Chapter 11
Astrobiology and the Relation of Fundamental Physics to Life

How did the laws of physics made it possible that life evolved? How did intelligent life evolve? How come that human beings are here on Earth today? Are we unique, or are we just one of many intelligent species populating the Universe? It is likely that in the vastness of the Universe we humans do not stand alone. Recent surveys have detected thousands of extrasolar planets, many within the circumstellar habitable zones of their host stars and consistent with rocky compositions and likely to contain secondary, volcanically outgassed atmospheres. In the near future we might be within reach of other forms of life and maybe of other civilizations; we must understand how to identify them, and, if possible, how to communicate with them. At the basis of all this is understanding what is life, and how it emerged on Earth and maybe elsewhere. The answer to these questions is written in the language of physics.

To understand the role of the human beings in the Universe is probably the ultimate quest of astrophysics, and in this sense it converges with many different sciences. Astrobiology is the study of the origin, evolution, distribution, and future of life in the Universe: both life on Earth and extraterrestrial life. This interdisciplinary field encompasses the study of the origin of the materials forming living beings on Earth, search for habitable environments outside Earth, and studies of the potential for terrestrial forms of life to adapt to challenges on Earth and in outer space. Astrobiology also addresses the question of how humans can detect extraterrestrial life if it exists and how we can communicate with aliens if they are technologically ready to communicate. This relatively new field of science is a focus of a growing number of NASA and European Space Agency exploration missions in the solar system, as well as searches for extraterrestrial planets which might host life.

One of the main probes of astrobiology is to understand the question if we are unique, or just one of many intelligent species populating the Universe. The most important discovery of all in astrophysics would probably be to communicate with different beings: this would enrich us and change completely our vision of ourselves and of the Universe. But the question of life and of its meaning is central also

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in many other sciences, from biology to philosophy. In particular, biology wants to answer many questions, as the question of how life was born from nonliving material (abiogenesis), a question that is central since Aristoteles. We are convinced that humans will soon be able to generate life from nonliving materials—and this will probably be the most important discovery of all in biology, again changing radically our vision of ourselves. This would probably help also in understanding our origin as humans.

We shall see how astroparticle physics can help us in this research.

11.1 What Is Life?

A proper definition of life, universally accepted, does not exist. We shall just try to clarify some of the conditions under which we might say that a system is living, i.e., to formulate a description.

Some of the characteristics most of us accept to define a living being are listed below.

- Presence of a body: this definition is sometimes nontrivial (think, for example, of mushrooms, or of coral).
- Metabolism: conversion of outside energy and materials into cellular components (anabolism) and decomposition of organic material (catabolism). Living bodies use energy to maintain internal organization (homeostasis), and the internal environment must be regulated to maintain characteristics different form the "external" environment. It can affect (even dramatically) the equilibrium of the environment, thus providing signatures of life to external observers.
- Growth: at least in a large part of life, anabolism is larger than catabolism, and growing organisms increase in size.
- Adaptation: living beings change in response to the environment. This is fundamental to the process of evolution and is influenced by the organism's heredity, as well as by external factors.
- Response to stimuli (can go from the contraction of a unicellular organism to external chemicals, to complex reactions involving all the senses of multicellular organisms): often the response generates motion—e.g., the leaves of a plant turn toward the Sun (phototropism).
- Reproduction: the ability to produce new individual organisms, imperfect copies of the previous ones. Clearly not everything that replicates is alive: in fact computers can replicate files and some machines can replicate themselves, but we cannot say that they are alive; on the other hand, some animals have no reproductive ability, such as most of the bees—reproduction has to be considered at the level of species rather than of individuals.

The above "physiological functions" have underlying physical and chemical bases. The living organisms we know have a body that is based on carbon: the molecules needed to form and operate cells are made of carbon. But, why carbon?

One reason is that carbon allows the lowest-energy chemical bonds, and is a particularly versatile chemical element that can be bound to as many as four atoms at a time.

However, we can think of different elements. If we ask for a material which can allow the formation of complex structures, tetravalent elements (carbon, silicon, germanium, ...) are favored. The tetravalent elements heavier than silicon are heavier than iron, hence they can come only from supernova explosions, and are thus very rare; we are thus left only with silicon as a candidate for a life similar to our life other than carbon. Like carbon, silicon can create molecules large enough to carry biological information; it is however less abundant than carbon in the Universe. Silicon has an additional drawback with respect to carbon: since silicon atoms are much bigger than carbon, having a larger mass and atomic radius, they have difficulty forming double bonds. This fact limits the chemical versatility required for metabolism. A tranquilizing view on silicon-based aliens would be that in case of invasion they would rather eat our buildings than us. However, carbon is more abundant than silicon in the Universe–not on Earth.

11.1.1 Schrödinger's Definition of Life

In the previous subsection we tried a descriptive definition of life. It would be useful to formulate a mathematical definition; attempts to do so, however, failed up to now.

Schrödinger tried to formulate a definition of life based on physics. In his view, everything was created from chaos but life tries to organize proteins, water atoms, etc.; Schrödinger said life fights entropy, and gave the definition of negative entropy, as for living organization, or space–time structures. He wrote: "When a system that is not alive is isolated or placed in a uniform environment, all motion usually comes to a standstill very soon as a result of various kinds of friction; differences of electric or chemical potential are equalized, substances which tend to form a chemical compound do so, temperature becomes uniform by heat conduction. After that the whole system fades away into a dead, inert lump of matter." A permanent state is reached, in which no observable events occur. The physicist calls this the state of thermodynamical equilibrium, or of "maximum entropy" and, as he said,"it is by avoiding the rapid decay into the inert state of 'equilibrium' that an organism appears so enigmatic. What an organism feeds upon is negative entropy." An organism avoids decay "by eating, drinking, breathing, and (in the case of plants) assimilating", and "everything that is going on in nature, means an increase of the entropy, and so a organism continually increases its entropy, and thus tends to the state of maximum entropy, which means death; it can only try to stay alive by continually drawing its environment of negative entropy".

In summary, according to Schrödinger, life requires open systems able to decrease their internal entropy using substances or energy taken in from the environment, and subsequently reject material in a degraded form.

11.1.2 The Recipe of Life

Our definition of life is necessarily limited by our understanding of life on Earth; however, the universality of the laws of physics can expand our view. In this section we will analyze what life needed and needs to develop on Earth, and what are the factors that influence it, trying to expand to more general constraints.

11.1.2.1 Water and Carbon

Liquid water is fundamental for life as we know it: it is very important because it is used like a solvent for many chemical reactions. On Earth, we have the perfect temperature to maintain water in liquid state, and one of the main reasons is the obliquity of Earth with respect to the ecliptic plane at about 23°, which allows seasonal changes.

Water can exchange organisms and substances with Earth, thanks to tides. The Moon is mostly responsible for the tides: the Moon's gravitational pull on the near side of the Earth is stronger than on the far side, and this difference causes tides. The Moon orbits the Earth in the same direction as the Earth spins on its axis, so it takes about 24 h and 50 min for the Moon to return to the same location with respect to the Earth. In this time, it has passed overhead once and underfoot once, and we have two tides. The Sun contributes to Earth's tides as well, but even if its gravitational force is much stronger than the Moon's, the solar tides are less than half that the one produced by the Moon (see the first exercise). Tides are important because many biological organisms have biological cycles based on them, and if the Moon did not exist these types of cycles might not have arisen.

But, how did Earth come to possess water? Early Earth had probably oceans that are the result of several factors: first of all, volcanos released gases and water vapor in the atmosphere, that condensed forming oceans. Nevertheless, vapor from the volcanos is sterilized and no organisms can actually live in it: for this reason, many scientists think that some liquid water with seeds of life may have been brought to Earth by comets and meteorites. The problem of how and where the water was generated on these bodies is not solved; it is, however, known that they carry water.

Life on Earth is based on more than 20 elements, but just 4 of them (i.e., oxygen, carbon, hydrogen, and nitrogen) make up 96% of the mass of living cells (Fig. 11.1). Water is made of the first and third most common elements in the Milky Way.

