Chapter 11
Astrobiological Potential of Planetary Bodies Within the Solar System

All the known planetary bodies and satellites in our Solar System are within reach of current technology for the detection of a number of the biosignatures and geosignatures that could indicate the possibility of harboring some form of life. In this chapter, we will review the strength of that possibility for each of the planets and the best studied dwarf planets and moons in our Solar System.

11.1 Terrestrial Planets

11.1.1 Mercury

The Solar System's innermost planet, Mercury, has little to commend it as a possible habitat for life. It is too small to hold an atmosphere, is the most heavily bombarded planetary body in the Solar System, has a very weak magnetic field, and no evidence of complex chemistry. It also appears no longer to be tectonically active, though volcanic activity may have continued on Mercury for longer than previously assumed, perhaps from the formation of the planet to about a billion years ago, based on data from the Messenger spacecraft (Goudge et al. 2014). Sunlight provides an abundance of energy, but the planet's proximity to the Sun and its lack of atmosphere results in temperature fluctuations between 430 °C in sunlight and −180 °C in darkness (Dinwiddie et al. 2008). The possibility of any kind of life on Mercury could be rated as negligible, but for two factors.

First, while its orbital period is 88 earth days, its period of rotation is 58.6 days, resulting in a slowly moving terminator (boundary between daytime and nighttime) where temperatures drop to an intermediate point between the extremes. Second, while most of the planet's surface appears to be totally desiccated, there is evidence that some ice exists in permanently obscured areas at the poles (Slade 1992). Thus, temperatures compatible with microbial life and the possibility of water-ice at the poles preclude total elimination of the prospect for life on Mercury.

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Yet, the odds are strongly against it. Even at the terminator, the temperature is estimated to be above 150 °C, so the surface must be totally dark by the time the temperature drops into a range tolerable for any known form on life on Earth, and there is no evidence of a liquid of any kind other than possibly at the poles, where there is virtually no light.

Even if some form of microbial life could have originated on Mercury or been delivered there, it seems most unlikely that it could ever have thrived there.

11.1.2 Venus

Venus has not always been the home of hellfire and brimstone that it is today. In *Cosmic Biology* (Irwin and Schulze-Makuch 2011) we detailed the argument that Venus in its early planetary history was a rocky water world, with conditions that would have made the evolution of an early biosphere as likely as the one we know occurred on Earth. As the temperature warmed, with increasing solar intensity and the heat-trapping effect of rising atmospheric humidity, evolution would likely have accelerated, possibly giving rise to a biodiversity exceeding that on Earth at the same time. Thermophilic autotrophs, nourished by abundant sunlight, may well have covered the planet in greater abundance and diversity than autotrophic life on Earth in the same time frame.

The contemporary reality, of course, has obliterated any plausibility that life exists on or near the surface of the planet today. As the Sun got brighter and greenhouse conditions worsened, abetted by catastrophic volcanic eruptions that persisted to less than 2.5 million years ago (Smrekar et al. 2010), water was driven from every reservoir and the planet's surface dried out and overheated (Kasting 1988). With a global temperature of 464 °C (Williams 2016) and no liquid at the surface today, Venus presents the most hostile habitat in the Solar System for life of almost any conceivable form. But that only applies to the surface and subsurface. Granted that this is where the search for life is naturally focused—given that Earth's biosphere is most dense and diversified at or near its surface. But the thick, multilayered clouds of the lower atmosphere of Venus differ drastically from its surface, and by their mass and global extent, they have attracted consideration as an alternative habitat for life.

Morowitz and Sagan (1967) long ago noted the presence of more benign conditions in the lower cloud layers, and suggested that "it is by no means difficult to imagine an indigenous biology in the clouds of Venus." We now understand the composition of the cloud layers in greater detail (Jenkins et al. 1994; Grinspoon 1997): A thick (~15 km), uppermost layer made up of tiny (0.1–0.2 micron) droplets of sulfuric acid with temperatures from −4 to −45 °C; a thin (~4 km) middle layer of larger (1.1–1.4 micron) droplets between 4° and 33 °C; and a lower layer from about 48 to 52 km above the surface, consisting of larger (~3.4 micron) droplets of water/sulfuric acid from 33° to 80 °C. The middle and lower layers are compatible with normophilic and thermophilic microbial life on Earth, respectively (Irwin and Schulze-Makuch 2011).

Grinspoon (1997, 2003), Morowitz (2011), and the authors of this book (Schulze-Makuch and Irwin 2002b, 2006; Schulze-Makuch et al. 2002b, 2004, 2013a) have been vocal advocates for the possibility of life in the clouds of Venus. We have even described chemically plausible scenarios for harvesting energy and sustaining a microbial metabolism in that environment (Schulze-Makuch et al. 2004; Irwin and Schulze-Makuch 2011). Similar ideas have been advanced by Limaye et al. (2018).

Missions to sample the cloud layers of Venus have been proposed (Schulze-Makuch and Irwin 2002a, b; Schulze-Makuch et al. 2002b, 2005b). Even though a sample return mission is technologically feasible and potentially easier than sample return missions from Mars or Europa (Schulze-Makuch et al. 2004), NASA has shown little interest in supporting such missions (Hand 2011), apparently based on devotion of limited funds to missions aimed at elucidating the formation of the Solar System, and a search for life as we know it on Earth. To be sure, survival of organisms in the confines of tiny droplets of liquid sulfuric acid with exposures to high levels of ultraviolet radiation would be a challenge by conventional Earth standards, but such extremophiles do exist, and microbial life up to high elevations in the atmosphere of Earth is abundant (Smith et al. 2012; Smith 2013).

In some ways, discovery of life on Venus would be more informative of the range of total possibilities for living systems, since directional selection on that planet would likely have driven the evolution of organisms with biochemistries substantially different from those known on Earth.

11.1.3 The Earth-Moon System

Even lacking an empirical observation of life on Earth, an alien observer at a level of technological development equivalent to ours within a distance of 10–15 light years would be highly likely to suspect the strong possibility of life on the third planet from the Sun in the Solar System.

At such a distance with instrumentation similar to ours, the alien scientist would probably be able to detect a strong signature for H_2O, H, N, O, S, C, and Si. Our observer might even be able to decipher the presence of an atmosphere rich in N_2 with about a fifth as much of O_2 and traces of CO_2, SO_2, H_2S, and methane. From infrared radiation, the temperature of the Earth could be deduced, and from the Sun's size and intensity, its age—hence the age of its orbiting planets and their moons as well—could be pegged at 4–6 billion years. Furthermore, radio signals emanating from the planet would likely be seen as an unnatural indicator of technological advancement.

The abundance of water and a global average temperature of about 15 °C would mean liquid water on the surface. The abundance of silicon would be consistent with a rocky planet, a fact confirmable by the planet's density if enough information were available to calculate that. The planet's relative proximity to the Sun would mean abundant sunlight. The presence of SO_2 and H_2S could reflect volcanic eruptions, indicating dynamic geological activity. The presence of both O_2 and methane would be a suspicious signature of biogenic processes. With all the elements necessary for carbon-based polymeric chemistry, with the abundance of liquid water quite likely interfacing with rocky continental masses, with chemical elements necessary for energy-yielding oxidation-reduction coupling reactions, not to mention the flood of sunlight and an atmosphere capable of protection against ultraviolet radiation and interplanetary debris, favorable conditions for the evolution of life would have to be assumed. Furthermore, as we know, a planetary history spanning four billion years is long enough for the evolution of life to a considerable degree of diversity.

The Earth's Moon is a different story. Despite formation in close proximity to the Earth—perhaps with material drawn from the early Earth itself (Mastrobuono-Battisti et al. 2015)—and at the same distance from the Sun, there is every indication that the Moon is totally lifeless. Not only is it lacking any geoindicators and bioindicators of life, no samples brought from the Moon back to Earth have contained anything resembling even complex biomolecules.

It seems likely that the Moon, along with the Earth, underwent a series of pulsatile bombardments up to around 3.8 Ga ago (Schmitt 2006). These early planetesimal collisions and bombardments by planetary formation debris could have delivered water to all the inner rocky planets and the Moon (Bottke et al. 2010), combined with magmatic outgassing, possibly even resulting in temporarily habitable conditions on the Moon (Schulze-Makuch and Crawford 2018). Organic chemicals could have been deposited in this manner as well. Whether because of its smaller mass, or other interplanetary dynamics, the Moon lost its atmosphere, probably early on, and that precluded its ability to hold any surface water. Whatever incipient organic chemistry may have been present was apparently lost, at least from the surface.

