21 Astrobiology

Is there life elsewhere in the universe? And if there is, are there any intelligent beings? How did life emerge on the Earth, and, as a matter of fact, how do we define life and intelligence? These are probably the most interesting unsolved questions in science. During the last few decades a whole new field of astrobiology has evolved around these problems.

21.1 What Is Life?

There have been several science fiction tv-series showing extraterrestrial life forms. Usually the sentient beings have appeared quite humanlike, except of some appendices or other rather trivial features that try to make them unattractive. They may even have sex with humans. However, if the foreign life forms have evolved independently, interbreeding would be totally impossible.

The chemistry of foreign beings could be totally different from ours. Could we even understand that they are living beings? In fact, what is life? It seems that life is an elusive concept, difficult to define in terms of just a few properties. We have only one example of life, and therefore it is difficult to make general conclusions of its properties. However, we can assume that certain properties of the known life forms may be generalised also to foreign life.

Common features of all terrestrial life forms are reproduction and evolution. If living beings produced exact replicas of themselves, there would be no evolution and no adaptation to changing environments. Thus the reproduction process must be slightly imperfect leading to a variety of descendants. This will give material for the natural selection, 'survival of the fittest'.

Natural selection is a fairly general principle, working in some sense also outside of biology. Are there any other general principles related to the evolution of life? If we could find even one example of life that evolved independently of ours, this would vastly improve our knowledge.

Energy consumption is also characteristic of life. Life requires increasing order, i.e. decreasing entropy. Local decrease of entropy is not against thermodynamics: it only means that a living being must be able to take energy in some form and utilise it for reproduction, growth, motion or other purposes.

To produce similar offsprings a living being must have the ability to store information and pass it to its descendants. All terrestrial life forms use DNA or RNA molecules composed of nucleotides for storing information (see next section).

Carbon can combine to form very complex molecules. Silicon can also form large molecules but they are not as stable as carbon compounds, and silicon cannot form rings like carbon. Maybe some simple life forms could be based on silicon, or on something quite different that we have not even thought of.

Also a liquid solvent is needed. Our own life would not be possible without water. It remains liquid in a much wider temperature range than most other substances, which makes it a good solvent. Yet in the astronomical sense the tempera-

H. Karttunen et al. (eds.), *Fundamental Astronomy*, DOI 10.1007/978-3-662-53045-0_21

ture range is rather limited. In a colder environment, methane or ammonium might act as the solvent.

The basic building block of all terrestrial life forms is the cell. It has a membrane surrounding liquid cytoplasm. The cell membrane is semipermeable and functions as a two-way filter that lets certain molecules go in and others come out; this selective transport is mediated via specific proteinaceous channels. There are two kinds of cells, simpler prokaryotic cells and more complex eukaryotic cells. In eukaryotic cells the genetic material, in the form of DNA molecules, is inside a nucleus, surrounded by a nuclear membrane. In the prokaryotic cells there is no separate nucleus, and the DNA floats coiled in the cytoplasm.

Terrestrial life is divided into three domains, *Bacteria*, *Archaea* and *Eukarya*. Both *Bacteria* and *Archaea* contain usually a single prokaryotic cell. *Eukarya* contains all more complex beings, like animals and plants.

According to this scheme viruses are not alive although they have certain properties common to living beings. There are also some other molecules, such as viroids and prions, that are not classified as living; yet they are not quite inanimate.

If even the definition of terrestrial life leads to such borderline cases, a more general definition of all possible kinds of life is truly challenging. Facing this problem we have to restrict our discussion to life that, at least to some extent, resembles our own.

21.2 Chemistry of Life

The set of really important elements is relatively small; it includes hydrogen (H), oxygen (O), nitrogen (N), carbon (C), sulphur (S) and phosphor (P). The heavier elements can be remembered by the mnemonic SPONC.

The importance of carbon is in its ability to make lots of different very complex molecules, which are essential for life. There are three basic types of molecules that function as common building blocks to all life: lipids for membranes, nucleotides and amino acids.

Amino acids consist of three different components, a carboxyl (COOH), an amine part (NH_2) and a side chain, which can be just a single hydrogen or a more complex structure. Altogether there are dozens of different amino acids, but only 20 of them are used in genetically coded proteins.

Amino acids can join to form more complex molecules, *proteins*. Typically, up to several hundred amino acids are needed for a protein molecule. Proteins have numerous functions: they support structures, they act as catalysts in nearly all biological reactions, in which case they are called *enzymes*, they carry messages as hormones, and so on.

Nucleotides are basic building blocks of the genetic material, DNA and RNA. A nucleotide has three components, a sugar, a phosphate group and a base. The phosphate parts are always the same. All DNA molecules have the same sugar part; also all RNA molecules have the same sugar part, which, however, differs from the sugar of the DNA molecules by having one additional oxygen atom. The base can be one of five different types, adenine (A), guanine (G), cytosine (C), thymine (T), or uracil (U). DNA molecules contain bases A, G, C and T, and RNA molecules A, G, C and U.

Nucleotides join to form long chains. The *deoxyribonucleic acid* or *DNA* (Fig. 21.1) consists of two such chains that are bound together as two intertwined helices. The corresponding bases join together by hydrogen bonds. The bases come always in matching pairs, AT, TA, CG, or GC.

A helix is like a screw that can be either left- or righthanded. All terrestrial DNA molecules have the same handedness or *chirality*: they are all of L-type, or lefthanded. The reason for the asymmetry is not quite understood.

The DNA molecule contains information on how to make proteins. Three consecutive base pairs form a code, called a *codon*, that specifies one amino acid. Usually thousands of such triplets together contain instructions for building a protein.