Water has many properties important for life: in particular, it is liquid over a large range of temperatures, it has a high heat capacity—and thus it can help regulating temperature, it has a large vaporization heat, and it is a good solvent. Water is also amphoteric, i.e., it can donate and accept a H^+ ion, and act as an acid or as a base—this is important for facilitating many organic and biochemical reactions in water. In addition, it has the uncommon property of being less dense as a solid (ice) than as a liquid: thus masses of water freeze covering water itself by a layer of ice which

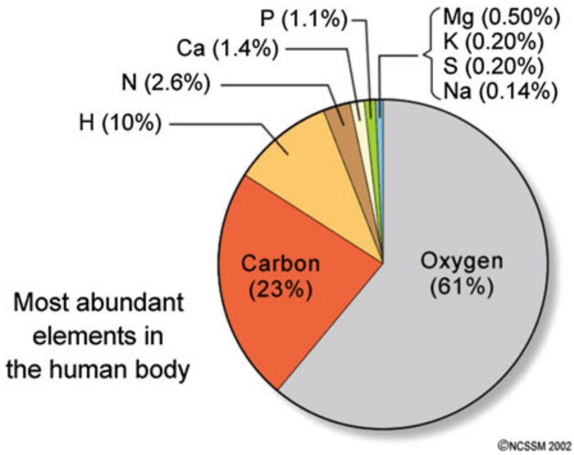

Fig. 11.1 Most abundant elements (in weight) that form the human body. From http://www.dlt.ncssm.edu/tiger/chem1.htm

isolates water from the external environment (fish in iced lakes swim at a temperature of 4 °C, the temperature of maximum density of water).

An extraterrestrial life-form, however, might develop and use a solvent other than water, like ammonia, sulfuric acid, formamide, hydrocarbons, and (at temperatures lower than Earth's) liquid nitrogen. Ammonia (NH_3) is the best candidate to host life after water, being abundant in the Universe. Liquid ammonia is chemically similar to water, amphoteric, and numerous chemical reactions are possible in a solution of ammonia, which like water is a good solvent for most organic molecules. In addition it is capable of dissolving many elemental metals; it is however flammable in oxygen, which could create problems for aerobic metabolism as we know it.

A biosphere based on ammonia could exist at temperatures and air pressures extremely unusual in relation to life on Earth. The chemical being in general slower at low temperatures, ammonia-based life, if existing, would metabolize more slowly and evolve more slowly than life on Earth. On the other hand, lower temperatures might allow the development of living systems based on chemical species unstable at our temperatures. To be liquid at temperatures similar to the ones on Earth, ammonia needs high pressures: at 60 bar it melts at 196 K and boils at 371 K, more or less like water.

Since ammonia and ammonia–water mixtures remain liquid at temperatures far below the freezing point of water, they might be suitable for biochemical planets and moons that orbit outside of the "zone of habitability" in which water can stay liquid.

11.1.2.2 Temperature and the Greenhouse Effects

A key ingredient affecting the development of life on our planet is temperature. One may think that the temperature on Earth is appropriate for liquid water because of the Earth's distance from the Sun; this is only partly true: for example, the Moon

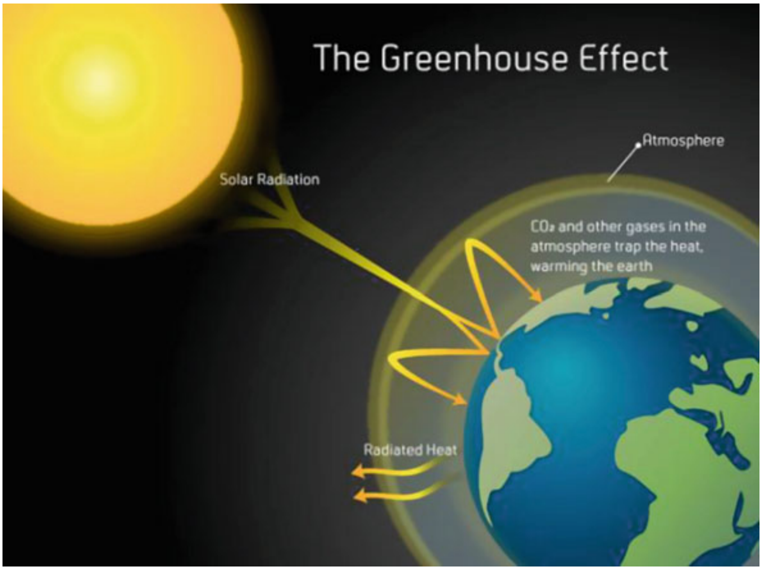

Fig. 11.2 Greenhouse gases trap and keep most of the infrared radiation in the low atmosphere. Source: NASA

lies at the same distance from the Sun but its temperature, during the day, is about 125 °C, and during night, −155 °C. The main reasons why the Earth has its current temperature are the interior heating and the greenhouse effect.

The greenhouse effect slows down the infrared light's return to space: instrumental to this process are gases, like water vapor (H_2O), carbon dioxide (CO_2), and methane (CH_4), that are present in the atmosphere. They absorb infrared radiation and subsequently they release a new infrared photon. This latter photon can be absorbed by another greenhouse molecule, so the process may be repeated on and on: the result is that these gases tend to trap the infrared radiation in the lower atmosphere. Moreover, molecular motions contribute to heat the air, so both the low atmosphere and the ground get warmer (Fig. 11.2).

If the greenhouse effect did not take place, the average temperature on our planet would be about −18 °C. A discriminating factor is the level of CO_2 in the atmosphere: on Earth most of the carbon dioxide is locked up in carbonate rocks, whereas only the 19% is diffuse in the atmosphere. This prevents the temperature to get too hot, like it is on Venus where CO_2 is mostly distributed in the atmosphere and the temperature is hotter than on Mercury.

11.1.2.3 Shielding the Earth from Cosmic Rays

Mammal life on our planet could develop because the atmosphere and the Earth's magnetic fields protect us from the high-energy particles and radiations coming from space. Cosmic rays are mostly degraded by the interaction with the atmosphere, which emerged in the first 500 million years of life from the vapor and gases expelled during the degassing of the planet's interior. Most of the gases of the atmosphere are thus the result of volcanic activity. In the early times, the Earth's atmosphere was composed of nitrogen and traces of CO_2 ($<0.1\%$), and very little molecular oxygen (O_2, which is now 21%); the oxygen currently contained in the atmosphere increased as the result of photosynthesis by living organisms.

High-energy cosmic rays are not the only danger: also the charged particles coming from the Sun (the solar wind), and some of the Sun's radiation, can also be dangerous for life.

UV rays can damage proteins and DNA. The ozone (O_3) layer in the upper atmosphere acts as a natural shield for UV rays, absorbing most of them.

The magnetic field of the Earth generates the magnetosphere that protects us from the lower energy cosmic rays that travel in the galaxy (Fig. 11.3), in particular from the solar wind; the associated amount of energy would destroy life in our planet if there were no magnetosphere that traps these particles and confines them. Some of the cosmic rays are trapped in the Van Allen belts. The Van Allen belts were discovered in the late 1950 s when Geiger counters were put on satellites. They are two main donut-shaped clouds:

- The outer belt is approximately toroidal, and it extends from an altitude of about three to ten Earth radii above the Earth's surface (most particles are around 4 to 5 Earth radii). It consists mainly of high-energy (0.1–10 MeV) electrons trapped by the Earth's magnetosphere.
- Electrons inhabit both belts; high-energy protons characterize the inner Van Allen belt, which goes typically from 0.2 to 2 Earth radii (1000–10000 km) above the Earth. When solar activity is particularly strong or in a region called the South Atlantic Anomaly,[1] the inner boundary goes down to roughly 200 km above sea level. Energetic protons with energies up to 100 MeV and above are trapped by the strong magnetic fields in the region. The inner belt is a severe radiation hazard to astronauts working in Earth orbit, and to some scientific instruments on satellite.

Close to the poles, charged particles trapped in the Earth's magnetic field can touch the atmosphere, and this reaction produces photons: this phenomenon is called Aurora Borealis in the North Pole, and Aurora Australis in the South Pole (Fig. 11.3).

11.1.2.4 Requirements for Life

From a priori assumptions and from the study of our only experimental example, life on Earth, a consensus has emerged that life requires three essential components: (1) an energy source to drive metabolic reactions, (2) a liquid solvent to mediate these reactions, and (3) a suite of nutrients both to build biomass and to fuel metabolic

[1] The nonconcentricity of the Earth and its magnetic dipole causes the magnetic field to be weakest in a region between South America and the South Atlantic; the solar wind can penetrate this region.

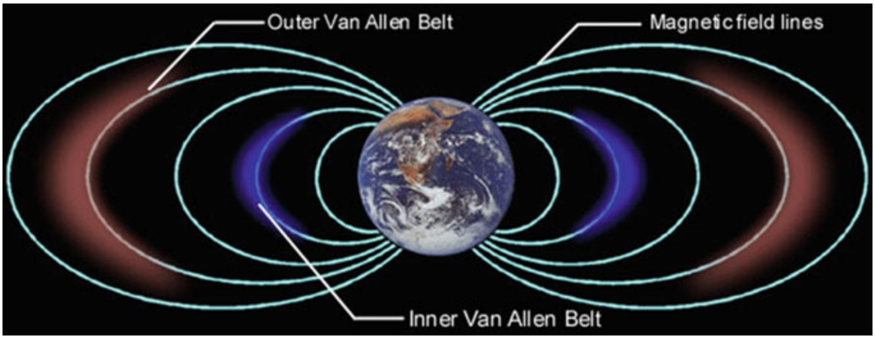

Fig. 11.3 The Earth's magnetic field and the Van Allen belts. From http://www.redorbit.com

reactions. Physics suggests that the liquid solvent is likely to be water, both because of the cosmic abundance of its constituents and of its chemical properties that make it suitable for mediating macromolecular interactions. Carbon chemistry is favored as a basis for biomass because carbon has a high cosmic abundance and carries the ability to form an inordinate number of complex molecules. These last two assumptions are made here provisionally, with the acknowledgement that while alternative biochemistries may exist.