Whether more than the slightest trace of water exists in the Moon's interior is a subject of controversy (McCubbin et al. 2010; Sharp et al. 2010). First suggested by neutron flux data from both poles (Feldman et al. 1998), water-ice has been convincingly detected near the Moon's south pole (Clark 2009), amounting possibly to as much as 1% by volume and 6% by mass within the upper 1–2 m of the surface (Kerr 2009). However, at the Moon's extremely low surface temperature, water almost surely never exists there in the liquid state (Kerr 2010). The apparent absence of this fundamental requirement for life, combined with the total lack of any biogenic material in any sample returned from the Moon, leaves us to rate the likelihood of any form of life on the Moon as negligible.

However, in the earliest stages of its history, when the Moon and Earth were much closer and likely shared much of their material substance, including possibly even a conjoined atmosphere, they could have shared the same prebiotic environment. Thus, even if totally lifeless today, water-ice on the Moon could hold evidence of prebiotic chemistry of the Earth-Moon system from very early Solar System history (Armstrong et al. 2002; Baker et al. 2005). Sampling water-ice from the Moon could therefore be a mission well worth undertaking.

11.1.4 Mars

There is now widespread agreement that in their early planetary histories, Mars and Earth harbored similar habitats. Strong evidence favors a warmer, wetter Mars with long-lasting seas and lakes lasting into the Amazonian, <3.0 Ga ago (Fairén et al. 2009). By this point in time on Earth, microbial mat ecosystems (Noffke et al. 2013) and probably photosynthesis (Tice and Lowe 2006) were widespread on Earth. There is no reason to believe that the same could not have been true on Mars.

However, as Mars lost its atmosphere, it turned colder, leading to a prolonged phase of a colder but still wet planet (Fairén et al. 2003; Fairén 2010). While some climate models of an early Mars subjected to 20% less insolation from the young Sun (the faint Sun paradox) indicate a cold planet almost from its origin, greenhouse gases, meteorite impacts, and volcanism could still have generated long-standing bodies of liquid water (Wolf and Toon 2013; Wordsworth et al. 2013). In either event, with dropping temperatures and atmospheric pressures, retention of surface water diminished, until the cold dry habitat of today was reached, well over 1 Ga ago (Fairén et al. 2010).

The extensive stores of water that once covered much of Mars did not disappear entirely (Irwin and Schulze-Makuch 2011). The Mars Odyssey Orbiter revealed vast amounts of water-ice just below the surface over broad areas of the planet (Bandfield 2007). The visible topography of Mars shows strong evidence of flowing water (Carr 1996)—in large volumes carving massive channels, and in smaller spillways down steeply sloping terrain which seem in some cases to be very recent. Dark streaks currently observed on Martian slopes, called Recurrent Slope Lineae (RSL), may also have an origin that involves water—possibly brines consisting of chlorates and perchlorates (Ojha et al. 2015).

As Mars evolved from a warmer wetter, to a colder wetter, to a colder dryer surface with extensive stores of subsurface water-ice, life on Mars would have retreated to a psychrophilic lifestyle beneath the surface or to environmental niches near the surface, such as hydrothermal regions and caves (Schulze-Makuch et al. 2005a, b). Sequestered environments such as lava tube caves (Fig. 11.1) would have been particularly favorable due to the increase in destructive UV radiation at the surface as the atmosphere eroded. Strong directional selection could have pushed putative Martian life to evolve alternating cycles between active and dormant forms, as well as the innovation of new traits adapted to challenging near-surface conditions (Schulze-Makuch et al. 2013a). Equally plausible is the transition from widespread edaphic communities to localized lithic communities and finally to communities exclusively found in hygroscopic substrates, reflecting the need for organisms to maximize access to atmospheric sources of water (Davila and Schulze-Makuch 2016). All of these scenarios are consistent with the possibility of life on Mars until relatively recent times, perhaps even to the present (Houtkooper and Schulze-Makuch 2007; Schulze-Makuch et al. 2008; Irwin and Schulze-Makuch 2011).

Diverse organic compounds of endogenous origin have been found on Mars (Glavin et al. 2014; Freissinet et al. 2015; Eigenbrode et al. 2018) and the presence

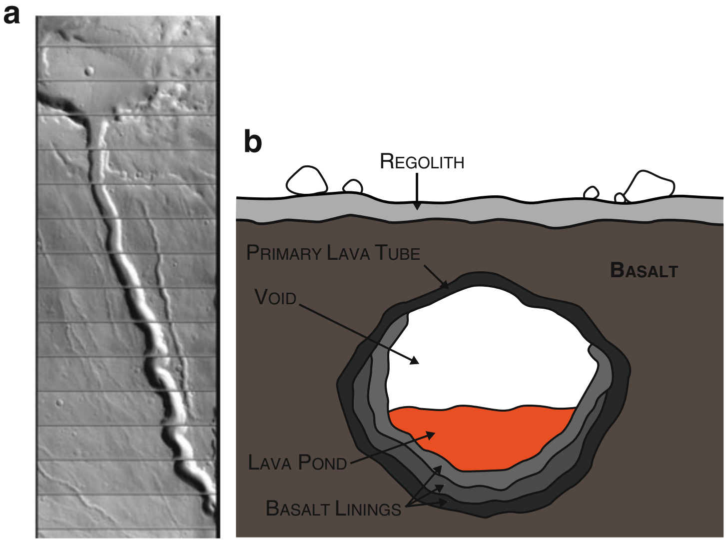

Fig. 11.1 Lava tubes on Mars. Under certain conditions, lava spills and flows can harden on top while magma continues to flow out, leaving a hollow tube which may (**a**) collapse, or (**b**) form caves that could sequester organisms, if life still exists on Mars. *Credit: (**a**) NASA/JPL-Caltech/ University of Arizona; (**b**) https://en.wikipedia.org/wiki/Martian_lava_tube, CC BY-SA 3.0*

of H_2O_2 (Clancy et al. 2004) and perchlorate (Webster and Cruz 2009) could serve as possible energy sources where sunlight is unavailable. While the traces of methane in the atmosphere of Mars could be produced abiotically, a biotic origin has not been ruled out (Krasnopolski et al. 2004).

Extremophilic microbes have been described on Earth that bolster the plausibility that such organisms could exist on Mars. Some bacteria living at the interface of ice and basalt on Earth can derive energy from Fe(II) in the igneous mineral olivine. These microbes can grow at temperatures as low as 5 °C using bicarbonate as a facultative source of carbon. This bacterium could thus live in near-surface, icy, volcanic environments on Mars (Popa et al. 2012). Wilhelm et al. (2012) have isolated a variety of psychrotolerant, halotolerant microbes capable of growing in ice wedges, in permanently cold, water-scarce, ice-rich environments. Species of *Carnobacterium* have been isolated from Siberian subsurface permafrost that grow in low temperature, low pressure, anoxic atmospheres (Nicholson et al. 2013); and 20 species of bacterial hypobarophiles capable of growth at 1–2 kPa have been recovered from arctic permafrost (Schuerger and Nicholson 2016).

In summary, the conditions for the origin or sustenance of life existed on Mars for at least a billion years early in its planetary history. Though conditions on Mars began to diverge dramatically about 3.5 Ga ago toward the cold and arid planet of today, directional selection should have promoted the evolution of organisms tolerant to cold and low pressure as conditions on the surface changed. With copious amounts of water-ice still permeating much of the Martian subsurface, as well as the presence of sinecures such as subterranean ice wedges, hydrothermal regions, and lava tube caves—living organisms, even including microbial mats and colonial aggregates in caves, may be present on Mars today. With the possible exception of subsurface oceans on some icy satellites, Mars seems the most likely planetary body in the Solar System other than Earth to have harbored life in the past, with the distinct possibility that a limited biosphere still exists there today.

11.1.5 Ceres

Ceres is the largest body in the asteroid belt between Mars and Jupiter. Because it resembles the rocky planets of the inner Solar System more than other bodies in the asteroid belt, it was classified as a dwarf planet in 2006. Its diameter of 952 km is slightly less than the width of the State of Texas. Its low density is consistent with a rocky core encased in a thick layer of water-ice, which could account for up to 25% of its volume (Fig. 11.2). This makes it comparable to many of the icy satellites in the outer Solar System.

Ceres is dominated by many small craters, with none greater than 280 km in diameter (Hiesinger et al. 2016). This, plus numerous indications of cryovolcanism and cryomagmatism (Buczkowski et al. 2016), suggests a geologically active body.