The basic units of heredity are called *genes*. They are regions of DNA whose final products are either proteins or RNA molecules.

Human cells contain some 25,000 genes, and the DNA consists of 3×10^9 base pairs. In plants

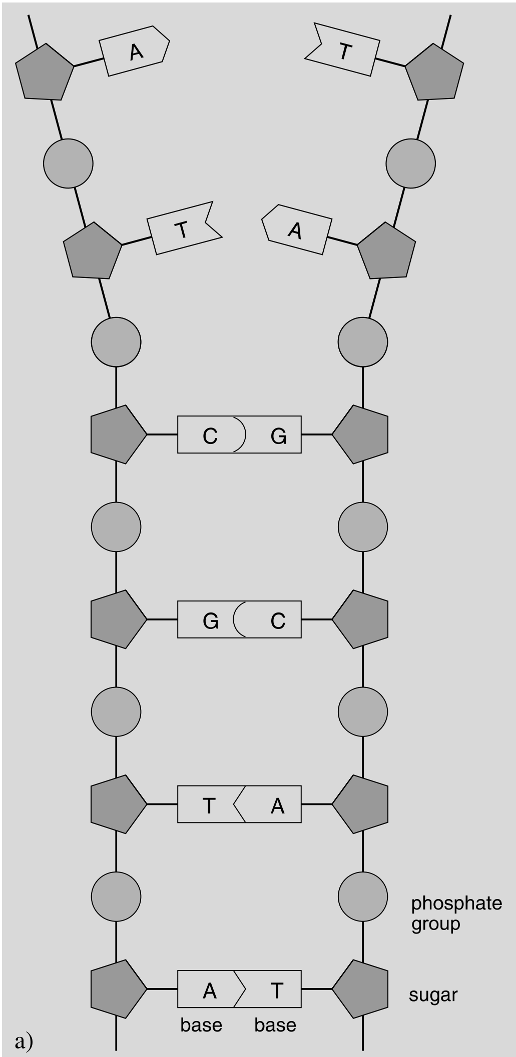

Fig. 21.1 (**a**) The DNA molecule consists of two strands of alternating phosphate groups and sugars connected by matching base pairs. When the information stored in a fragment of the DNA is needed, the strands separate and the bases are used to produce an RNA molecule that will contain the same information. (**b**) The strands coil to form a double helix. (Webb: *Where is everybody?*)

the numbers can be much higher, but the simplest known bacterial genomes have only a few hundred genes. It has been estimated that the minimum number of genes needed for a living being is about 200–300.

Actually, only a part of the DNA contains genetic information. The rest is called junk-DNA since it has no known function. The fraction of

Fig. 21.1 (Continued)

the junk-DNA is highly variable; in some bacteria the amount is very small.

The DNA is the storage of the genetic code, but the code is not functional directly from the DNA. Instead a complex molecular translation machinery is needed to execute the instructions.

First, the instructions encoded in the genetic sequence are copied (or transcribed) into another type of nucleic acid. This *ribonucleic acid* or *RNA* resembles the DNA but has one more oxygen atom in its sugar. Different RNA molecules serve several roles in the translation process. Messenger RNA (mRNA) carries the information in the DNA to an organ called ribosome, composed of several RNA's and multiple proteins. There another RNA, the transfer RNA (tRNA), brings amino acids into the reaction site, and still another RNA molecule, or one of the ribosomal RNA's (rRNA) forms the linkages (peptide bonds) between the adjacent amino acids.

RNA molecules have to carry instructions for making just one protein, and thus they are much shorter than DNA molecules. Still they contain similar information, and in some simple life forms like viruses they can act as the storage of the genetic code.

21.3 Prerequisites of Life

Just after the big bang there were hardly any other elements than hydrogen and helium. Heavier elements are needed, both for life itself and for solid planets on which life can evolve. Thus at least some of the earliest stars had to explode as supernovas and eject their fusion products to the interstellar space.

Most stars in elliptic galaxies and globular clusters are very old and have a low metallicity. Therefore they are not very probable locations for life. The most suitable places for life seem to be the disk populations of spiral galaxies, containing young stars with high abundances of heavier elements.

Not all places of the galactic disk are equally profitable. Far out from the galactic centre the star birth rate and consequently the metallicity is low. Close to the centre, metallicity is high but the environment is rather hostile. Star density is very high, and therefore radiation is intense, and nearby stars disturb planetary orbits. A rough estimate is that only about 20 % of the stars of the Milky Way or a similar galaxy lie within the *galactic habitable zone*.

Assume that a star is in the galactic habitable zone. The star has its own habitable zone where habitable planets can exist. This zone is usually defined as the region where the temperature is between the freezing and boiling points of water. For a fast-rotating perfect blackbody ($A = 0$ in Eq. (7.51)) orbiting the Sun this would mean that its distance should be in the range 0.56–1.04 au. Planets, however, are not blackbodies, and the real situation is more complicated. If a planet has a high albedo, it reflects away most of the incident radiation and its temperature will be much lower. But depending on the chemical composition of the atmosphere and possible clouds the greenhouse effect may increase the temperature considerably. Many gases are transparent to visible light, allowing it to heat the surface. Most of the energy is emitted back in the infrared region, which is effectively absorbed by these greenhouse gases, such as water vapour, carbon dioxide and methane, and thus remains trapped in the atmosphere.

If the star is cool, the habitable zone is very narrow. Hot stars have wider habitable zones, but their main sequence phase is short, giving little time for life to evolve. Thus main sequence stars not too different from the Sun are usually considered the best candidates for having habitable planets.