11.1.3 Life in Extreme Environments

To provide further constraints on life and derive ideas on how to find it in the Universe, we can examine the most extreme living forms we know. We shall use this knowledge to define a *habitable region*—i.e., a region fulfilling a set of conditions under which we know life might occur, and limit our search region. It is obviously not excluded that the actual conditions of life are wider than what we shall foresee, also in view of the caveats of the previous section.

Thanks to homeostasis, organisms on Earth called *extremophiles* exist, that can survive in extreme environments, such as:

- hot and cold places;
- salty and dry environments;
- acidic and basic places;
- environments of extreme pressure and radiations.

Let us analyze experimentally what are the extreme conditions in which extremophiles can survive.

- Hot and cold environments. Examples of hot places are volcanos in the deep oceans: there the temperature can go up to 180 ℃ and some organisms, called *hyperthermophiles*, evolved their proteins and membrane to resist at such high

temperatures. An example of these organisms is represented by the *Metharopyrus kandleri*, discovered on the wall of a black smokers in the Gulf of California at a depth of 2000 m; these organisms can survive and reproduce at 220 ℃.
On the opposite side there are organisms that can survive at very low temperatures. The Vostok Lake in the Arctic region is an example of a cold place on Earth; *psychrophiles* evolved their membrane to survive at –15 ℃, as they create "antifreeze" proteins to keep their internal space liquid and protect their DNA.
- Salty and dry environments. *Halophiles* can live in salty environments, with an external concentration of salt of 15–37% while keeping their own internal salts at a correct level; such organisms can be found in places like the Great Salt Lake (Utah, USA), Owens Lake (California, USA), the Dead Sea (Israel–Palestine–Jordan). Organisms called *xerophiles* can also live in very dry places with humidity lower than 1%, like the Atacama Desert in Chile.
- Acid and basic places. *Acidophiles* can live in acid places like sulfuric geysers, with $pH < 2$, and *alkaliphiles* can live in basic places, with $pH > 11$, like the soda lakes in Africa, while still maintaining their own pH neutral.
- Extreme pressure and radiation. On Earth we can find examples of organisms, called *piezophiles*, that survive at high pressures, like e.g., the Mariana Trench where pressure reaches 380 atmospheres, and *radio-resistant* organisms that can survive high level of radiation that would ordinarily ionize and damage cells: the most radio-resistant known organism is the *Thermococcus gammatolerans*, that can tolerate a radiation of gamma rays of 30000 Gy (a dose of 5 Gy is sufficient to kill a human), and was discovered in the Guaymas Basin, Baja California.

In astrobiology, a specific class of extreme-resistant organisms is particularly important: the *polyextremophiles*, organisms that can simultaneously tolerate several extreme life conditions; an example is the *Deinococcus radiodurans*, a bacterium that can live within high levels of radiation, at cold temperatures, and in dry environments.

11.1.4 The Kickoff

For thousands of years philosophers, scientists, and theologians have argued how life can come from nonlife. Also in the interpretation of St. Augustine life came from nonliving forms, although this biogenic process was mediated by God: "And God said, let the Earth bring forth the living creature after his kind, cattle, and creeping thing, and beast of the Earth after his kind: and it was so." Thus, God transferred to the Earth special life-giving powers, and using these powers the Earth generated plants and animals: "The Earth is said then to have produced grass and trees, that is, to have received the power of producing." To avoid entering in controversial discussions, we shall assume here that at a certain time, somewhere in the Universe, life has emerged from nonlife (abiogenesis), remaining within scientific boundaries.

Many think that, if all the essential ingredients and appropriate conditions were present, life might have been generated in a long enough time—maybe having cosmic radiation as a catalyst. On the assumption that life originated spontaneously, many experiments showed that self-replicating molecules or their components could come into existence from their chemical components. However, there is no evidence to support the belief that life originated from nonlife on Earth. We eagerly expect the day, maybe not far we think, when biologists on Earth will produce life from nonlife.

An experiment by Miller and Urey in the 1950 s used water, methane, ammonia, and hydrogen sealed inside a sterile glass flask connected to a flask half-full of liquid water to simulate the primordial atmosphere. The liquid water in the smaller flask was heated to induce evaporation, and the water vapor was allowed to enter the larger flask. Continuous electrical sparks were fired between the electrodes to simulate lightning in the water vapor and gaseous mixture, and then the simulated atmosphere was cooled again so that the water condensed and trickled into a U-shaped trap at the bottom of the apparatus. Electric discharges might be present in some parts of the solar system, or the same catalytic effect could be provided by UV rays, or cosmic rays. The experiment yielded 11 out of 20 aminoacids needed for life.

A popular hypothesis—called panspermia—is that life came to the Earth from other places, and that it can be transmitted to other places. According to this hypothesis, microscopic life—distributed by meteoroids, asteroids, or other small solar system bodies, or even pushed by micro-spaceships—may exist throughout the Universe. The earliest clear evidence of life on Earth dates from 3.5 billion years ago, and is due to microbial fossils found in sandstone discovered in Australia. Cosmic dust permeating the Universe contains complex organic substances. The panspermia hypothesis just pushes elsewhere and in some other time the problem of abiogenesis.

The problem of the very origin(s) of life, despite tremendous advances in biochemistry and in physics, remains however a mystery. And also when, hopefully during the present century, the problem of the abiogenesis will be hopefully solved, it will certainly take longtime before understanding the transition from simple cells to complex organisms.

11.2 Life in the Solar System, Outside Earth

The closest place to look for extraterrestrial life is our solar system. However, the possibility of a life at our level of civilization presently in the solar system, apart from humans, is reasonably excluded—we would have received communications from such aliens and probably observed their artefacts.

What about forms of life unable to communicate? A first step to search for life in the solar system is to try to define a "habitable zone" that corresponds to the region where temperature and the presence of water allow (or allowed) liquid water, there is an atmosphere, and appropriate conditions apply. Extremophiles suggest how life has a large range of conditions, and that there is not a universal definition of habitability that suits every organism.

A wide range of habitable zone (Fig. 11.4) lies likely between Venus and Mars. This zone is not fixed because planets change their internal structure and conditions:

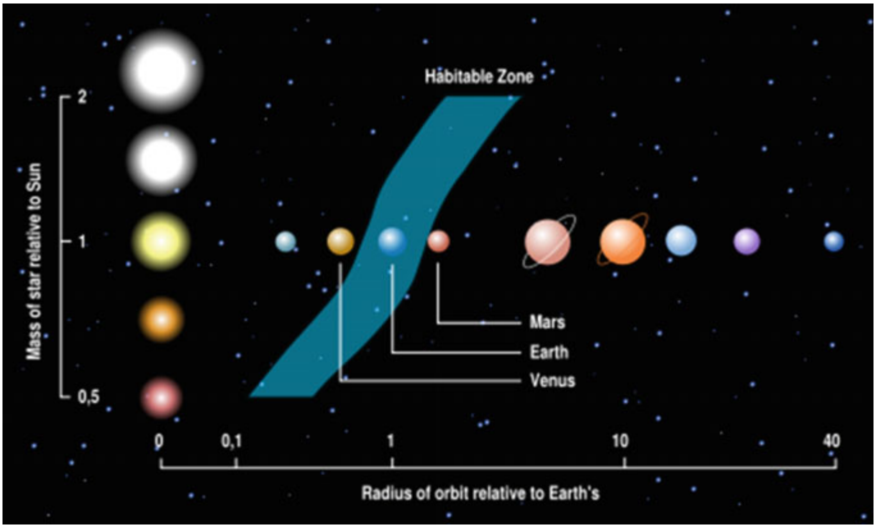

Fig. 11.4 The solar system's habitable zone. From http://www.universetoday.com/34731/habitable-planet

they can get hotter or colder, and so they may not be forever habitable. Mercury, the first planet from the Sun—just 58 million km away—has a temperature ranging from about 457 ℃ in the day to −173 ℃ in the night, not allowing the presence of liquid water; it has no atmosphere, and its thus exposed to meteoric and cometary impacts. The giant planets Jupiter and Saturn on the outer solar system, having respectively a mass of about 318 and 95 times the Earth's mass, seem also a very unlikely place for life. Jupiter, for example, is composed primarily of hydrogen and helium, plus small amounts of sulfur, ammonia, oxygen, and water. Temperatures and pressures are extreme. Jupiter does not have a solid surface, either—gravity can move a solid body to zones with high pressure. Saturn's atmospheric environment is also unfriendly due to strong gravity, high pressure, strong winds, and cold temperatures. Some of the moons of Jupiter and Saturn, however, can be thought as possible hosts of life. Finally, the planets external to Saturn are too cold to be life-friendly.