In 2014, scientists at the Herschel space observatory detected the expulsion of water vapor from the surface of Ceres (Küppers et al. 2014). Data collected by the *Dawn* spacecraft which arrived at Ceres in 2015 detected water-ice, probably of relatively recent origin, on the surface, as well as a variety of mineral hydrates indicative of formation in contact with water (Combe et al. 2016). Evidence of widespread clays on the surface of Ceres raises the intriguing possibility that the

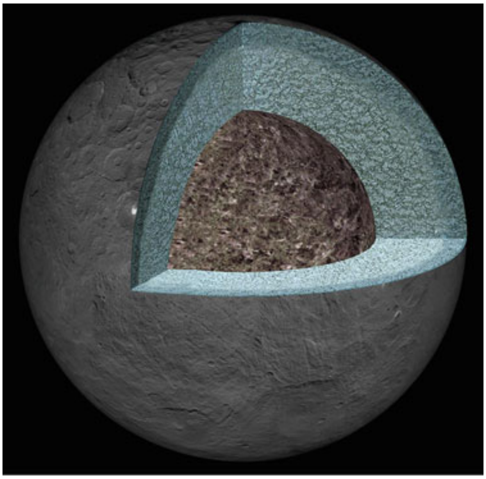

Fig. 11.2 Internal structure of Ceres. This artist's conception is based on gravimetric data collected by the *Dawn* spacecraft. Ceres appears to be differentiated into an internal core, probably of hydrated silicates, surrounded by a volatile-rich layer, encased in a crust of mixed material. *Credit: NASA/JPL-Caltech/UCLA/MPS/DLR/IDA*

subsurface ocean could be a very muddy reservoir of liquid water (De Sanctis et al. 2015). Eventually organic compounds were detected on the surface as well (De Sanctis et al. 2017). Thus, the ingredients for prebiotic chemistry are present on Ceres (Küppers 2017).

If a subsurface ocean lies beneath the outer crust (O'Brien et al. 2015), and if life had arisen on, or been delivered to, Ceres at an early stage of its planetary history, some forms of marine life could still exist beneath its surface. Such a possibility has long been suggested for Europa, and more recently for Enceladus, both of which are discussed below; and what applies to them could be the case for Ceres.

11.2 Outer Solar System

11.2.1 Gas and Ice Giants

The four giant planets of our Solar System—Jupiter, Saturn, Uranus, and Neptune—consist of planetary-sized cores enveloped by gases compressed by gravity into progressively denser and warmer layers, with no apparent sharp boundaries between gas, liquid, and solid or metallic plasma states.

Jupiter's mass is 2.5 times the mass of the other seven planets combined. Its atmosphere is 90% hydrogen, with helium and traces of methane and ammonia composing the other 10%. It has a very rapid period of rotation, making a complete revolution on its axis every 9.93 h. Beneath high, wispy clouds of ammonia race thick billowy clouds of various hydrocarbons. The temperature is about −145 °C at the top of the cloud layer, but reaches room temperature (~21 °C) at a depth where the pressure is ~10 bars. The warmer gasses deep in the atmosphere rise to the top, while the cooler gasses sink. This vertical movement, combined with the Coriolis Effect of the high rate of rotation, generates bands of strong winds circling the planet at up to 400 km/h (Irwin and Schulze-Makuch 2011).

Saturn's atmosphere is 96% hydrogen, with helium and trace compounds including ammonia and ammonium hydrosulfide making up the rest. It makes one revolution every 10.5 h, features clouds of different composition including methane and hydrocarbons at different levels. High winds blow at around 500 m/s (1800 km/h), and high altitude storms occur periodically (Dinwiddie et al. 2008). The equatorial temperature is about −188 °C at the top of the troposphere where the pressure is 100 mbars (Orton and Yanamandra-Fisher 2005).

The atmosphere of Uranus has a lower content of hydrogen (82.5%) and higher content of helium (15.2%) than the two larger gas giants. Methane, ammonia, water, and other trace compounds make up the remainder. Voyager 2 recorded a cloud top temperature of −214 °C. Beneath the placid surface, which appears smooth due to an ultraviolet light-induced haze of methane, dozens of discrete cloud features and banded zonal structures appear. Deeper into the atmosphere, a thick layer of water, methane, and ammonia ices is presumed to encase the rocky core. Beneath the gaseous layer, Uranus is thought to consist of a thick layer of water, methane, and ammonia ices (Dinwiddie et al. 2008). Wind velocities of 218 m/s (785 km/h) have been measured on Uranus (Hammel et al. 2005).

Neptune is the smallest, coldest, and windiest of the four giants. Cloud top temperatures are about −200 °C, and equatorial winds reach a staggering 600 m/s (2160 km/h). The atmosphere is 79% hydrogen, 18% helium, with methane and other trace gases making up the remainder (Dinwiddie et al. 2008). A thin methane cloud is found at 1.5 bars, and other clouds, probably of ammonia and other constituents, appear at 3 bars (Stone and Miner 1989). Like Uranus, the interior of Neptune is believed to be primarily composed of a fluid mixture of methane and water (Lee and Scandolo 2011), but at temperatures that make the stability of macromolecules unlikely (Baker et al. 2005).

More than 40 years ago, Carl Sagan and E. Saltpeter (1976) speculated that organisms in the form of thin gas-filled balloons could float at levels of atmospheric density great enough to support them. They envisioned an ecosystem consisting of autotrophic “sinkers” that would serve as food for a primary level of consumers, named “floaters,” which in turn would supply nutrients for a secondary level of “hunters.”

The availability of energy and abundance of building blocks for biomolecules, such as methane, ammonia, and sulfur compounds in the atmospheres of the giant planets, compel consideration of the possibility that some form of life could persist among them; and the fanciful idea of Sagan and Saltpeter seems as good a guess at the nature of that life as any. It is only at high enough altitudes for the atmosphere’s constituents to be gasses that temperatures would be compatible with macromolecular structures and metabolism, so if life exists at all on the giant planets, it must be in the form of organisms that fly or float.

Opposing the theoretical possibility of life in the giants are three strong theoretical arguments against it, given in detail in our previous work (Irwin and Schulze-Makuch 2011). In summary, they are (1) lack of historical circumstance, (2) absence of solid substrates, and (3) atmospheric instability. By lack of historical circumstance, we mean that no clear path for the evolution of life can be envisioned in such an amorphous and unstable environment. The lack of solid substrates or sharp interfaces where constituents could be concentrated, and self-perpetuating metabolism could take hold is a severe apparent limitation. And even once formed, the survival of fragile organisms in such turbulent environments would be a challenge. Thus, we consider the existence of living organisms on any of the gas giants as extremely unlikely.

Besides the theoretical arguments against life on the gas giants is the total lack of any empirical evidence for the presence of any molecules of significant complexity within their atmospheres.

Notwithstanding the dilute concentration of precursors for biomolecules, it is not inconceivable that microscopic organisms able to survive in severely nutrient-depleted environments could have been delivered to the atmospheres of the giant planets by panspermia from a more benign point of origin. But all the giants are a long way from Earth, the only habitat for life known with certainty at this time. If life had taken hold on any of the nearby satellites of the gas giants, delivery from them is more likely. The possibility that life could have arisen and could exist on other planetary bodies in the outer Solar System will now be considered.

11.2.2 Io

The innermost and largest satellite of Jupiter, Io is the fourth largest moon in the Solar System. Stretched and compressed by the alternating alignment of the outer Galilean satellites (Europa, Ganymede, and Callisto) relative to the strong gravitational pull of Jupiter, frictional heating makes Io the most volcanically active planetary body in the Solar System (Matson and Blaney 1999). There is no lack of energy; and a rich mix of inorganic compounds—CO, CO_2, H_2S, SO_2, NH_3, with traces of H_2O and CH_3OH (Sandford and Allamandola 1993)—could in principle provide precursors for biomolecules.

Contrary to these potential advantages for the existence of life on Io is the stark hostility of the environment, which features temperatures as high as 2000 K (McEwen et al. 1998) in erupted lava and as low as 80 K (-193 °C) at the surface away from lava flows. The high temperatures are not compatible with macromolecular stability, and the low temperatures would make metabolism in a water-based medium impossible. Though a very small amount of water is found on Io (Salama et al. 1994), it could not exist in liquid form except as part of a mixed ice slurry of H_2S, SO_2, and H_2O at local warm spots (Salama et al. 1990). The surface and near subsurface of Io is subjected to wandering plumes of volcanic emissions and spreading lava fields which, at their edges, vaporize the SO_2 snow fields prevalent on the surface and probably liquefy the composites of H_2S, SO_2, H_2O, and whatever other compounds might be liquefiable (Kieffer et al. 2000).

