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Astrobiology: From the Origin of Life on Earth to Life in the Universe

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> This chapter covers the different theories about the steps toward the origin and evolution of life on Earth, and the major requirements for these processes and for life at large are discussed. Conclusions are drawn on the likelihood of life originating and persisting on other places of our Solar System, such as the terrestrial planets and the moons of the giant planets, or beyond in the Universe.

1.1
General Aspects of Astrobiology

1.1.1
Historical Milestones

Humans in every civilization have always been intrigued by their origin and the origin of life itself. For thousands of years, the comforting theory of spontaneous generation seemed to provide an answer to this enduring question. In ancient China, people thought that aphids were spontaneously generated from bamboos. Sacred documents from India mention the spontaneous formation of flies from dirt and sweat. Babylonian inscriptions indicate that mud from canals was able to generate worms.

For the Greek philosophers, life was inherent to matter. It was eternal and appeared spontaneously whenever the conditions were favorable. These ideas were clearly stated by Thales, Democritus, Epicurus, Lucretius, and even by Plato. Aristotle gathered the different claims into a real theory. This theory safely crossed the Middle Ages and the Renaissance. Famous thinkers such as Newton, Descartes, and Bacon supported the idea of spontaneous generation.

The first experimental approach to the question was published in the middle of the 17th century, when the Flemish physician Van Helmont reported the gener-

ation of mice from wheat grains and a sweat-stained shirt. He was quite amazed to observe that they were identical to those obtained by procreation. A controversy arose in 1668, when Redi, a Toscan physician, published a set of experiments demonstrating that maggots did not appear when putrefying meat was protected from flies by a thin muslin covering.

Six years after Redi's treatise, the Dutch scientist Anton Van Leeuwenhoek observed microorganisms for the first time through a microscope that he made himself. From then on, microorganisms were found everywhere and the supporters of spontaneous generation took refuge in the microbial world. However, Van Leeuwenhoek was already convinced that the presence of microbes in his solutions was the result of contamination by ambient air. In 1718, his disciple Louis Joblot demonstrated that the microorganisms observed in solutions were, indeed, brought in from the ambient air, but he could not convince the naturalists.

Even Buffon, in the middle of the 18th century, thought that nature was full of the germs of life able to scatter during putrefaction and to gather again, later on, to reconstitute microbes. His Welsh friend John Needham undertook many experiments to support this view. He heated organic substances in water in a sealed flask in order to sterilize the solutions. After a while, all solutions showed a profusion of microbes. The Italian priest Lazzaro Spallanzani argued that the sterilization was incomplete. He heated the solutions to a higher temperature and killed all the microbes, but he could not kill the idea of microbial spontaneous generation.

The controversy reached its apotheosis one century later when Felix Pouchet published his treatise in 1860. He documented the theory of spontaneous generation in the light of experiments that, in fact, were the results of contamination by ambient air. Pasteur gave the finishing blow to spontaneous generation in June 1864 when he designed a rigorous experimental set up for sterilization. By using flasks with long necks that had several bends and were filled with sterilized broth or urine, he showed that no life appeared in the infusions as long as the flask remained intact.

The beautiful demonstration of Pasteur opened the fascinating question of the historical origin of life. Because life can originate only from preexisting life, it has a history and therefore an origin, which must be understood and explained by chemists.

Charles Darwin first formulated the modern approach to the chemical origin of life. In February 1871, he wrote in a private letter to Hooker:

> If (and oh, what a big if) we could conceive in some warm little
> pond, with all sorts of ammonia and phosphoric salts, light, heat,
> electricity, etc., present that a protein compound was chemically
> formed, ready to undergo still more complex changes, at the present
> day such matter would be instantly devoured or adsorbed, which
> would not have been the case before living creatures were formed.

For 50 years, the idea lay dormant. In 1924, the young Russian biochemist Aleksander Oparin pointed out that life must have arisen in the process of the evolution of matter thanks to the nature of the atmosphere, which was considered

to be reducing. In 1928, the British biologist J. B. S. Haldane, independently of Oparin, speculated on the early conditions suitable for the emergence of life. Subjecting a mixture of water, carbon dioxide, and ammonia to UV light should produce a variety of organic substances, including sugars and some of the materials from which proteins are built up. Before the emergence of life they must have accumulated in water to form a hot, dilute "primordial soup." Almost 20 years after Haldane's publication, J. D. Bernal conjectured that clay mineral surfaces were involved in the origin of life. In 1953, Stanley Miller, a young student of Harold Urey, reported the formation of four amino acids – glycine, alanine, aspartic acid and glutamic acid – when he subjected a mixture of methane, ammonia, hydrogen, and water to electric discharges. Miller's publication really opened the field of experimental prebiotic chemistry (see Chapter 3).

1.1.2
Searching for Emerging Life

Defining life is a difficult task, and the intriguing and long lasting question "What is life?" has not yet received a commonly accepted answer, even for what could be defined as *minimal life*, the simplest possible form of life. On the occasion of a Workshop on Life, held in Modena, Italy, in 2003, each member of the International Society for the Study of the Origins of Life was asked to give a definition of life. The 78 different answers occupy 40 pages in the proceedings of the workshop.

Perhaps the most general working definition is that adopted in October 1992 by the NASA Exobiology Program: "Life is a self-sustained chemical system capable of undergoing Darwinian evolution." Implicit in this definition is the fact that the system uses external matter and energy provided by the environment. In other words, primitive life can be defined, *a minima*, as an open chemical system capable of self-reproduction, i.e., making more of itself by itself, and capable of evolving. The concept of evolution implies that the chemical system normally transfers its information fairly faithfully but makes a few random errors. These may potentially lead to higher complexity/efficiency and possibly to better adaptation to changes in the existing environmental constraints.