During the main sequence phase a star will become a little brighter, which will push the habitable zone slightly outwards. Thus the region where the temperature remains suitable for a long period of time is narrower than the habitable zone at any given moment. The continuously habitable zone can be defined as the region that remains habitable for a time that is comparable to the main sequence phase of the star. For the Sun the estimates of the width of this region vary at least from 0.06 au up to 0.2 au. The problem is how to model albedo and greenhouse effects over a very long period of time.

Binary stars are very common, but at least earlier it was thought that they could not have habitable planets, since planetary orbits would be complicated or unstable. However, there are two kinds of possible orbits that might be suitable. If the components of a binary are far away from each other, each component could have a planetary system of its own. Or, if it's a close binary, there can be distant planets orbiting the whole binary system.

21.4 Hazards

Even if life could emerge, there are many hazards that may wipe it out. By looking at the Moon we can see that meteor bombardment was very intense in the young solar system. Collision of a big asteroid or comet could be fatal, the immediate devastation caused by the explosion being only one of the consequences. The collision would eject a lot of dust to the atmosphere cooling the climate for several years. The mass extinction 65 million years ago seems to have been caused by

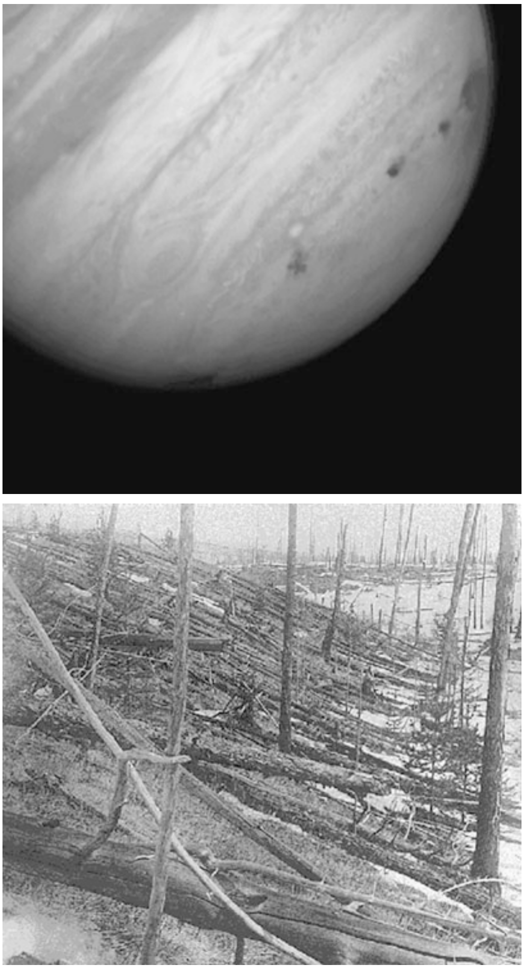

Fig. 21.2 In the young solar system small objects collided continuously to larger planets, threatening seriously the evolution of life. Later collisions and perturbations by planets have cleaned away most of the potentially dangerous objects. Still collisions take place even nowadays. In 1994 comet Shoemaker-Levy collided to Jupiter after disintegrating into several parts. Traces of the collisions of the fragments were seen as dark spots in the atmosphere of Jupiter. In June 20, 1908, an explosion happened in Tunguska, Siberia, hewing down trees in a couple of thousand square kilometres. The explosion was possibly caused by a comet with a diameter of about hundred metres

such an event. As the comet Shoemaker-Levy hitting Jupiter (Fig. 21.2) in 1994 showed, such collisions are still possible. Fortunately they are not very frequent any more.

Almost all of the currently known exoplanets are Jupiter-like giants. They seem to be necessary for habitable planets, because their perturbations clean the young solar system from debris by ejecting it outside the planetary system. However, many of the known giant planets move on highly eccentric orbits, and they may disturb also the orbits of earthlike planets. Thus it is further required that the giant planets should be on nearly circular orbits and not too close to the star.

Also smaller planets have participated in clearing the regions around their orbits, which is reflected in the new definition of a planet (Sect. 7.1).

Seasons depend on the obliquity of the rotation axis and the eccentricity of the orbit. High values will lead to strong seasonal temperature variations. In the case of the Earth the Moon seems to have a stabilising effect; without the Moon the tilt of the axis would have varied much more, possibly causing more severe ice ages fatal to life. Hence also a relatively big moon seems to be in the shopping list of a habitable planet. However, recently there have been some objections to this requirement.

We have only recently started to understand the rather delicate balance and complex feedback effects working in the atmosphere. Currently the climate is warming due to the increasing greenhouse effect, but the Earth has experienced also quite opposite phases. If the albedo increases, the amount of energy reaching the surface decreases, glaciers and snow cover expand, and the amount of clouds increases till most of the atmospheric humidity is solidified as snow and ice. All this will increase the albedo further, speeding up this icehouse effect. There is geological evidence of global glaciation periods 750–580 million years ago and possibly also 2.3 billion years ago. The Snowball Earth hypothesis assumes that the climate cooled down for millions of years and the whole surface was covered by a layer of ice at least one kilometer thick. During the long cold period most of the living organisms, all of which at that time lived in water, became extinct. Volcanic activity was still going on, adding more carbon dioxide to the atmosphere. Finally the resulting greenhouse effect started to warm the climate.

There are many factors that seem to be crucial for life. Some of them may not look very important, but might still have made it impossible for life to emerge. However, in many cases we don't know how important they really are or if they are equally crucial for foreign life forms.