We have previously speculated that local warming by moving boundaries of lava across the frozen surface of Io could liquefy pockets of H_2S, SO_2, NH_3, and H_2O, providing temporary habitats for the resurrection of dormant microorganisms (Schulze-Makuch 2010; Irwin and Schulze-Makuch 2011). This assumes that life could have arisen on or been transported to Io when conditions for the sustenance of life were more benign; though whether such conditions ever existed on a moon coalescing so close to the intense radiation and gravitational pull of Jupiter is a fair question. Our point here is simply that the possibility of life on Io cannot be summarily dismissed.

11.2.3 Europa

The next satellite out from Jupiter is Europa, the smallest of the Galilean moons, and a world hard to imagine more different from Io. The density of Europa can best be explained by a metallic core surrounded by a rock mantle, encased in an ice-salt water ocean 70–180 km deep (Fig. 11.3; Anderson et al. 1998; Carr et al. 1998). The

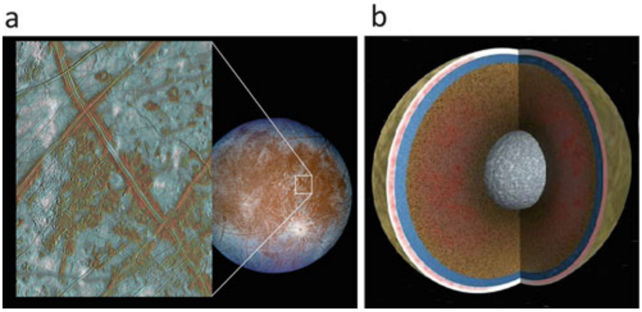

Fig. 11.3 Europa, surface and interior. Constant gravitational flexing has ground Europa's surface into the smoothest in the Solar System. (**a**) Close-up of surface showing criss-crossing lines and fractures reflecting dynamic forces that allow subsurface materials to erupt from the ocean below. The absence of craters indicates a young surface under constant reconstruction. (**b**) Artist's conception showing Europas's interior to consist of a metallic core, encased in a rocky mantle, surrounded by a global ocean frozen at the surface. *Credit: NASA/JPL/University of Arizona*

surface of the ocean is frozen solid to a depth thought to be at least 19 km (Schenk 2002), and possibly much more (Spohn and Schubert 2003). The ice may be much thinner in some areas, such as the Chaos region, where the surface appears heavily broken. The more recent detection of water plumes springing through the Europan crust (Roth et al. 2014) supports the notion that the crust may be quite thin in some regions. Many cracks, fissures (linnae), and separated blocks are evident (Sullivan et al. 1998; Figueredo et al. 2003), indicating translational forces presumably arising from tidal flexing between Europa's huge neighbors, Jupiter and Io, inside her orbit, and the significantly larger moons, Ganymede and Callisto, outside her orbit (Hoppa et al. 1999). Some surficial features on Europa are reminiscent of mid-ocean ridges and the process of subduction on Earth, hinting that some type of plate tectonics may also be occurring (Kattenhorn and Prockter 2014). Hydrated salt minerals such as magnesium sulfates and sodium carbonates have been detected in the optically darker areas of Europa, including the lineaments, and may represent evaporite deposits formed by water, rich in dissolved salts, reaching the surface from the ocean underlying the ice crust (McCord et al. 1998). Europa's surface is relatively devoid of craters, further suggesting a young age (Pappalardo et al. 1998).

Light cannot penetrate more than a few meters of the ice shell on Europa. Conceivably, some algae sequestered within liquified chambers in the ice near the surface could harvest sunlight for energy, perhaps as descendants of ancestral phototrophs that evolved before the ocean froze over. This one conceivable exception aside, if life exists on Europa, it must rely on forms of energy other than light.

Europa has a tenuous oxygen atmosphere, formed from oxygen dissociated by sputtering of ice by energetic particles from the Jovian magnetosphere (Hall et al. 1995; Sieger et al. 1998). Estimates of whether and how long it would take for oxygen to migrate through the ice to the ocean below have varied from a low probability and slow movement (Schenk 2002) to a high level of exchange between the atmosphere and the ocean (Greenberg 2010). The strong oxidant, hydrogen peroxide, has also been detected on Europa's surface (Carlson et al. 1999; Loeffler and Hudson 2015).

Europa is large enough to generate heat internally from radiolytic decay, so the prospect of thermal emissions at the rocky interface at the bottom of the ocean, analogous to hot spots on the floor of the oceans on Earth, is a tempting speculation. If, as on Earth, such hydrothermal emissions on Europa include H_2, energy might be obtained by reduction of the various sulfate salts known to be present in the ocean (Zolotov and Shock 2003), or by reduction of iron from Fe(III) to Fe(II). If CO_2 is present, energy could also be obtained by methanogenesis (McCollom 1999; Schulze-Makuch and Irwin 2002a). For chemical reactions to serve as a consistent and long-term energy source, reduced compounds have to be re-oxidized to maintain the oxidation-reduction cycle. Thus O_2 or H_2O_2 from the surface, or unknown oxidants at depth, have to be available to complete the cycle. As shown in Chap. 5, chemotrophy is a competitive alternative to phototrophy as an energy source for living systems, so the absence of light beneath the shell of ice that encases Europa is not a barrier to the evolution and persistence of life there. Other sources of energy that could be available in the subsurface ocean of Europa include thermal and ionic gradients, and the kinetic energy of ocean currents generated by tidal excursions (Schulze-Makuch and Irwin 2002a; Irwin and Schulze-Makuch 2011).

The attraction of Europa as a potential abode for life has long rested on three characteristics of the satellite: (1) The abundance of salty water containing an inventory of complex molecules, providing the possibility of redox chemistry; (2) the sequestration of the putative biosphere beneath a protective and insulating layer of thick ice; and (3) the availability of other forms of energy not including light. Most observers have tied speculation about the nature and extent of the putative biosphere to assumptions about the amount of energy that is actually available. We calculated a model ecosystem based on methanogenic producers (Irwin and Schulze-Makuch 2003). Making reasonable assumptions about the amounts of hydrogen and methane that could be available and using known efficiencies of energy transfer between trophic levels within ecosystems on Earth, we calculated that 1 g of biomass (about the size of a tadpole) could be found for every 32.5 cubic meters of ocean (about the volume of a small residential swimming pool). Using a similar strategy, Chyba and Phillips (2001) proposed an ecosystem based on oxidation of formaldehyde by radiolytically generated oxygen which yielded a global biomass nearly five times greater than our estimates, while Zolotov and Shock (2003) calculated a biomass over five orders of magnitude lower than ours for their ecosystem based on sulfate reduction. The large degree of uncertainty due to lack of actual data makes it impossible to gauge whether any of these models approaches reality, but they at least show that a biosphere of some magnitude could be supported in the ocean of Europa without making assumptions that are illogical or contrary to known facts.

We have provided the most detailed projection of what a biosphere on Europa could look like (Irwin and Schulze-Makuch 2011). We have envisioned a complex ecosystem based initially on chemoautotrophic producers (with descendants evolving to harvest energy from osmotic gradients, ionic gradients, and ocean currents) and three trophic levels of consumers—some of which inhabit the ice undersurface while others live on the ocean floor, along with benthic detrivores. Our guess is that the producers are largely stationary, and that motility is limited at all but the highest trophic levels, so that marine life on Europa would be more plant-like than animal-like. The availability of energy is the rate-limiting resource for motility. Until that information becomes available, the nature of life on Europa (if it exists) will remain largely guesswork.

11.2.4 Ganymede and Callisto

The two outermost and largest of the four Galilean satellites are larger versions of Europa, except that heavy cratering indicates older and more stable surfaces on both moons than on Europa. Tenuous atmospheres of O_2 have been detected on Ganymede, and of CO_2 on Callisto. Ganymede is well differentiated into a metallic core, silicate mantle, and a substantial water-ice ocean (Anderson et al. 1997), while Callisto may be only partially differentiated, with a water-ice shell which may be liquid below the frozen cover (Sohl et al. 2002). Equilibrium models of thermal conductivity predict that the ice shell of an ocean that is 95% H_2O and 5% NH_3 will be around 60 to 80 km thick atop oceans that may be 200 to 350 km deep (Spohn and Schubert 2003).

All that was said above about the plausibility of life on Europa applies to Ganymede and Callisto, with one caveat. While the subsurface ocean on Europa is thought to be in direct contact with the underlying rocky mantle, the oceans of Ganymede and Callisto are likely sandwiched between two layers of ice, which would make hydrothermal vents as they exist on Earth and possibly on Europa difficult to envision. Also, the stability of their surfaces indicates that the two larger moons have been subjected to much less tidal flexing than Europa, so forms of energy derived from gravitational forces, such as kinetic energy from ocean currents, may be less in play. A stable surface also may make migration of oxidants into the subsurface ocean more difficult. Another consideration derives from models that suggest that Ganymede and Callisto formed at lower temperatures than Europa (Consolmagno and Lewis 1976), which could have had a bearing on the ease with which life may have originated there. With those possibly limiting factors in mind, the plausibility of life on Ganymede and Callisto appears less than for Europa, but still well above negligible.

