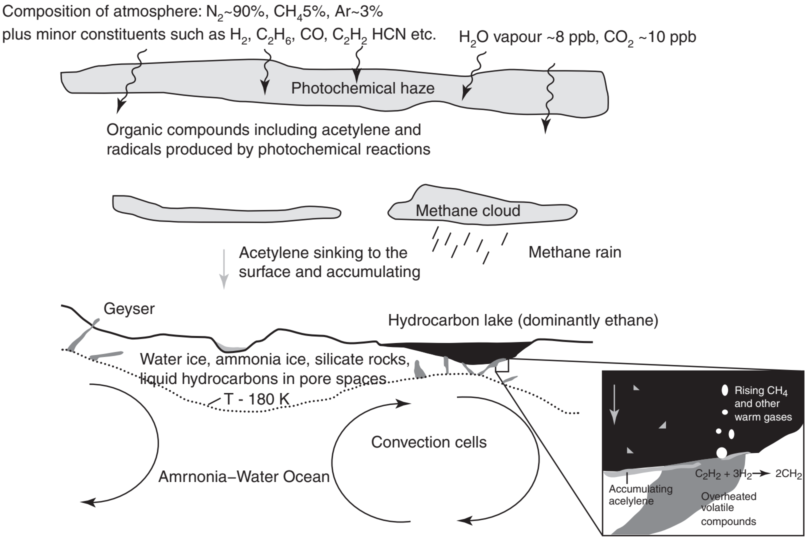

FIGURE 4.11 Methane cycle, environmental meteorology and biology in Titan's atmosphere. (Adapted from F. Bagenal's LASP class, http://lasp.colorado.edu/~bagenal/3720/CLASS23/23Titan.html. Sketch by D.Grinspoon.)

can also be made between the current organic chemistry on Titan and the prebiotic chemistry which was active on the primitive Earth. In spite of the absence of permanent bodies of liquid water on Titan's surface, the chemistry is quite similar.

4.3.1.1 Titan's organic chemistry throughout the atmosphere

Our previous understanding of Titan's chemistry was constrained to the stratospheric region, basically between 100 and 500 km, because that was where previous Voyager measurements probed the atmosphere. But with Cassini and its Ion and Neutral Mass Spectrometer (INMS), a major discovery was made: the haze surrounding the satellite forms more than 1000 km above the surface, through a combination of ion and neutral chemistry initiated by energetic photon and particle bombardment of the upper atmosphere. This energetic chemistry in the ionosphere produces large molecules such as benzene, which condense out to create the haze we see today on Titan (Figure 4.12). The thick haze layer where the organics detected on Titan precipitate could be an analogue to the UV-protective smog that sheltered the early Earth. As the haze particles fall through the atmosphere, they accrete and increase in size, becoming large polymers. Measurements throughout the atmosphere have indicated the presence of numerous hydrocarbon and nitrile gases, as well as a complex layering of organic aerosols (tholins) that persists all the way down to the surface (Figure 4.12). In the presence of nitrogen and methane, Titan's atmosphere is among the most appropriate environments known for prebiotic synthesis, and indeed, several of the organic compounds we find on Titan today, such as hydrogen cyanide (HCN), cyanoacetylene (HC_3N) and cyanogen (C_2N_2), were major players in the Earth's prebiotic chemistry. In particular, the presence of benzene is extremely interesting, as it is the only polycyclic aromatic hydrocarbon (PAH) discovered on Titan today. The presence of PAHs on Titan's atmosphere is important as they may contribute to the synthesis of biological building blocks. Moreover, the combination of the liquid deposits on the surface of Titan and the low temperature could create the proper environment for this biosynthesis.

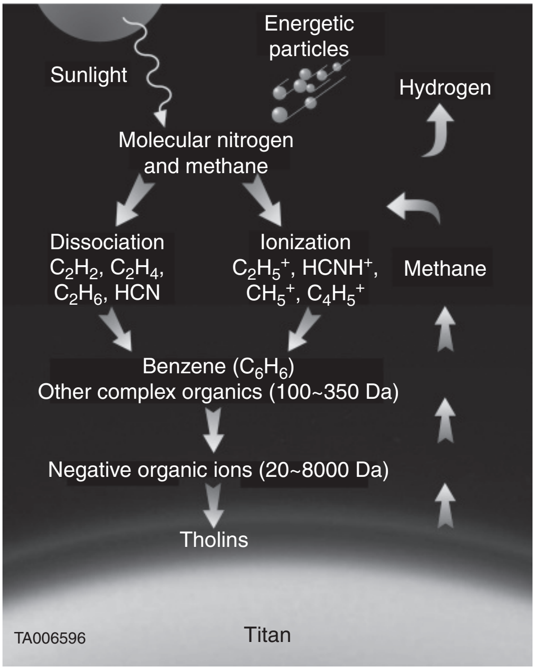

FIGURE 4.12 Titan's complex organic chemistry and its structure with the atmospheric layers as updated after the discoveries made by the Cassini–Huygens mission INMS, UVIS, CIRS and GCMS instruments. For colour version, see plates section. (Image courtesy of NASA/JPL/H. Waite.)

Recent laboratory experiments have shown that aromatic compounds have a good chance of being produced on icy surfaces.

The large molecules and aerosols produced on Titan strongly absorb solar and visible radiation and are thus essential in heating Titan's stratosphere (between 100 and 500 km) and forming wind systems in the middle atmosphere, a situation similar to ozone's contribution in the Earth's middle atmosphere. The large organic inventory of Titan's atmosphere is eventually deposited on Titan's surface, forming dunes and other deposits. Ninety per cent of the energy at the surface of Titan is held in by a greenhouse effect due to nitrogen, methane and hydrogen. These are symmetrical molecules which normally do not have a greenhouse effect on Earth, but they do on Titan, owing to the dense atmosphere. More interesting still, Titan is the only world in the Solar System to have an 'anti-greenhouse' effect, caused by the haze layers in the atmosphere, that lets light in and stops infrared. This anti-greenhouse effect is half as strong as the greenhouse effect. The tropospheric emission temperature (near the tropopause, at 40 km altitude) is determined by the anti-greenhouse effect and is 9 K cooler than the effective temperature (that is, the temperature equivalent to a black body emitting the same total amount of electromagnetic energy). The increase in temperature of 21 K from the tropopause to the surface is due to a greenhouse effect resulting from thermal infrared radiation emitted from the lower atmosphere and warming the surface. The surface is not in radiative balance, because convective motions account for an energy flux of 1 per cent.

Hence, on Titan, the upper thermosphere is linked intimately with the middle atmosphere and even the surface. But more than that, it is possible that the scheme we have found to be operating for the production of organic molecules on Titan is also the explanation for the production and delivery of prebiotical components to the early terrestrial oceans, much as the Miller–Urey experiment hypothesized.

Furthermore, the Gas Chromatograph and Mass Spectrometer (GCMS) on board the Huygens probe, which successfully landed on Titan's surface on 14 January 2005, did not detect a large variety of organic compounds in the lower atmosphere. In a 2006 article, François Raulin and colleagues indicated that 'the mass spectra collected during the descent show that the medium-altitude and low stratosphere as well as the troposphere are poor in volatile organic species, with the exception of methane' (Raulin *et al.*, 2006). Condensation of these species on aerosol particles is a probable explanation for the absence of the volatiles in the measurements. They were captured and analysed by the Huygens Aerosol Collector and Pyrolyzer (ACP) instrument on board the Huygens probe, which found them to be made of refractory organic nuclei covered with the volatile compounds that would have condensed on them. During pyrolysis, ammonia and hydrogen cyanide were released, supporting the tholin hypothesis, but there is still a need to measure the abundances of the condensates and their elemental composition, and to determine their molecular structure.

The measurements by the Cassini instruments of gases and aerosols, and in particular tholin material, are supported by laboratory simulation experiments that try to reproduce the organic chemistry detected on Titan, integrating the information available on the energy sources and the processes as well as possible. Several teams, led by experts in this field such as Bishun Khare, François Raulin and Hiroshi Imanaka, have conducted such experiments on the chemical evolution of N_2–CH_4 mixtures on Titan. The results, which are quite representative of what is found on Titan, tend to indicate that this work is essential since it manages to mimic the real chemical processes in Titan's atmosphere.

Titan is thus the largest abiotic organic factory in the Solar System. Indeed, as estimated and demonstrated by Ralph Lorenz, the quantities of methane and its organic byproducts in Titan's atmosphere, seas and dunes exceed the carbon inventory in the Earth's ocean, biosphere and fossil fuel reservoirs by more than an order of magnitude (Lorenz, 2008). The degree of complexity that can be reached from organic chemistry in the absence of permanent liquid water bodies on Titan's surface is still unknown, but it could be high.

