Chapter 9
Signatures of Life

In this chapter we will elaborate on how evidence for life on other worlds can be sought, and if present, possibly detected. The best evidence for extraterrestrial life, of course, would be recovery of actual specimens or their fossils. For the next one or two decades, the possibility of obtaining such direct evidence is almost surely restricted to samples from Mars and Venus, and possibly from some moons of the outer Solar System such as Europa and Enceladus. So detection of life beyond our nearest neighbors will be dependent for the near future on remote sensing. As technology of robotic exploration and remote sensing improves, the possibility of detecting extraterrestrial life will grow. While the size of individual organisms makes their detection at a distance virtually impossible, organisms in the aggregate alter their environments, generating signatures of their functional processes. These direct consequences of biological activity are referred to as "biosignatures". Other effects of the presence of living systems may be detected in global or geological features. These alterations of the geological environment due to life processes, we call "geosignatures". Even on worlds too remote, small, or difficult for whatever reason to monitor for the existence of explicit signatures of life, certain planetary characteristics can be detected that are more likely to be consistent with the presence of life than others. These we refer to as "geoindicators." They consist of parameters that are consistent with life as defined in Chap. 2, and the requirements for life as described in subsequent chapters, including a flow or gradient of energy, presence of an appropriate solvent, and availability of complex polymeric chemistry. While geoindicators point to the potential for supporting life, they do not confirm its existence. Most geoindicators can be detected by remote sensing methods with relative ease, however, and thus can be used in assessing the plausibility of the existence of life. At the end of the chapter, we apply our discussion of signatures and indicators of life to assess the relative plausibility for the existence of life on other bodies in our Solar System. How to detect and confirm living processes with life detection experiments will be discussed in Chap. 10.

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9.1 Searching for Signatures of Life

Examples of biosignatures and geosignatures of life are given in Table 9.1. None of these signatures are known to exist on any planetary body of our Solar System other than Earth. Thus, there is presently no available evidence for life as we know it elsewhere in the Solar System. Life could exist nonetheless, either in a form known or unknown to us, that does not give rise to any of the biosignatures or geosignatures indicated in Table 9.1, if it (1) occurs beneath an opaque surface, (2) is too small to cause environmental transformations extensive in magnitude or spatial extent, or (3) is insufficiently complex to generate complex phenomena, such as roads or radiowaves. Other difficulties are that extraterrestrial life may involve dynamic processes that occur on (1) a spatial scale too small to be detected by current remote technology, and (2) a time scale too prolonged to be sampled feasibly (Schulze-Makuch et al. 2002a). Also, there are many mineralogical features that look like biosignatures, but are entirely abiotic (e.g., Garcia-Ruiz et al. 2017). A recent discussion of the reliability of biosignatures has been provided by Fox and Strasdeit (2017).

Notwithstanding these reservations, several types of biosignatures may become relevant for the detection of life in the near future, either in our own or in another Solar System (Table 9.1)

9.1.1 Atmospheric Composition of a Planetary Body

An often cited geosignature of life is the presence of molecular oxygen and particularly the presence of ozone in an atmosphere. For example, Akasofu (1999) suggested the use of the green oxygen line at 557.7 nm from auroral emissions to

Table 9.1 Some examples of biosignatures and geosignatures of life

Observation	Signature
Organic macromolecules larger than 500 daltons	Biosignature
Atmospheric gas composition, such as O_2 and CH_4, resulting from biogenic processes	Geosignature
Rocks and sediments produced by biogenic processes such as the banded-iron formation (BIF) and stromatolite deposits of early Earth	Geosignature
Known biogenic substances such as chlorophyll not explicable by naturally occurring inorganic chemical processes	Biosignature
Rate and type of erosion consistent with biological processes	Geosignature
Structural complexity, such as geometric regularity (roads, canals) or unnatural local aggregates (cities) not explicable by natural geological processes	Geosignature
Distribution and magnitude of emitted heat inconsistent with an abiotic origin	Biosignature
Energetic emissions such as radiowaves, which are neither highly regular, as from a pulsar, or highly random, as in the universal background radiation	Biosignature

search for extraterrestrial life. Ozone was suggested to be more suitable than molecular oxygen because its abundance increases nonlinearly with the abundance of molecular oxygen (Leger et al. 1993) and ozone absorbs UV radiation known to be detrimental for terran life on extrasolar planets. Any such spectroscopic remote observation has two major technical challenges: the weak signal and the huge background from the parent star (Frey and Lummerzheim 2002). However, for the detection of the habitability of planets in other Solar Systems this may be the only reasonable approach for the near future. In our view, an oxygen atmosphere or ozone layer alone, in the absence of other abnormal concentrations of gases such as methane, should be regarded only as a geoindicator consistent with the presence of life, not as a geosignature. For example, Jupiter's moon Europa currently has a thin oxygen atmosphere from interactions of radiation with surface ice (Hall et al. 1995) and it can easily be envisioned that it had a much thicker oxygen atmosphere and possibly an ozone layer for part of its geological history. When the Solar System formed Europa most likely had oceans of water on its surface and a water vapor atmosphere. Given the high radiation environment of the Jovian system, water would have split into hydrogen and oxygen with the hydrogen escaping to space and the oxygen being retained for longer time periods because of its higher molecular weight. Thus, the presence of a high amount of molecular oxygen and even ozone for some time period is absolutely plausible based on physical means alone (Europa likely experienced global re-melting events for which the above scenario may be valid as well).

