6 Life and its Origin on Earth

Suppose that somewhere in the universe there is another Earth-like planet. How likely is it that life will develop there? Two approaches can be taken to answer this question. The first is to set up detailed search programs for extraterrestrial life, both inside and outside the solar system. Although unsuccessful so far, this procedure, as will be seen in Chap. 8, is potentially very powerful and has a high chance of detecting extraterrestrial life in the near future. The second approach is to study how life formed and evolved on Earth, based on the assumption that on other Earth-like planets life does appear for similar reasons. The present chapter therefore outlines the basic chemical tools and processes employed by life, and summarizes the biology of cells, because these are the basic units of living organisms. After considering the likely environment on the early Earth, the important question is then addressed: How did life form? Let us begin first by asking: What is life?

6.1 What is Life?

This question has always puzzled man and seems very difficult to answer even today. However, with the recent DNA sequencing of a wide variety of organisms, and particularly of the most primitive life forms successfully completed, the goal of understanding what constitutes life is within reach. As the complete information about the mycoplasmas (see below) is contained in a few hundred genes, the full unraveling of their function will give us the precise definition of life.

In antiquity, Aristotle in his lecture notes *De Anima* argued that life and the soul are the same. Aristotle taught that everything that lives has a soul and that at death the soul leaves the body. He distinguished three levels of life: vegetative life (plants), sensitive life (animals), and conscious life (man). The large qualitative differences between these three levels of life that impressed Aristotle are seen even today as fundamental stages of sophistication of biological organisms, ultimately made possible by the laws of nature. Since we are interested in the future development of life, we may well ponder the question of whether nature holds more of these fundamental stages in store both for mankind and for the extraterrestrials, stages of greater sophistication which, since the birth of our universe, are waiting to be realized (this question will be discussed in more detail in Chap. 10).

In textbooks of biology, life is usually described phenomenologically. An organism lives when it shows the following basic properties: metabolism (application of chemical processes), growth (directed development), energy utilization, individuality (preservation of information of its own identity), procreation, and mutation (change of the hereditary information). In addition, a characteristic of living organisms is that they are in principle able to maintain these properties in a completely abiotic environment. Viruses, for example, do not satisfy these criteria, because they do not show metabolism and they need biological organisms for survival and reproduction. Therefore they cannot be considered as "alive".

6.2 The Special Role of Organic Chemistry

Life on Earth is intimately connected with organic chemistry. This is very likely a consequence of the unique compound-forming role of carbon among all other elements, resulting in a huge number of different substances. We know today that for every inorganic compound there are at least 50 organic compounds (Chap. 5). The reason for this special role of carbon is that it has four directed atomic bonds, which allow the building of extended spatial structures, as opposed to the three bonds of nitrogen and the two bonds of oxygen, which produce planar and linear structures, respectively. Elaborate spatial structures are also not possible with undirected ionic bonds such as those of Na or Cl. In addition, carbon often has the strongest binding energy and only this atom forms aromatic rings. Finally, CO_2 is a gas that can easily interact in biological processes while, for example, SiO_2 (quartz) or Al_2O_3 (corundum) are hard solids that do not interact. For the uniqueness of carbon as universal building block for life and the low probability for life based on Silicon see also Schulze-Makuch and Irwin (2004).

While the most frequent elements (except Si and Al) of the Earth's mantle usually play some role in living organisms, the prominent role of carbon is surprising because, although being the fourth most abundant element in the cosmos, it is not very abundant in the outer crust of terrestrial planets (see Table 1.2). The reason for the intimate relation between organic chemistry and life therefore seems to be the ability of carbon to provide the huge variety of specialized compounds and building blocks for the very complex structures of biological organisms.

6.3 The Elements of Biochemistry

Since life on Earth is based on organic chemistry and employs biochemical processes, it is necessary, if we want to understand what life is, that the elements of biochemistry are briefly discussed. In biological systems there are four major classes of organic compounds: *proteins*, *carbohydrates*, *lipids*, and *nucleic acids*. In addition to the catalytic substances that help to synthesize carbohydrates and lipids, there exist *three characteristic mechanisms* to replicate the master archive DNA, to transcribe the information from DNA onto the blueprint RNA, and finally to translate it into proteins. In addition, there is a *language* (genetic code) in which DNA and RNA are written, and an *energy carrier* (ATP) that powers all this construction activity.