Moreover, Titan is the only planetary object, besides Earth, with long-lived, exposed bodies of liquid on its surface (Figure 4.13). The features range in size from less than 10 km^2 to at least 100000 km^2. They are limited to the region poleward of 55° N. By 2009, Cassini's instruments had identified and mapped almost 655 geological structures referred as lakes and/or basins, mostly in the northern polar region. Large cloud systems, some of which attain the size of terrestrial hurricanes (1000 km across), appear occasionally, while smaller, transient and temporary features exist on a daily basis above these lakes and also can be found at mid-latitudes. It has been theorized that the lakes on Titan could be the result of condensation and even rain processes in Titan's atmosphere above. The hydrocarbon cycle

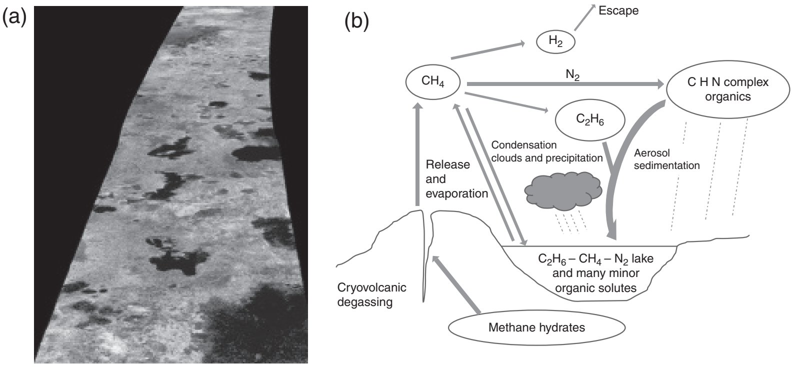

FIGURE 4.13 Hydrocarbons on Titan. (a) The dark spots are liquid hydrocarbon lakes detected in Titan's northern hemisphere. For colour version, see plates section. (Image courtesy of NASA/JPL-Caltech/USGS.) (b) Methane (CH_4) is released into the atmosphere from Titan's interior stores through volcanic action, and evaporates from the lakes of methane and ethane (C_2H_6) identified by the Cassini spacecraft on the satellite's surface. Chemical reactions in the atmosphere convert it to ethane, complex organic aerosols and hydrogen gas (H_2), which escapes into space. Ethane and methane partly condense, forming clouds and hazes that rain out, replenishing the lakes and depositing many organic species in solution. (Image © F. Raulin, LISA, Université Paris Est-Créteil Val de Marne, France.)

involving methane and ethane causes the liquid to be re-injected into the atmosphere where it rains out again after some time, producing the seas but also the fluvial features observed by Huygens near the equator.

In spite of the low temperature prevailing on Titan, we are not talking about a replica of a frozen Earth: the chemical system is evolving, and it may well produce compounds of (astro)biological interest, in particular on the surface where the organics are deposited after their descent through the atmosphere. Some experiments have even argued for the creation of amino acids through the reaction of the organics on the surface with any possible liquid water or even water-ice. Those processes could be particularly favourable in zones of Titan's surface where cryovolcanism might be occurring, or deeper in the interior where hydrothermal vents, similar to Earth's black smokers, may exist, albeit in different conditions, as has been suggested in recent research. Even with the detection of the large lakes in the north, Cassini was unable to detect any viable source that could re-supply the total amount of methane currently found into the atmosphere. Cryovolcanic outgassing has been hypothesized to re-inject methane into the atmosphere, yet over what timescales and through which internal processes remains unknown, even though several areas are currently believed to have been formed under the influence of cryovolcanism.

Cryovolcanism is considered to be one of the principal geological processes that has shaped several of the icy moons' surfaces. This activity can be described as ice-rich volcanism, while the cryovolcanic ejecta are referred to as cryomagma. The cryomagma might appear in the form of icy liquid and, in some cases, partially crystallized slurry, with unknown precise composition. There are currently three major cryovolcanic candidate regions, all of which are located close to Titan's equator. Moreover, modelling of Cassini/VIMS data taken from these regions from several flybys is providing signs of albedo variations with time, suggesting possible fluctuating deposition of material from the interior and from the atmosphere. If further analysis confirms this suggestion, then cryovolcanism will undoubtedly be considered as one of the top processes that replenish methane in the atmosphere and reshape and change the surface.

Cassini–Huygens also found that the inventory of geological processes shaping the surface – aeolian, fluvial, impacts, tectonics, cryovolcanism, etc. – is broadly similar to the Earth's (called 'morphotectonics'), more so than for Venus or Mars. This makes Titan our best analogue so far to an active terrestrial planet, albeit with different materials and physical conditions. Cosmic rays reaching Titan's surface could well irradiate any liquid bodies present there, thus assisting organic syntheses. In addition, the interface between the liquid phase and the solid icy deposits on the ground may include sites of catalytic activity favourable to chemical reactions. Titan's lakes present an ideal place to look for such effects.

4.3.1.2 Methane-based biology and the lakes

Earth-like life needs liquid water. This is currently impossible on Titan's surface, given the low temperatures, but may have been possible in the past, through impacts which could have created ephemeral pools of water in their craters from melting ice, temporarily allowing the emergence or growth of life. In addition, although the chemical reactions that lead to life on Earth need liquid water as a solvent, they take place almost entirely between organics. In the search for life and habitable conditions in the Solar System, one should therefore not ignore the study of organic chemistry, and Titan is a good place to start.

Titan's organic inventory has been known for quite some time now, ever since the discovery of hydrocarbons in its atmosphere by Kuiper, Gillett and others in the middle of the twentieth century. We now know, thanks to Cassini, that in addition to the atmosphere, organics are also widespread across the surface in different phases and in the lakes, seas, dunes and channels. Thus, all the ingredients that are supposed to be necessary for life to appear and even develop – liquid water, organic matter and energy – seem to be present on Titan.

Consequently, it cannot be ruled out that life may have emerged on or in Titan at some point in its history, in spite of the extreme and inhospitable conditions of its current environment. As we have seen in Chapter 2, life may have been able to adapt and to persist for some time even if the conditions (pH, temperature, pressure, salt concentrations) are not compatible with life as we know it. However, the detection of any potential biological activity in Titan's current internal water ocean seems very challenging – more so when we note that besides Earth-like lifeforms, other possible forms of living organisms have been speculated to exist on Titan.

Chris McKay and Heather Smith in 2005 noted the astrobiological importance of the liquid hydrocarbon lakes on Titan and hypothesized that a lifeform called 'methanogens' might consume hydrogen instead of oxygen, a hypothesis that could be tested against measurements in the lower atmosphere. In other research work by Darrell

Strobel and co-workers in 2010, based on data from the Cassini orbiter focusing on the complex chemical activity on the surface of Titan, hydrogen was shown to be precipitating through Titan's atmosphere and then mysteriously disappearing on the surface in a fashion similar to oxygen consumption on Earth. If this effect was produced by a living organism on Titan it would have to be markedly different from an Earth-like organism, but even so it has attracted interest as a hypothetical second form of life without the need for water. However, in more recent work it has been shown that the atmospheric haze can also absorb and desorb the hydrogen, thus providing the missing sink without any requirement for life.

Another measurement result that has been interpreted as a possible indicator for some sort of lifeform existing on Titan is the lack of acetylene on the surface: there is no clear evidence so far of this compound in the data received from Cassini, although it is expected to have been deposited through the atmosphere. Roger Clark and colleagues (2010) have suggested that this could be because some living organism on the surface is using acetylene as an energy source. This theory is much debated and controversial among the scientific community, especially because the phenomenon could be of non-biological origin, but it has the merit of inspiring new and interesting astrobiological theories. According to one theory put forth by astrobiologists, a hypothesized 'methane-based life' would consume not only methane but also hydrogen. However, another possibility, formulated by Mark Allen of JPL (2010), is that 'sunlight or cosmic rays are transforming the acetylene in icy aerosols in the atmosphere into more complex molecules that would fall to the ground with no acetylene signature'.

To date, methane-based lifeforms are hypothetical; they have not been detected anywhere in our Solar System, although we do find 'methanogens' on Earth, which are liquid-water-based microbes that feed on methane or produce it as waste. At Titan's low temperatures, and in the absence of any liquid water, which as we have seen would be frozen on the surface, a methane-based organism would need to resort to liquid methane or its byproducts such as ethane. However, as we have seen, liquid water is not a strict requirement, nor does it have to be on the surface. In Titan's putative ocean, organics penetrating through the icy crust might find the liquid water and produce a different methane-based lifeform. But with current technological means and plans, we are not even close to proving its existence.

4.3.1.3 Subsurface ocean on Titan

A combination of different land-shaping processes, such as aeolian, fluvial, and possibly tectonic and endogenous cryovolcanic processes, operates on Titan. Linear features and possible cryovolcanic spots are found, in general, close to the equator. In particular, elevated as well as fractured crustal features are observed, and the fact that these features are locally regrouped indicates a morphotectonic pattern. Their shapes, sizes and morphologies suggest that they are tectonic in origin, although it may be a different form of tectonism from the terrestrial one, originating from internal compressional and/or extensional activities. The triggering mechanism that leads to such dynamic movements is possibly Saturn's tidal pull, whose effects concentrate around the equator.

Titan is tidally locked with respect to Saturn and thereby subject to periodic tidal forcing of its interior and surface. The recent detection of periodic tidal stresses on Titan, caused by Saturn's gravity as the satellite revolves around the planet, shows deformations that are larger (perhaps as big as 10 m) than would be expected in a purely solid rocky body, and this may be consistent with a global ocean at depth (Figure 4.14).