However, the atmospheric composition of Earth is a prime example of a signature of life (Table 9.1). Earth's atmosphere is the peculiar product of a particular biological process: photosynthesis. Oxygen by itself could not be considered a signature, as explained above. Further, it was shown that titanium (IV) oxide can produce abiotic oxygen from liquid water under near-ultraviolet light (NUV) on the surface of exoplanets (Narita et al. 2015). However, the high amounts of oxygen on Earth (about 21%) combined with the presence of hydrogen (H_2), methane (CH_4), ammonia (NH_3), methyl chloride (CH_3Cl), and methyl iodide (CH_3I), along with various sulfur gases can best be explained by the continuous metabolic production of these compounds faster than they can react with each other (Sagan 1994). These gases, highly reactive when mixed, would not coexist at such high concentrations unless their levels were being actively maintained. It is this type of disequilibrium, in combination with high amounts of oxygen that can be used as an indicator for oxygen producing photoautotrophs. These gases would be visible through their spectral signatures in the mid-IR and visible to near-IR wavelength ranges, thus providing not only valuable information regarding possible biosignatures but other planetary properties as well (Des Marais et al. 2002).

The spectral signature of photosynthesis on Earth has also been suggested as a signature for life on other planets. The reflectance spectra of most photosynthetic organisms exhibit a so-called red edge, although the exact spectrum varies quite a bit between different types of organisms (Kiang et al. 2007a, b). Photosynthesis can also be quite diverse, as exhibited by the two types of photosynthesis existing on Earth. Other types of light-driven metabolism have been suggested as well, such as chlorinic photosynthesis—the photolytic oxidation of aqueous Cl^- by organisms to form dihalogen or halocarbon products, coupled with the assimilation of carbon dioxide (Haas 2010). This hypothetical type of geochemically, physically, and energetically feasible metabolic pathway would result in a different type of spectrum.

A very thorough approach to listing possible gases in the atmosphere of exoplanets was taken by Seager et al. (2016). They showed that more than 600 gases from an initial list of about 14,000 molecules are known to be produced by life on Earth, and thus could serve in principle as potential biosignatures. A different approach was employed by Domagal-Goldman et al. (2011), who focused only on biogenic sulfur gases as remotely detectable biosignatures on anoxic planets. Currently, the ability to detect atmospheric biosignatures remotely is still in its infancy, demonstrated by the high likelihood of both false negatives (Reinhard et al. 2017) and false positives (Rein et al. 2014).

9.1.2 Geological Evidence

Particular signatures also exist for chemoautotrophic organisms. An example are the limestones and ironstones produced by biological activity on the early Earth. Both types of rocks can form from inorganic processes. The large quantities produced during Earth's early history, however, can hardly be explained by abiotic processes. For example, microbial life dominated the ecosystems of Precambrian shallow marine environments, and is likely to be implicated in widespread carbonate formation, and possibly also in the precipitation of other evaporates (Wrights and Oren 2005). The large amounts of deposited Banded Iron Formation (BIF) rocks are even less imaginable without microbial participation. Similar processes might be occurring on Mars. For example, Parro et al. (2005) described the development of technology to detect iron-powered chemosynthetic microbes. Chemosynthesis generates various chemical end-products depending on the exact metabolic process. Nevertheless, the chemical end-product may provide a useful marker, especially if produced in a large enough amount over an extended period of time to make it a signature of chemotrophic life. The biochemical end products often exhibit large-scale geomorphological characteristics such as stromatolite colonies and coral reefs, some of them large enough to be observed with the naked eye from the Moon such as the Great Barrier Reef.

Minerals themselves—particularly rare minerals—may serve as a biosignature as well. They may have played essential roles in the origin of life, or been formed, directly or indirectly, by biological processes (Hazen and Ausubel 2016). For example, Earth has many more minerals, and more rare minerals, than Mars due to a much larger diversity of environments. Thus, the distribution of rare minerals may constitute an important biosignature, reflecting the co-evolution of the geosphere and the biosphere.

The high rates of erosion and types of erosion observed on Earth due to biological and chemical weathering induced by living organisms provide another example of a geosignature. The biomass of fungus-lichen rock dwellers is estimated to be enormous, by one account 13×10^{13} tons (Margulis 1998). Thus, the effect of these rock dwellers on chemical weathering from metabolic by-products is immense. Rates and types of erosion can be inferred from the visible and microwave wavelengths of the electromagnetic spectrum (Schulze-Makuch et al. 2002a), but are traditionally not considered as a signature of life. Dietrich and Perron (2006) suggested the search for a topographic signature of life based on the quite apparent impact of life on rock weathering, soil formation and erosion, and slope stability and river dynamics, even over short time scales. But even for a topographical signature of life, high-resolution images are necessary to have confidence in the detection, and at present this type of resolution is only available for the inner planets of our Solar System. It would not be expected to be available for any extra-solar system planets, particularly not for any encased by an atmosphere.

