Chapter 8
Habitats of Life

There are four principal habitats in which life may exist—the surface of a planetary body, its subsurface, its atmosphere and space. From our own experience we know that life does exist on the surface of a planet, in its subsurface and transiently at least in the atmosphere. Where it is present, it exists in a surprising diversity and in a variety of microhabitats, from deep caverns (Hose et al. 2000; Melim et al. 2001) and water droplets (Meckenstock et al. 2014) to hydrothermal fluids and hot springs of various chemistries (Jannasch 1995; Rzonca and Schulze-Makuch 2002; Martin et al. 2008), to the frozen deserts of Antarctica (Friedmann 1982; Sun and Friedmann 1999; Goordial et al. 2016). In this chapter we will elaborate on the principle habitats, the constraints they impose on life, and the possibilities they provide.

8.1 Life on the Surface

We live on the surface of our planet, which makes us biased towards it being the common case. However, there are various factors that make life on the surface of a planetary body challenging. Life on the surface is much more exposed to environmental extremes of temperature, wind, radiation and humidity than, for example, life thriving in the subsurface protected by thick layers of soil and rock. A planet or moon with life on its surface requires an atmosphere to keep essential liquids on the surface from evaporating into the vacuum of space, to protect life on the surface from harmful cosmic and UV radiation (the degree of protection depending on the composition and thickness of the atmosphere), and to protect the surface to some degree from potentially devastating meteorite impacts. Smaller meteorites burn up in the atmosphere and the effect of larger ones is mitigated. However, meteorites still pose a grave threat to life on the surface of any planet. For example, the surface of our planet may have been sterilized several times early in Earth's history (Sleep and Zahnle 1999). In that case life could have only survived deep in the crust and then resettled the surface again after the effects of the impact were diminished with time.

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Life on the surface is also very susceptible to large-scale climatic fluctuations. Earth experienced several episodes of global freezing ("Snowball Earth") events (Hoffman et al. 1998; Kirschvink et al. 2000), when it substantially or perhaps completely froze over. Mars is currently a cold, arid planet with little or no liquid water on its surface, though it probably had oceans on its surface earlier in its history (Dohm et al. 2000; Head et al. 1998; Di Achille and Hynek 2010; Fairén 2010). Venus, probably wet and somewhat Earth-like early in its history, experienced a run-away greenhouse effect with current surface temperatures above 400 °C. If life as we know it ever existed on the surface of Venus, it does not anymore.

8.2 Life Beneath the Surface

Microbes, fungi, and small animals have lived in the upper layers of the soil since their first expansion from water onto the land. More recent evidence suggests that microbial life penetrates to great depths, beneath the surface of both the land and ocean bottom, deep into the crust (Johnson and Party 2003; Pedersen and Ekendahl 1990; Klein et al. 2015). Estimates indicate that the total amount of carbon in subsurface organisms may equal that of all terrestrial and marine plants (Table 8.1).

Microbial life appears to be abundant in various types of subsurface habitats such as the oceanic crust, and continental sedimentary and igneous rocks. While the overall number of organisms generally decreases with depth (Table 8.2), because of the huge amount of volume, the total subsurface biomass is enormous (Gold 1992).

However, life on the surface does provide two critical advantages: (1) the use of visible light as an energy source and (2) space to expand. Life on Earth without photosynthesis would be much more limited and may have remained in the microbial evolutionary stage. The biomass contribution via photosynthesis is immense; the total carbon content of plants is estimated to be 560 Pg (1 Pg $= 10^{15}$ g) for terrestrial plants and 1.8 Pg for marine plants (Schlesinger 1997, Table 8.1). Space to expand may not be very important to microbial life, because most microbial life easily fits into the pore spaces of rocks. However, for complex multicellular life the surface does provide a challenging but suitable environment for growth and development to macroscopic forms. Thus, it is not a surprise that we as macroscopic organisms populate a planet in a climatically fairly stable environment with enormous amounts of liquid water. However, life remains very vulnerable on a planetary surface.

Table 8.1 Total carbon content in 10^{15} g of carbon

Ecosystem	Plants	Soil and aquatic prokaryotes	Subsurface prokaryotes
Terrestrial	560	26	22–215
Marine	1.8	2.2	303
Total	561.8	28.2	325–518

Note: Data from Whitman et al. (1998)

Table 8.2 Total number of prokaryotes in unconsolidated subsurface sediments

Depth interval (m)	Cells/cm^3, $\times 10^6$	Deep oceans (no. of cells, $\times 10^{28}$)	Continental shelf and slope (no. of cells, $\times 10^{28}$)	Coastal plains (no. of cells, $\times 10^{28}$)
0.1–10	220	66.0	14.5	4.4
10–100	45.0	121.5	26.6	8.1
100–200	6.2	18.6	4.1	1.2
200–300	19.0	57.0	12.5	3.8
300–400	4.0	12.0	2.6	0.8
400–600	7.8	NA	10.1	3.2
600–1200	0.95	NA	3.7	1.2
1200–2000	0.61	NA	3.2	1.0
2000–3000	0.44	NA	2.6	0.9
3000–4000	0.34	NA	NA	0.7

Note: Data from Whitman et al. (1998); NA = not available

Threats include a large meteorite impact that could destabilize the climate or sterilize the surface of the planet, a cosmic disaster such as a nearby supernova-explosion that showers the surface with radiation, or exhaustion of fuel in the planet's central star, leading to the engulfment of the planet, similar to our Sun which will expand to become a red giant.