21.5 Origin of Life

One way to try to understand the origin of the terrestrial life is to start with the available atoms and molecules and see if they could produce life. During the last decades there has been considerable progress, but the process is very complicated and not yet well understood. Here we can only outline briefly how it might have happened.

In a famous experiment in 1953 Harold Urey and Stanley Miller sent energy in the form of electric sparks through a gas mixture supposed to be similar to the early atmosphere of the Earth, containing methane, ammonia, hydrogen and water vapour. After a few days the solution contained several organic compounds, including some amino acids. At that time it was assumed that the early atmosphere was reducing. More recent studies suggest that this is not quite true, and the earliest atmosphere was rather neutral, containing mostly CO_2, CO, N_2, H_2O and maybe some H_2. Such an atmosphere would have produced organic compounds much slower, if at all.

Some amino acids have been found in meteorites. Thus they seem to have been already present in the nebula from which the planetary system condensed. Complex organic molecules have been found also in interstellar molecule clouds (Sect. 15.3). There have even been claims of detecting the simplest amino acid, glycine, but the results are controversial.

The next step, putting the basic blocks together to form DNA or RNA molecules, is much more difficult. This looks like the chicken and egg paradox: the information contained in the DNA is needed to make proteins, and proteins are needed to catalyse the production of the nucleotides, which are the building blocks of the nucleic acids. So which came first?

In the 1980's Sidney Altman and Thomas Cech found that some RNA molecules can act as catalysts. Since RNA resembles DNA, it can store genetic material to some extent. Thus there is no need for the DNA and proteins. Even RNA fragments cannot be synthesised easily, but as they act as enzymes and can replicate, it is assumed that the initial chemical evolution first led to short and relatively simple RNA molecules. Eventually some of then combined to more complex ones, some of which were better adapted to the environment either by replicating faster or by being more durable. Thus the natural selection started to produce more complex molecules; this chemical evolution was working already before actual life emerged.

The first cell-like structures could evolve from asymmetric molecules or lipids, one end of which attracts water and the other end repels water. In water such molecules tend to form bi-layered membranes where the hydrophilic or water-attracting end points outwards and hydrophobic or water-repelling end inwards. Further on, such membranes form spontaneously spherical vesicles. If RNA happened to get inside such a membrane, it may have been protected from the environment, and could have been contained within its own chemical environment. In some cases this could have improved its replication, and thus led to further increase its concentration within the vesicle.

A rather common assumption is that the first primitive life forms were RNA life. However, recently this theory has been challenged. RNA has some drawbacks. It is not as stable as DNA, and its replication is not as accurate as the protein mediated replication of DNA. If the life was initially based on RNA, evolution led finally to the appearance of DNA molecules. Since DNA is superior to RNA due to its stability, it soon took over the role of information carrier.

Currently the energy of sunlight is utilised by plants and some bacteria in photosynthesis, which produces carbohydrates from water and carbon dioxide. There are also organisms that do not need sunlight but can use chemical energy to produce organic matter in a process called chemosynthesis. Such organisms have been found e.g. near hydrothermal vents on mid-ocean ridges (Fig. 21.3). These vents eject hot mineral-rich water to the ocean. Even though the temperature can be as high as 400 °C, the

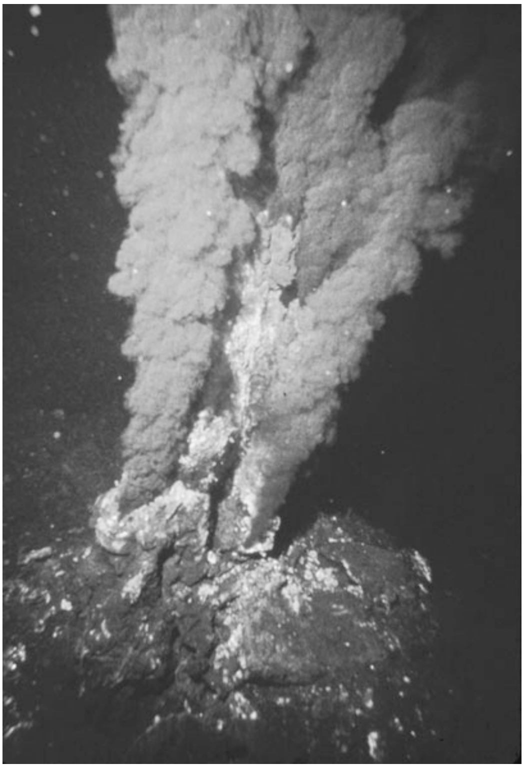

Fig. 21.3 Black smokers in the Mid-Atlantic Ridge are hydrothermal vents that sprout hot mineral-rich water. (Photo: P. Rona, Credit: OAR/National Undersea Research Program (NURP); NOAA)

high pressure prevents the water from boiling. Although this is too hot for life, there are regions around the vents where the temperature is suitable for such thermophiles. They could have been the first life forms, in which case life did not emerge in a Darwinian warm pond but in a hot pressure kettle. However, this is also a matter of debate.

This kind of bottom-up approach tries to build life from the simple constituents already available in the interstellar space. Another approach, the top-down method, tries to trace life back in time as far as possible.

The oldest sediment rocks on the Earth, found in Isua in western Greenland, are 3.8 Ga old. Since they contain sediments, deposited by water, and pillow lavas, formed in water, the temperature at that time could not have a value very different from the current one. The solar luminosity was then lower than nowadays, but the difference was compensated by a higher amount of decaying radioactive materials and remanent heat of the recently born Earth.