11.2.5 Enceladus

Enceladus is a small moon, 512 km in diameter, that orbits Saturn just 4 Saturnian diameters from the surface of the gas giant. The much larger moon Titan (5150 km in diameter) orbits Saturn at a distance of just under 20 Saturnian diameters. Periodic gravitational pull from two directions, therefore, has a strong effect on Enceladus.

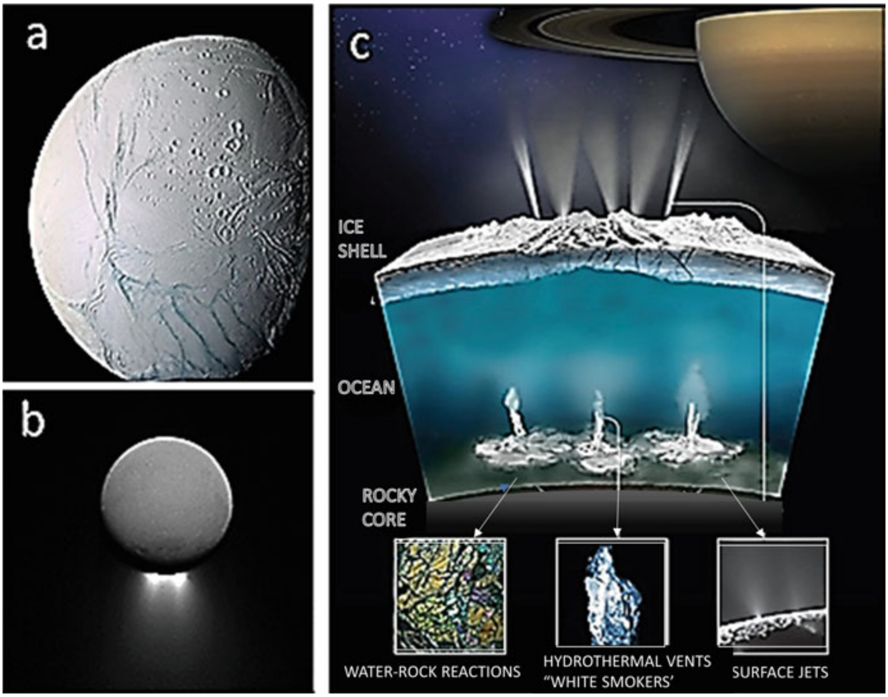

Fig. 11.4 Volatile activity on Enceladus. (**a**) View of Enceladus showing "tiger stripes" at the south pole; (**b**) Distant view of Enceladus showing ejection of vapor-granular composite; (**c**) artist's conception of how volatiles are created and ejected from the ocean floor through the "tiger stripe" ruptures on Enceladus. *Credit: NASA/JPL/Photojournal*

The southern polar region of Enceladus is characterized by a relatively smooth surface, indicative of resurfacing, broken by linear gashes referred to as "tiger stripes" (Fig. 11.4a). Gaseous and granular material is ejected at a high velocity (Fig. 11.4b) in volumes sufficient to account for the E ring around Saturn (Hansen et al. 2006; Spahn et al. 2006). These ejections are likely correlated with tidally controlled periodic rifts in the ice shell (Hurford et al. 2007). Energy driving the ejections could come from shear heating by tidally driven lateral (strike-slip) fault motion associated with the tiger stripes (Nimmo et al. 2007), hydrothermal vents beneath the ice (Hsu et al. 2015; Postberg et al. 2016), or aqueous ammonia methane clathrate decomposition (Kieffer et al. 2006; Shin et al. 2012).

Evidence for a subsurface ocean of liquid water is now strong (Schmidt et al. 2008). Gravitational field measurements suggest a regional south polar subsurface ocean of about 10 km thickness located beneath an ice crust 30–40 km thick (Iess et al. 2014; Hsu et al. 2015) at higher latitudes, but as little as 5 km thick at the south pole (Postberg et al. 2016).

Plumes ejected from Enceladus include organic carbon, biologically available nitrogen, redox energy sources, and inorganic salts (Postberg et al. 2009; McKay et al. 2014). Cassini's Cosmic Dust Analyzer picked up nanoparticles of ice with silica inclusions consistent with origin from ocean floor vents (Postberg et al. 2016).

Molecular hydrogen in the plumes ejected from Enceladus signals a hydrothermal interaction of water with rock that signals thermodynamic disequilibrium which would favor the formation of methane from CO_2 (Waite et al. 2017). The prebiotic constituents of life and the potential of a redox chemical as well as a thermal source of energy thus are present in a marine environment on Enceladus.

While the chemical, solvent, and energetic requirements of life are potentially met beneath the surface of Enceladus, the question remains of whether life could have originated there. Since it seems unlikely that a surface with standing liquid water ever existed for very long if at all on Enceladus, life would either have to have been generated at the water rock interface—likely at hydrothermal vents—or been delivered to Enceladus from another point of origin. To the extent that either of those possibilities is real, Enceladus could be one of the most promising places to search for life beyond Earth in the Solar System (McKay et al. 2008, 2014, Deamer and Damer 2017)—rivaled recently only by the dwarf planet Ceres (see Sect. 11.1.5 above). Thus, Enceladus has advanced to becoming a prime target for astrobiology and astrobiology-related missions (Porco 2017; Mathies et al. 2017)

11.2.6 Titan

While every planetary body in the Solar System has turned out to be unique, Saturn's largest moon, Titan, is more unique than most. Enshrouded in a dense atmosphere of nitrogen and volatile organic compound, obscured by a thick layer of larger organic molecules (tholins), the surface features of Titan were not revealed until the Huygens lander descended through its thick atmosphere for a soft landing on 14 January 2005 (Fig. 11.5).

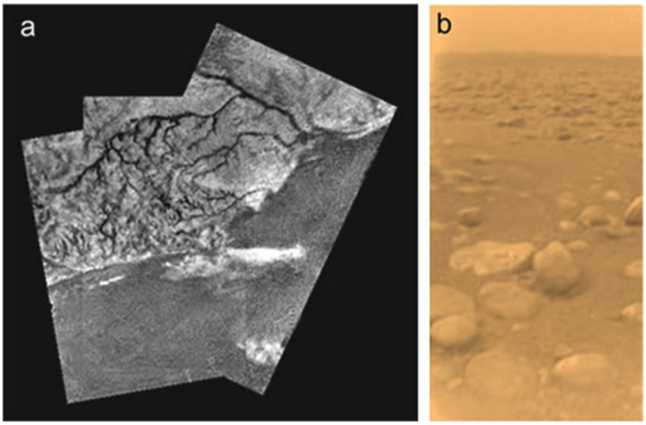

Fig. 11.5 The surface of Titan, revealed as the Huygens Probe (**a**) descended below its opaque atmosphere, and (**b**) landed on a substrate with the consistency of wet sand, provoking a brief expulsion of methane gas. *Credit: NASA/JPL/Caltech*

Subsequent investigations have disclosed a world with a surface so cold that water ice is frozen solid, but holds ponds and lakes of liquid hydrocarbons, charged by ethane rain precipitated from the skies and methane released at the surface (Raulin 2008; Moskowitz 2014). Channels apparently cut by flowing liquids, and other depressed areas, are coated with a dark substance thought to consist of tholins. There is now good evidence of a global layer of a water-ammonia mix beneath the frozen crust (Lorenz et al. 2008; Kerr 2012). Tidal stresses may be responsible for cryovolcanic activity, and provide possible pathways for liquid water-ammonia outbursts on Titan's surface, and the release of methane in its atmosphere (Sohl et al. 2014).

The most plausible reconstruction of planetesimal history for Titan is that it emerged from the generative stages of the Saturnian system, warm enough initially to hold oceans of liquid water (Schulze-Makuch and Grinspoon 2005) and massive enough to retain an ammonia-rich atmosphere with increasing amounts of methane and ethane (Coustenis and Lorenz 1999). As the satellite cooled, the aqueous ocean froze and became submerged by an ethane/methane-drenched surface of silica and tholins, as radiolytic conversion of the carbon compounds turned them into more complex organic polymers (Waite et al. 2006), and radiolysis dissociated the ammonia into hydrogen which escaped, leaving the N_2-rich atmosphere that exists today (Irwin and Schulze-Makuch 2011).