In addition, the presence of an internal liquid water ocean on Titan is supported by models based on radar and gravity Cassini measurements and those from the Atmospheric Science Instrument on the Huygens probe (HASI). Indeed, the extremely low-frequency electric signal recorded by HASI measurements was recently interpreted as a Schumann resonance between Titan's ionosphere and a conducting ocean, probably of small dimensions and located at some 50 km under the surface. A Schumann resonance is manifested by the presence of extremely low frequency (ELF) radio waves, detected, in the case of Titan, in electric conductivity measurements acquired by the Huygens

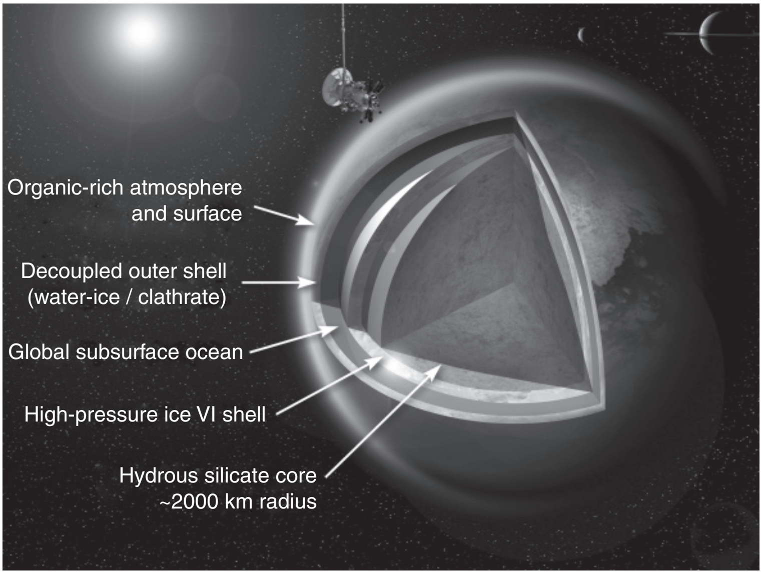

FIGURE 4.14 Layers of Titan's interior. For colour version, see plates section. (Image courtesy of A. D. Fortes/UCL/STFC, via NASA.)

probe during the descent. Such waves are also found on Earth where they are reflected by both the surface and the ionosphere in a configuration where the Earth's atmosphere resembles a giant 'sound box' where certain frequencies of ELF waves resonate and become stronger, while others die away. On Titan, however, the surface is a poor reflector because of its low conductivity and so these waves penetrate the interior where they may have been reflected by the liquid–ice boundary of a subsurface ocean of water and ammonia. Thermal evolution models of Titan by Ralph Lorenz and colleagues concur with this interpretation, suggesting that the moon may have an ice crust between 50 and 150 km thick, lying atop a liquid water ocean a couple of hundred kilometres deep. On Titan, unlike Ganymede or Callisto, the presence of nitrogen in the atmosphere suggests that ammonia could be found in the interior where, as we have seen above, it could act as an antifreeze. Beneath this one would find a layer of high-pressure ice.

In 2012, Luciano Iess and co-workers suggested the existence of a globe-encircling, shallow liquid water ocean as the most probable interpretation of Cassini's measurements of the tidal contributions to the non-spherical part of Titan's gravity field (Iess *et al.*, 2012). Indeed, the determination of the tidal potential Love number (which defines the capability for a rigid body to deform under tidal stresses) from Cassini gravity measurements indicates a fluid response on a tidal timescale. In addition, Cassini's measurement of asynchronicity in Titan's rotation can be interpreted to be a result of decoupling the crust from the deeper interior through the presence of a liquid layer.

Although we have some observational evidence today for suspecting the presence of a liquid water–ammonia ocean on Titan, more measurements are needed. In particular, precise knowledge of tidally induced distortion and tilt variation at the surface would allow us to address the thickness of Titan's outer ice shell, thereby confirming the possible existence of the liquid water ocean beneath. Definitive detection of this ocean of water and ammonia under an icy layer could be provided by the Radio Science Subsystem aboard Cassini, by measuring the principal components of Titan's and Enceladus' gravitational potential. This will also provide important constraints on the satellites' internal differentiation.

If a liquid body exists in Titan's interior it could be an efficient medium for converting simple organics to complex molecules, and chondritic organic material – brought in by carbonaceous chondrites and micrometeoritic impacts – into prebiotic compounds. In addition to this kind of exogenous input which could be stored in the lakes, one should consider endogenous supply by organic syntheses occurring in the bottom of Titan's primordial oceans through the presence of hydrothermal vents like the black smokers that we discussed in Subsection 2.2.2.

But the presence of a subsurface liquid water ocean on Titan does not by itself guarantee the presence of life therein. Although at some point early in Titan's history this hypothetical ocean may have been in direct contact with the atmosphere on the one hand, and with the internal bedrock at the bottom on the other hand, presenting important analogies with the primitive Earth, the data we currently have do not tell us whether there are indeed such contacts. This kind of information would also have an impact on our understanding of the mystery of methane replenishment on Titan. A liquid water ocean containing ammonia could become buoyant and cause outgassing of methane through the crust. Such an ocean could also serve as a deep reservoir for storing methane and might possibly shelter organisms which would have to survive high pressures and concentrations of ammonia, as well as low temperatures – extreme conditions, but not dissimilar to some found on Earth. Methanogens, discussed above, have been shown to be able to exist in high concentrations of ammonia at neutral pH.

A significant geophysical difference then becomes evident when one compares Titan and Europa: on Titan, as we have seen, the liquid water layer, if real, would in all probability not currently be in contact with a silicate core. The surface of Titan appears (like Mars or Europa) an unlikely location for life at present, at least for terrestrial-type life. Nevertheless, some scientists note that Titan's internal water ocean might support terrestrial-type life, which could have been introduced there or formed early in Titan's history when liquid water was in contact with silicates. In addition, there exist photochemically derived sources of free energy on Titan's surface, which could support some lifeforms using liquid hydrocarbons as solvents. Conversely, some studies have shown that terrestrial bacteria might satisfy their energy and carbon needs by 'eating' tholin, which is abundant in Titan's atmosphere and therefore provides a means to capture the free energy from ultraviolet light and make it available for metabolic reactions.

4.3.1.4 Titan and the primitive Earth

There are obvious analogies between the organic chemistry activity currently occurring on Titan and the prebiotic chemistry which was once active on the primitive Earth, prior to the emergence of life.

As we saw in Chapter 2, theories of the primitive Earth suggest an oxygen-less atmosphere before the appearance of life. For example, in 2007 Laura Schaefer and Bruce Fegley predicted that Earth's early atmosphere contained CH_4, H_2, H_2O, N_2 and NH_3, similar to the components used in the Miller–Urey synthesis of organic compounds, often noted to be similar to the atmospheric inventory of Titan and Enceladus. However, most of the arguments in favour of the presence of a reducing greenhouse gase like ammonia in the early Earth atmosphere have now been put into perspective, as discussed extensively by Feulner *et al.* (2012), as it would have been destroyed by photodissociation quite quickly, and other means exist for the production of prebiotic molecules (meteoritic impacts, deep-sea hydrothermal vents, etc.). As a consequence, ammonia is no longer the favourite dominant component in the primitive Earth's atmosphere; instead, N_2 is now favoured, outgassing rapidly on the early Earth from the interior, creating a secondary atmosphere in which the nitrogen concentration would have quickly attained today's value. Furthermore, recent studies have looked at the heating and haze forming processes on our planet at those primitive times and found many similarities with Titan for what could have served as a primary source of organic material to the surface. Indeed, the presence of methane (at abundances as high as 100–1000 parts per million per volume) and of CO_2 as warming agents for the Archaean period is now advocated: this could have contributed first to warming the atmosphere in order to survive the faint young Sun and then to forming the organic haze, thus igniting an anti-greenhouse effect which would have subsequently decreased the temperature of the atmosphere and created a habitable environment on our planet. Titan offers similar possibilities in that its atmosphere is essentially composed of nitrogen of possibly the same origin and includes several thick methane haze layers, leading to the formation of an equivalent anti-greenhouse effect, albeit not caused by CO_2. Titan's current atmosphere is then even more suited for studying conditions on the primitive Earth.

Although Titan lacks oxygen and sufficiently elevated temperatures, unlike the primitive Earth, different evolutionary pathways on Titan may still have led to the creation of polyphenyls (these ether phenyl polymers, or complex hydrocarbons, afford excellent thermo-oxidative stability and radiation resistance). The abundances of liquid hydrocarbons on Titan are hundreds of times higher on Titan than all the oil and natural reserves on Earth. And in the atmosphere we find hydrogen cyanide and other prebiotic molecules which are among the starting materials for biosynthesis. The existence of hydrocarbons, and in particular acetylene and benzene, has really enlarged the borders of photochemical organic products. Moreover, the temporal variations that the hydrocarbon trace gases on Titan experience during a full Titan year are probably also influenced by local or regional sources and sinks.