Some distinct advantages over life at the surface can readily be appreciated. Temperatures and vapor pressures are stable, and protection from damaging radiation is afforded. The obvious disadvantages are the unavailability of sunlight as an energy source, and limitations on organismic size. The latter restriction results from the fact that pore spaces that serve as habitats are generally small in size, and become smaller with increasing depth. Thus, life at any substantial depth is probably restricted to microscopic dimensions, but this allows for a great range of living systems, as evidenced by the variety of microbial life within the crust of the Earth. Microbes indigenous to crustal rocks have been isolated from a depth of 2800 m in continental sedimentary rocks (Onstott et al. 1999) and 5300 m in igneous rocks (Pedersen 2000). Temperature increases with depth and imposes an absolute limit on the temperature and pressure conditions under which water can remain in the liquid state. The amount of dissolved solids in the ground water also tends to increase with increasing temperature adding osmotic stress to any organism. Thus, there is an absolute limit to the depth at which organisms can thrive (Schulze-Makuch et al. 2017). The absolute limit of this depth, however, is very variable due to the heterogeneous conditions in the crust and variable geothermal gradients.

While sunlight is not available to provide energy in a subsurface environment, other sources of free energy are readily available. Chemical energy, both inorganic and organic, may be found in abundance, depending on the planetary body in question. Other energy sources such as those discussed in Chap. 5 may also be an option for certain subsurface environments. Availability of energy should not be a problem, if the planet or moon is large enough to have a metallic core and decaying radioactive elements as an energy source. In principal, energy in many forms can be transformed into biologically usable energy (Holm et al. 2015). If the availability of energy, then, is not an issue, and the living system is microscopic in size, the advantages of the subsurface habitat become overwhelmingly favorable for the persistence of life.

Although the subsurface clearly favors microbial life, there are a few niches and possibilities for macroscopic life. A bizarre example of a macroscopic subsurface organism is a fungus of the *Armillaria* family, which is pathogenic to trees (Armillaria root disease). These fungi are incredibly large, with one *Armillaria ostoyae* organism of genetic uniformity detected at a size of 9.65 km^2 (Ferguson et al. 2003). A subsurface niche particularly favorable for macroscopic forms is the cave environment, to which various types of animals on Earth are ideally adapted (Romero 2009). Caves do not occur only where karstic sedimentary rocks are present, but also commonly form in cooling lava flows. Thus, they can be expected to be common on other planetary bodies as well. Several locations have been suggested for Mars (Fig. 8.1). Due to the relatively low gravity on Mars, lava tube caves can be expected to be larger and more common than on Earth.

On all the terrestrial planets and all the larger satellites, subsurface strata probably exist where thermal stability and some solvent in liquid form can exist. Thus, the presence of at least microbial life at multiple sites beneath the surface of planets and some of their satellites throughout the Solar System is distinctly possible. The larger icy satellites that show evidence of tidal flexing or other energetic perturbations, such as Europa, Ganymede, Enceladus, Iapetus, Titania, and Triton, have at least the

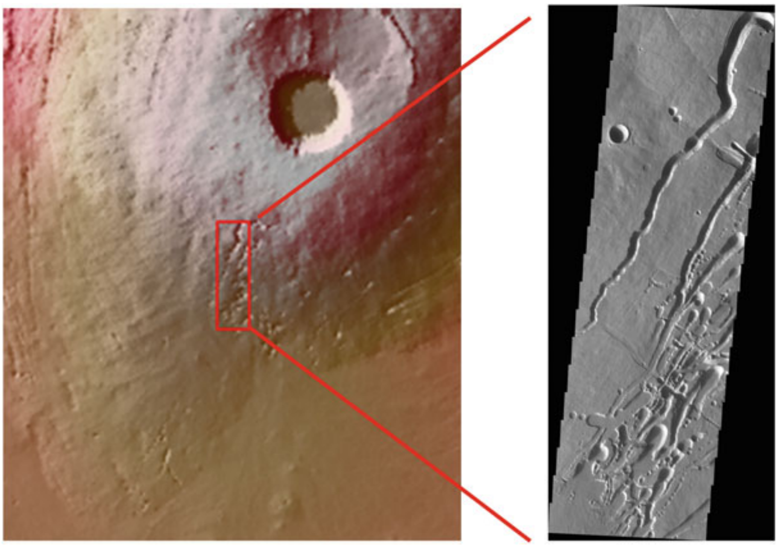

Fig. 8.1 Collapsed lava tubes on the side of Pavonis Mons. The linear features are believed to be lava tubes where the ceiling has collapsed into the free space below. *Credit: NASA/JPL-Caltech/ASU*

potential for liquid water beneath their icy crusts (Carr 1986; Chyba 1997; Coustenis and Lorenz 1999; Khurana et al. 1998; McKinnon and Kirk 1999; Irwin and Schulze-Makuch 2011). Evidence for a substantial amount of ground water within the upper crust of Mars is now compelling (Boynton et al. 2002; Carr 1996; Malin and Edgett 2000a, b; Schulze-Makuch et al. 2004). Thus, aquatic life approximately as we know it on Earth is even possible in those situations. While the surface of Io is normally frozen, periodic lava flows heat it from above, and tidal flexing heats this rocky planetoid from below. Titan is colder still, but as the second largest satellite in our Solar System, it is obviously large enough for radiogenic heating to possibly liquefy mixtures of ammonia, water, and organic compounds which may be sequestered beneath its surface (Coustenis and Lorenz 1999). Both of these satellites represent more unusual but certainly possible subsurface habitats for life. Even Mercury and the Moon, both of which show evidence of some polar ice (Showstack 1998; Slade 1992), and even Venus, where liquid silicates or water in a supercritical state could exist beneath the surface, cannot be completely ruled out as sites of possible subsurface life (Schulze-Makuch et al. 2002b). "Run-away" planets that were ejected from their Solar System and are now moving through empty space represent another theoretical possibility (Stevenson 1999; Strigari et al. 2012).