9.1.3 Fossil and Isotopic Evidence

Fossil remnants and isotopic fractionation caused by biotic processes are other examples of biosignatures. One controversial example is the Martian meteorite ALH84001 in which McKay et al. (1996) claimed to have found evidence of fossilized microbes. However, these claims have come under intense scrutiny as have some of the oldest known records of life such as stromatolites and microfossils (Pasteris et al. 2002; see also Chap. 10). Biogenic textures have been described from oceanic crust and in pillow lavas from 3.4 billion year old rocks from the Barberton Greenstone Belt of South Africa (Fliegel et al. 2010), but the validity of these biosignatures has been disputed as well (Grosch and McLoughlin 2014). A similar skepticism has greeted claims that ancient sediment structures on Mars resemble macroscopic morphology and spatial and temporal relationships as observed in terran microbialites (Noffke 2015). Ruff and Farmer (2016) reported that opaline silica structures discovered on Mars by the Spirit rover are remarkably similar to active hot spring and geyser discharge channels at El Tatio in northern Chile, where complex sedimentary structures are produced by a combination of biotic and abiotic processes. Evaporite sediments such as gypsum seem to be especially suitable for preserving biosignatures, including microfossils (Schopf et al. 2012). Stüeken (2016) suggested that high nitrogen abundances in ancient muds can be considered a biosignature, and Nadeau et al. (2016) proposed microbial morphology and motility as possible biosignatures for outer planet missions.

The search for reliable biosignatures is currently a very active area of research, in part because it is extremely challenging to determine what a reliable biosignature is, and what type of life process it indicates (Fox and Strasdeit 2017). One approach to this challenge is to identify biosignatures that would be expected to be found in specific environments, created by the life processes occurring there. Lava tube caves are one example of such an environment (Boston et al. 2004).

Isotopic signatures of carbon, sulfur, nitrogen, hydrogen, iron and other elements are another form of fossil evidence (Schidlowski et al. 1983) that can also be interpreted as a biosignature. Observations from terran organisms show that chemically lighter isotopes are preferred resulting in a net fractionation of lighter isotopes. A carbon isotope fractionation, typical for biological processes, has been found in the geological record for the last 3.5–3.8 billion years of Earth's history (Schidlowski 1988). More recently Yeung et al. (2015) reported that biological factors influence the clumped isotope signature of oxygen produced during photosynthesis. They found that photosynthetic O_2 is depleted in $^{18}O^{18}O$ and $^{17}O^{18}O$ relative to a stochastic distribution of isotopes and speculated that similar biosignatures may be widespread in nature.

A robotic mission would be needed to detect these signatures of life unless a rare fortunate circumstance would bring a meteorite from that world to Earth where it can be analyzed by in-situ methods. However, microbial biofilms that become preserved on rock surfaces could possibly be identified with remote sensing methods if (1) spectroscopically identifiable compounds exist that display unique adsorption, diffraction, and reflection patterns characteristic of biogenerated organic compounds (e.g. chlorophylls, carotenes, melanins), (2) biogenic geomorphological features are exhibited (e.g. biopitting, biochipping, bioexfoliation), and (3) biominerals are detected that are produced in association with biofilms that occupy rock surfaces such as oxalates and certain types of carbonates and sulfides (Gorbushina et al. 2002).

9.1.4 Macromolecules and Chirality

Among the most powerful biosignatures are macromolecules that are directly linked to biogenic metabolism or other cellular functions. Chlorophyll is the prime example and can be identified by radiance spectra in the visible region (Gordon et al. 1980; Hovis et al. 1980) and by advanced very high-resolution radiometer (AVHRR) measurements (Gervin et al. 1985; Tucker et al. 1985). Methylhopanoids have also been suggested as biomarkers and have the additional advantage of distinguishing between cyanobacteria (2-methyl) and methanotrophic (3-methyl) bacteria (Farrimond et al. 2004). Proteins, polypeptides and phospholipids are other examples of macromolecules that are linked to life. Lipids have also been suggested as universal biosignatures of extraterrestrial life (Georgiou and Deamer 2014). In general, any macromolecule of a size larger than 500 daltons (protein-size) could be considered a possible biosignature (Table 9.1). Davila and McKay (2014) introduced the concept of necessity and chance: that some of these macromolecules or terran building blocks of life are an endowment of prebiotic processes and likely to be found also in extraterrestrial life, while others were introduced through the evolutionary process by chance, and thus are not likely to be shared with other forms of life from a different origin. An evolutionary approach was also taken by Dorn et al. (2011), who suggested that life leaves a distinct chemical signature in its environment, because it synthesizes only those molecules that maximize its fitness. In a lifeless environment, small, easily formed, low-formation-energy molecules prevail, while the measurement of chemical concentration ratios of monomers that would be contradictory to equilibrium thermodynamics or formation kinetics would indicate the likely presence of life. As examples they pointed to an apparent biotic bias toward even-numbered carbon chains in monocarboxylic acids and specific abundance patterns in amino acids.