4.3.2 Enceladus: water pockets far from the Sun

Saturn's geyser-spewing moon, Enceladus, is a very small satellite, only 500 km in diameter (Figure 4.15). How something so small, buried inside an ice crust, derives the energy to eject a plume 900 km out of its south pole into space is still something that puzzles scientists, who are trying to determine the heat sources that prevent this tiny moon from being frozen all over, like the others orbiting Saturn. At the same time, Enceladus poses a major challenge to traditional models of the habitable zone, since it seems to show that liquid water exists a long way (10 AU!) from the Sun, albeit underneath the surface.

Whether it is possible for life to exist in pockets or liquid water oceans underneath its surface is an even more compelling question that has interested planetary researchers since 2005, when Cassini's magnetometer first spotted the influence of the plume on the field lines before it was optically recorded by the mission's cameras. During an early flyby, Cassini passed within 97 km of the moon's surface, sampling the ejecta.

Nobody knows exactly how these plumes of gas located at or close to the 'tiger stripe' ridges near the moon's south pole are formed. Several theories have been proposed, one of them based, as for other satellites, on the gravitational pull of Saturn on this small moon,

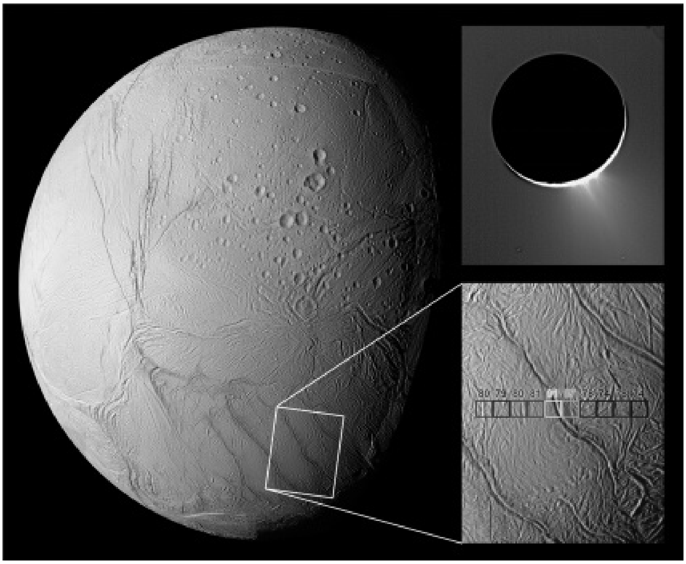

FIGURE 4.15 Surface of Enceladus, with focus on tiger stripes and an optical image of the jets emerging therefrom. The right lower zoom indicates the temperature scale across a south polar region, with the warmest temperatures detected at the 'tiger stripe' location (in yellow). For colour version, see plates section. (Image courtesy of NASA/JPL/Space Science Institute.)

perhaps causing the formation of rifts through the interior to the surface. In homage to the other geysers we know of in the Solar System, in our own Yellowstone, such models bear the names of 'Old Faithful', 'Cold Faithful' and 'Frigid Faithful' geysers. Of the two most favoured theories, one basically advocates the presence of liquid water under the surface directly supplying the plumes (Figure 4.16), while the other favours ice friction under tidal effects for their origin. The consensus tends to be that the observed heat signatures indicate that liquid water exists down there, but although this would have significant implications for astrobiology, the question is far from settled.

As an example, the 'Old Faithful' radiolytic model proposed by John Cooper and colleagues in 2009 suggests that the surface of Enceladus would be irradiated by Saturn's inner magnetospheric

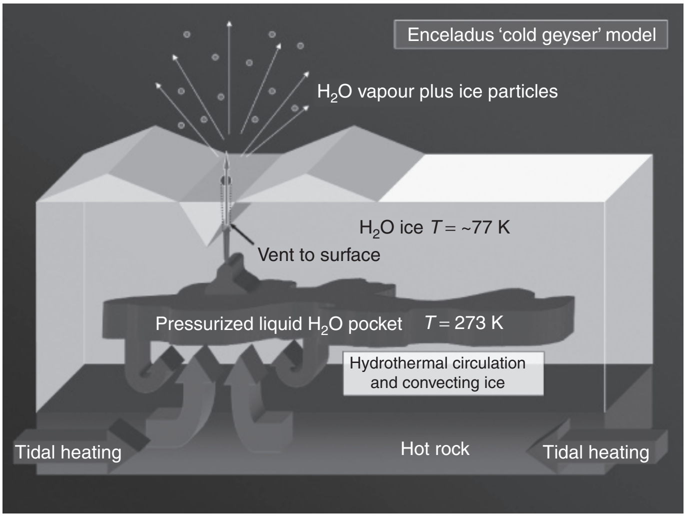

FIGURE 4.16 Enceladus 'cold geyser' interior model for the creation of the plumes observed emerging from the south pole. (Image courtesy of NASA/JPL/Space Science Institute.)

electrons, producing radiolytic oxidants. During episodic overturn of the moon's south polar terrain, these oxidants might find their way to the putative undersurface ocean where they would form carbon dioxide and other gases over long timescales, leading in good time, through some venting cracks, to cryovolcanism responsible for the plumes. This process is a means for the satellite to remain in one piece. Such a radiolytic process could also be an explanation for the geysers on Neptune's moon Triton (see hereafter), and on any icy body immersed in a radiation environment, including Eris and Haumea located beyond Pluto. Finally, the radiolytic model for Enceladus has direct implications for the habitability potential of this and other active moons like Jupiter's Europa or Ganymede, where one finds the irradiated environment but no plumes.

4.3.3 *Future exploration of Kronian satellites*

In summary, all of the satellites we have discussed in the above sections have habitable potential. Europa, Ganymede, Enceladus and

Titan may all have subsurface oceans, but we do not know how deep we need to search to get to them and whether they could really host life.

Ganymede and Europa in the Jovian system are currently major targets for finding an internal liquid water ocean among the giant planets satellites. More dedicated exploration is required before this can be established and characterized, but the astrobiological potential has been recognized for quite some time now and begs for further investigation, which is currently under way, as we have seen and discussed in Subsection 4.2.3.

In the Kronian system, Titan certainly is of considerable interest in terms of habitability and astrobiology not least because of its methanological cycle, an analogue to the terrestrial hydrological cycle, and its complex organic chemistry both in the atmosphere and on the surface. These, along with studies of Titan's interior and search for the methane reservoir, make Titan a high-priority target for future exploration if we are to understand how organic-rich worlds evolve.

In addition, the geologically active moon Enceladus and its fascinating geological features, like the south pole plumes probably caused by heated subsurface water pockets, require further long-term exploration of the Saturnian system with suitable mission components and instrumentation. Open issues have been identified for the purpose of future exploration within the Titan and Enceladus Mission (TandEM) concept (proposed to ESA as a large mission within the framework of the Cosmic Vision 2015–2025 programme, and which then became the Titan Saturn System Mission (TSSM), a joint study by the two space agencies, ESA and NASA; Coustenis *et al.*, 2009). These issues include:

- determining the organic chemistry of the two Saturnian satellites Titan and Enceladus;
- determining their present-day structure and precisely identifying whatever levels of activity they may have;
- determining whether the satellites have been subject to significant tidal deformation, and whether they possess cryovolcanism or any eruptive and seismic processes;

- identifying heat sources and internal reservoirs of volatiles (in particular methane and ammonia);
- searching for the presence of intrinsic or induced magnetic fields;
- searching for prebiotic compounds formed on Titan's surface or near subsurface. Long-term chemical evolution is impossible to study in the laboratory: *in situ* measurement of Titan's surface thus offers a unique opportunity to study some of the many processes which could have been involved in prebiotic chemistry, including isotopic and enantiomeric fractionation.

Although the Cassini–Huygens mission is a remarkable success, answering many outstanding questions about the Saturnian system and Titan in particular, it has also perhaps raised more questions. It is clear that Titan's organic chemistry and the presence of a subsurface ocean remain to be investigated. In particular, joint measurements of large-scale and mesoscale topography and gravitational field anomalies on Titan from both an orbiter and an aerial platform would impose important constraints on the thickness of the lithosphere, the presence of mass anomalies at depth and any lateral variation of the ice mantle thickness. It is astrobiologically essential to confirm the presence of such an internal ocean, even though the water layer may not be in contact with the silicate core as in Europa. However, the detection of potential biological activity in the putative liquid mantle seems challenging.

An important limitation of the Cassini–Huygens mission, as far as concerns Titan, is the insufficient spatial and temporal coverage allowed by its limited orbit around Saturn. One needs to remember that Cassini is not an orbiter dedicated to Titan or to any of the moons. For a body as special and complex as Titan, the minimum possible flyby altitude of 950 km and the uneven latitudinal coverage have impeded our attempts to explore the full set of atmospheric chemical processes. So far, opportunities for occultation have been rare, so we have not properly explored the magnetospheric downstream region. Furthermore, in spite of the wonderful opportunity offered by Huygens, we have only obtained one vertical profile of the atmosphere, and thus our understanding of horizontal transport and latitudinal variations is incomplete.

The surface of Titan, as revealed by both the Huygens probe and the Cassini orbiter, offers us an opportunity to stretch our current models in an effort to explain the presence of dunes, rivers, lakes, cryovolcanoes, ridges and mountains in a world where the rocks are composed of water-ice rather than silicates and the liquid is methane or ethane rather than liquid water, but the limited high-resolution spatial coverage restrains our view of the range of detailed geological processes on this body. The exciting results from the Huygens post-landing measurements, although providing a valuable 'ground truth', are limited to a fixed site and short timescales, and do not allow for direct subsurface access and sampling.