11.2.1 Planets of the Solar System

In this section, we will discuss the possibility that conditions for life to develop may exist in other planets of the solar system, close to the habitability zone just defined.

11.2.1.1 Venus

Venus' structure and mass are very similar to the Earth's. However, although Venus, unlike Mercury, has an atmosphere, carbon-and water-based life cannot develop on Venus. The main problem is the high temperature of more than 400 °C, due to the greenhouse effect. This effect is particularly strong on Venus because of volcano activity that fills the atmosphere with a large amount of gases. Pressure too is very high (∼90 atmospheres), a condition that on Earth can be found only in the deepest oceans.

Spacecraft have performed various flybys, orbits, and landings on Venus. A 660 kg vehicle separated from the Soviet orbiter Venera 9 and for the first time landed in 1975. However, to overcome the severely inhospitable surface conditions, landers need advanced technologies, and several proposals are under discussion.

11.2.1.2 Mars

Mars orbits at approximately 228 million km from the Sun, and its mass is ∼11% the Earth's (Fig. 11.5). Its atmosphere was originally similar to Venus' and Earth's (early) atmospheres, due to similar conditions during their formation.

Mars has always been one the best candidates for extraterrestrial life: a long time ago, it was probably warmer, it had liquid water (on its surface we recognize structures which can be attributed to past rivers, as shown in Fig. 11.5), and it must have had a deep atmosphere with gases produced by volcanic activity. But things have changed: volcanic activity stopped, and Mars has quickly lost its internal heat (due to its small mass) and most of its atmosphere (only about 0.5 radiation lengths today). Mars was no longer protected by cosmic radiations and particles, also due to a very weak magnetic field, and it began to cool down. This process lead to its current conditions: no liquid but frozen water, and temperatures impervious to life (27 °C to −130 °C).

Starting 1960, the Soviets launched a series of probes to Mars including the first intended flybys and landings. The first contact to the surface of Mars was due to two Soviet probes: Mars 2 and Mars 3 in 1971. In 1976, two space probes (called the

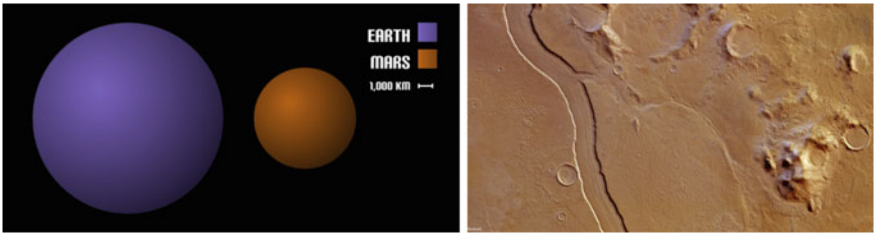

Fig. 11.5 Left: Mars and Earth sizes. http://space-facts.com/mars-characteristics/. Right: a structure on Mars' surface that can be related to the presence of ancient rivers. Source: NASA

Vikings) landed on the surface to find evidence of life, but found none. In July 2008, laboratory tests aboard NASA's Phoenix Mars Lander identified frozen water in a soil sample.

Three scientific rovers landed successfully on the surface of Mars sending signals back to Earth: Spirit and Opportunity, in 2004, and Curiosity, in 2012. They were preceded by a pathfinder landed in 1997.

Several proposals have been accepted for future missions, and for sure we shall know a lot more about Mars in the next years. Many scientists think that a human mission to Mars would be worth, perhaps eventually leading to the permanent colonization of the planet.

11.2.2 Satellites of Giant Planets

Although giant planets do not appear adequate for life, some of their moons can be good candidates. In this section, we will examine the particularities of three moons within the solar system: Europa (a satellite of Jupiter), and Titan and Enceladus (satellites of Saturn), where appropriate conditions could be encountered.

11.2.2.1 Europa

Jupiter's four main satellites are Io, Europa, Callisto, and Ganymede (the Galilean moons). Some of them may have habitats capable of sustaining life: heated subsurface oceans of water may exist deep under the crusts of the three outer moons—Europa, Ganymede, and Callisto. The planned JUICE mission will study the habitability of these moons.

Europa is seen as the main target. It is the smallest of the four, having roughly the same size as our Moon. Its temperature reaches −160℃. At such temperatures there is no liquid water, but what makes Europa so fascinating is hidden under its frozen surface: planetary geologists found out that only the oldest cracks appear to have drifted across the surface, which is rotating at a different rate respect to its interior, probably due to an underlying, 50 km thick, ocean layer of liquid water, methane, and ammonia. Figure 11.6 shows the hypothetical structure of Europa.

11.2.2.2 Titan

Titan (Fig. 11.7, left) is the largest moon of Saturn. Having a diameter of 5700 km it is bigger than Mercury, but has less than half its mass. Titan has an atmosphere because it is situated in one of the coldest regions of the solar system. With a pressure of 1.5 atmospheres and a temperature of −170 ℃, it can host solid, gas, and liquid methane: in 1997 the Cassini space probe captured evidence of a giant methane lake, the Kraken sea (Fig. 11.7, right), that has a surface of about 400 000 km^2.

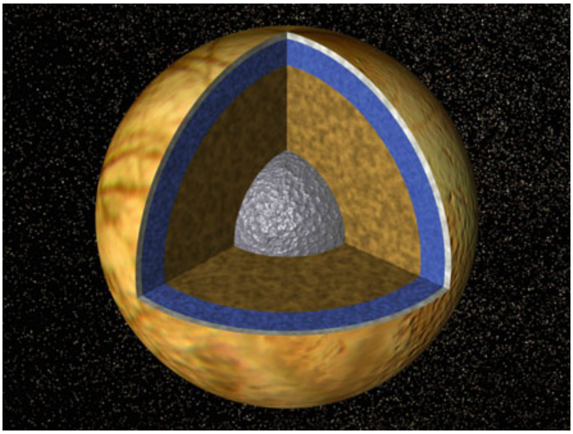

Fig. 11.6 Hypothetical structure of Europa: from outside in, we find the iced crust, the ocean, the rocky mantle, and the nuclear iron core. From NASA/Galileo Project and the University of Arizona

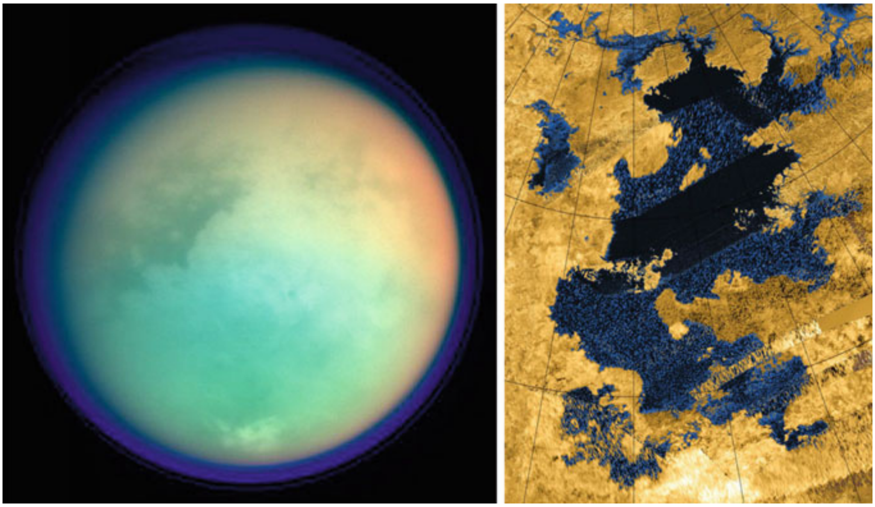

Fig. 11.7 Left: Titan, a satellite of Saturn. Right: Detail of Titan: note the presence of lakes on its surface. Credits: NASA (Cassini)

11.2.2.3 Enceladus

Discovered in 1789 by William Herschel, Enceladus is the sixth largest moon of Saturn; its diameter is about 500 km, roughly a tenth of that of Titan. It is mostly covered by ice, and the surface temperature at noon only reaches −200 °C. In 2005, the Cassini spacecraft discovered that volcanos near the South Pole shoot geyser-like jets of water vapor, other volatiles, and solid material, including sodium chloride crystals and ice particles, into space; some of the water vapor falls back as snow. Cassini later discovered a large subsurface ocean of liquid water with a thickness of around 10 km. Enceladus is geologically active, and suffers tidal forces from another satellite (Dione). This moon could provide a habitable zone for microorganisms in the places where internal liquid from its interior is jetting out of its surface: some extremophiles living on Earth could live on Enceladus' geysers. In view of the relatively accessible distance of Saturn's satellites, it is conceivable to think of a return space mission.