Stabilizing selection, which tends to narrow variation and optimize adaptive advantages (Chap. 4), is particularly effective in relatively constant habitats over long periods of time. Thus, life that has been optimized by stabilizing natural selection for a subsurface existence should be extremely durable and persistent. It also tends to be static, evolving little from the form and function that characterized it upon its introduction to the stabilized habitat. Subsurface environments may thus be repositories for early forms of life that have changed little since conditions made life on the surface untenable. On Earth, the microbes that are found at the greatest depths beneath the surface tend to be members of the evolutionarily ancient archaea, or eubacteria with ancestral forms of chemoautotrophic metabolism, and may include some types of extremely small microorganisms (Luef et al. 2015). It follows that life on other worlds is most likely to be found beneath the surface of those worlds, where it is probably microscopic and relatively unchanged from an ancestral state.

8.3 Life in the Atmosphere

The possibility that the gaseous envelope of planets and those satellites that hold an atmosphere could serve as a suitable environment for life is generally viewed with skepticism. This probably derives from our familiarity with the nature of the atmosphere and of life on Earth. We are aware of the diversity of terran life, both in the subsurface and on the surface of Earth, but no organism that spends its entire life cycle in the atmosphere has been documented. The lack of green clouds is visual evidence for the absence of concentrated airborne photosynthesis. And even the smallest organism has a higher density than air. Nevertheless, it has been recognized for some time that bacteria exist in cloud aerosols on Earth (Gislén 1948) and that rain and fog water rich in nutrients may provide a good substratum for microorganisms (Fuzzi 2002; Herlihy et al. 1987). While microbial taxa from every biological lineage have been detected in the upper atmosphere of Earth (Smith 2013), the claim that microbes independently grow and reproduce in Earth's atmosphere is controversial. Dimmick et al. (1979) reported the division of bacteria on airborn particles and Sattler et al. (2001) analyzed condensing clouds at the Sonnblick Observatory in Austria at an altitude of 3106 m, and suggested growth and reproduction of microbes in super-cooled cloud droplets.

However, in general the atmosphere of Earth is a poor analogy for atmospheric habitats where life would be more likely; namely that of planetary bodies or satellites where gases are denser, and liquids are found in larger aggregates with longer survival times. Also, any particles in the Earth's atmosphere have typically a short residence time in the range of several days only. Most atmospheres of other planetary bodies we know are dynamically much more stable in the vertical direction and particles do not precipitate out as frequently (e.g., Venus), thus particle residence times are much longer. On other planets various chemical compounds might serve as nutrient sources, such as H_2S in the case of Venus (Schulze-Makuch and Irwin 2002b) or complex carbon compounds in the case of gas giants like Jupiter (Boston and Stoker 1983; Stoker et al. 1990) or carbon-rich moons like Titan. The composition of some planetary atmospheres is provided in Table 8.3.

If, instead of the unstable and thin atmosphere of Earth, the denser atmospheres of Venus, Titan, and the gas giant planets are taken as a prototypical atmospheric habitat where life could exist, some positive advantages can be noted. For instance, many of the denser atmospheres are more stable and more richly endowed with organic molecules. Sunlight, especially in the ultraviolet frequencies, breaks apart simple organic molecules in the planetary atmosphere, producing ions, free radicals, and other highly reactive molecules that combine to form complex, energy-rich

Table 8.3 Composition of some planetary atmospheres (modified from Lewis 1995)

Planetary body	Major compounds	Minor compounds	Trace compounds
Venus	CO_2 (96.5%), N_2 (3.5%)	SO_2, Ar, CO, H_2O, He, Ne, H_2S	HCl, Kr, HF, COS
Earth	N_2 (78.1%), O_2 (20.9%), Ar (0.9%)	H_2O, CO_2, Ne, He, CH_4, Kr	H_2, N_2O, CO, Xe, O_3, NH_3, SO_2, H_2S, CH_2O, NO_2, NO, HCl,
Mars	CO_2 (95.3%), N_2 (2.7%), Ar (1.6%)	O_2, CO, H_2O, Ne,	Kr, Xe, O_3, CH_4
Jupiter	H_2 (82%), He (18%)	CH_4, H_2O, NH_3, C_2H_6, PH_3	H_2S, C_2H_2, CH_3D, HCN, CH_3NH_2, N_2H_4, GeH_4, CO
Saturn	H_2 (94%) He (6%)	CH_4, H_2O, NH_3, C_2H_6, PH_3	H_2S, CH_3NH_2, C_2H_2, CH_3D, HCN, N_2H_4, GeH_4,CO
Titan	N_2 (94%), CH_4 (6%)	Ar, H_2, CO, C_2H_6, C_3H_8, C_2H_2	C_2H_4, HCN, CH_3 CCH, HC_4H, HC_3N, NCCN, CO_2

Note: Major compounds are defined here as those compounds that have a mole fraction larger than 0.005 in the respective atmosphere, minor compounds as having a mole fraction between 0.005 and 10^{-6}, and trace compounds as having a mole fraction smaller than 10^{-6}

compounds. These heavier molecules sink until they reach a level where they are destroyed by temperature and pressure, as likely occurs on the gas giants, or they accumulate on the planetary surface, as on Titan. Sagan and Salpeter (1976) suggested that life could exist at a level of the Jovian atmosphere where descending organic molecules could be captured and used for energy. The organic rich atmosphere of Titan, with a density 50% greater than that of Earth, conceivably could support life in the same way.