Several concepts for future missions that could answer such questions and more have been considered by ESA and NASA. The Titan Saturn System Mission (TSSM) (http://www.lesia.obspm.fr/cosmicvision/tssm/tssm-public/) was considered in 2008–2009: its focus was on enhancing our understanding of Titan's and Enceladus' atmospheres, surfaces and interiors, determining the pre- and protobiotic chemistry that may be occurring on both objects, and deriving constraints on the satellites' origin and evolution, both individually and in the context of the complex Saturnian system as a whole. The mission was an ambitious and challenging combination of three elements for remote observations (by a dedicated orbiter) and *in situ* observations (with a montgolfière and a lake lander; Figure 4.17). Since then, more focused and simpler mission concepts for an orbiter, an aerial aerostat and a lake lander separately have been proposed to the space agencies, but at the time of writing, nothing has been definitively decided in terms of follow-up investigations after Cassini–Huygens.

4.4 COMETS

Comets and some asteroids (the most primitive ones) are of major interest for astrobiology, because, as mentioned above (Subsection 2.3.3), they might have fed the terrestrial atmosphere with prebiotic molecules in its early ages, especially at the time of the Late Heavy Bombardment. In addition, comets are the most water-rich bodies in the Solar System (about 80 per cent by mass); they are unaltered

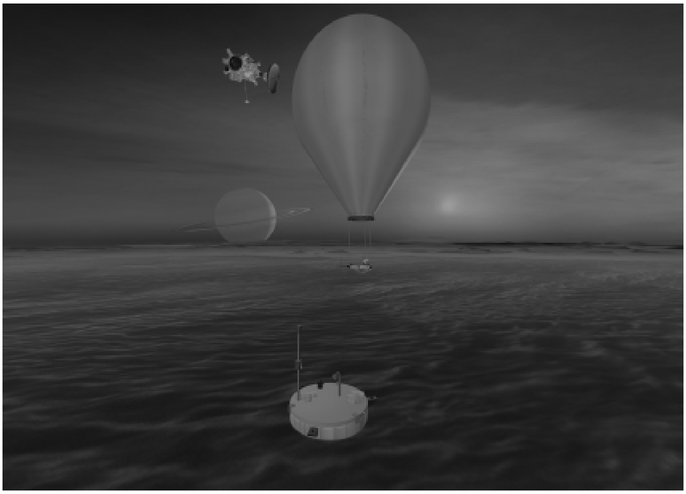

FIGURE 4.17 The Titan Saturn System Mission concept with the dedicated orbiter, the lake lander and the floating hot-air balloon; artist's view. For colour version, see plates section. (Image by C. Waste, courtesy of NASA/JPL.)

remnants of the conditions and processes at work in the early Solar System, and their chemical composition shows striking similarities with interstellar matter. For all these reasons, these small bodies can provide precious information in our search for extraterrestrial habitats.

4.4.1 Comets: back to the origins

Because of their peculiar – sometimes spectacular – appearance in the sky, comets have been known from antiquity (Figure 4.18). Their origin was a mystery for scientists until Tycho Brahe (1546–1601) demonstrated, by measuring the parallax of a comet, that the apparition was not an atmospheric phenomenon. Their orbits were later determined by Isaac Newton (1644–1727) and Edmund Halley (1656–1742) who demonstrated that a comet reappeared periodically. He successfully predicted the 1758 return of a famous periodic comet. The apparition took place long after his death, and the comet was then given his name.

We now know that comets are small bodies, less than a few kilometres in size, which travel on very elliptic orbits between the

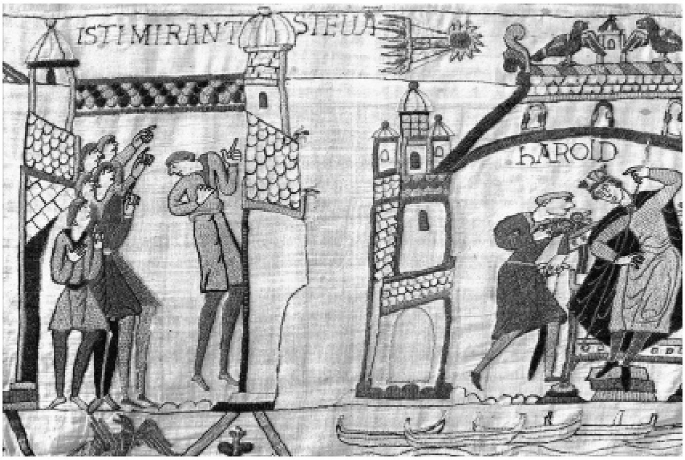

FIGURE 4.18 Comet Halley as shown on the Bayeux tapestry relating the conquest of England by William the Conqueror (1066). For colour version, see plates section. (Image courtesy of Wikipedia, http://en.wikipedia.org/wiki/Halley's_Comet.)

outer Solar System where they spend most of their time and the inner Solar System, with a typical period between a few years and a few tens or hundreds of years. They are mostly made of water and ices with some fraction of organics and rocks; because they have remained mostly unaltered since their origin, comets are precious witnesses to the conditions of formation and early evolution of the Solar System.

The observation of a comet is difficult. Far from the Sun, the comet is a cold object that only consists of its nucleus, too faint to be easily imaged or observed by spectroscopy from the ground. When the comet approaches the Sun, the surface of the nucleus sublimates under the effect of solar radiation; water and other gases evaporate, carrying jets of dust, and form the coma which scatters the Sun's light and becomes brighter and brighter (Figure 4.19). The observer can thus analyse the components of the coma – parent molecules, daughter molecules, radicals and ions resulting from solar ultraviolet irradiation – but the nucleus itself remains hidden behind the coma.

FIGURE 4.19 Comet P/Halley as taken on 8 March 1986 by W. Liller, Easter Island, part of the International Halley Watch (IHW) Large Scale Phenomena Network. For colour version, see plates section. (Image courtesy of NSSDC/NASA.)

4.4.2 *Origin of comets: two distinct reservoirs*

What is the origin of comets? Information is provided by the study of their orbits. Comets can be divided into two classes: the short-period ones (with periods less than a few tens of years) and the long-period ones (including the parabolic and hyperbolic ones that never return). By studying the orbits of long-period comets and taking into account perturbations due to the giant planets, the Dutch astronomer Jan Oort (1900–1992) demonstrated that all these objects were coming from a very distant shell – now called the Oort cloud – located at about 50 000 AU from the Sun. This discovery was later confirmed by Brian Marsden (1937–2010).

The Oort cloud could well contain some hundred billion comets or even more; however, its total mass is estimated to be just a few times the mass of the Earth. The comets were not formed in the Oort cloud itself, because there was probably not enough available material at such great distances from the Sun; most likely, they were formed in the vicinity of the giant planets' orbits and expelled outward as an effect of their gravitational perturbations (see Chapter 1). Occasionally, owing to some external gravitational perturbation, an object can be ejected from the Oort cloud, approach the inner Solar System and be captured on a periodic orbit as a result of planetary perturbations; such is the case for comet Halley. Comets coming from the Oort cloud are characterized by a long period, a large eccentricity and a random inclination.

The other main class of comets includes short-period objects with low inclinations and low eccentricities. These comets are believed to originate from the Kuiper Belt, at 40–100 AU from the Sun, and are thus called Kuiper Belt comets (Figure 4.20). The toroidal nature of the Kuiper Belt, different from the isotropic Oort cloud, explains the low eccentricity and low inclination of these objects. The study of their orbital history shows that they often spend part of their lives in orbit around Jupiter, hence their appellation of 'Jupiter-family comets'.

It is important to remember that Oort comets and Kuiper Belt comets originated from different reservoirs, located at different heliocentric distances, and their composition may reflect the associated different conditions at the time of the comets' formation. Because of their shorter periods, Kuiper Belt comets have experienced more

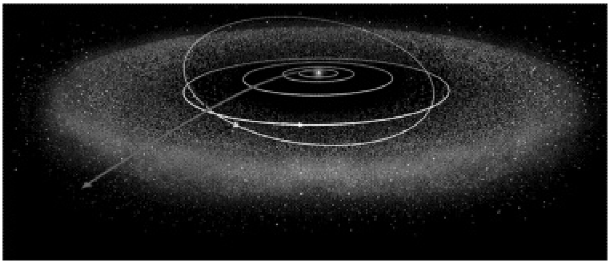

FIGURE 4.20 An artist's representation of the Kuiper Belt, beyond the orbit of Neptune. The circular orbits of Jupiter, Saturn, Uranus and Neptune, as well as the eccentric one of Pluto extending well into the Kuiper Belt, are shown for comparison. The arrow indicates the trajectory of the New Horizon mission. (Image courtesy of NASA.)

perihelion passages than the Oort cloud ones, losing material each time they approach the Sun. For this reason they are usually weaker and more difficult to observe.

In addition to these two main reservoirs, a third one has recently been proposed, in the outer part of the asteroidal main belt; these comets might have been responsible for bringing water to Earth (see Section 3.5).