11.3 Life Outside the Solar System, and the Search for Alien Civilizations

In the previous section, we saw how difficult is to find life on the other planets and moons of the solar system, because they hardly have the characteristics that life based on liquid water and carbon needs. But, what about the rest of the galaxy? Are we alone?

Our galaxy is 30 kpc large, and it contains about 4×10^{11} stars, most with a planetary system: it seems unlikely that we represent the only forms of life. And intelligent life is not excluded.

11.3.1 The "Drake Equation"

This "equation" was conceived in 1961 by American astronomer and astrophysicist Frank Drake, and it provides a benchmark estimate of the number of possibly communicative civilizations N_T in our galaxy:

$$N_T \simeq R \times f_p \times n_E \times f_l \times f_i \times f_c \times L \, , \qquad (11.1)$$

where:

- R is the yearly rate at which suitable stars are born;
- f_p is the fraction of stars with a planetary system;
- n_E is the number of Earth-like planets per planetary system;
- f_l is the fraction of those Earth-like planets where life can develop;
- f_i is the fraction of these planets on which intelligent life can develop;
- f_c is the fraction of planets with intelligent life that could develop technology;
- L is the lifetime of a civilization with communicating capability.

Let us examine each factor in it. We can distinguish among astronomical, planetary, and biological factors.

Astronomical Factors. The astronomical factors are the star formation rate R in our galaxy, and the fraction f_p which develop a planetary system. The star formation rate R is estimated to be 2–3 stars/yr. The current estimate of f_p is about 0.5: thanks to technological innovation in the search for extraterrestrial planets, we discovered that a large fraction of stars have a planetary system.

Planetary Factors. The planetary factor in the equation is n_E, which depends on the "habitable zone" that corresponds to the zone of the solar system where the temperature and pressure allow liquid water. In the solar system, the habitable zone (Fig. 11.4) lies between Venus and Mars: the Earth is the only planet located in the solar system's habitable zone today. As we discussed before, this zone is not fixed because conditions change: planets can get hotter or colder, and so they may not be forever habitable. We estimate, based also on the recent results on searches for extrasolar planets, that $n_E \sim 1 - 2$.

Biological Factors. These are the most difficult to estimate, and the values we assume here are just guesses. f_l the fraction of the planets where life can develop, f_i the fraction of planets where intelligent life can develop, f_c the fraction of intelligent beings who can develop communication technology, and L the lifetime of civilization. Even if it is very difficult to give a range to these factors because we do not know the probability to find life based on liquid water, Drake estimated f_l to range from 0.1 to 1; more recent studies suggest $f_l \sim 1$. As for the other factors: $f_i \sim 0.01 - 1$, $f_c \sim 0.1 - 1$, while L is valued to have a range from 10^3 to 10^6 years, being 10000 years a conservative estimate.

The number of communicative civilization in our galaxy can thus be estimated to be:

$$N_T \simeq (2 \times 0.5) \times 1 \times (1 \times 0.1 \times 0.1 \times 10\,000) \sim 100\,.$$

Due to the large uncertainties one cannot exclude that the value is just one (we know it has to be at least one). On the contrary, it is very unlikely that the chance to have intelligent life in a galaxy like the Milky Way is smaller than 0.01, which, given the fact that there are 10^{11} galaxies in the Universe, makes it very likely that life exists in some other galaxies. However, communication with these forms of civilization is, at the present state of technology, very difficult to imagine.

The Drake equation can be used to determine the odds of a habitable zone planet ever hosting intelligent life in the galaxy lifetime; the most likely result is that the probability that a galactic civilization like ours never existed in another planet is about 2×10^{-11}. It is thus unlikely that Earth hosts the only intelligent life that has ever occurred, and reinforces the idea of panspermia. If we would know we are at the end of our civilization, would we send space missions with biological material trying to spread around our life in the Universe?

A final warning is linked to the fact that the Drake equation is based on an idea of development of life:

$$star \rightarrow planet \rightarrow water \rightarrow life \rightarrow intelligence\,;$$

however we cannot give a definition of life, and we cannot rule out that some form of life could be based, for example, on silicon instead of carbon, so all the factors in

Drake's equation could take different values if we assume that life could also develop in extreme condition, for example where no liquid water exists.

11.3.2 The Search for Extrasolar Habitable Planets

Discovering extrasolar planets (also called exoplanets) suitable for life is important, since it provides us with targets for study and possible attempts of communication. In addition, n_E and f_l are critical factors in Drake's equation: their estimated value is influenced by the number of habitable planets we discover in planetary systems. Technological evolution allows us to discover more and more exoplanets.

When scientists search for new habitable planets orbiting a star, they first want to determine the position of the star's habitable zone, and to do that they study the radiations emitted by the star: in fact, bigger stars are hotter than the Sun and so their habitable zone is farther out; on the contrary, the habitable zone of smaller stars is tighter.

Since planets are very small and dark compared to stars, how can they be detected? If scientists cannot look at the planets, they study the stars and the effects that orbiting planets have on them. Four of the main methods to detect extrasolar planets orbiting a star (Fig. 11.8) are listed below.

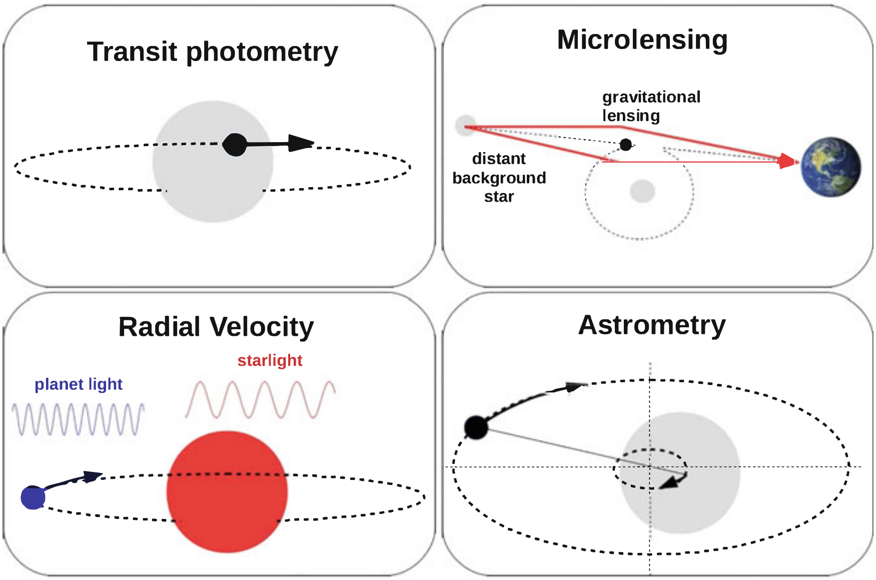

Fig. 11.8 Exoplanet detection techniques. Adapted from [F11.6]

- Radial velocity measurement via Doppler spectroscopy. This method is the most effective. It relies on the fact that a star moves, responding to the gravitational force of the planet. These movements affect the starlight spectrum, via a periodic Doppler shift of the emission wavelengths.
- Astrometry. The same planet-induced stellar motion is measured as a periodic modulation of the star position on the sky.
- Transit photometry. With this method scientists can detect planets by measuring the dimming of the star as the planet that orbits it passes between the star and the observer on the Earth: if this dimming is periodic, and it lasts a fixed length of time, there is likely a planet orbiting the star.
- Microlensing. This is the method to detect planets at the largest distances from the Earth. The gravitational field of a host star acts like a lens, magnifying the light of a distant background star. This effect occurs only when the two stars are aligned. If the foreground lensing star hosts a planet, then that planet's own gravitational field can contribute in an appreciable way to the lensing. Since such a precise alignment is not very likely, a large number of distant stars must be monitored in order to detect such effect. The galactic center region has a large number of stars, and thus this method is effective for planets lying between Earth and the center of the galaxy.

The first extrasolar planet (HD114762b) was discovered in 1989; its mass is 10 times Jupiter's mass. Looking for habitable planets, scientists want to find planets with mass, density, and composition similar to the Earth: in large planets like Jupiter, the gravity force would be too strong for life; too small planets could never trap an atmosphere. Only recently the technology allowed detecting Earth-like exoplanets. The most important mission to detect Earth-like planets outside our solar system is presently the NASA Kepler Mission; the spacecraft was launched in March 2009. A photometer analyzed over 145 000 stars in the Cygnus, Lyra, and Draco constellations, to detect a dimming of brightness which could be the proof of the existence of an orbiting planet.