Several challenges to life in an atmosphere must be met. A main problem is that the density of gas molecules in an atmosphere is much lower than on a planetary surface, so to achieve the level of interactions between molecules required for living processes, the density of the organism is inevitably going to exceed that of its surroundings, and buoyancy will be a problem. However, atmospheres can be very dense, achieving liquid-like states at sufficiently high pressures. And just as fishes evolved air bladders to give them buoyancy in water on Earth, an airborne microbe conceivably could evolve a gas-filled organelle that radically increases its volume to a point where its average density is sufficiently low to keep it afloat in the air. Another potential problem could be exposure to high radiation levels, thus conditions that would promote the survival of atmospheric organisms would favor the evolution of radiation protection mechanisms.

A critical problem for indefinite survival in the atmosphere is the question of a suitable solvent for the support of life-sustaining reactions. Both liquids and solids are generally present in an atmosphere, such as liquid water and aerosols in Earth's clouds. But their abundance in the atmosphere compared to the planetary surface is very low. To be effective solvents, the liquids need to be condensed into droplets of sufficient size and longevity to provide a transiently stable pool of airborne liquid. Such droplets do appear to exist in the upper atmosphere of Venus (Grinspoon 1997), and perhaps in other dense atmospheres elsewhere.

Another potential problem is the scarcity of a solid substratum. The interface of a liquid solvent with a solid surface is presumed to provide a much more likely circumstance for the development of complex chemistry, simply because the degrees of freedom for interacting components is reduced from three dimensions to two. Thus, the origin of life in particular, seems much more likely to come about at interfaces than in three-dimensional volumes of gasses or liquids. Once underway in its confined cellular compartments, life would have an easier time of surviving in three-dimensional volumes, as many organisms in water, and some forms in air, do on Earth. The plausibility of life in an atmosphere is thus higher on those planetary bodies where conditions at the surface were amenable for the origin or early cultivation of life on a solid substrate. This would mean that Venus and Titan, for example, would have experienced a greater chance for the origin of surface (or subsurface) life that eventually evolved adaptations for an airborne existence, than would the gas giant planets, where a solid substrate may never have existed under conditions appropriate for life to originate or take hold. For an alternative view, see Feinberg and Shapiro (1980) who consider that the absence of a surface might be an advantage, because it would allow free motion between different environments, making it possible for an organism to invent its own disequilibrium by moving from one condition to another.

Certainly, as summarized above, any form of life residing permanently in the atmosphere faces many challenges. However, the case has been made that atmospheres represent a viable target in the search for habitable zones on other worlds (Smith 2013). As an instructive example, we will consider the case of Venus in more detail. There is evidence for an early ocean on Venus while the early Sun was fainter than it is now. Life on Earth developed very fast once conditions became appropriate (Chap. 4). The same could have occurred on Venus. Alternatively, life may have been transplanted from Earth or Mars to Venus via meteorite impacts. Either way, life may have become established on Venus at an early point in its history. We know that conditions on the surface of Venus are now inhospitable to life as we know it, with temperatures around 733 K (~450 °C) and extreme desiccation. The change in planetary surface conditions was presumably caused by a run-away greenhouse effect as the Venusian atmosphere moved toward its present composition of 97% CO_2. If the environmental transformation occurred slowly enough, microbial life could have adapted to life in the clouds of Venus by directional selection (Schulze-Makuch et al. 2003, 2013a, b). More recent modeling supports the notion that relatively benign conditions could have prevailed on Venus for billions of years (Way et al. 2016).

Several factors would support such a life style in the atmosphere of Venus: (1) The lower atmosphere is thick, so under liquid-like conditions microbial transport between the surface and the cloud layer would be easier than in Earth's atmosphere. (2) The clouds of Venus are much larger, providing more continuous and stable environments than clouds on Earth. (3) Current conditions in the lower cloud layer of Venus are relatively benign at 300–350 K, 1 bar pressure and a pH of 0—conditions of temperature, pressure and pH under which thermoacidophilic microbes are known to thrive on Earth (these are also some of the oldest known forms of life on Earth!) (4) Cloud particles are projected to last for several months in the Venusian atmosphere compared to only days on Earth (Grinspoon 1997). (5) The Venusian atmosphere is super-rotating, thus cutting the nighttime significantly and thereby allowing for more photosynthesis. (6) Water vapor is reasonably dense in the lower cloud layers of Venus. (7) Oxygenated species such as SO_2 and O_2 coexist and are in thermodynamic disequilibrium with reducing species such as H_2S and H_2 in the Venusian atmosphere.