Oldest signs of life are almost as old. These signs are, however, just isotope ratios that can be interpreted as results of bacterial life. The carbon isotope ^{12}C is about 100 times as abundant as the heavier isotope ^{13}C. The lighter isotope is somewhat more reactive and tends to be enriched in living organisms. In the Isua rocks there are sediments with a small excess of ^{12}C, which might indicate some kind of life.

In the Warrawoona Group in Australia there are 3.5 Ga old formations that look like stromatolites, mounds consisting of layers of microbial cells and calcium carbonate. If they are real stromatolites, they may have been formed by cyanobacteria, but this is still a matter of debate.

In the early times, at least for a billion years, photosynthesis was non-oxygenic. Cyanobacteria were possibly the first organisms capable of oxygenic photosynthesis. They started to produce oxygen, but initially it was dissolved in water and consumed in different oxidation reactions. Eventually also the amount of atmospheric oxygen started to rise, and 2.2 Ga ago it reached 10 % of the current value, i.e. about 2 % of the total abundance in the atmosphere.

First eukaryotes appeared in the fossil record 2.1 Ga ago and multicellular organisms 1.5 Ga ago. The fossil evidence becomes much clearer towards the end of the Proterozoic era. The Ediacara fauna, which is about 600 million years old, contains the oldest fossils of big and complex animals. These were softbodied animals. At the end of the Cambrian period 543 million years ago traces of the Ediacara fauna disappear and are replaced by a huge variety of new animals, many with protecting shields. This increase in the variety of life forms is called the Cambrian explosion.

All life forms use similar genetic codes, which indicates that they have the same origin. This forefather of all life is called LUCA, the Last Universal Common Ancestor.

Relationships of living beings can be studied by comparing their DNA or RNA. The more the molecules of two species differ, the more distant the species are in the evolutionary sense. These

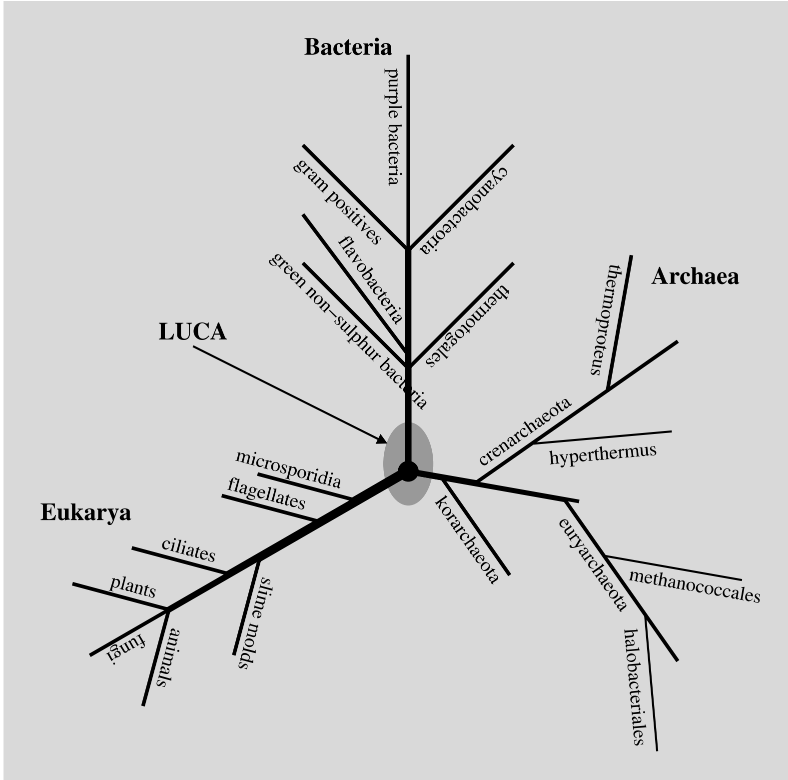

Fig. 21.4 A simplified phylogenetic tree. A branch is the older the closer it is to the last common ancestor, LUCA. (Adapted from Webb: *Where is everybody?*)

distances can be plotted as a map, called the phylogenetic tree (Fig. 21.4).

The phylogenetic tree, as we now know it, has three branches, the domains of *Archaea*, *Bacteria* and *Eukarya*. The organisms closest to the root are thermophiles that live close to hydrothermal vents or in hot water. Obviously, the LUCA lived in such a hot environment. However, RNA molecules do not remain intact in such hot environments. If the earliest life was RNA life, it would have evolved in a cooler environment. Currently we do not know the real birthplace of life.

Although the phylogenetic tree points to a common origin, there may have been other starts, too, but natural selection has eliminated the other ones that were less competitive.

21.6 Are We Martians?

Mars and the Earth have very similar rotation periods and axial tilts. Since the notorious 'discovery' of canals, Mars and its inhabitants have been a popular subject in science fiction stories. Later observations revealed a very thin atmosphere and low temperature, which make Mars a rather hostile place. Finally, the Viking landers showed a marred planet. Yet the possibility of some simple life forms cannot be excluded.

In 1984 a meteorite was found in the Allan Hills region in Antarctica and labelled as ALH 84001 (Fig. 21.5). The piece of rock was estimated to be 3.9 Ga old. Chemistry of the meteorite shows that it had originated on Mars; an impact had thrown it to an orbit that brought it to the Earth.