Chirality, or non-racemic handedness, is a fundamental property of biogenic molecules on Earth and thus may be used as an indicator of possible extraterrestrial life detectable by remote sensing in the near future. Large macromolecules are not symmetrical and thus inevitably exhibit chirality. Plaxco and Allen (2002) pointed out that all terran life uses well-structured, chiral, stereo-chemically pure macromolecules of 500 or more atoms as their metabolic catalysts. Xu et al. (2003) argued that all life would employ these types of macromolecules irrespective of the specifics of their chemistry. They pointed out that these molecules strongly absorb at terahertz frequencies and exhibit significant circular dichroism, which they consider an unambiguous biosignature. Left- and right-handed circularly polarized light interacts differentially with chiral molecules, especially at blue-green and shorter wavelengths (Van Holde et al. 1998). Salzman et al. (1982) found that organisms also scatter circularly polarized light differentially, with angular and wavelength spectra somewhat characteristic of particular organisms or strains. Evidence presented by these authors and by Nicolini et al. (1991), Diaspro et al. (1991) and Lofftus et al. (1992) indicates that the configuration of DNA in organisms strongly affects their differential scattering.

Winebrenner (2008) developed an experimental system for the detection of biogenic molecules by means of circularly polarized light scattering with a polarization-dependent resonance at 436 nm. Sparks et al. (2009) reported on the detection of circular polarization in light scattered by photosynthetic microbes and proposed that circular polarization spectroscopy could provide a powerful biosignature for remote sensing searches for life. Creamer et al. (2017) described two capillary electrophoresis methods capable of resolving amino acid enantiomers down to a detection limit of 5 nM for the neutral amino acids and 500 nM for acidic amino acids, even with very little sample preparation. Once the collection of samples in situ can be achieved, the incredible sensitivity of today's technology, indicated by these examples, could provide a critical step toward the confirmation of biosignatures of life on other worlds.

9.1.5 Presence of Metabolic By-Products and End-Products

Metabolic by-products and end-products are well known for organisms on Earth. They include various biochemical compounds such as ATP and lipids, but also electron donor and acceptor pairs such as Fe^{3+}/Fe^{2+}, NH_3/N_2, and H_2S/S enriched in lighter isotopes. This isotope enrichment or fractionation occurs as part of the metabolic reactions for organisms on Earth and may also occur for life elsewhere. While biochemical macromolecules such as ATP are very specific signatures for certain biological processes, using isotopically light electron donors or acceptors as signatures for life is more challenging. An endless number of possible electron donor/acceptor pairs could potentially be used for energy-harvesting reactions on other worlds, and there are also numerous inorganic processes that lead to isotopic fractionation, many of them poorly understood. One promising approach might be the use of the oxygen isotopic ratio of phosphate, which was suggested as a means for detecting enzymatic activity since the exchange of oxygen isotopes between water and phosphate requires enzymatic catalysis at low temperatures (Blake et al. 2001). Also, the presence of gaseous electron acceptors and donors (e.g. H_2S, COS, CH_4) enriched in lighter isotopes may constitute a signature of life that can be screened readily by remote sensing methods. One example is the presence of CH_4 on Titan, which is isotopically lighter than would be expected from Titan formation theory (Lunine et al. 1999). However, any such interpretation is limited by our understanding of the physical and chemical processes occurring on a planetary body as foreign to us as Titan.

A related biosignature may be the metabolic multistep pathways that run close to equilibrium for some internal steps, but are coupled to a last step, which is energetically downhill, thus pulling the whole reaction to completion (Voet and Voet 2004). Baross et al. (2007) considered this feature as a possible universal biosignature as it exploits most economically a surrounding chemical disequilibrium.

9.1.6 Production of Biogenic Heat

Another possible signature of life is biogenic heat that may be detectable in the future by more advanced technologies. Living systems exist in thermodynamic disequilibrium by drawing energy from their environments. A consequence of the biochemical reactions that an organism needs to carry out to sustain itself is the production of "unorganized energy", commonly in the form of heat. The production of heat follows as a consequence of the 2nd Law of Thermodynamics. Organisms by their very nature have to be structured and organized. However, in order to conform to the tendency of the physical world toward a state of greater disorder, any organism has to give up a portion of its energy in the form of heat or other type of disorganized energy. The distribution and magnitude of heat produced by living systems or colonies of living systems may be possible to detect by in-situ monitoring or remote sensing techniques in the near future, thereby serving as a biosignature if an abiotic origin can be ruled out.

9.1.7 Signatures of More Advanced Life

Signatures of life also include structural complexity produced by biogenic processes ranging from termite mounds to artificial constructions such as streets. Materials associated with our civilization, such as concrete, elemental aluminum, various plastic compounds, and radionuclides that change very little over geological time, would be examples of biosignatures for technologically advanced life (Waters et al. 2016). Evidence for a much further advanced civilization would be a Dyson Sphere—a spherical shell constructed around a star for absorbing most of its visible and shorter wavelength radiation (Dyson 1960; but see also Harrop and Schulze-Makuch 2010). Energetic emissions, such as radiowaves, which are neither highly regular, as from a pulsar, nor highly random, as in the universal background radiation, are currently used by SETI (Search for Extraterrestrial Intelligence) to scan the skies for signs of extraterrestrial intelligence. These kinds of signatures, of course, would be linked directly to the presence of more technologically advanced forms of life than microbes, but, if present, would also imply the presence of microbial life based on the presumption that more complex organisms would have to have evolved from simpler ancestors.