In April 2014, Kepler announced the discovery of the first extrasolar Earth-like planet, orbiting a M-star (dwarf star) in the first habitable zone discovered outside our solar system: Kepler-186f (Fig. 11.9), in the constellation Cygnus, 500 ly from us. Many of its characteristics, composition and mass, make it similar to our planet. M-dwarfs, which have masses in the range of 0.1–0.5 solar masses, make up about 75% of the stars within our galaxy. Kepler-186f has a period of revolution around its sun of 130 days, it is likely to be rocky, and it is the first new discovered planet with dimensions similar to the Earth: in fact its radius is 1.1 times the Earth's one, and its estimated mass is 0.32 the Earth's one. It receives from its star one-third the energy that Earth gets from the Sun, although it is much closer (just 0.36 astronomical units): it is thus a cold planet, and it could not host human life. Kepler-186f is located in a five-planet system; the other four planets in this system, Kepler-186b, Kepler-186c, Kepler-186d, and Kepler-186e, orbit around their sun with periods of 4, 7, 13, and 22 days, respectively; they are too hot for life as we know it to develop.

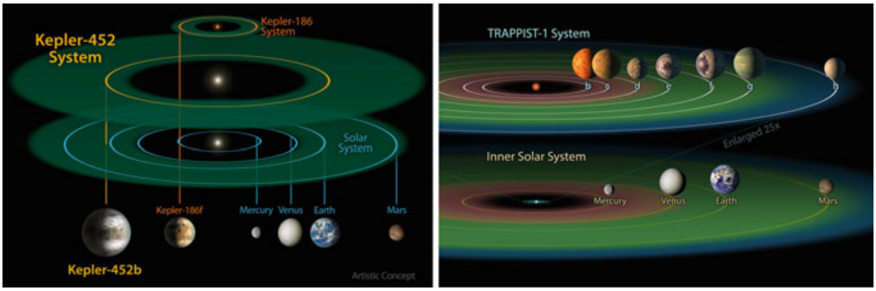

Fig. 11.9 Left: Kepler-186f and Kepler-452b in their solar systems: comparison with the habitable zone of our solar system. Right: Same, for the exoplanets discovered in the TRAPPIST-1 system. Source: NASA

In July 2015, NASA announced the discovery of the first extrasolar Earth-like planet (potentially rocky) within the habitable zone of a Sun-like star (G star). At a distance of 1400 ly from the Earth and located in the constellation Cygnus, it has a revolution period of 385 days. The star is six billion years old, i.e., 1.5 billion years older than our Sun; Kepler-452b is receiving a power close to the one we receive from our Sun. The similarities with the Earth are amazing.

In August 2016 the European Southern Observatory announced the discovery of an exoplanet orbiting within the habitable zone of the closest star to the Sun–the red dwarf Proxima Centauri, located about 4.2 ly away in the constellation of Centaurus.

In February 2017 NASA announced the discovery of a system of seven Earth-sized planets in the habitable zone of a single star, called TRAPPIST-1, at 40 ly from us, all of them with the potential for liquid water on their surface.

As of 1 January 2018, we discovered 3726 planets in 2792 systems, with 622 systems having more than one planet; some 15–40 are in the habitable zone. The future promises more candidates possibly able to host a carbon-based life. In Fig. 11.10 we show the distance from their sun of some of the extrasolar planets discovered up to now, and the energy flux of their host star; thanks to the scientific and technological innovation, we can find now planets similar to the Earth.

11.3.3 The Fermi Paradox

Given the Drake's equation and the discovery of so many potentially habitable planets, a contact with alien civilizations could have been already established. Enrico Fermi in 1951 tried to give an explanation to the lack of detection of alien communication; this is called the "Fermi paradox": where is everybody? Several possible answers have been suggested.

- We are alone. We have not received any signal just because nobody sent it, and life needs some proprieties, like liquid water, carbon, right temperature, that we

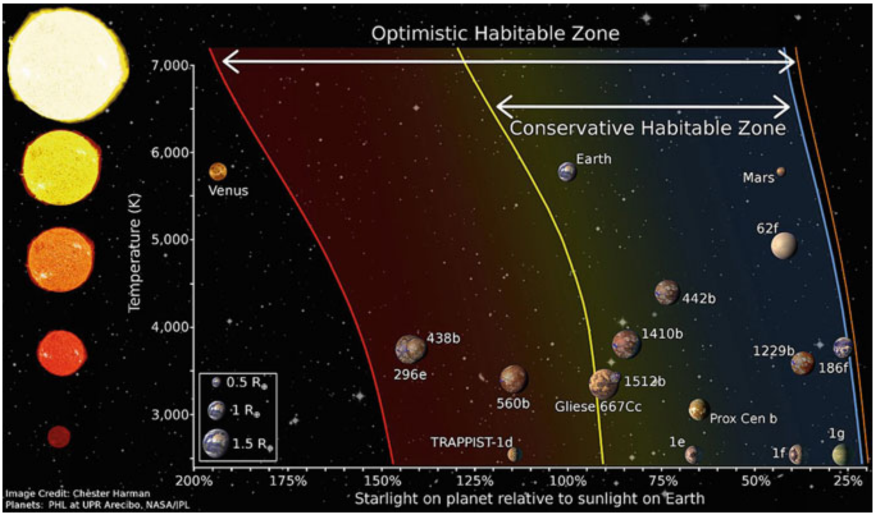

Fig. 11.10 Some of the discovered extrasolar planets as a function of the distance from their sun, and of the stellar energy flux. The Earth, Venus and Mars are included as a reference. Credit: NASA

can find just on Earth. This opinion is difficult to accept—also because we cannot give a univocal definition of life.

- The evolution of civilizations able to communicate not last for long. There are two main reasons why a civilization can fall:

1. Cultural reasons: populations evolute enough destroys themselves.
2. Natural reasons: catastrophic events, like meteorites or cometary impacts.

- Communicative extraterrestrial civilizations do exist, but they are too far away from us. The galaxy is so extended (30 kpc) that any signal would take thousands of years to get from a planet to another, and in this time a civilization could even become extinct. The problem would be worse for extragalactic civilizations.
- They do not want to communicate with us, maybe because they are afraid of our possible reaction. If we knew there are civilizations weaker than us in our galaxy, would we attack them?
- We cannot understand their signals. All our attempts of communication are based on electromagnetic waves, but maybe they have already sent us signal based on neutrinos, or gravitational waves, that we are barely able to detect.

11.3.4 Searching for Biosignatures

If we cannot communicate with different forms of life, can we detect signatures of their existence? The term "biosignature" indicates signatures of life. Particularly important are atmospheric biosignatures, i.e., detectable atmospheric gas species whose presence at significant abundance strongly suggests a biological origin. For example, the O_2/CH_4 ratio in the Earth's atmosphere is far from thermodynamical equilibrium, which would be a strong evidence for life for aliens studying our planet, that methanogenic bacteria operate the chemical reaction

$$H_2 + CO_2 \rightarrow CH_4 + H_2O\,.$$

Of course many "false-positive" detections are possible, since an individual molecule could be of geophysical origin. One needs to combine several indicators–for example, using the metabolism of vegetables as a benchmark.

The most powerful techniques for atmospheric observations take advantage of transmission spectroscopy, possible only when the planet transits its host star along the line of sight, and of emission spectroscopy, providing evidence of thermal structure of the atmosphere and the emission/reflection properties of the planetary surface. Key wavelengths are in the infrared and visible regions, sensitive to molecular spectroscopy.

Due to limitations of the present instruments, searches performed up to now were concentrated on Jupiter-size exoplanets, and gave no result. NASA/ESA's James Webb Space Telescope, with launch expected in 2020, will enjoy an unprecedented thermal infrared sensitivity and provide powerful capabilities for direct imaging of Earth-like planets.

11.3.5 Looking for Technological Civilizations: Listening to Messages from Space

One of the main unknowns is how could aliens communicate with us, and how can we receive and decrypt their signals. In this section we will describe what kind of signals we are trying to detect.

How far a signal can reach depends on how much energy a civilization can use for transmitting. In 1964, Kardashev defined three levels of civilizations, based on the order of magnitude of power available to them:

- Type 1. Technological level close to the level presently attained on Earth, with power consumption $\simeq 4 \times 10^{12}$ W (four orders of magnitude less than the total solar insulation).
- Type 2. A civilization capable of harnessing the energy radiated by its own star (if the host star is Sun-like, $\simeq 4 \times 10^{26}$ W).
- Type 3. A civilization in possession of energy on the scale of its own galaxy (for the Milky Way, a power of about 4×10^{37} W).