These events left Titan with two distinct habitats: a subsurface aquatic domain, and a scatter of hydrocarbon ponds, lakes, and seas on the surface (Fig. 11.6). The subsurface aquatic habitat could in principle be similar to that of Europa, except for probably being highly alkaline because of the ammonia content of the ocean. Anaerobic methane thiol degradation has been observed in highly alkaliphilic (pH 10) communities collected from several alkaline sediments on Earth, though growth required mesophilic (30 °C) conditions (van Leerdam et al. 2008), so applicability to Titan is questionable. Organisms on Earth are known to exist in highly alkaline environments, so that alone would not preclude the possibility of a subsurface aquatic biosphere.

Our ability to speculate about the possibility of a biosphere inhabiting the hydrophobic liquids on the surface is challenged by the fact that no such life exists to our knowledge on Earth. Microbes are known that can digest hydrocarbons at mesophilic temperatures (Prince 1993; Marcano et al. 2002; Wang et al. 2009a), but again, applicability to Titan is questionable. More problematic is envisioning how an organism could maintain structural integrity in a highly hydrophobic solvent, though a new type of membrane composed of small organic nitrogen compounds capable of forming and functioning in liquid methane at cryogenic temperatures has been proposed (Stevenson et al. 2015a, b), and additional adaptations have been noted for the fungus, *Fusarium alkanophyllum*, which can grow in saturated hydrocarbons with little or no oxygen or water requirements (Marcano et al. 2002). That hydrocarbon-dwelling organisms could exist, therefore, cannot be excluded.

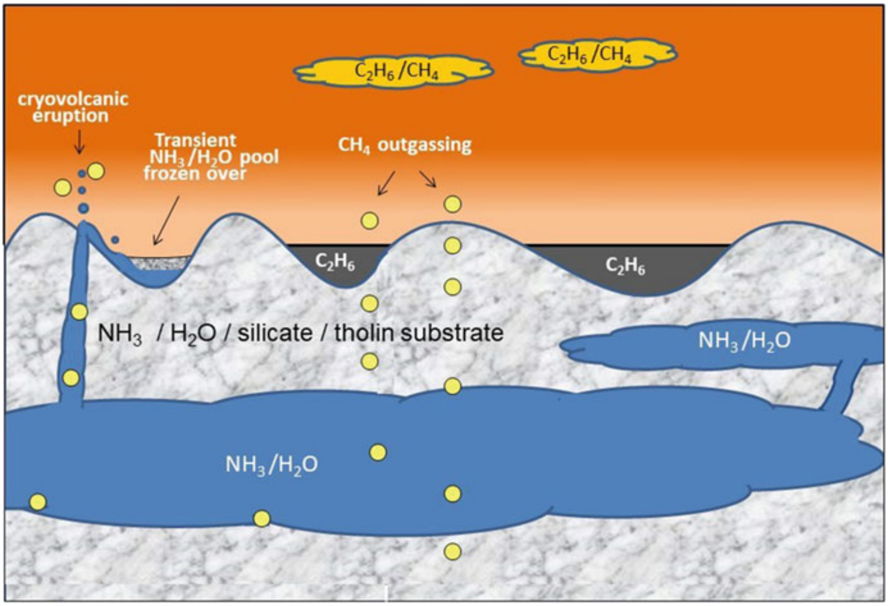

Fig. 11.6 Two possible biospheres on Titan. Circumstantial evidence supports the existence of an underground hydrosphere of NH_3 and H_2O, while pools of C_2H_6 and CH_4 constitute a liposphere on the surface. Occasional cryovolcanic eruptions disgorge the H_2O/NH_3 onto the surface where it quickly freezes over. *Credit: Art by Louis Irwin, from Irwin and Schulze-Makuch (*2011*), with permission*

A particularly suitable habitat for microorganism may lie at the bottom of the hydrocarbon lakes and seas, especially if heated ammonia-water is infiltrating from beneath (Schulze-Makuch and Grinspoon 2005). An analog for this scenario might be Pitch Lake in Trinidad, a natural asphalt lake which contains infiltrated droplets of salt water. Microbes within these droplets were found degrading hydrocarbons (Meckenstock et al. 2014).

Energy is another potential barrier for the support of life on Titan. Sunlight diminished to 1–2% of its intensity on Earth, and extremely frigid temperatures of <100 K (-173 °C) limit the availability of energy from those sources at the surface. A number of suggestions for chemical sources of energy have been offered, from photochemically produced organics, particularly acetylene, in Titan's atmosphere that could be reduced with atmospheric hydrogen (McKay and Smith 2005; McKay 2016), to recombination of radicals created in the atmosphere by ultraviolet radiation (Schulze-Makuch and Grinspoon 2005). Though Titan has an abundance of organic molecules for fuel, it has very little oxygen or other obvious oxidizing agents, so it could be simply a world with an abundance of potential chemical energy, but with no way to release it.

Beneath the surface, potential energy sources would be the same as on Europa, though kinetic energy generated by tidal excursions would presumably be less. Evidence of cryovolcanic activity on Titan suggests the release of energy from the interior, either from radiogenic heating (Kerr 2005), the release of methane from clathrates (Grasset and Pargamin 2005; Tobie et al. 2009), or other unknown sources.

We have repeatedly stressed, as have others, that the absence of Earth-like conditions on other worlds does not mean that forms of life unknown to us cannot exist there (Schulze-Makuch 2002; Benner 2002; Grinspoon 2003; Schulze-Makuch and Irwin 2004, 2006; Ward 2005; Baross et al. 2007; Irwin and Schulze-Makuch 2011). This is particularly true when a trajectory for the evolution of exotic forms from more familiar ancestral forms can be traced at least in theory (Schulze-Makuch et al. 2015a, b). We have done this in detail for Titan, showing how two diversified biospheres could exist in principle in both the hydrospheric and lipospheric habitats there, respectively (Irwin and Schulze-Makuch 2011). Nonetheless, until analog organisms can be shown to exist under the conditions on Titan, or at least until models of such organisms can be envisioned to a credible degree, a skeptical assessment of the possibility of life on Titan is not unreasonable.

11.2.7 Triton

Triton is the largest moon of Neptune—larger even than Pluto—with which it most likely shared an origin as a Kuiper Belt planetesimal at the outer edge of the Solar System. Most astronomers believe that Triton was captured by Neptune, as evidenced by the former's retrograde rotation and its orbital plane highly inclined to the ecliptic. Like most of the outer Solar System satellites, it consists of a rocky core encased in a shell of water frozen rock solid, along with other frozen volatiles (Fig. 11.7). In fact, Triton is so cold—38 K (−235 °C)—that even N_2 is frozen on its surface (Abelson 1989; McKinnon and Kirk 1999).

Fig. 11.7 Complex topography of Triton. The southern hemisphere's surface is relatively young, lacking extensive cratering. Wispy streaks of grey material extruded from the interior show a consistent downwind scatter to the northeast, amid light-colored nitrogen frost. The cantaloupe features perhaps related to diapirism of softer subsurface matter are visible in the mid-latitudes. *Credit: NASA/JPL-Caltech*

Models of Triton's capture by Neptune, which may well have involved tearing it away from a co-rotating twin (Agnor and Hamilton 2006), suggest that its initial orbit would have been highly elliptical, with radical gravitational excursions sufficient to heat Triton enough to keep water liquid for millions of years, even if the surface froze quite soon. If accurate, Triton can be presumed to have followed a trajectory that took it through a Europa-like stage to something like Titan. The youth of Triton's surface, indicated by visible evidence of cryovolcanic eruptions and the lack of much cratering, suggests that internal energy still drives its geological activity, supplemented by explosive outgassing of N_2 from the polar regions that alternate facing the Sun (Abelson 1989; McKinnon and Kirk 1999). The peculiar cantaloupe topography of Triton's mid-latitudes may be evidence of diapir-driven activity by softer material below the surface, and the orange-pink coloration may be indicative of organic compounds generated by radiation-driven interactions in its upper tenuous atmosphere (Thompson and Sagan 1990).

If Triton indeed evolved as Europa did, first covered with liquid water that froze on top, then progressed through a phase like Titan with some mix of precipitated organics, and proceeded beyond that to an even colder world with solidified N_2 at its surface, then Triton could harbor not just two, but three putative habitats for life (Irwin and Schulze-Makuch 2011): (1) a subsurface marine habitat, (2) inclusions of H_2O (or mix of H_2O and NH_3) at water-ice interfaces or in channels encased in ice, and (3) inclusions of liquid N_2 at interfaces with solid N_2 or in liquid channels encased within frozen N_2. If water really did stay liquid for hundreds of millions of years on Triton's surface, life would have had time to originate and begin evolving. As Triton cooled, directional selection could have led to microorganisms that occupied the more constricted habitats of ice-water and nitrogen inclusions or interfaces (Irwin and Schulze-Makuch 2011).