6.3.1 Proteins, Carbohydrates, Lipids, and Nucleic Acids

In biological systems, more than 170 *amino acids* have been identified. Of these, there are 20 (listed in Table 6.1) that are coded by DNA and function as building blocks of proteins. They are all of the geometrically distinct l-chiral (left-handed) type, except for glycine. Amino acids are both acidic and basic; that is, they have a COOH carboxy end that easily loses an H^+ ion and an NH_2 amino end that readily takes up an H^+. The 20 coded amino acids consist of the five elements C, O, N, H, and S.

Table 6.1. The 20 amino acids coded by DNA (after Hart et al. 1995)

Alanine	Glutamic acid	Leucine	Serine
Arginine	Glutamine	Lysine	Threonine
Asparagine	Glycine	Methionine	Tryptophan
Aspartic acid	Histidine	Phenylalanine	Tyrosine
Cysteine	Isoleucine	Proline	Valine

Proteins consist of chains of amino acids linked together by so-called peptide bonds. These amino acids are selected from the set of 20 amino acids coded by DNA. While water makes up 70% of a cell's weight, proteins account for more than 50% of the cell's remaining weight (Alberts et al. 1994). One currently knows more than 20 000 different proteins in man (HPRD 2005). They have many functions: structure proteins, enzymes, hormones, transport proteins, protection proteins, tractiles, toxines, and so on.

The sequence of amino acids determines the biological function of proteins. Proteins consist of several tens to several thousand but typically around 300 amino acids, and many of them occur in the form of several subunits which are held together by bonds. These bonds between different subunits and parts of the same subunit give proteins a distinct three-dimensional spatial structure, that is essential for their specific biochemical function. The most important bond in proteins is the *peptide bond*, where the COO^- end of one amino acid is joined to the H_3N^+ end of the next amino acid, forming the sequence OC$-$NH, whereby a water molecule, H_2O, is liberated. The macromolecules resulting from this fusion are also called *polypeptides*.

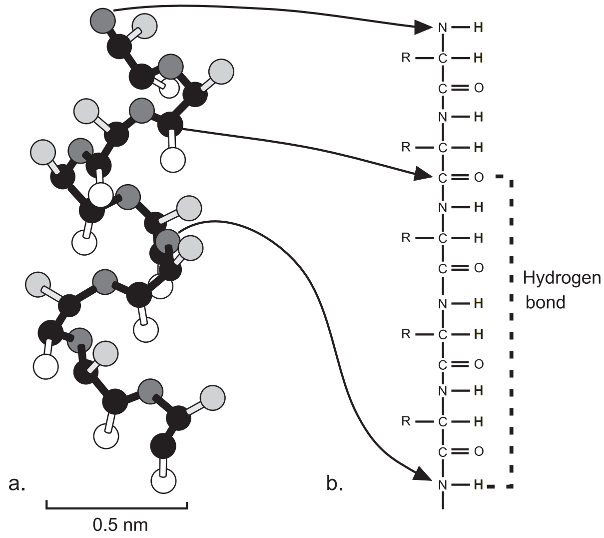

Fig. 6.1. The structure of a protein. **a.** Ball and stick model showing C (*black*), N (*dark gray*) and O (*white*) atoms. The H-atoms are not shown. R (*light gray*) are the amino acid rests. **b.** The structural formula. Arrows show corresponding atoms (after Green et al. 1993)

Proteins have a hierarchy of structure. The primary structure is the amino acid sequence determined by the DNA (Fig. 6.1b). The secondary one is either the winding up of this chain to form an α-helix type spiral (see the CCN backbone in Fig. 6.1a, marked solid), or a back and forth folding of the chain onto itself, called a β-sheet. Both polypeptides are stabilized by hydrogen bonds. The tertiary structure is the three-dimensional shape into which these macromolecules fold due to disulfide bonds and the hydrophobic interaction. In a fourth type of structure, several protein subunits combine into a complete three-dimensional protein. For example, hemoglobin consists of four subunits.

Carbohydrates and *lipids* are two other basic building blocks of living organisms. Among the carbohydrates, cellulose serves as a structural material in plants. Starch and glycogen are the most important storage forms of energy in plants and animals, while sugars are used in energy transport. Sugars also constitute essential components of the nucleic acids. Lipids are familiar as fats and oils. Composed of glycerol and fatty acids, they are insoluble in water but soluble in organic solvents. Lipids serve many functions, of which their capacity for efficient energy storage is best known. One class, the *phospholipids*, constitute the structural basis of the cell membranes, both of the outer cell membrane and the inner membranes separating the organelles from the cytosol (cell plasma) in eukaryotic cells. Figure 6.2 shows a section of the cell membrane, which is built employing a phospholipid bilayer. In this bi-