The above jumps might look too steep. The scientist and science-fiction writer Carl Sagan suggested defining intermediate values by interpolating the values given above:

$$K = \frac{\log_{10} P - 6}{10}$$

where value K is a civilization's rating and P is the power it controls. Using this extrapolation, humanity's civilization in 2016–average power was 19.2 TW–was of 0.73.

In general, the inverse square law for intensity applies: $I = f P/4\pi d^2$, with P the power of the signal and f is a focusing factor > 1. A rule of thumb for the distance that can be reached with a radio signal, most economic within the electromagnetic spectrum, with top technological devices at present technology (50 m dish size), is:

$$d \simeq 1\,\mathrm{kpc}\sqrt{\frac{P}{1\,\mathrm{GW}}}\,. \tag{11.2}$$

It seems thus difficult for a Type 1 civilization to reach beyond the scale of a galaxy based on radio communication.

11.3.5.1 Search for ExtraTerrestrial Intelligence (SETI)

The term SETI (search for extraterrestrial intelligence) refers to a number of activities to search for intelligent extraterrestrial life. As already discussed, communicating in space can be quite prohibitive, the main reason being cosmic distances. Receiving the visit of a spacecraft is extremely unlikely, so SETI is looking for radio waves that might have been sent by extraterrestrial intelligent civilizations. SETI looks for "narrow-band transmissions" which can be produced only by artificial equipment: the problem with these communications is that they are very difficult to single out from the many of them produced on Earth; not even the world's biggest supercomputers could manage the task of studying all these noises of the Universe. An Internet-based, public-volunteer computing project, called SETI@home, was set up: after downloading and installing an appropriate software on a personal computer, the executable gets switched on when the computer is not in use, receives 300 kb data by Internet from the Arecibo radio telescope in Puerto Rico, and tries to find regularities in these data.

The rationale in the search is that we expect that the communication will be narrow-band, and periodical; thus we can isolate them with Fourier analysis or autocorrelation studies, tested at different wavelengths.

If aliens ever sent us messages, the real problem is if we can receive them or not, distance being the main cause that could prevent signals from reaching us: as seen in the previous subsection, the distance from which a telescope could detect an extraterrestrial transmission depends on the sensitivity of the receiver and on the strength and type of the signal.

Most SETI are based on radio waves, but it is possible that the aliens would try to communicate using visible light, or other forms of energy/particles. Some SETI efforts are indeed addressed to search such signals. Distant civilizations might choose

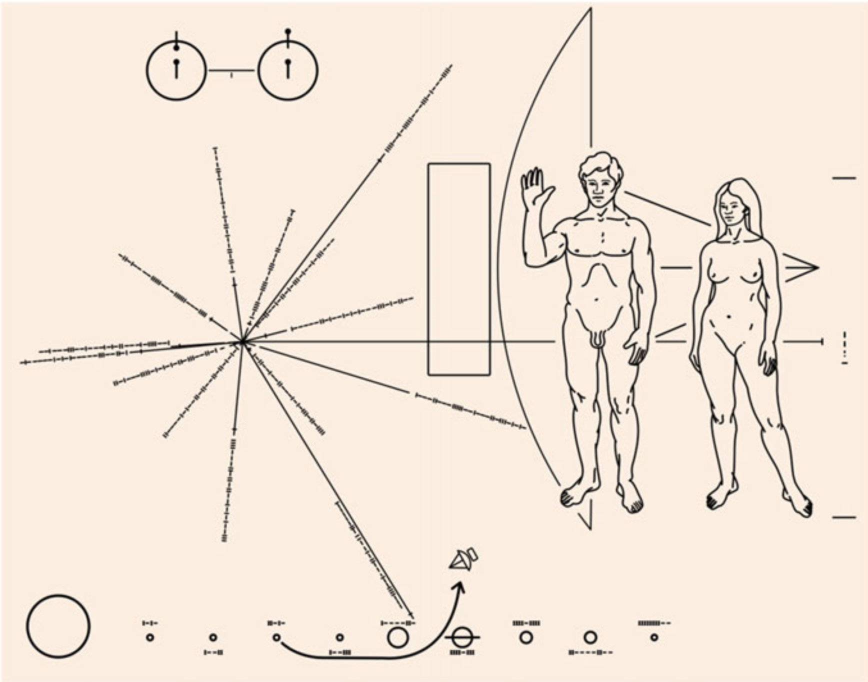

Fig. 11.11 The plaque onboard the Pioneer 10. Source: Wikimedia Commons

to communicate in our ways, like with ultraviolet light or X-rays—in particular infrared light has a potential value because it can penetrate interstellar dust—but all these forms of light are much more expensive in terms of energy cost. Some have suggested that extraterrestrial civilizations might use neutrinos or gravitational waves but the problem with these kind of messengers is that they might involve technology we are not able to manage, yet. Some carriers of information offer the possibility to beam the emission, lasers in the visible range for example. Using current technology available on Earth (10 m reflectors as the transmitting and receiving apertures and a 4 MJ pulsed laser source), a 3 ns optical pulse could be produced which would be detectable at a distance of 1000 ly, outshining starlight from the host system by a factor of 10^4. It is not unlikely that our civilization could reach the full galaxy with a beamed signal—which means that we should be able to choose our targets. In this case, Cherenkov telescopes, being equipped with the largest mirrors, would be the ideal target for aliens. Indeed, some effort has been done to look for extraterrestrial signals in Cherenkov telescopes, with no success.

11.3.6 Sending Messages to the Universe

We also try to communicate with alien civilizations, hoping that they will decrypt our signal and possibly answer. This field of investigation is called active SETI, or METI (messaging to extraterrestrial intelligence).

A largely symbolic attempt was tried sending directly a "message in a bottle": a handcraft gold plate (Fig. 11.11) placed onboard the satellite Pioneer 10, a US space probe launched in 1972, and also onboard the subsequent mission, Pioneer 11. The plate contained information about the space mission and mankind:

1. Hyperfine transition for neutral hydrogen, the most abundant element. The interaction between the proton and the neutron magnetic dipole moments in the ground state of neutral hydrogen results in a slight increase in energy when the spins are parallel, and a decrease when antiparallel. The transition between the two states causes the emission of a photon at a frequency about 1420 MHz, which means a period of about 7.04×10^{-10} s, and a wavelength of $\sim$21 cm. This is the key to read the message.
2. The figures of a man and a woman; between the vertical column brackets that indicate the height of the woman, the number eight can be seen in binary form 1000, where the vertical line means 1 and the horizontal lines mean 0: in unit of the wavelength of the hyperfine transition of the hydrogen, the result is 8×21 cm $= 168$ cm, which was at the time the average height of a woman. The right hand of the man is raised, as a good will sign, and it can even be a way to show the opposable thumb and how the limbs can be moved.
3. Relative position of the Sun to the center of the galaxy, and 14 pulsars with their period; on the left, we can see 15 lines emanating from the same origin, 14 of the lines report long binary numbers, which indicate the periods of the pulsars, using the hydrogen transition frequency as the unit. For example, starting from the unlabeled line and heading clockwise, the fist pulsar we find matches the number 1000110001111100100011011101010 in binary form, which corresponds to 1178486506 in decimal form: to find the period of this pulsar relative to the Sun we have to multiply this number by 7.04×10^{-10} s, which is the period of the hyperfine transition of hydrogen. The fifteenth line extend to the right, behind the human figures: it indicates the Sun's distance from the center of the galaxy.
4. The solar system with the trajectory of Pioneer. In this section the distances of every single planet from the Sun are indicated, relative to Mercury's distance from the Sun: for example the number relative to Saturn is 11110111, that is 247 in decimal form and means that Saturn is 247 times farther from the Sun than Mercury.
5. The silhouette of Pioneer relative to the size of the humans.