9.2 Geoindicators of Life

With the exception of our nearest Solar System bodies, the detection of life elsewhere in the Universe for the foreseeable future will likely focus on remote detection, given our current state of technology (Schulze-Makuch et al. 2002a). Retrieval of samples for direct analysis for years to come will be limited to meteorites, comet or asteroid material returned to Earth, and possibly collecting ejected material from Ceres or Enceladus. Retrieving samples from the atmosphere of Venus and the surface of Mars will be feasible technologically within the next decade or two. Yet, for the foreseeable future it is not feasible practically and economically to send robotic landers to each planetary body of our Solar System and beyond. Further, even on a planetary body with life the detection may be unsuccessful if (1) the site is unsuitable or sparsely populated, or (2) life detection experiments are not set up appropriately to detect life thriving in that particular environment.

Under these circumstances, the more sophisticated and abstract definitions of life alluded to in Chap. 2 may provide the basis for a set of parameters that could point to conditions favorable for generic forms of life, either known or unknown to us. Specifically, (1) the maintenance of disequilibrium from the environment requires the availability of energy flow (hence gradients of energy) for sustaining low entropy states; (2) the level of chemical complexity required to transform and store energy appears to require a fluid medium where concentrations can be high but molecular mobility can be maintained; and (3) the storage and transmission of information in organic forms of life appears to require polymeric chemistry that can involve the making and breaking of covalent bonds with relative ease. Parameters that indicate the presence of any of these conditions, and therefore imply that life could be present though not confirming its existence, are defined here as geoindicators. Based on the forgoing discussion primary geoindicators of life would include evidence of (a) an atmosphere or ice shield, (b) thermal gradients and chemical disequilibrium conditions, (c) internal differentiation of the planetary body, implying the capacity for radiogenic heating, (d) complex polymeric chemistry, (e) energy flow or gradients, and (f) a liquid medium as a solvent. The advantage of these geoindicators is that remote sensing can detect all of them readily in principle.

9.2.1 Presence of an Atmosphere or Ice Shield

It is difficult to envision the presence of life on the surface of any planetary body that is not shielded by an atmosphere. Without an atmosphere any liquid or gaseous compound will vaporize into the vacuum of space. Aside from the gas giants, relatively dense atmospheres exist only on Earth (1 bar), Venus ($\sim$90 bar) and Titan ($\sim$1.5 bar). However, for life to thrive at planetary surface temperatures on Venus (very hot) and Titan (very cold) would require a biochemistry with properties unfamiliar to life forms on Earth. The surface of both Venus and Titan is obscured from visual light penetration by a thick atmosphere. On Titan, organic compounds such as methane and ethane are present in the atmosphere (Coustenis and Lorenz 1999; Lorenz 1993), and Titan is also the only planetary body with a significant atmosphere other than Earth known to have nitrogen as the most abundant atmospheric gas. The high nitrogen content in Earth's atmosphere has been interpreted to result from biological processes (Lovelock 2000). Since Titan's atmosphere can only be penetrated by narrow frequency windows between bands for methane and radar with current remote sensing technology (Griffith et al. 1991; Lorenz and Lunine 1997), probes have to be sent to explore the physical conditions and chemistry of the surface (e.g. the Huygens probe which descended through Titan's atmosphere in January of 2005). On Titan a warmer subsurface could be a suitable habitat for microbial life. Venus, on the other hand, would provide very little hospitality for microbes in the subsurface habitat, unless they were able to use water that might possibly be present in a supercritical state. Instead, if life evolved on Venus, it may have retreated toward cooler conditions in the atmosphere (Schulze-Makuch and Irwin 2002b). Mars has a much thinner but still significant atmosphere dominated by CO_2. The Martian atmosphere would not provide much protection for any life on its surface, but life would be possible in protected niches such as caves or beneath the surface (Boston et al. 1992).

The Jovian moons Europa and Ganymede, and possibly Callisto, as well as Saturn's moon Enceladus and Neptune's moon Triton, do not have significant atmospheres, but suitable conditions for life in a subsurface ocean, if it exists, would be shielded by an ice crust. This ice crust would act as a shield preventing subsurface compounds from evaporating into space and would also provide a shield against cosmic rays. Planetary oceans capped by an ice shield may in fact be much more common in the Universe than “naked” or “near-naked” oceans as on Earth (Schulze-Makuch 2002).

9.2.2 *Internal Differentiation*

Life is easier to envision on any planetary body that is differentiated into a radioactive core, a mantle and a crust. Internal differentiation is a sign of endogenic activity that is powered by radioactive decay. The likelihood of internal differentiation, in turn, is directly related to global mass, and that can be deduced by a planetary body’s influence on orbiting or passing probes and by the gravitational attraction it exerts on other planetary bodies or light.