An ultraviolet absorber has been detected in the Venusian atmosphere that may be related to microbial UV protection and possible photosynthesis (Schulze-Makuch et al. 2004; Fig. 8.2), and the flux of ionizing radiation to which the Venusian atmosphere is exposed was shown likely not to pose a hazard to habitability in the zone ranging from an elevation of 51–62 km (Dartnell et al. 2015). These and other aspects of the possibility of life in the clouds of Venus have been raised by different authors over the years (Sagan 1961; Feinberg and Shapiro 1980; Grinspoon 1997; Schulze-Makuch et al. 2004, 2013a, b). They have also been discussed in the context of a proposed sample return mission to Venus (Schulze-Makuch and Irwin 2002a, b; Schulze-Makuch et al. 2003, 2005a). These authors concluded that Venus provides

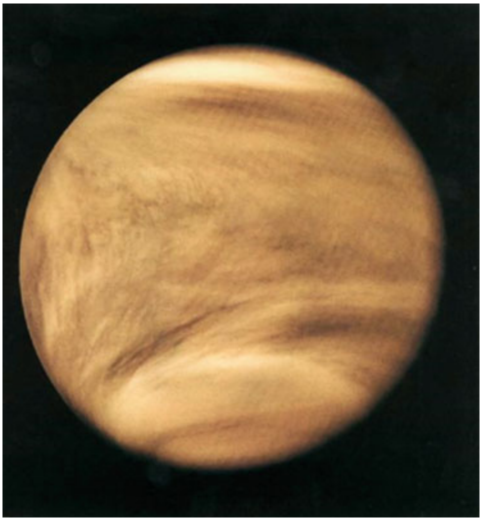

Fig. 8.2 Ultraviolet image of the clouds of Venus as seen by the Pioneer Venus Orbiter (5 February 1979). The dark streaks are produced by absorption of solar UV radiation. Source: NSSDC, http://nssdc.gsfc.nasa.gov/photo_gallery/photogallery_venus.html, image pvo_uv_790205

one of the best possibilities for harboring atmospheric life in the Solar System. Since it is also the most accessible planetary body beyond the Moon a sample return mission lies within the capabilities of existing technology.

Venus illustrates nicely the theoretical potential for atmospheric life. Nonetheless, the problems for persistence of living systems in an atmospheric habitat are formidable, so their existence warrants a lower probability than life on the surface, and much lower than life beneath the surface, on other worlds.

8.4 Life in the Space Environment

If the low density of matter would make life-supporting interactions between molecules in a gaseous atmosphere difficult to maintain, the problems are much more severe in space. The damaging potential of ultraviolet and particle radiation, the extremely low temperature and nonexistent vapor pressures, and the homogeneity of empty space further add up to such a hostile environment that outer space cannot be regarded as a likely habitat for life. However, the possibility that life could survive interplanetary travel through space in the protective sanctuary of meteorites or even dust particles cannot be discounted. There is increasing evidence that microbes, especially when in the dormant spore form, can survive space conditions fairly well (Horneck 1981; Koike et al. 1991; Nicholson et al. 2000; Horneck et al. 2008, 2012). This is especially the case if the microbe is surrounded by a thin layer of solid material that would shield it from cosmic and UV radiation. The effect of space vacuum is another constraint. Some space experiments have shown that up to 70% of bacterial and fungal spores survive 10 days exposure to space vacuum, even without any protection (Horneck 1993). Survival rates increased when *Bacillus subtilis* spores were embedded in salt crystals or if they were exposed in thick layers (e.g. 30% spore survival after nearly 6 years when embedded in salt crystals (Horneck et al. 1994). Spores from thermophilic bacteria are generally more resistant to heat than mesophilic spores (Ashton and Bernard 1992). Other studies showed that bacterial survival rates decreased by 2 to 4 orders of magnitude when exposed to space vacuum and short wavelength UV radiation (Saffary et al. 2002), but confirmed the protection provided by salt crystals (Mancinelli 1989). An intriguing example of microbial survival under space conditions was the reported recovery of living bacteria from the Surveyor 3 spacecraft after 3 years of exposure on the lunar surface (Mitchell and Ellis 1971), although this claim has been disputed. Nevertheless, microbes do apparently have the possibility to survive for extended periods in space. *Deinococcus radiodurans* appears to accomplish its resistance to radiation and desiccation by having multiple copies of DNA, large organelles, a large nucleus, a thick membrane, having the DNA in a ring-like structure (Levin-Zaidman et al. 2003), and by possessing a high redundancy of repair genes, but most microbes accomplish this feat by sporulation. During sporulation cytoplasm and genetic material is sealed off by the inner cell membrane. The DNA is then protected by thick layers of protective membranes (Fig. 8.3), which are only permeable to nutrients that the organism needs for germination.

Microbes can survive in this type of dormant phase for extremely long time. Cano and Borucki (1995) isolated a strain of *Bacillus sphaericus* from an extinct bee trapped in 25–30 million year old amber, while Vreeland et al. (2000) claimed to have isolated a 250 million year old halotolerant bacterium from a salt crystal.