Triton is intriguing as probably the only sizable body in the Solar System where N_2 conceivably could be a solvent, and silicon in the form of silanes could possibly serve as a building block for living systems. Nitrogen is liquid between $-210°$ and -196 °C (Fig. 7.4), a thermal range that must occur at some depth beneath the surface. Si theoretically could replace C as a building block for biomolecules in conditions of extreme cold, high pressure, lack of oxygen and liquid water, and the presence of compatible organic solvents like methane and ethane (see Sect. 6.4.4.1). The presence of silicon-based life sequestered in layers or microchannels of liquid N_2 beneath the surface of Triton, while highly speculative, can therefore not be precluded.

11.2.8 Dwarf Planets of the Outer Solar System

The Pluto-Charon couple and Eris are the two largest known dwarf planets in the outer Solar System. Eris is the largest by mass (1.27 times that of Pluto) and most distant from the Sun. It has a highly elliptical orbit that varies from roughly 40 to 97 AU. At such a distance, it is very poorly characterized, but reasonably could be assumed to resemble Pluto in composition, as both are presumed (along with Triton) to have originated in the Kuiper Belt. Pluto and Charon form a double-planet pair that was visited by the *New Horizons* space craft.

Pluto's diameter is about two-thirds that of Earth's moon, but is much less dense, suggesting a rocky core encased in a substantial shell or frozen water and other volatile compounds—especially nitrogen and methane. It has a highly elliptical orbit which brings it close enough to the Sun at perihelion to sublimate its volatile compounds into a thin atmosphere of N_2 and CH_4, while at its maximum distance from the Sun of 49 AU, the atmosphere likely freezes back onto the surface.

Images taken from the *New Horizon* spacecraft's closest approach to Pluto in July 2015 reveal a surprisingly complex topography (Fig. 11.8). Pluto contains expansive, smooth plains—features suggestive of active geological processes (Stern et al. 2015). There are high jagged mountains, long rifts, troughs, and valleys, and peculiar "snakeskin" contours on the surface somewhat reminiscent of the cantaloupe regions of Triton. Sputnik Planitia—a prominent tear-drop-shaped depression approximately 1000 km in diameter—is characterized by a smooth, craterless plain 3–4 km beneath the surrounding rugged uplands. The floor appears to be the surface of a massive block of actively convecting volatile ices of N_2, CH_4, and CO, which may float above a subsurface ocean (Bertrand and Forget 2016; Keane et al. 2016). The age of Sputnik Planitia's surface has been estimated at only about 10 million years (Trilling 2016). Elsewhere on Pluto, evidence of cryovolcanism and dark areas suggestive of tholins are present (Shekhtman et al. 2018).

Pluto's smaller (about half-sized) companion, Charon, shows evidence of the presence of water-ammonia ice, which often is associated with flow like features on many icy satellites (Brown and Calvin 2000). It appears to have been geologically active in the past like Pluto, but currently may be less so, perhaps owing to its smaller size.

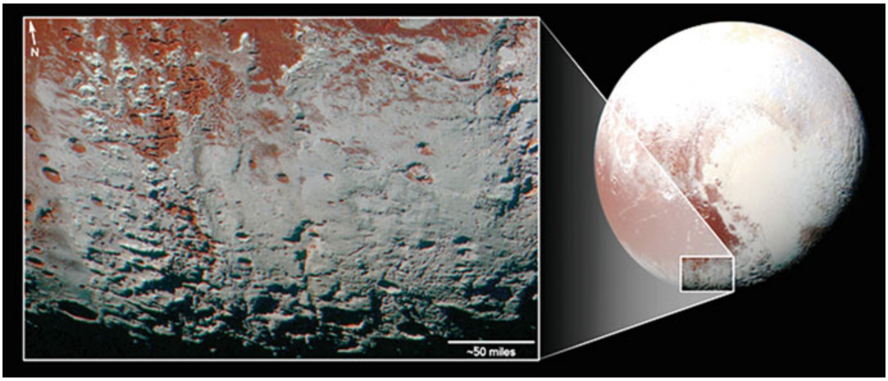

Fig. 11.8 Complex topography near Pluto's south pole. The close-up image reveals many troughs and scarps, elongated valleys, as well a smooth plains. Only a few craters are visible, indicative of a relatively young surface. Much of the surface is covered by nitrogen and methane snow. *Credit: NASA/Johns Hopkins University Applied Physics Laboratory/Southwest Research Institute*

The chance that these extremely frigid Kuiper Belt planetary bodies could harbor aquatic-based life as we know it seems extremely small. In their composition and characteristics, they resemble Triton, and Titan to a lesser extent. Inasmuch as exotic forms of life unknown to us could exist on those larger bodies, as discussed above, the possibility that life could exist in the Kuiper Belt as well cannot be totally dismissed.

11.3 Small Bodies

Billions of bodies smaller than dwarf planets swirl about within and around the Solar System. As potential habitats for life, they seem unlikely in the extreme. But they have turned out to be a surprisingly rich reservoir of chemicals that may have contributed the building blocks of biomolecules that took hold on larger, more stable planets and moons where life had a better chance to unfold.

11.3.1 Asteroids

Asteroids are the remnants of rocky accretions that failed to form planets before multiple collisions and the gravitational stress of other planets (especially Jupiter) tore them apart. Most asteroids orbit the Sun in the main asteroid belt between Mars and Jupiter, though some have orbits closer to Earth, outside the main belt, and others, called Trojans, occupy the same orbit as Jupiter either 60° behind or ahead of the huge planet. The largest asteroid by far is Ceres, now designated a dwarf planet, as discussed above.

The complex chemistry and water discovered on Ceres (Sect. 11.1.5) may not be unusual for asteroids. For example, gullies possibly cut by water were also found on Vesta, the second largest object in the asteroid belt (Scully et al. 2015). Evidence increasingly indicates that complex organic molecules and even amino acids are ubiquitous on small bodies in the Solar System (Cronin et al. 1988; Anders 1989; Chyba et al. 1990a, b; Küppers 2017). Asteroid impacts could also influence the genesis and trajectory of life by promoting the formation of certain biomolecules (Mimura and Toyama 2005), by melting ice to provide transient liquid habitats, and by affecting the ecology of planets where life may exist by opening new niches into which life can expand, as in the case of the evolutionary radiation of mammals after the Cretaceous-Tertiary (K-T) boundary caused by a major asteroid strike on Earth (Cockell and Bland 2005).

There is thus far no evidence for any form of life on an asteroid, though Ceres is close and accessible enough for a sample return mission that could investigate the possibility of life on that dwarf planet.

11.3.2 Comets

Comets are smaller bodies that orbit the Sun in highly irregular orbits. Most come from the Oort Cloud, a spherical conglomerate of residues from the early formation of the Solar System that has a radius of about 1.6 light years and contains trillions of small objects akin to rocky, dusty snowballs that become visible as they near the Sun and their volatile compounds sublimate away.

Like asteroids, comets contain biomolecular precursors (Greenberg 2000; Sandford 2008; Bockelee-Morvan and Biver 2017). A diverse suite of organic molecules was captured in dust from the comet 81P/Wild 2 by the Stardust spacecraft (Sandford et al. 2006). The recent Rosetta mission to the comet 67P/Churyumov-Gerasimenko detected volatile glycine accompanied by methylamine and ethylamine (Altwegg et al. 2016), consistent with data from the Stardust mission, despite previous concerns about contamination (Spencer and Zare 2007). The discovery of these molecules has been accompanied by the demonstration of plausible pathways to the creation of nucleosides (Nuevo et al. 2009; Becker et al. 2016). Some of the chemical ingredients for living systems would thus appear to be present in comets. However, the low-temperature extremes, the absence of liquid, and the lack of consistent sources of energy on comets render the chances that they could harbor living organisms extremely remote.

11.4 Metrics for the Plausibility of Life in the Solar System

We will now summarize what we think about the possibility of life throughout our Solar System in terms of metrics proposed as systematic and quasi-quantitative approaches to assessing the plausibility of life on other worlds. One of the first metrics proposed was our Plausibility of Life (POL) index (Irwin and Schulze-Makuch 2001; Schulze-Makuch and Irwin 2008). The POL index is based on criteria for the existence of life such as the presence of (1) a fluid medium, (2) a source of energy, and (3) constituents and conditions compatible with polymeric chemistry under the key assumptions that (a) life arises quickly under appropriate formative conditions and (b) remains static in stable environments or adapts to changing environments. We assigned a POL rating for each major planetary body in our Solar System, while pointing out that the rating must be regarded as a dynamic value consistent with the information currently available. Though quantitative, it should not be viewed as a measure of probability that life exists on the body in question, but only a relative measure of the plausibility that life could exist there, given the planetary history of the body and its past and current conditions. An updated definition of the POL categories with some examples are given in Table 11.1. An updated POL rating for all planets and major satellites in our Solar System consistent with knowledge at the time of this writing is provided in Tables 11.2 and 11.3.