4.4.3 What are comets made of?

Thanks to the extension of the observable spectral range accessible to astronomers, our knowledge about the composition of comets has made huge progress over the past 50 years. Until the 1950s, cometary spectroscopy was limited to the visible range, and only daughter products (mostly C_2, CN and CH) were known. Then, in the 1970s, ultraviolet observations revealed emissions from atoms and radicals (H, O, C, S, CS, OH…). Starting in the 1980s, infrared and millimetre observations led to the detection of parent molecules that bear key information about the chemical composition of cometary nuclei: H_2O, CO_2, CO, HCN, H_2CO and others.

The return of comet Halley in 1986 provided astronomers for the first time with the opportunity to detect parent molecules. In addition to an unprecedented international ground-based observing campaign, five spacecraft encountered the comet as it crossed the ecliptic plane in March 1986 (see Subsection 2.3.3). For the first time, images of a cometary nucleus were obtained (Figure 4.21); they revealed that the nucleus was not spherical but elongated and highly irregular, partly covered with ice and partly with dark refractory material, most likely of carbonaceous origin. Water was at last unambiguously identified. Its presence as a major component had been strongly suspected, following the famous 'dirty snowball model' proposed in 1950 by the American astronomer Fred Whipple (1906–2004); the major argument in its favour was the equal abundance of H and OH, the two most abundant daughter products measured in several comets, and also the presence of the H_2O^+ ion.

FIGURE 4.21 The nucleus of comet Halley as imaged by the camera of Giotto in March 1986. (Image © Halley Multicolor Camera Team, Giotto Project, ESA.)

The water was identified through its infrared emission around 2.7 μm, both from space and from the Earth, using the Kuiper Airborne Observatory. Other parent molecules were detected in the infrared range: CO_2, CO, OCS, H_2CO and more complex organic molecules, both aromatic and aliphatic; HCN was detected in the millimetre range. In addition, *in situ* measurements of the cometary gas and dust, using mass spectrometry, revealed that the cometary matter was very primitive, with large abundances of H, C, O and N. Altogether, the exploration of comet Halley demonstrated the close link between cometary and interstellar matter.

Subsequent observations of bright comets confirmed this discovery. The most spectacular event was the arrival of comet Hale–Bopp in 1997. This exceptionally bright object, coming from the Oort cloud for the first time, had a diameter of about 50 km. It was observed by ground-based telescopes, especially in the millimetre and

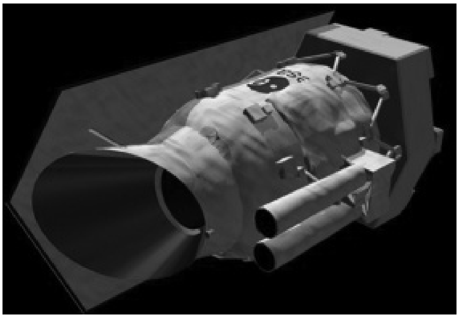

FIGURE 4.22 The Infrared Space Observatory. This infrared satellite, launched by ESA in November 1995, operated in Earth orbit until April 1997. (Image © ESA.)

submillimetre range, and by the Infrared Space Observatory (ISO; Figure 4.22) in the infrared range. ISO observations revealed the spectacular similarity in chemical composition between cometary and interstellar dust. By decreasing abundance order in cometary ices, the main parent molecules are H_2O (80 per cent by number), then CO and CO_2 (about 10 per cent); then CH_3OH, NH_3, CH_4 and H_2CO (about 1 per cent). About 20 gaseous parent molecules were identified in comet Hale–Bopp, all also present in the interstellar medium, including an 11-atom molecule, ethylene glycol ($HOCH_2CH_2OH$). ISO also observed the spectrum of Hale–Bopp over the whole infrared range and established the exact nature of cometary dust, dominated by forsterite, a special type of magnesium-rich olivine (Mg_2SiO_4), which has also been detected in the dusty envelope surrounding the star HD69830, a star which also has a system of three exoplanets. The cometary solid phase also includes carbonaceous material, as detected on comet Halley, and also, most likely, polycyclic aromatic hydrocarbons (PAHs).

Apart from the nucleus, carbonaceous grains present in the comet are a potential source for cometary molecules. Some molecules, such as CO, H_2CO, OCS, HCN, CN show a distributed source which could originate from the thermal degradation of grains. Laboratory simulation experiments suggest that polyoxymethylene or POM $(H_2CO)_n$, hexamethylenetramine HMT ($C_6H_{12}N_4$), HCN polymers, or carbon suboxide poymers $(C_3O_2)_n$ are plausible cometary

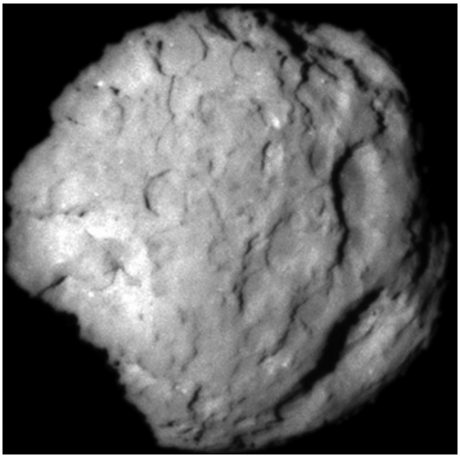

FIGURE 4.23 Comet Wild 2, as observed by the Stardust mission on 2 January 2004. Launched on 7 February 1999, the spacecraft collected samples of the comet's dust and returned them to Earth on 15 January 2006. (Image courtesy of NASA Discovery.)

compounds which could explain the observed distributed sources of gaseous cometary species.

Another source of information has come from the Stardust space mission. The spacecraft, launched by NASA in 1999, collected samples from the coma of the comet 81 P/Wild 2 (Figure 4.23) and returned them to Earth in 2006. Cometary and interstellar particles were collected in an aerogel substrate. Careful analyses revealed the presence of organic compounds including aliphatic chains, methylamine CH_3NH_2, ethylamine $CH_3CH_2NH_2$ and possibly glycine NH_2CH_2COOH. PAHs were also tentatively identified in Stardust samples.

In 2005, NASA performed another experiment to study the internal composition of a comet. On 4 July 2005, the Deep Impact mission sent an impactor into the surface of comet Tempel 1, creating a 30-m crater. Analyses of excavated material (which appeared to be more dust than ice) revealed clays, carbonates, sodium and crystalline silicates; the presence of clays and carbonates was unexpected as it usually implies the presence of liquid water. The spacecraft, renamed Epoxi after the Tempel 1 impact, was later retargeted toward another Kuiper Belt comet, Hartley 2, which it encountered on 4 November 2010. The comet exhibited an unexpected peanut shape, with evidence for different morphological regions, and several bright jets of water vapour and carbon dioxide, well separated in space.

It has been known for decades that the chemical composition of comets is not uniform; in particular, the dust to gas ratio varies as well as the carbon abundance, initially measured through emission lines of the C_2 radical in the visible range. Using the C_2 diagnostic, observations apparently show a carbon depletion among the Kuiper Belt comets; however, this trend does not seem to be confirmed by the abundances of their parent molecules. It is true, however, that the observation of Kuiper Belt comets in the infrared and millimetre range is much more challenging than that of Oort comets, which are typically brighter. More observations will be needed to refine this analysis.

4.4.4 *Isotopic ratios and ortho/para ratios*

Observations provide two other diagnostics about the formation conditions of comets. The first is the measurement of isotopic ratios, and in particular D/H, already mentioned earlier (Subsection 1.2.3; Figure 4.24).

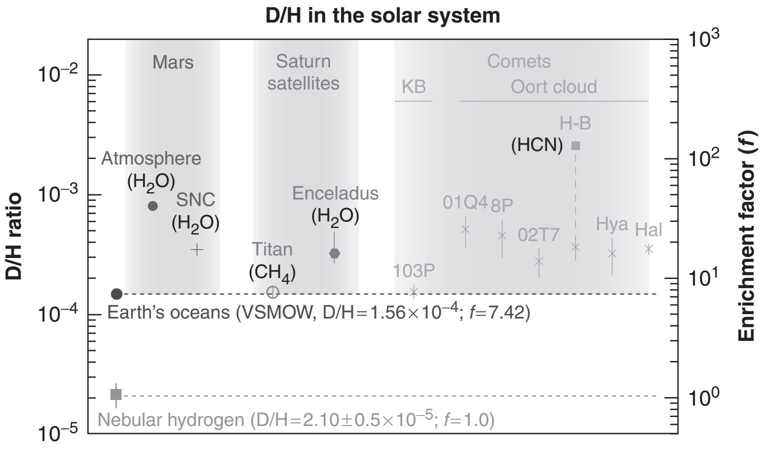

FIGURE 4.24 The D/H ratio in comets, compared with other Solar System values. KB, Kuiper Belt. (Figure adapted from Mumma and Charnley, 2011.)