In 1996 a group of NASA scientists announced that the meteorite contained structures resembling fossilised microbes and compounds that could be products of living organisms, such as polycyclic aromatic hydrocarbons (or PAH) and magnetite. However, they can be produced by other processes, too. Not surprisingly, the results and the implications of Martian life caused a lot of scepticism. Only further Mars expeditions and

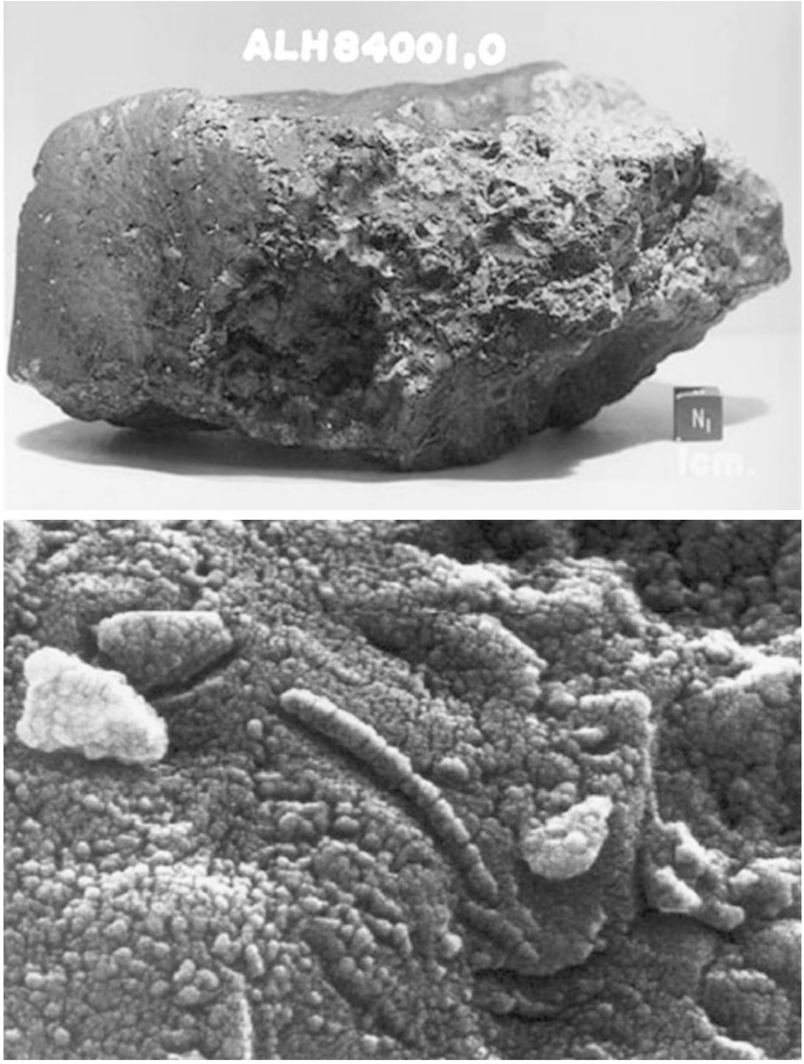

Fig. 21.5 The meteorite ALH 84001 found in Antarctica has a chemical composition that indicates its Martian origin. The meteorite contains substances that can be produced by living organisms. The wormlike structures resemble bacteria. It is, however, reasonable to ask whether one single sample can prove that once there was life on Mars. (NASA)

possible *in situ* experiments can decide whether there has been life on Mars.

In case there has really been life on Mars, there are several possibilities:

- Life originated independently on the Earth and Mars.
- Life originated only on the Earth and was then transported to Mars.
- Life originated only on Mars and was transported to the Earth.

It seems that life on the Earth emerged almost as soon as the conditions became favourable. It has been argued that the life appeared even too quickly. This problem would be solved if life originated on Mars. The surface of the more distant and smaller Mars had cooled down faster to become habitable before the Earth. Thus life would have had more time to evolve on Mars, and was transferred to the Earth when conditions here became suitable. Thus our earliest ancestors could be Martian bacteria. Presently such considerations are, however, just speculations.

The idea of life spreading from one celestial body to another is known as *panspermia*. The idea dates back to the antiquity, but its first serious advocate was the Swedish chemist Svante Arrhenius, who published a book on the subject in 1908. Of the later proponents, Sir Fred Hoyle was the most famous. Panspermia fit well to his cosmology: the universe had no beginning, neither did life, but had always existed. Thus the tough problem of the origin of life was neatly avoided.

Now panspermia, in a certain more limited sense, begins to seem a little more possible theory. Primitive life forms can survive inside meteorites in the coldness and lethal radiation of the interplanetary space long enough to travel from one planet to another. Interstellar distances, though, are too long, and the probability of a meteoroid from one planetary system hitting another system is too low. It seems obvious that our life has originated here in our own solar system.

21.7 Life in the Solar System

Once there may have been life on Mars. Although probes have not detected signs of life, it is not impossible that there might still be some microscopic life, but we cannot expect to find any macroscopic life forms. The same is true for other places in our solar system.

Mercury has no atmosphere, Venus is too hot, and the giant planets have no solid surface. Besides the Earth and Mars this leaves only some satellites as possible habitats. It has also been speculated that there might be living things floating in the atmospheres of the giant planets, but the emergence and evolution of such things seems rather improbable.

Europa as well as some other icy satellites are nowadays considered potential places for life. Their surfaces are too cold, but tidal heating keeps the interiors warm enough. Big satellites rotate synchronously, but if the orbit is not perfectly circular, the orbital velocity varies according to Kepler's second law. Thus the satellite librates just like our Moon, which means that the direction of the tidal distortion keeps changing. Also the distance to the planet varies, and therefore the magnitude of the tidal force varies, too. These effects deform the satellite continuously giving rise to tidal heating.