However, the most effective way possible for our technology is to broadcast a radio signal. Given Eq. 11.2, one can optimistically reach a distance of 25 000 light-years. The first attempt to send an interstellar radio message was made in 1974 at

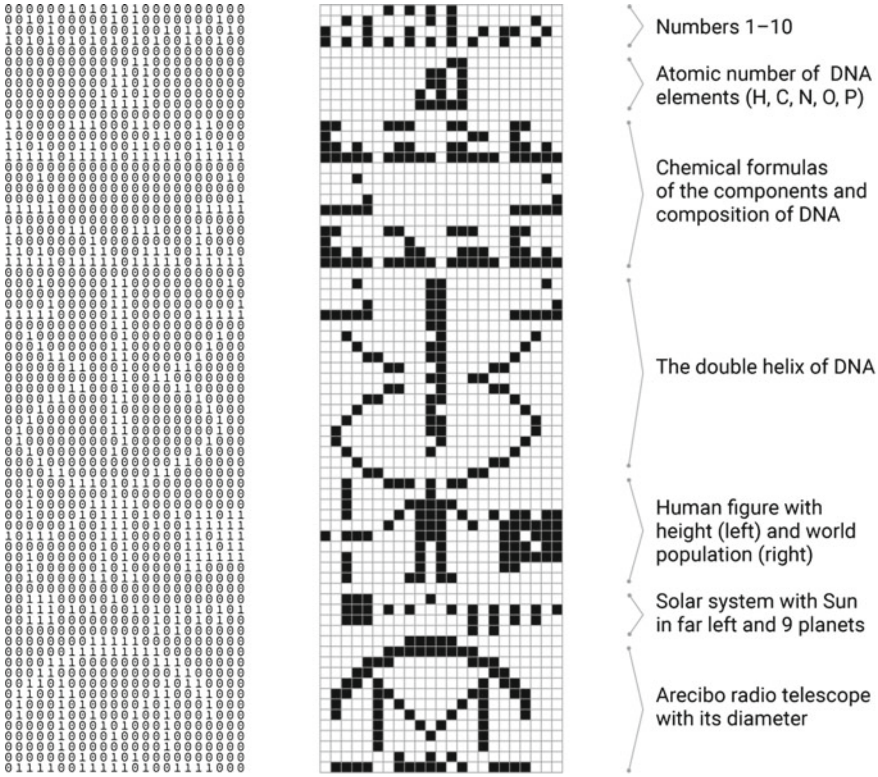

Fig. 11.12 Left: The Arecibo Message in binary form. Right: Decrypting the binary message. From http://www.marekkultys.com/img/lingua-extraterrestris

the Arecibo Observatory in Puerto Rico to send a message to other worlds, known as the Arecibo Message. Further messages (most famous are Cosmic Call, Teen Age Message, Cosmic Call 2, A Message From Earth) were transmitted in between 1999 and 2010 from the Evpatoria Planetary Radar, targeting several objects, including extrasolar planets.

The Arecibo Message came from an idea of Drake, with help from Sagan, among others. It is composed by 1679 binary symbols (Fig. 11.12). The message was aimed at the current location of globular star cluster M13 some 25 000 light-years away because M13 is a large and close collection of stars–possible decoders from different galaxies were anyway welcome. 1679 is the product of two prime numbers, 23×73. Translating the number 1 into a black square and the number 0 into a white square results in a matrix 23×73 (Fig. 11.12), that contains some information about our world.

1. The numbers from 1 to 10 written in binary form, where in each column the black square at the bottom marks the beginning of the number: for example, the first number written in binary form of the left is $1 = 1 \times 2^0$ which is 1 in

decimal form; then, we can find the number written in binary form 10 which is $0 \times 2^0 + 1 \times 2^1 = 2$ in decimal form; then, the number 111 is written in binary form, that correspond to $1 \times 2^0 + 1 \times 2^1 + 1 \times 2^2 = 3$, and so on. The numbers 8, 9, 10 are written on two columns.

2. The atomic numbers 1, 6, 7, 8, and 15 of , respectively, hydrogen, carbon, nitrogen, oxygen, and phosphorus, i.e., the component of the DNA.
3. Nucleotides present in the DNA: deoxyribose (C_5H_7O), adenine ($C_5H_4N_5$), thymine ($C_5H_5N_2O_2$), phosphate (PO_4), cytosine ($C_4H_4N_3O$), and guanine ($C_5H_4N_5O$).
   They are described as a sequence of the five atoms that appear on the preceding line. For example, on the top left the number 75010 is written in binary form, that matches the deoxyribose C_5H_7O: 7 atoms of hydrogen, 5 atoms of carbon, 0 atoms of nitrogen, 1 atom of oxygen, and 0 atoms of phosphorus.
4. The helix structure of the DNA, and the number of the nucleotides: the number in binary form is 11111111111101111111101101011110, that is in decimal form 4294441822 which was believed to be the case in 1974, when the message was sent—we think now that there are about 3.2 billion nucleotides that form our DNA.
5. In the center the figure of a human, with the typical height of a man, i.e., 1.764 m, which is the product of 14 times the wavelength of the message (126 mm); on the right, the size of human population in binary form–the number is 000011111111110111111011111111110110 (4 292 853 750 in decimal form).
6. Our solar system, where the Earth is offset and the human figure is shown standing on it.
7. A drawing of the Arecibo Telescope with below the dimension of the telescope, 306.18 m, which is the product of the number 2 430 written in binary form (100101111110) in the two bottom rows, read horizontally and the black square on the low right in the central block marks the beginning of the number, multiplied by the wavelength of the message.

Several concerns over METI have been raised: according to Hawking, alerting extraterrestrial intelligences about our existence and our technological level is crazy–he suggested, considering history, to "lay low". According to many it is not obvious that all extraterrestrial civilizations will be benign, or that contact with even a benign one would not have serious repercussions on Terrestrials.

A program called Breakthrough Message studies the ethics of sending messages into deep space. It also launched an open competition with a million US dollars prize to design a digital message representative of humanity and planet Earth that could be transmitted from Earth to an extraterrestrial civilization– however, with the agreement not to transmit any message until there has been a scientifical and political consensus on the risks and rewards of contacting advanced civilizations.

11.4 Conclusions

Technological and scientific innovation is contributing to discover new Earth-like planets where life could develop. But, what will happen in 30 years? What will we be able to discover? Where will the next mission take us? What will scientists study?

Scientists will analyze the light of planets around their stars to detect oxygen and other complex molecules that suggest the presence of an atmosphere, map other Earth-like planets, and study the presence of liquid water, volcanic activity, and possibly of biosignatures. Already in the next years atmospheric characterization through transmission spectroscopy will be possible thanks to the James Webb Space Telescope (JWST). The next mission devoted to the discovery of extrasolar planets after Kepler will be the ESA satellite PLATO, foreseen for the year 2024–2026. With an array of 34 telescopes mounted on a sun-shield, PLATO will allow 5% of the sky to be monitored at any time, and more than a million stars will be scrutinized for Earth-sized planets, providing a sensitivity an order of magnitude higher than Kepler: hundreds of Earth-like planets potentially habitable will be discovered.

Scientists will possibly study with new telescopes stars of nearby galaxies, to better estimate the number of communicative extraterrestrial civilizations. They will listen to the sound of gravity waves and neutrinos in the Universe: this will give to mankind the ability of detecting signals at larger distances.

Finding evidence of extraterrestrial life, if it exists, will require innovation, investment, and perseverance.

Further Reading

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[F11.6] O. Guyon, "Habitable exoplanets detection: overview of challenges and current state-of-the-art", Optics Express 25 (2017) 28825.

Exercises

1. *Effects of the Sun and of the Moon on tides.* The mass of the Moon is about 1/81 of the Earth's mass, and the mass of the Sun is 333 000 times the Earth's mass. The average Sun–Earth distance is 150×10^6 km, while the average Moon–Earth distance is 0.38×10^6 km (computed from center to center).

   (a) What is the ratio between the gravitational forces by the Moon and by the Sun?

(b) What is the ratio between the tidal forces (i.e., between the differences of the forces at two opposite sides of the Earth along the line joining the two bodies)?

2. *Temperature of the Earth and Earth's atmosphere.* What is the maximum temperature for which the Earth could trap an atmosphere containing molecular oxygen O_2?
3. *Equilibrium temperature of the Earth.* Assuming that the Sun is a blackbody emitting at a temperature of 6000 K (approximately the temperature of the photosphere), what is the temperature of Earth at equilibrium due to the radiation exchange with the Sun? Assume the Sun's radius to be 7000 km, i.e., 110 times the Earth's radius.
4. *The Earth will heat up in the future.* In 1 Gyr, the luminosity of the Sun will be 15% higher. By how much will the effective temperature of the Earth change?
5. *Moons of giant planets could be habitable.* Although Jupiter is far outside the habitable zone of the Sun, some of its moons, such as Europa, seem possible habitats of life. Where does the energy to sustain such hypothetical life come from? What is the possible role of the other moons?
6. *Titan.* Why is Titan interesting to study?
7. *Abundance of elements in the Universe and in living beings.* Look up the average abundance of the chemical elements in the Universe (Chap. 10). Why hydrogen, carbon, oxygen, and nitrogen, the main building blocks for life on Earth, are so abundant? Why is helium not a common element in life?
8. *Detection of exoplanets with astrometry*. What is the shift of the position of the Sun due to the Earth's orbit? What are the characteristics of an instrument that an alien living near Alpha Centauri would need to detect the Earth using solar astrometry?
9. *Radial velocity measurement via Doppler spectroscopy*. What is the Doppler shift of the light emission from the Sun due to the Earth's orbit? What are the characteristics of an instrument that an alien living near Alpha Centauri would need to detect the Earth using Doppler spectroscopy?
10. *Biosignatures.* Try to discuss some of the molecules in the atmosphere which could be indicators of life.