Table 11.1 Astrobiology plausibility categories (modified from Irwin and Schulze-Makuch 2001)

Category	Definition	Examples
I	Presence of liquid water, available energy, organic compounds, atmospheric or surface shielding, and strong evidence of biogenic processes.	Earth
II	Evidence for past or present liquid water, availability of energy, inference of organic compounds, and planetary history favorable for genesis of life.	Mars, Europa, Enceladus, Ceres
III	Physically extreme conditions, but with evidence of energy sources and complex chemistry possibly suitable for life forms unknown on Earth	Titan, Venus
IV	Persistence of life very different from on Earth conceivable in isolated habitats, or reasonable inference of past conditions suitable for the origin of life prior to the development of conditions so harsh as to make its perseverance at present unlikely but conceivable in isolated habitats	Triton, Io
V	Conditions so unfavorable for life by any reasonable definition that its origin or persistence cannot be rated a realistic probability	Giant planets, Sun, Moon

Table 11.2 Plausibility of Life (POL) index for planets in our Solar System

Body	POL index	Reasoning for rating
Mercury	IV	Intense solar radiation; little if any geological cycling and no atmosphere, but thermal gradients at terminator and water ice at poles,
Venus	III	Extreme heat at surface and highly caustic atmosphere; but primordial ocean likely, water vapor in atmosphere, minute amounts of organic compounds, active geology with chemical recycling likely, and moderate temperatures in lower atmosphere
Earth	I	Salt water oceans, fresh water on surface, plate tectonics provide geological recycling, and oxygen-rich atmosphere with protective ozone layer. Life is present.
Mars	II	Oxidized surface, thin atmosphere, and some geological cycling in recent planetary history, but ample evidence for liquid water on surface in the past and subsurface water now; surface temperatures sometimes above freezing point of water, polar ice caps with some water ice, and evidence for presence of organic compounds.
Ceres	II	Salty water beneath ice cap; cryovolcanism and possible subsurface heat; clay minerals and organic compounds in ejecta from interior
Jupiter Saturn Uranus Neptune	V	Giant planets with indistinct physical transitions; temperature and pressure extremes; abundant energy and presence of organic and nitrogen compounds, but lack of solid substrates except at core.
Pluto/ Charon	IV	Extreme cold, density ~2.1 implies rock/ice composition; mix of light and dark features implies complex chemistry, and tidal flexing could provide energy, but likely origin as asteroids makes genesis of life improbable.

Table 11.3 Plausibility of Life (POL) index for major satellites in our Solar System

Body	POL index	Reasoning for rating
Moon	V	Extremely dry, no protective atmosphere, water ice at poles but no geological cycling.
Io	IV	Sharp thermal gradients and geochemical cycling; volcanic activity generates thin atmosphere and liquid sulfur compounds near surface for some time periods; coloration implies complex chemistry; but temperature fluctuations and radiation doses are extreme.
Europa Ganymede	II	High radiation and extremely low temperature at surface, but planetary ocean likely beneath ice shell. Surface coloration implies complex chemistry and frequent resurfacing implies geological activity.
Callisto	III	High radiation and extremely low surface temperature; possible subsurface liquid water, but little energy flux.
Tethys Dione Rhea	IV	Little evidence for liquid water at present; very low density and high albedo imply mostly water-ice composition; high radiation environment; extremely cold.
Enceladus	II	High radiation environment, extremely cold, and too small for significant radiogenic heating; but extensive resurfacing with evidence of ice geysers suggest geological activity, subsurface liquid water, and energy from tidal flexing
Iapetus	IV	High radiation environment, extremely cold, with no evidence for liquid water at present; low density and moderate albedo imply mostly ice composition; but dark leading edge suggests possible hydrocarbon chemistry.
Titan	III	Dense, colored atmosphere implies complex organic (reducing) chemistry; liquid hydrocarbons present on surface with possible water-ammonia liquid beneath surface; density of ~1.8 implies organic liquids and/or water-ice with solid core.
Titania	IV	Possible subsurface or recent surface liquid with evidence of liquid flow in canyons; relatively small for radiogenic heating, but tidal flexing could provide energy; extremely cold at surface.
Ariel Miranda Umbriel Oberon	IV	Small size and insufficient evidence of energy gradients; high albedo and density of ~1.5–1.7 imply rock/ice composition; extremely cold.
Triton	IV	Coloration implies complex chemistry; tidal flexing, radiogenic heating, or chemistry could provide energy; possible subsurface liquid water or water-ammonia mixes; density of ~2 implies rocky core with water/ice surface; but has coldest surface recorded in solar system.
Comets	V	Extreme cold, no atmosphere, no persistent internal energy source, rock/ice mixtures in composition, abundant water ice with possible hydrothermal alteration in parent bodies

Earth is the only body in our Solar System that qualifies for the highest POL rating. Based on information from recent robotic probes, the following planets and satellites now meet the criteria for Category II: Mars, Ceres, Europa, Ganymede, and Enceladus. Category III bodies consist of Callisto, Titan and Triton—exotic worlds with characteristics amenable to life in forms yet unknown to us. Based on our knowledge at this time, these eight worlds are the most likely, and perhaps the only likely habitats for life beyond Earth in our Solar System.

In the next chapter, we consider several other metrics for assessing the plausibility of life on other worlds. Different assumptions underlying each metric lead to slightly different plausibility estimates. For example, newer data used to recalculate the Planetary Habitability Index (Schulze-Makuch et al. 2011) result in the highest ratings after Earth for Mars, Titan, Europa, and Enceladus, in that order. If sample return missions in the future bring back more information from Ceres and the clouds of Venus, those two bodies could be added as higher possibilities for life elsewhere in the Solar System.

The only realistic chances for the evolution of multi-tiered biospheres consisting of organisms larger and more complex than microbes extant today would appear to be on bodies with sizeable subsurface oceans in contact with rocky cores: Europa foremost, with Enceladus, Ceres, Titan, Triton, and Pluto as distant possibilities. Mars and Venus may have harbored conditions sufficient and long enough for the origin and diversification of complex biospheres at one time. There appears to be no chance that such forms of life survive on Venus today; and on Mars, the habitat possibilities for life more complex than microbes are likely restricted to extreme niche environments such as lava tubes near the surface. For that reason, lava tubes on Mars should be a priority for future missions.

11.5 Chapter Summary

Conditions for the origin of life were probably good in the early history of four planetary bodies in the inner Solar System: Venus, Earth, Mars, and Ceres. Microbial life conceivably could still exist in the clouds of Venus, and beneath or near the surface of Mars. Organisms more complex than microbes could even persist in sequestered habitats, like lava tubes, on Mars. If Ceres does contain an extended body of salty water beneath its icy shell, some forms of complex life could even exist there as well.

The outer Solar System is dominated by giant planets and their satellites. While the gas (Jupiter and Saturn) and ice (Uranus and Neptune) giants provide no credible habitats for life, some of their satellites do. At Jupiter, Europa consists of a massive, global ocean with several putative energy sources beneath a frozen surface. It holds perhaps the greatest promise of any body in the Solar System beyond Earth of harboring a multi-tiered ecosystem. Recent evidence from Saturn's small satellite, Enceladus, reveals many characteristics similar to Europa, so it too along with Ceres, should be given serious astrobiological attention.

Saturn's large moon, Titan, and Neptune's sizable captured satellite, Triton, are both exotic worlds with abundant organic chemistry and probably aquatic-ammonia-salt habitats beneath their surfaces. If life exists on those worlds, it could be fragmented into different forms according to the habitat in which it thrives; and in any case would almost surely include forms totally unlike any living system on

Earth. The Pluto-Charon pair of dwarf planets resemble Triton. Like Titan and Triton, their planetary histories may have taken them from a Europa-like origin to their current state, where remnants of life from an earlier biosphere conceivably could persist.

By various metrics, the most likely habitats for life beyond Earth are near-surface and sequestered spaces on Mars, and sub-surface aquatic habitats on Europa, Ceres, and Enceladus. More speculative but distinct possibilities lie in the clouds of Venus and various habitats on Titan, Triton, and Pluto.