Findings such as these lend new credibility to the idea of panspermia (Arrhenius 1903, 1908), the transfer of organisms between planetary bodies. However, any organism taking this type of journey would have to survive a series of hazards, including (1) survival of the meteorite impact that ejects the organism into space from the planet of its origin, (2) maintenance of viability for long durations of time inside the meteoritic material, (3) intense UV and cosmic radiation, cold, and

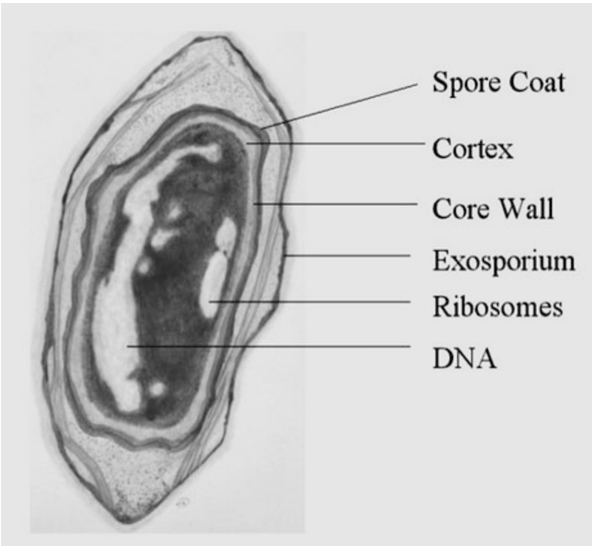

Fig. 8.3 *Bacillus subtilis* spore, schematic. The DNA is contained in the nucleoid (light regions) within the spore core. The core is surrounded by the protective cortex. The long axis of a *B. subtilis* spore is about 1.2 micrometers (Nicholson et al. 2000). Drawing provided by Chris D'Arcy, Dragon Wine Illustrations, El Paso, Texas

vacuum, and (4) the shock and heat of impact on the planetary body to which the organism is transferred. Mileikowsky et al. (2000) and Clark (2001) provided estimates on the likelihood of microbial survival for the different steps. Davies (1996) analyzed this scenario for the Mars-Earth case and concluded that it is a plausible scenario. A critical parameter is travel time, which can be as little as 2 months for microscopic particles from Mars to Earth (Moreno 1988). Boulder-size rocks, however, have been estimated to need a mean travel time of several hundred thousand to millions of years for the same distance (Melosh 1988). Nevertheless, interplanetary travel from one planetary body to another within a solar system is a definite possibility. The scenario is different for panspermia between different solar systems. Although the first interstellar asteroid, named Oumuamua, has recently been discovered (Keller et al. 2017), we rate chances for the transferal of dormant life from one solar system to another as slim, because the asteroid (1) would be exposed to cosmic radiation for a much longer time, effectively sterilizing the near surface of that planetary body and (2) would experience much more force upon impact due to the higher velocity of such an object compared with an asteroid originating from within the Solar System. Also, (3) the probability that an interstellar asteroid would strike a fairly small terrestrial planet, as opposed to the much larger gravity sink of the central star, or perhaps a gas giant, is very low.

It should be pointed out that viability in the space environment very likely involves only dormant forms of life. Active forms of life as speculated by Hoyle (1959; see Sect. 13.2) could not exist due to the harsh radiation environment, cold vacuum conditions and low density, plus the problem of origin. The idea that an ancestor of such an organism would have originated on a planetary surface and later adapted to life in space similar to marine animals and plants that conquered the land during Earth's history, seems unreasonable. There are many transitional habitats between land and sea, but not between a planetary atmosphere and space. Evolutionary pressure would have had to push certain types of organisms to adapt to life in the atmosphere, then pressed it to higher and higher levels of the atmosphere until finally the organism would have to be capable of living in space. Over Earth's history of immense evolutionary pressure during certain time periods, only a tiny fraction of terrestrial organisms adapted even to a life style involving the atmosphere. The major problem appears to be that chemical nutrients that are needed for growth in addition to light are not present in high enough concentrations in the higher atmosphere and certainly not in space.

8.5 Cosmic Biogeography

The possibility of worlds beyond our own has been appreciated since the speculations of the early Greeks. In 1584, Giordano Bruno asserted that there were "countless Suns and countless earths all rotating around their Suns," but confirmation of other Solar Systems with rotating, planar clouds of dust and gas that could lead to planet formation was not made until infrared observations were conducted of such a disk of dust surrounding the star Beta Pictoris, in the 1980s (Smith and Terrile 1984). Today we know of many extrasolar planets and even many star systems with multiple planets, but are they inhabited? Cockell et al. (2016) defined habitability as the ability of the environment to support the activity of at least one organism. But supporting life once it has formed is subject to fewer constraints than the origination of life and its persistence over time. Thus, a planetary body that is potentially habitable in theory is not necessarily occupied by a stable biosphere. In fact, most exoplanets may be devoid of life largely because of much stricter constrains on the origin of life than on its perpetuation (see also Chap. 3). As pointed out by Cockell and Westall (2004), the assessment of actual or past habitats on other planets poses a variety of problems for different reasons: (1) it is logistically difficult for scientists to visit extraterrestrial sites of interest, (2) data are limited and may have been acquired by just a few spacecrafts or by ground observations from Earth, (3) the data gathered may not have an astrobiological focus, because that might not have been the focus of the mission in the first place, and (4) environmental conditions on other planetary bodies are often very different from conditions known to support life on Earth, thus inhibiting any analog parallels that can be used to assess the possibility of life.

The traditional approach to habitability is to define a "Habitable Zone (HZ)". The concept of the HZ of a star is based on equating the possibility of life with the existence of liquid water on the surface of a planet orbiting the star. This is motivated by the fact that liquid water is thought to be an important precondition for most, if not all forms of life (Bennett et al. 2003; Goldsmith and Owen 2003). The position and extent of the HZ depends on the stellar luminosity, even though the exact boundaries of circumstellar HZs vary from system to system because planets have different volatile inventories, albedos, and masses, which affect the rate of atmospheric escape of water near the inner edge and the rate of global refrigeration near the outer edge. The limits of the solar HZ often quoted are those of Kasting et al. (1993) obtained by a radiative-convective model for the Sun-Earth system. However, life may also be present outside of a traditionally defined HZ, such as in the putative subsurface ocean of Jupiter's moon Europa (Figueredo et al. 2003; Schulze-Makuch and Irwin 2002a), or in the clouds of Venus (Schulze-Makuch et al. 2004). A life style between dormant and proliferative forms may expand the outer edge of the HZ, as it requires only periodic stability of liquid water on a planetary surface (Schulze-Makuch et al. 2005b). Also, life may be based on a novel biochemistry with different HZ requirements around a star.