To the extent that the evolution of life on Earth is a typical example, plate tectonics, which are driven by the internal heat of Earth, or some other effective recycling mechanism for minerals and nutrients appears to be important for the persistence of living systems. Nutrients and minerals would otherwise be quickly exhausted and evolving life, especially when still in its infant stage and not well established, would not be able to meet its nutrient demands within a relatively short time frame (on a planetary time scale). On Earth and probably early Mars the recycling mechanism has been plate tectonics (Connerney et al. 1999; Sleep 1994). Plate tectonics on Earth have also constantly produced greenhouse gases that have acted as a global thermostat providing stability for the evolution of life (Ward and Brownlee 2000). The presence of plate tectonics can be identified with remote sensing methods based on measured magnetic properties of the rock, visible symmetry along a spreading axis, and specific patterns in fracture orientation and propagation.

9.2.3 *Polymeric Chemistry*

Chemical complexity is based at the molecular level on polymeric molecules joined by covalent bonds (Lwoff 1962). For reasons elaborated in Chap. 6, other life in the Universe, except under very exotic conditions, is likely to be based on polymers of carbon. Polymeric organic compounds are in general detected by their absorption spectra.

On an active planet, polymeric organic compounds will be subject to chemical cycling. This can be inferred from spectra and gradients in surface coloration, and it appears to be widespread in our Solar System. Io, Europa, Enceladus, Iapetus, and Triton, in addition to all the planets, provide examples. On Earth, chemical cycling occurs through oxidation-reduction reactions that are actively maintained by organisms, though they can occur inorganically as well.

9.2.4 Energy Source

A flow of energy is required to organize the material of the living state and to maintain its low entropic state (Morowitz 1968), thus an external energy source is a minimal requirement for life. Light and the oxidation of inorganic compounds provide the energy for the Earth's biosphere, so wherever light and a means for sustaining oxidation-reduction cycles can be demonstrated, the possibility for maintaining life is present. Light is a highly effective form of energy on Earth, and phototrophic organisms are responsible for the high oxygen content in the Earth's atmosphere. Light from the Sun could serve as the principle energy source for living systems on all the inner planets of our Solar System, and possibly as far as the Jovian and Saturnian systems. Light is directly measurable using remote sensing and thus a good indicator for the theoretical possibility of photosynthesis. In general, energy gradients can fairly well be detected by remote sensing as detailed in Table 9.2. On Earth, all these energy sources are present. However, the availability of certain energy sources, such as heat, motion or pressure, does not necessary imply that life relies on them, but merely that the planetary body in question is active and meets one of the prerequisites for life.

Table 9.2 Remote detection of energy gradients (modified from Schulze-Makuch et al. (2002a)

Type of energy	Examples within the Solar System	Examples of remote detection
Light	Mercury to Saturnian system	Directly measurable
Chemical Cycling	Io, Europa, Iapetus, Triton	Molecular absorption spectra, surface reflectance spectra, imaging spectroscopy, polarimetry, radar measurements, detection of alteration minerals, gradients in surface coloration
Thermal	Mercury, Titan, Jovian satellites, Triton	Gradients of infrared radiation, thermal radiometry, infrared to visible spectral imaging, distance to Sun, mass sufficient for internal differentiation of planetary body (gravitational measurements), microwave radiometry to detect geothermal heat flows
Motion	Venus, Mars, Enceladus, Jovian satellites, Triton, Titan	Doppler imaging, radar inter-ferometry, electromagnetic indications of a conducting liquid (e.g. Europa), thermal and infrared imaging (volcanic movement)
Gravitational Tides	Jovian and Saturnian satellites, Triton	Visible evidence of surface fragmentation and resurfacing, microwave radiometry
Pressure	Venus, Titan, Gas Giant planets	Visible clouds, changing atmospheric patterns (e.g. Red Spot on Jupiter), direct measurement by robotic probes
Electromagnetism	Jovian and Saturnian system	Measurement of electromagnetic field fluctuations, detection of energetic particles

Thermal gradients are commonly available energy sources throughout the inner Solar System, and also among some larger satellites as shown from gradients of infrared and thermal infrared radiation (e.g., Io and Titan). Thermal energy can be derived from solar emissions or from radioactive heating if the mass of a planetary body is sufficient for differentiation into a radioactive core, as in the major Jovian satellites, and in Titan and Triton. Multispectral remote sensing methods are suitable for detecting rocks altered by hydrothermal heat and solutions, because their reflectance spectra differ from those of unaltered host rock. Thermal radiometry has been used, for instance, to determine that night-time temperatures on Europa are colder at the equator than at mid-latitudes for some longitudes, apparently due to latitude-dependent thermal inertia (Spencer et al. 1999, 2001). Thermal radiometry has also been used extensively on Io (Spencer et al. 2000) and Mars (Christensen et al. 2003).

Kinetic energy is possible wherever gas or fluids exist. Atmospheric motion can be detected directly from visible clouds that move, such as those of Mars, Venus, the gas giant planets, and Titan from visible and reflected infrared images. Speed and direction of moving objects can be determined by Doppler imaging at various wavelengths in an atmosphere or on a planetary surface. Active faults on which earthquakes may occur can be identified by observation of topographical features from space using radar (Tapponnier and Molnier 1977). Changes in the shape of a volcano caused by an expanding or contracting magma chamber can be determined by radar interferometry. Increased emissions of gas and heat of volcanoes can be identified with thermal infrared images and movements of plumes by images in the visible or infrared wavelengths. Electromagnetic measurements with the magnetometer instrument on board the Galileo orbiter were used to infer a conducting liquid in Europa's interior (Khurana et al. 1998; Kivelson et al. 2000).