We have seen that D/H in ices (and in particular in water) is enriched as a result of ion–molecule and intermolecule reactions at low temperature: at the surface of a grain, the deuterium atom, being twice as heavy as the hydrogen atom, is more easily captured. As a result, the D/H ratio is enriched in H_2O ice, and the measurement of D/H in H_2O in different small bodies of the Solar System provides an indication of the formation temperature of the body where it is measured (note that D/H measured in the atmospheres of the terrestrial planets tells a different story, as the D/H enrichment in Mars and Venus is due to differential escape, a totally different mechanism).

The D/H ratio was first measured in comet Halley (an Oort comet) in 1986 by mass spectrometry aboard the Giotto spacecraft, with a value of 3×10^{-4}, twice the VSMOW terrestrial value measured in the oceans. The same result was later reported on two other Oort comets, Hyakutake in 1996 and Hale–Bopp in 1997, this time using submillimetre remote sensing spectroscopy. It was then inferred that terrestrial water could not have been brought in only by comets. But the situation evolved again in 2011 with the first measurement of D/H in a Kuiper Belt comet, Hartley 2, using submillimetre spectroscopy with the Herschel spacecraft. This time D/H was found to be equal to the VSMOW value, thus reactivating the debate. Future measurements on Kuiper Belt comets are obviously necessary before a firm conclusion can be drawn (see Section 3.5).

Another precious diagnostic of cometary formation conditions is provided by the ortho/para ratio (OPR). What is this parameter? It comes from the two different possible states of the hydrogen molecule H_2, ortho or para, depending on the spin value (+1/2 or −1/2) of the rotational direction of the proton of each atom. If the nuclear spins are in opposite directions, the H_2 molecule is called para; in the other case it is ortho. The same states apply to H_2O. They can be identified spectroscopically from their spectral lines, which occur at slightly different frequencies. The relative abundances of the two states can thus be measured, and they bear information on the temperature of the molecule at the time of its formation. At ambient temperature, the

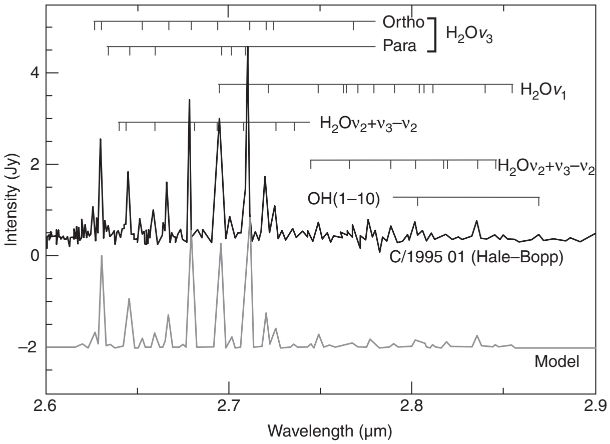

FIGURE 4.25 The spectrum of comet Halley as observed by the Infrared Space Telescope. The ortho/para ratio in cometary water is retrieved for the relative abundances of the ortho and para transitions. (Figure adapted from Crovisier *et al.*, 1997.)

ortho/para value is 3:1 (its 'normal' value), but it decreases with temperature down to very low values if the temperature is low. The OPR was first measured in comet Halley in 1986, using infrared transitions around 2.66 micrometres observed from the Kuiper Airborne Observatory (Figure 4.25). The measurement was repeated with ISO on two other comets, Hale–Bopp and Hartley 2. On these three objects (two from the Oort cloud and one from the Kuiper Belt), very low formation temperatures were measured, lower than 35 K.

Isotopic and OPR measurements are more easily made on water as it is the most abundant molecule. However, the properties of isotopic abundances and OPRs mentioned above also apply to other molecules. Nitrogen-bearing species are of special interest, because the NH_2 radical can be measured in the visible range. In a recent analysis by Shinnaka *et al.* (2011), the OPR in NH_3 has been inferred (from its ratio in NH_2) in 15 comets, together with the $^{15}N/^{14}N$ ratio. All objects are found with formation temperatures lower than 35 K, which confirms the water measurements.

4.4.5 *Comets and the origin of life*

The panspermia hypothesis (Box 2.2), which suggests that life might have been brought to Earth from extraterrestrial sources, has been known since antiquity. We find the first mention of it in the work of the Greek philosopher Anaxagoras five centuries BCE; a millennium later, Giordano Bruno (1548–1600) might have been influenced by this theory. More recently, Fred Hoyle (1915–2001) and Chandra Wickramasinghe (b. 1939) revived this concept. Originally, the idea was that living organisms could have travelled through interplanetary (or even interstellar) space to fertilize the Earth. However, it is unlikely that microorganisms would survive the very harsh radiation field of the interplanetary environment. A more pertinent question is whether prebiotic molecules could have been carried to Earth from outside. The answer is yes, as we know that amino acids have been found in the Murchison meteorite. Could comets have brought prebiotic molecules to Earth? Part of the answer will be obtained if prebiotic molecules are found in comets.

Scientists have placed much hope in the European Rosetta space mission (Figure 4.26), launched in 2004 and now on its way to a Kuiper Belt comet, 67-P/Churyumov–Gerasimenko. The spacecraft will orbit the comet as it approaches the Sun, monitoring the onset of its activity, and, in November 2014, will send a lander to its surface. A suite of remote sensing and *in situ* experiments will study the chemical

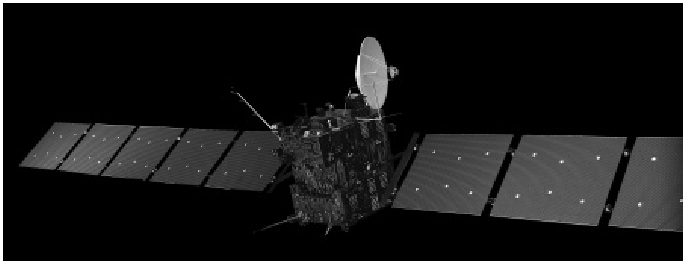

FIGURE 4.26 The Rosetta spacecraft. Launched by ESA on 2 March 2004, the spacecraft will encounter comet Churyumov–Gerasimenko early in 2014. On 10 November 2014, a lander will be deposited on the comet's surface for an *in situ* exploration of its composition and structure. (Image © ESA.)

composition of the coma and the surface, as well as the physical properties of the nucleus. This exploration is expected to help us reach a milestone in our knowledge of comets and their possible link to the appearance of life on Earth.

Could comets be habitats in themselves? Water is present in the form of ice and vapour, but, according to models of cometary interiors, the presence of liquid water is unlikely. Liquid water would require a heating source, which could be provided by the radioactivity of ^{26}Al or possibly by the phase transition between amorphous and crystalline water; but it also requires sufficient pressure, which can be reached only inside big objects, of about 100 km in size. Kuiper Belt objects (see below) would a priori be better targets as potential habitats.

4.5 AT THE ORBIT OF NEPTUNE AND BEYOND

Over the past two decades, the discovery of a new class of objects beyond Neptune's orbit has opened a new window on the formation and evolution of the outer Solar System; it has also provided a link with the debris disks that are now commonly discovered around nearby stars. Major milestones were the discovery of Pluto in 1930 by Clyde Tombaugh (1906–1997), the prediction of the existence of a population of objects beyond Neptune by Kenneth Edgeworth and Gerard Kuiper in 1943 and 1950 respectively, and finally the discovery of the first Kuiper Belt object, 1992QB1, by David Jewitt and Jane Luu in 1992.

About 1350 trans-Neptunian objects or TNOs are known today. They are divided into different classes based on their orbital properties. The classical objects (about 60 per cent) have a low eccentricity and a moderate inclination; Makemake is the largest object of this category. The resonant objects (about 12 per cent) are, like Pluto, in 3:2 mean motion resonance with Neptune; the largest object of this category, after Pluto, is Orcus. The scattered objects have large eccentricities and perihelion distances close to Neptune's orbit; a typical representative is Eris whose size is very similar to (if not larger than) the size of Pluto. Finally, the detached objects have large eccentricities ($e > 0.24$) and perihelion distances beyond Neptune's orbit. The origin of this last category is still unclear; a representative object is Sedna, with a semi-major axis of about 500 AU.

4.5.1 Cryovolcanic Triton

Further out, around Neptune, revolves another satellite, Triton, with unique characteristics among which are an atmosphere and geysers (Figure 4.27). Triton's characteristics, in particular its large size (it is the biggest of the Neptunian moons) and its retrograde orbit, suggest that it is an object from the Kuiper Belt region captured around the planet during one of its excursions. The Voyager 2 flyby in 1989 revealed that Triton has a nitrogen and methane atmosphere, extending 950 kilometres above the surface, with a ground pressure of 14 microbars. The

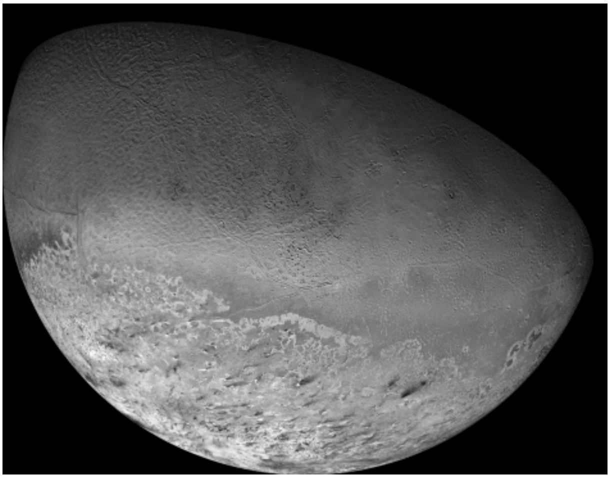

FIGURE 4.27 The surface of Neptune's largest moon, Triton, at its sub-Neptunian hemisphere. This image is a false-colour mosaic taken in 1989 by NASA's Voyager 2 spacecraft. It is one of only three objects in the Solar System known to have a nitrogen-dominated atmosphere (the others are Earth and Saturn's moon, Titan). Its frozen surface is made mainly of nitrogen ice, with some methane ice at the south pole (bright, pinkish terrain in the lower part of the image). Voyager 2 observed dust deposits left by nitrogen gas geysers (dark maculae shown as dark spots on the image). The smoother greenish region above includes the Triton 'cantaloupe terrain' and cryovolcanic and tectonic features. For colour version, see plates section. (Image courtesy of NASA/JPL/USGS.)

surface temperature is about 35.6 K. The moon's surface also has nitrogen, methane and carbon dioxide ices. As Triton's density is high, it is suspected that it has a large core of silicate rock.