The concept of the habitable zone as classically described thus is limited by its exclusion of the possibility of life in habitats more exotic than those found on Earth. With this limitation in mind, Lammer and his colleagues (2009) have proposed an expansion of the concept to include four different classes of habitats. Class I includes bodies on which stellar and geophysical conditions allow Earth-analog planets to evolve so that complex multi-cellular life forms may originate. Class II consists of bodies on which life may evolve but due to stellar and geophysical conditions evolve toward Venus- or Mars-type worlds. Class III habitats are planetary bodies where subsurface water oceans exist which interact directly with a silicate-rich core. Class IV habitats have liquid water layers between two ice layers, or liquids above ice.

However, following the traditional approach, the inner edge of the current HZ of our Solar System lies between 0.95 AU, where the Earth's stratosphere would become moist, and 0.84 AU, where the surface temperature would climb dramatically because of a positive feedback loop (Kasting et al. 1993). The outer edge of the HZ is determined by the formation of CO_2 clouds, which cool a planet's surface by increasing its albedo and by lowering the convective lapse rate. Thus, the outer edge of the HZ would be between 1.40 and 1.46 AU (or up to 2.0 AU for a larger planet than Mars), where clouds would snow out on to the ground causing atmospheric CO_2 levels and surface temperatures to decrease irreversibly (Forget and Pierrehumbert 1997; Williams and Kasting 1997). Work by Mischna et al. (2000) argues that the HZ of the Sun might extend up to 2.0 AU or more, allowing Mars at 1.52 AU to be well inside the HZ if it had a thick atmosphere with a strong greenhouse effect.

By analogy to the circumstellar habitable zone, the term of a Galactic Habitable Zone (GHZ) has been suggested as well (Gonzalez et al. 2001). The GHZ is defined as that region in the Milky Way where biogenic elements are available and where any life would be far enough away from the galactic center to not be exposed to disruptive gravitational forces or to too much radiation. The GHZ has been quantified by Lineweaver et al. (2004), who modeled the GHZ as an annular region between 7 and 9 kiloparsecs from the galactic center that widens with time and is composed of stars between 4 and 8 billion years old. Their assumptions for the presence of a GHZ were based on (1) the presence of a suitable host star, (2) enough heavy elements to form terrestrial planets, (3) sufficient time for biological evolution, and (4) an environment free of life-extinguishing supernovae. The concept of a GHZ has the same advantages and drawbacks as the concept of a circumstellar habitable zone. While these concepts are useful in prioritizing astrobiology targets, especially in a search for life as we know it, they do not take into account any life based on a different biochemistry, or life that simply utilizes adaptative mechanisms that don't require permanent liquid water on the planetary surface.

Much of the search for extrasolar planets (see Chap. 12) is motivated by the quest for terrestrial planets, for the common-sense reason that we are better qualified to recognize life as we know it, and therefore more likely to find it on smaller, rocky planets such as our own. It is important to consider, however—as we argue at numerous points in this book—that life in forms unfamiliar to us could flourish under conditions alien to the life with which we are familiar. There may thus be specialized niches for some forms of life on gas giants, or on their satellites, or on brown dwarfs or orphan planets, within radiation fields of high intensity, in liquids other than water, using metabolic systems and energy sources unlike anything we have ever seen. We have already been surprised to find, for example, that our closest star belongs to a triple star system (Alpha Centauri A, Alpha Centauri B and Proxima Centauri), and that one of them, Proxima Centauri is apparently orbited by a terrestrial planet (Anglada-Escudé et al. 2016), and we are just starting to explore other solar systems. The broader mandate for space and planetary science should therefore be to characterize the full range and variety of solar systems, and seek in the pattern of their distribution the clues that will lead us to consider how exotic our consideration of life on other worlds should remain.

The most extreme planetary body in our Solar System in this respect is Titan, being both extremely reducing (practically devoid of molecular oxygen and carbon dioxide) and extremely cold (surface temperature <100 K), with seas of liquid methane/ethane on its surface. However, due to Titan's potential to reveal alternative pathways for prebiotic chemistry and possibly even life, it has received much attention (Baross et al. 2007), and was even rated as the mission target of highest priority in our Solar System by Shapiro and Schulze-Makuch (2009). Could polymerized hydrocyanic acid with its structural and electronic variability push prebiotic chemistry to increased complexity on Titan (Rahm et al. 2016)? Could there even be exotic organisms that may use azotomes, compounds that contain polar nitrogen groups, to play the role of liposomes in terran biochemistry (Stevenson et al. 2015a, b)? The spectroscopic detection of vinyl cyanine (Palmer et al. 2017) provides a first support for such possibilities, but more is needed. And, could we possibly detect evidence of alien metabolism, which might be based on radical chemistry rather than redox chemistry in this type of cryogenic environment (Schulze-Makuch and Grinspoon 2005)? Might we even detect macromolecules with repeating backbone charges that act as a genetic polymer for life on Titan (Benner 2017). These are only a few of the questions we would like to be able to answer; and to achieve this we have to complete the step from fanciful speculations to predictions that can be tested by future missions to Titan. Such missions to Saturn´s largest moon should be of the highest priority if we truly want to understand the full "landscape" of life, not only on Earth, but universally.