Europa's surface is covered by ice. In some places the ice cover is broken into plates that obviously have moved relative to each other. The rotation period of the surface differs from the rotation period of the magnetic field, which is frozen to the interior. Observations seem to indicate that the ice cover floats on an ocean.

The illumination under the ice is too dim for photosynthesis, but there might be thermal vents as in the oceans of the Earth. Hence the ocean could be a habitat for microbes that can utilise the thermal energy.

Titan is the only satellite with a thick atmosphere. The atmosphere is also rich in organic compounds, like methane. Methane dissociates rapidly, and thus the high methane content means that there must be a source of new methane. Living organisms are one such source, but because of its coldness Titan does not look like a promising place for life. A more plausible theory was that there was a methane ocean on Titan but the Huygens probe revealed a rather dry landscape, which, however, has signs of liquid flows. Radar images sent by the Cassini probe show some dark areas that might be methane lakes (Fig. 8.25).

21.8 Detecting Life

If we find a potentially habitable planet, is there any hope that we can see if life has emerged on it? The question can be answered by studying whether we can find life on the Earth from satellite observations. In 1990 the Galileo probe made just such experiments, and it seems that it is indeed possible to detect life, at least the kind of life we have on the Earth. Similar observations of the Moon showed no traces of life.

The detection is based on spectroscopic observations that can reveal some signatures of life. These signatures are in the infrared part of the spectrum, thus requiring observations made outside the atmosphere.

There are two emission features that are strong indicators of life, ozone and methane. Photosynthesis is the most probable source of molecular oxygen, which is then broken into two oxygen atoms by ultraviolet radiation. The free oxygen atoms join to molecules to form ozone. Methane is also produced by living beings. It is quickly oxidised, and has to be continuously replenished to keep the level noticeable. However, there can be large reservoirs of methane, particularly in cold environments. Thus methane itself is not a sign of life, but if it is found together with ozone, the evidence becomes more convincing.

Another feature is the infrared reflectance spectrum of the green plants. Chlorophyll absorbs visible light, particularly blue and red, but there is a distinct cutoff called the red-edge, seen as a steep gradient of the spectrum between 690 and 740 nm. Longer wavelengths are very effectively reflected to avoid excessive heating.

21.9 SETI—Detecting Intelligent Life

Mankind has been sending radio transmissions for almost a century. Our radio signals are now filling a sphere with a radius of almost one hundred lightyears. Another civilisation orbiting a nearby star might be able to pick up this transmission with a big radio telescope. Such leakage radiation is, however, very weak. Sensitivity of our own radio receivers has increased enormously since they were invented. Thus it has been possible to reduce the power of the transmitters, and the signals leaking to space have become weaker. Also, more and more signals are sent in cables and optical fibres. If another civilisation has undergone similar development, detecting leakage signals is extremely difficult. Chances are much better if the signal has been sent intentionally towards potential receivers in the hope that somebody will detect it.

One might think that galaxies and star clusters are worth listening, since there are many stars in the narrow beam of the telescope. Unfortunately, it is not quite so. Other galaxies are so far away that the signal could be too weak to be detected. Globular clusters consist of very old stars with low metallicity. Thus the probability of finding a habitable planet is tiny indeed. Open clusters are relatively young, and life may not have had time to evolve to a communicating civilisation. Thus galaxies and star clusters are not the best places to search for signs of life.

What frequency should we use? If the sending and receiving party have developed radio astronomy, they must be aware of certain common frequencies, like the hydrogen 21 cm radiation. Such a wavelength itself may not be a good choice because of the background noise, but some of its multiples or a sum of two common frequencies might fall in the quiet part of the radio spectrum. A good frequency could be the H_2O maser emission at 22 GHz. Around this frequency the sky is pretty quiet except for a few sources. But it is not enough to listen to those frequencies only, since they are Doppler shifted due to the relative motion of the transmitter and receiver. And if the transmitter and/or receiver are on planets orbiting a star, the Doppler shift will change periodically. Fortunately, current receivers are capable of following millions of frequencies simultaneously.

Radio emission from natural sources can be steady noise or vary in a periodic, quasiperiodic or chaotic manner. If we want to send a signal to be recognised as artificial, it should contain a pattern that cannot arise naturally. It could e.g. contain an increasing number of pulses representing the first few prime numbers.

Although most SETI research concentrates on radio frequencies, also optical wavelengths have recently been considered seriously. Pulsed lasers pack a lot of energy to a short pulse (lasting typically one nanosecond) confined to a very narrow wavelength band and a narrow beam. The flash can be even brighter than the central star. If such a signal were pointed towards us, it should be relatively easy to detect. Such optical SETI research, or OSETI, has already been started, but it is still behind the radioastronomical SETI.

In 1974 Frank Drake used the Arecibo radio telescope to send a message towards the globular cluster M13 (which is not a good place for life). The message contained 1679 pulses (Fig. 21.6). This number has exactly two factors, 23 and 73. Thus the receiver, who obviously must understand some mathematics, could guess that the message contains a two-dimensional picture. If we ever detect such a message, we can be pretty certain of its artificial origin, even if we were not able to interpret the message.