The atmospheric temperature profile shows a troposphere (lower part of the atmosphere just above the surface) formed at around 8 km in altitude owing to turbulence at the surface, but no stratosphere above. Work in recent years by Candice Hansen and William McKinnon has determined the atmospheric and surface structure of Triton. A well-structured thermosphere (where heat is transported by conduction), an ionosphere and an exosphere also exist. The exospheric temperature reaches 95 K. The Hubble Space Telescope and occultation observations have shown that the atmosphere is actually even denser than suggested by Voyager 2, and that the temperature is increasing, but the mechanism for this is unknown. The lower atmosphere of Triton contains a variety of condensates. Most of the atmosphere contains a diffuse haze which probably consists of hydrocarbons and nitriles produced by the photolysis of nitrogen and methane. Discrete clouds can be distinguished at the limbs, most probably consisting of condensed nitrogen. The plumes seen by Voyager 2 near 50° S rising to altitudes as high as 8 km, and named Mahilani and Hili, could be ejections of liquid water, or could be purely atmospheric phenomena with the same composition as the rest of the atmosphere, with nitrogen rather than methane evaporating into the atmosphere and subsequently condensing (Figure 4.28).

In addition to these exciting atmospheric phenomena, it has recently been hypothesized that the capture of Triton and tidal friction during its subsequent evolution towards a circular orbit might have led to the formation of a subsurface ocean. Such a liquid ocean might have formed between the rocky core and an icy surface shell, and scientists think that it could have survived until now, but the question is how. Although radiogenic heating (heat caused by the decay of radioactive isotopes within a moon or planet, which can create heat for billions of years) contributes several times more heat to Triton's interior than tidal heating (friction from tides), radiogenic heat alone is not enough

FIGURE 4.28 Artist's view of Triton's geysers. Triton is scarred by enormous cracks. Voyager 2 images showed active geyser-like eruptions spewing nitrogen gas and dark dust particles several kilometres into the atmosphere. For colour version, see plates section. (Image © Ron Miller, courtesy of International Space Art Network, http://spaceart1.ning.com/photo/triton-geyser.)

to keep the subsurface ocean in a liquid state over long periods, and certainly not for the lifetime of the Solar System (4.5 billion years). However, tidal dissipation focuses the heat towards the bottom of the ice shell, causing the growth and expansion of the ice to slow down and even to stop. This tidal dissipation is stronger for larger values of eccentricity, meaning it would have played an even more important part in the past in maintaining the liquid water–ammonia ocean. However, several uncertainties remain in our knowledge of this body.

For instance, we do not know with certainty when Triton was captured by Neptune or how long it took for its orbit afterwards to become almost perfectly circular, as it is today. This circularization takes place thanks to tidal heating effects that we must study further to understand how they affect the internal structure. From this we derive information on a possible subsurface liquid water ocean and its depth, which could vary as the tidal forces are not constant across the globe but tend to focus on the poles in some cases. Another uncertainty is the size of Triton's putative ocean, which depends on the size of the rocky core (also not known with precision); the larger the core, the more radiogenic heating is available, thereby augmenting the size of any existing ocean. As we have seen previously in this chapter, current estimates suggest that icy bodies of the outer Solar System could contain as much as 15–20 per cent ammonia. When ammonia is mixed in a liquid, it helps to lower the temperatures at which the liquid (here the water) can remain unfrozen, and thus favours the existence of a liquid ocean underneath the surface for all these cold objects.

Recent research by Jodi Gaeman, Saswata Hier-Majumder, and James Roberts (Gaeman *et al.*, 2012) has shown that the ammonia that might be present in a putative Triton subsurface water ocean would act to lower its freezing point and maintain it in liquid form, possibly making it suitable for life. But such an ocean would probably still be very cold, about 176 K or –97 °C). As in the case of Titan and Enceladus, this would considerably slow down biochemical reactions and prevent evolution. However, as discussed in Chapter 2, enzymes working at temperatures as low as 170 K exist on Earth, and they have been shown to reverse this tendency and make the biochemical reactions more efficient.

Another (albeit more remote) possibility discussed by these scientists is that Triton might host a different type of life, one based on silicon rather than carbon (see Subsection 2.2.3). Silicon in the form of silanes is more apt to survive in low temperatures, but all this remains hypothetical at the time of writing.

Thus, in spite of many similarities and interactions, the icy satellites that we have examined in these sections are very different bodies with different exchange processes that need to be further investigated.

4.5.2 *Trans-Neptunian objects*

The exploration of trans-Neptunian objects (TNOs) is obviously limited to remote sensing analysis and spectroscopy, until the NASA space mission New Horizons, launched in 2006, encounters Pluto and its satellite Charon in 2015, and possibly another TNO later on. The surface composition of about 200 TNOs has been analysed by photometry in the visible and near-infrared range, and the brightest TNOs have also been studied by spectro-photometry at the same wavelengths. For the Pluto–Charon system we also have information from mutual occultation events and stellar occultation (Figure 4.29).

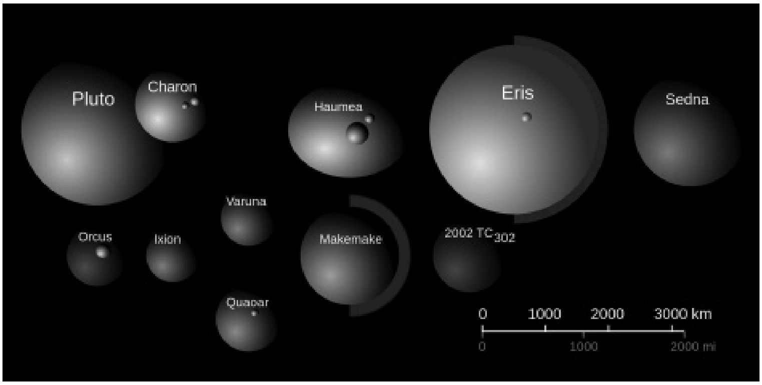

FIGURE 4.29 Some of the largest trans-Neptunian objects. The arcs around Makemake and Eris indicate the uncertainties in the size, given the unknown albedo. For colour version, see plates section. (Image courtesy of Wikimedia Commons.)

Colour photometry seems to indicate a correlation between the colour, the size and the inclination, with the smaller objects of low inclination and low eccentricity being significantly redder in most cases; this population could be more primordial than the other one. Spectroscopy of the brightest TNOs indicates a surface composition dominated by CH_4 and N_2 with, in some cases, CO, hydrocarbons (C_2H_2 and C_2H_6) and water.

What can TNOs tell us about the early history of the Solar System? Their orbital properties allow us to decipher their dynamical history, which is of key importance to understand the migration of the giant planets and also provides an explanation to the origin of the Late Heavy Bombardment. Their surface and interior properties also provide information about the physical processes that they have encountered since their origin. TNOs are considered to be pristine objects, but they have been subject to many external and internal modifying processes. First, their surface has been submitted to cosmic-ray bombardment, leading to an alteration of their molecular composition. Laboratory simulation experiments have shown that an irradiation mantle is formed, molecules in ice are broken and radicals are formed, hydrogen escapes, and a carbonaceous dark material is formed; the same layer was observed on the surface of comet Halley. Second, collisions between TNOs play an important role on the surface but also in the interior if the object is disrupted. Finally, internal processes due to short-lived radiogenic elements or accretion-generated heating may take place in the case of the largest objects. These might be responsible for the presence of crystalline water found at the surface of some objects, and not expected in view of its permanent irradiation. The water could be due to cryovolcanism, as observed on Neptune's satellite Triton; another possible origin could be micrometeoritic impacts.

What is the relevance of TNOs for astrobiology? These distant objects are too far from the Earth to have contributed to its meteoritic bombardment, as comets and asteroids did. But, as we saw for Triton, their interior probably contains a significant amount of water and, in the case of the largest objects, their internal heat (both from accretion and radioactive decay) might have been sufficient for water to be liquid. In this case the largest TNOs could possibly be considered, like some outer satellites as Triton, as potential habitats.