Gravitational tides are exhibited by planetary bodies and major satellites that are in periodic alignments such as the Earth-Moon system, the Neptune-Triton system, and Jupiter and its four major moons. Significant tidal fluctuations in these sufficiently massive bodies are visible by the evidence of surface fragmentation and resurfacing of the planetary or lunar surface. For example, arcuate lineaments of vast extension on Europa have been interpreted as surface expressions of these enormous tidal forces (Hoppa et al. 1999).

Pressure gradients in an atmosphere can be inferred from banded cloud patterns and measurements of their rotational velocities by large storm systems such as Jupiter's famous Red Spot and less dramatic but similar examples on the other gas giants. Also, stratification as measured at Jupiter is another indicator of pressure gradients. Osmotic pressure gradients may also exist in planetary oceans that could be conducive for the support of life (Schulze-Makuch et al. 2002a). Those gradients are difficult to confirm directly, but could be inferred by a subsurface probe analyzing ocean chemistry, or possibly by remote determination of the solute content of a liquid eruption to the surface.

Electromagnetism is another energy source that occurs wherever eletromagnetic fields are traversed or induced (Schulze-Makuch and Irwin 2001). Jupiter's magnetospheric plasma corotates with the planet at a velocity of 118 km/s, thereby creating a strong magnetic field (Beatty and Chaikin 1990). Energetic ion and electron intensities throughout the Jovian magnetosphere were measured by the Galileo orbiter using an energetic particle detector. Saturn generates a less massive but still large magnetosphere that will be mapped in detail by the Cassini orbiter. More benign electromagnetic fields and their fluctuations can be measured directly using a magnetometer.

9.2.5 Liquid Medium

Finally, a liquid medium appears to be favorable for living processes because macromolecules and nutrients can be concentrated within a bounded internal environment without immobilizing interacting constituents. This assumption is usually taken to mean an aqueous medium, though organic compounds and water mixtures with ammonia and other miscible molecules can exist in liquid form at temperatures well below the freezing point of water. The possibility that life could exist in dense atmospheres has also been suggested (Grinspoon 1997; Sagan and Salpeter 1976; Schulze-Makuch and Irwin 2002b). There is for example both experimental and observational evidence for organic synthesis in Jupiter's atmosphere (Guillemin 2000; Raulin and Bossard 1985; Sagan et al. 1967). However, it is difficult to envision how the boundary conditions necessary for compartmentalizing the flow of energy and restraining the population of interacting molecules could be established under such conditions. However, once originated in a liquid medium, life could adapt to thrive in a gaseous environment (Schulze-Makuch et al. 2002b, 2004).

Major amounts of liquid water are known for certain only on Earth, but very likely exist as subsurface water on Mars in underground aquifers (Carr 1996; Greeley 1987; Malin and Edgett 2000a, b; Malin et al. 2006), and on Europa and Ganymede, where subsurface oceans are inferred from electromagnetic measurements from the Galileo orbiter (Khurana et al. 1998; Showman and Malhotra 1999) and from the presence of hydrated salt minerals on the surface (Kargel et al. 2000). Mixtures of water-ammonia-organic compounds are another possibility on cold planetary bodies, since these mixtures are liquid at much lower temperatures than water (Jakosky 1998). Theoretical models indicate the presence of subsurface stores that are liquid at extremely cold temperatures on Titan (Coustenis and Lorenz 1999; Fortes 2000) and possibly some of the satellites of Uranus and Neptune. Liquid water at or close to the surface can easily be detected by radar, gamma-ray spectrometry, and the absorption spectrum of water, but not when it is present in the deep subsurface or shielded by a thick layer of ice.

Liquid ethane and methane are assumed to be present on Titan's surface (Lorenz et al. 2003), and could provide an alternative solvent for life (Schulze-Makuch and Grinspoon 2005). Liquid sulfur compounds are inferred to exist on Io (Kieffer et al. 2000), and sulfur dioxide or hydrogen sulfide could play a role as solvent as well. Liquid compounds on a planetary surface can most easily be identified by visible and radar images of the erosional features that they cause.

9.3 Geoindicators for Life in our Solar System

Neither biosignatures nor geosignatures have been identified unambiguously on any planetary body beyond Earth to date, though the search should continue as resolution improves. Mars, Venus, and perhaps Ceres are the only other planetary bodies where life as we know it could plausibly be discovered by direct sampling in the foreseeable future. Thus, missions to Mars should remain a priority as they are currently with NASA and ESA, particularly lander missions (e.g. Viking 1 and 2, Pathfinder, Spirit, Opportunity, Phoenix, Mars Science Laboratory, and ExoMars). In addition, the ease of reaching Venus and the possibility of an atmospheric habitat suitable for life there argue for an atmospheric sampling mission to Venus (Schulze-Makuch and Irwin 2002b; Schulze-Makuch et al. 2005a, b). In the meantime and for the coming decades, search for habitats suitable for life beyond the terrestrial inner planets of our Solar System should focus on geoindicators such as those listed above. The current emphasis on visualization of surface features by the Mars Global Surveyor, Mars Odyssey, Mars Express, Mars Reconnaissance Orbiter, and the visual data collected from the Jovian system by the Galileo orbiter and the Saturnian system by the Cassini orbiter, are compatible with this strategy. These missions have the ability to detect energy gradients, organic chemicals, and near-subsurface as well as surface water.