Another example of where research should be expanded is the possibility of habitable planets around M stars rather than G stars like our Sun (Tarter et al. 2007). As of this writing there have now been detected several Earth-size planets, some of which might be habitable, and we are just at the cusp of detecting the first exomoon. M stars (also known as red dwarfs or dM stars) are the most common stars in the Universe and most of the discovered planetary bodies are and will be orbiting M stars. Based on their longevity and constant luminosities many of these are likely to be habitable (Guinan et al. 2007). Heath et al. (1999) even suggested higher plant habitability for red dwarf planets based on possible moderate climates and global water cycles on these bodies. They also pointed to the availability of photosynthetically active radiation in the sunlight of M stars. Some properties of red dwarf stars and their relationship to planetary habitability are listed in Table 8.4.

Finally, the notion of cosmic habitability could be expanded even further. Recent research efforts, especially into the cosmological idea of inflation, suggest the highly speculative possibility of many universes existing in parallel with ours, all with different values for the cosmological constants such as the Boltzmann constant, Newton's constant, the charge of the electron, electric permittivity, magnetic permeability, the speed of light, Fermi's constant, the Planck constant, etc. If that speculation is correct, many universes could exist which would be essentially unrecognizable to us, as, of course, would be any life existing within them. Another suggested alternative is that the fundamental constants have changed with time (Olive and Quian 2004), which, if true, would tie habitability in the Universe closely to time. At the core of this problem lies a version of the anthropic principle: our

Table 8.4 Properties of red dwarf (dM) stars and their relationship to planetary habitability (modified from Guinan et al. 2007)

M star property	Astrobiological assessment
Nearly constant luminosities over tens of billions of years	M star planets provide a stable environment for life to form and evolve within fixed habitable zones
M stars are ubiquitous, comprising >70% of stars	High chance for at least some habitable planets
Long life times (>50 Gyr)	Especially beneficial for evolution of complex/intelligent life, because of greater evolutionary time span (compared to 4.5 Gyr for evolution on Earth)
There are many old M stars (>5 Gyr)in our galaxy	Very old, metal poor, M stars would likely not be able to form rocky planets because of the paucity of metals. A low metal environment would also be problematic for the development of life
Theoretical studies by Boss (2006) indicate that "Super Earths" can easily form in the protoplanetary disks of M stars	Planets hosted by M stars should be at least as common as those hosted by solar-type stars. Even without much effort, several M stars have been found to host planets
HZ is located very close to the host star at <0.1–0.4 AU	The planet would easily become tidally locked, reducing likelihood of global habitability
Unlike solar-type stars, M stars have essentially no photospheric continua in the UV (<2500 Å), because of their low temperatures	While generally harmful to organisms, UV irradiation is a powerful force in evolutionary adaptation, and may also play a role in the origin of life
M stars have very efficient magnetic dynamos resulting in strong coronal X-ray, transition region FUV and chromospheric FUV-UV emissions	While generally harmful, these types of radiation are easily filtered out by planetary atmospheres and may be evolutionarily beneficial

Universe, however unique among all the possibilities, harbors a form of life that can see it because that life evolved under those same unique constraints. Whether our Universe is only a random chance event within an incredibly large number of other universes, a kind of bubble in a multiverse (Leslie 1996; Linde 1986; Rees 2001; Susskind 2005), and whether life can exist only in our type of universe, cannot currently be answered, and is perhaps not resolvable by the scientific method at all.

8.6 Chapter Summary

The human perspective of life as a planetary surface phenomenon is deceiving. The surface provides a heterogeneous environment conducive for the diversification of life over time as conditions change. It is just these circumstances, in all probability, that have given rise to macrobiological complexity on Earth. But the part of the biosphere that lies beneath the surface provides for a more stable and secure abode for life, and may even on Earth harbor a greater total biomass than is found above ground. Thus, life in the subsurface is much more likely to be the rule than the exception on other worlds. If this is so, there are compelling theoretical reasons for believing that in the vast majority of cases, such life is microscopic and relatively ancestral.

The gaseous atmosphere that surrounds planetary bodies is a much less favorable habitat for living systems. But at high densities with an appropriate mixture of chemicals and available free energy, atmospheres could harbor life. Like their subsurface counterparts they would probably be microscopic for reasons having to do with buoyancy, but because of the peculiar evolutionary trajectory that likely led to their adaptation to an aerial existence, they are more likely to be highly derived in form and function from their ancestors. Active life in space is highly improbable due to the harsh radiation environment, cold vacuum conditions and low density, relative homogeneity, and the problem of origin. However, organisms have developed protective mechanisms that allow them to travel passively through space for some time.

Habitable worlds might be widespread and would likely include planets that orbit other (e.g. M or K) stars. However, habitable does not mean inhabited, as there may be many uninhabited worlds that could potentially support life but that do not because the constraints for the origin of life on those planets are likely to be more stringent than for the persistence of life once it has originated. A first attempt to search for habitable planetary bodies would consist of defining habitable zones around stars and by quantifying galactic habitable zones within our own Galaxy. However, the traditional approach of the habitable zone concept is to consider only those planetary bodies as habitable that exhibit stable liquid water on their surfaces. This approach most likely omits many habitable worlds.