The first serious SETI project (Search for ExtraTerrestrial Civilisations) was carried out in 1960, also by Frank Drake. This project Ozma observed two nearby stars, τ Cet and ε Eri, at the 21 cm wavelength. Since then radio technology

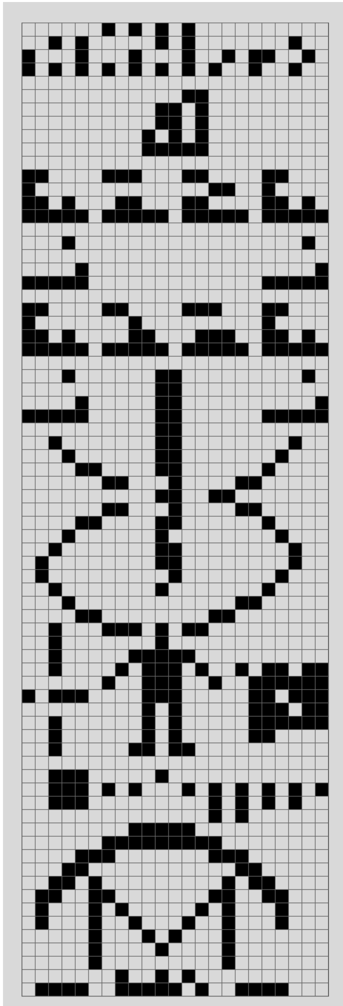

Fig. 21.6 The signal sent with the Arecibo radio telescope consists of 1679 pulses. The number 1679 has only two factors, 23 and 73, so obviously the signal represents a twodimensional image of 23 × 73 pixels. A lot of information about the sender is coded in the image, but it is difficult to say whether the receiving civilisation could interpret it. In any case, the artificial origin of the signal is indisputable

has improved enormously, and currently we are able to listen to a huge number of channels at the same time.

There are two basic search strategies. In a targeted search we listen to a few objects that are potential candidates for harbouring life. In a wide-sky survey large areas of the sky are scanned. Most current projects belong to the latter category.

Observing time with large telescopes is expensive, and priority is given to projects that can be expected to produce positive results. In some projects, like SERENDIP, this problem is avoided by having the receiver sit piggyback on some other instrument and listen to whatever the telescope happens to be observing. Thus the SETI project does not need any dedicated time of its own. The drawback is, of course, that many of the target areas may not be interesting in the SETI sense.

Detecting a potentially artificial signal among the huge amount of data requires a lot of computing power. The seti@home project has connected millions of computers to an enormous virtual machine to analyse the data. Anyone with a computer connected to the Internet can load a screensaver program that will automatically fetch packets of data and send back the results.

Thus far not a single message sent by another civilisation has been confirmed. There have been some interesting cases, but they have been single bursts of unknown origin. They have not been detected later, not even with more sensitive instruments.

21.10 Number of Civilisations

Although no extraterrestrial civilisation has been found, we can try to estimate their number. The SETI pioneer Frank Drake suggested a formula for calculating the number of civilisations in the Milky Way capable of communication at a given instant:

$$N = R \times f_\mathrm{p} \times f_\mathrm{h} \times f_\mathrm{l} \times f_\mathrm{i} \times f_\mathrm{c} \times L, \quad (21.1)$$

where N is the total number of communicating civilisations in the Milky Way, R is the annual birth rate of stars, f_p is the fraction of stars possessing planets, f_h is the fraction of planets being habitable, f_l is the fraction of habitable planets having some kind of life, f_i is the fraction of these planets having intelligent life, f_c is the fraction of intelligent civilisations that have developed means for interstellar communication, and finally L is the time in years that such a civilisation has been communicating. All the f-factors are probabilities that are in the range [0, 1].

The astronomical factors (R, f_p and f_h) are the only ones that are known with any accuracy. The biological factors, f_l and f_i, involve a lot of guesswork. The last two factors, f_c and L, are even harder, since they are related to the sociological behaviour of the exocivilisation.

Actually, the formula was intended as the basis of the agenda of an influential SETI meeting held in Green Bank in 1961. It splits the problem nicely into smaller subproblems that can be discussed separately. But using the formula to find the actual number of civilisations is not very meaningful, since so many of the factors are totally unknown. In the most "optimistic" case we could find out that the distance between neighbouring civilisations is just a few parsecs, but giving the probabilities small (possibly more realistic) values, their product might be so minute that we ought to be alone in the Milky Way. At least the formula shows how little we know.

Even if favourable conditions and evolution of communicating civilisations were relatively common, the last factor may turn out to be the limiting one. If the lifetime of a civilisation is short compared to the age of the universe, the chances of hearing a message from another star are poor.

Earlier many astronomers seemed to think that exocivilisations would not be that rare, while biologists showed that the evolution of life had so many obstacles that we should not expect to find other civilisations in our neighbourhood. Now we understand better both the biochemistry of early life and the many problems in having a habitable planet. Although opinions vary considerably, we might guess that very simple microbe-like life is relatively common, but intelligent, communicating beings might be extremely rare.

21.11 Exercises

Exercise 21.1 Calculate the limits of the habitable zone of the Sun assuming the planet is a fast-rotating blackbody with a Bond albedo of 0.3. What is the continuously habitable zone, if the luminosity of the Sun was originally 0.7 times the current value?

Exercise 21.2 Assume there are n stars in a cubic parsec and a fraction p of them have communicating civilisations. What is the average distance between two neighbouring civilisations? Apply the result to the solar vicinity. The stellar density can be estimated from Table C.17. What is the average distance between nearest civilisations, if the probability of a star having a planet with a civilisation is (a) 0.01, (b) 0.00001?

Exercise 21.3 An asteroid with a diameter of one hundred metres is approaching the Earth. Estimate the minimum value of the kinetic energy released in the collision. Compare the result with the Hiroshima atomic bomb. The energy of the bomb was equivalent to 15 kilotons of TNT. One ton of TNT corresponds to the energy of 4.184×10^9 joules.