The Huygens probe, which landed on Titan in January 2005, added detailed knowledge of that body’s atmosphere, weather, and surface chemistry. Because of the apparent similarity of its atmosphere to that of the early Earth, and its abundance of organic constituents, Titan should remain a high-priority target for exploration. In fact, geoindicators discussed here point to Titan as a suitable environment for life (Table 9.3), thus Titan should be considered a priority target of astrobiological significance (Shapiro and Schulze-Makuch 2009).

Attention should also be given to some of the less known satellites. Organic constituents appear to be present on Triton and possibly Iapetus. Triton and Titania show evidence of resurfacing that would indicate the generation of internal energy. The Cassini orbiter detected water plumes on Enceladus (Porco et al. 2006), indicating geothermal activity on this moon of Saturn. Similar evidence has accumulated for the dwarf planet, Ceres. Geoindicators indicative of the possibility of habitable environments throughout the Solar System are given in Table 9.3. A full discussion of the plausibility that life could exist elsewhere in our Solar System is presented in Chap. 11.

Table 9.3 Geoindicators for the possibility of life on the planets and major satellites of our Solar System based on current knowledge (modified from Schulze-Makuch et al. (2002a))

Major planetary body	Atmosphere	Thermal gradients/ chemical disequilib	Internal differentiation	Polymeric chemistry	Energy source	Liquid solvent
Mercury	No	Yes	Yes	No	LH	None
Venus	Yes	Yes	Yes	Yes?	LCHP	H_2O, H_2SO_4
Earth	Yes	Yes	Yes	Yes	LCHKGPM	H_2O
Moon	No	No	Yes	No	LG	None
Mars	Yes	Yes	Yes	Yes?	LCH	H_2O
Jupiter	Yes	Yes	Yes	Yes	LCHKPM	?
Io	No	Yes?	Yes	Yes	CLHMG	H_2S?
Europa	Yes*	Unknown	Yes	Yes	CHKGOM	H_2O
Ganymede	Yes*	Unknown	Yes	Yes	CHKGOM	H_2O
Callisto	Yes*?	Unknown	Yes	Yes?	CHKGOM	H_2O
Saturn	Yes	Yes	Yes	Yes	CHKPM	None
Tethys	No	Unknown	No	Yes?	M	H_2O?
Dione	No	No	No	Yes?	M	H_2O?
Rhea	No	Unknown	No	Yes?	M	H_2O?
Enceladus	No	Yes	No?	Yes	CHKM	H_2O
Iapetus	No	Yes?	No	Yes	CM	H_2O?
Titan	Yes	Yes?	Yes	Yes	CHM	C_2H_6, CH_4, NH_3-H_2O?
Uranus	Yes	Yes?	Yes	Yes?	CHKPM	None
Titania	No	Yes?	Yes?	Yes?	CHG	H_2O?
Ariel	No	No?	No	No?	C?H?	None?
Miranda	No	No?	No	No?	C?H?	None?
Umbriel	No	No?	No	No?	C?H?	None?
Oberon	No	No?	No	No?	C?H?	None?
Neptune	Yes	Yes?	Yes	Yes?	CHKPM	None?
Triton	Yes*	Unknown	Yes?	Yes	CHGO	H_2O/ NH_3/ N_2?
Pluto/ Charon	Yes*	Yes?	Yes?	Yes?	CG	H_2O/ NH_3/ N_2?
Comets and Asteroids	No	No	Some	Some	L for some	None

Legend: L = light energy, C = chemical cycling, H = heat energy, K = kinetic energy (motion), G = gravitational energy (tides), P = pressure energy, O = osmotic gradients (in a possible high-salinity subsurface ocean), M = electromagnetic energy. Asterisks indicate a protective ice shield and trace atmosphere. Question marks indicate uncertainty, but with our estimate of probability in the indicated direction

9.4 Chapter Summary

The search for extraterrestrial life everywhere but on our planetary neighbors (Mars, Venus, and possibly Ceres) is limited for the foreseeable future by our inability to obtain physical samples. Therefore, information that can only be obtained by remote sensing and robotic probes will for now provide the only clues concerning the existence of life elsewhere. Biosignatures, which are reliable and clear indicators for specific life processes, are critical for identifying planets inhabited by ancient or current life. The search parameters we have proposed emphasize the importance of detecting the presence of physical and chemical gradients of all kinds, because of their potential for generating free energy. Other geoindicators that would enhance the prospects for life include evidence for polymeric chemistry in association with chemical cycling, the presence of an atmosphere or ice shield, sufficient mass for endogenic heating, and the availability of a liquid that may act as a solvent to enhance chemical reactions. Also, any unusual topographical features or surface patterns that cannot be easily explained by well understood geological and geochemical processes should be regarded as evidence for the possibility of environmental changes induced by living systems.