Schematically, the premises of an emerging life can be compared to parts of "chemical robots." By chance, some parts self-assembled to generate robots capable of assembling other parts to form identical robots. Sometimes, a minor error in the building generated more efficient robots, which became the dominant species.

In a first approach, present life, based on carbon chemistry in water, is generally used as a reference to provide guidelines for the study of the origins of life and for the search for extraterrestrial life. It is generally assumed that the primitive robots emerged in liquid water and that the parts were already organic molecules. The early molecules that contain carbon and hydrogen atoms associated with oxygen, nitrogen, and sulfur atoms are often called the CHONS, where C stands for carbon, H for hydrogen, O for oxygen, N for nitrogen, and S for sulfur.

1.1.3
The Role of Water

Liquid water played a major role in the appearance and evolution of life by favoring the diffusion and exchange of organic molecules. Liquid water has many peculiarities. Water molecules establish hydrogen bonds with molecules containing hydrophilic groups. In water, organic molecules containing both hydrophilic and hydrophobic groups self-organize in response to these properties. This duality generates interesting prebiotic situations, such as the stereo-selective aggregation of short peptide sequences of alternating hydrophobic– hydrophilic residues into thermostable β-sheet structures endowed with chemical activity, as shown below.

In addition to H-bonding capability, water exhibits a large dipole moment (1.85 debye) as compared to alcohols (<1.70 debye). This large dipole moment favors the dissociation of ionizable groups such as $-NH_2-$ and $-COOH$-generating ionic groups, which can form additional H bonds with water molecules, thus improving their solubility.

With a high dielectric constant ε of 80, water is an outstanding dielectric compound. When organic groups with opposite charges Q and Q', separated by a distance r, are formed, their recombination is unfavorable because the force of attraction for reassociation is given by

$$F = Q \times Q'/\varepsilon \times r^2. \tag{1.1}$$

This is also true for metal ions, which have probably been associated with organic molecules since the beginning of life.

Liquid water was probably active in prebiotic chemistry as a clay producer and heat dissipator. Further, liquid water is a powerful hydrolytic chemical agent. As such, it allows pathways for chemical combinations that would have few chances to occur in an organic solvent. Liquid water is therefore generally considered as a prerequisite for the emergence of life on Earth.

1.1.4
The Physicochemical Features of Carbon-based Life

Life is autocatalytic in essence and is able to evolve. To evolve, i.e., to increase its diversity, the molecules bearing the hereditary memory must be able to be extended and diversified by combinatorial dispersive reactions. This can best be achieved with a scaffolding of polyvalent atoms. From a chemical viewpoint, carbon chemistry is by far the most productive in this respect. Another clue in favor of carbon is provided by radio astronomers: about 90 carbon-containing molecules have been identified in the interstellar medium while only 9 silicon-based molecules have been detected (see Chapter 2). To generalize, a carbon-based life is not just an anthropocentric view, it appears as a highly plausible prerequisite.

Carbon atoms exhibit two remarkable features relative to life, one-handedness and stable isotope distribution. One-handedness, also called homochirality (from

the Greek *kheiros,* the hand), of the proteins synthesized via the genetic code is a characteristic of all living systems (see Chapter 3). Each central carbon atom of the amino acid molecule occupies the center of a tetrahedron. Except for the amino acid glycine, the four substituents of the central carbon atom are different. The carbon atom is therefore asymmetrical and it is not superimposable onto its mirror image. Each amino acid exists in two mirror-image forms called enantiomers (from the Greek *enantios,* opposed). All protein amino acids have the same handedness: they are homochiral. They are left-handed and hence known as L-amino acids. Their right-handed mirror images are known as D-amino acids. L-amino acids engaged in a protein chain generate right-handed, single-strand α-helices and asymmetrical, multi-strand β-sheet structures. Nucleotides, the building blocks of the nucleic acids DNA and RNA, are also homochiral. Their nomenclature is more complex because each nucleotide possesses four asymmetrical carbon atoms. In this case, the geometry of a selected carbon atom was chosen. Following this convention, nucleotides are right-handed. Right-handed nucleotides generally generate right-handed helical nucleic acids.

Pasteur was probably the first to realize that biological asymmetry could best distinguish between inanimate matter and life. Life that would simultaneously use both right- and left-handed forms of the same biological molecules appears very unlikely for geometrical reasons. For example, enzyme β-pleated sheets cannot form when both L- and D-amino acids are present in the same molecule. Because the catalytic activity of an enzyme is intimately dependent upon the geometry of the chain, the absence of β-pleated sheets would impede, or at least considerably reduce, the activity spectrum of the enzymes. The use of one-handed biomonomers also sharpens the sequence information of the biopolymers. For a polymer made of *n* units, the number of sequence combinations will be divided by 2^n when the system uses only homochiral (one-handed) monomers. Taking into account the fact that enzyme chains are generally made up of hundreds of monomers, and that nucleic acids contain several million nucleotides, the tremendous gain in simplicity offered by the use of monomers restricted to one handedness is self-evident.

Finally, if the biopolymers to be replicated were to contain L- and D-units located at specific sites, the replication process would have to not only be able to position the right monomers at the right place but also select the right enantiomer from among two species, which differ only by the geometry of the asymmetrical carbon atoms. For example, the bacterium *Bacillus brevis* is able to synthesize the peptide gramicidin A, which is constructed on a strict alternation of left- and right-handed amino acids. However, the biosynthesis of this peptide involves a set of complex and sophisticated enzymes that are homochiral.

Life on Earth uses homochiral left-handed amino acids and right-handed sugars. A mirror-image life, using right-handed amino acids and left-handed sugars, is perfectly conceivable and might have developed on another planet. Thus, homochirality is generally considered a crucial signature for life.

The uptake of carbon dioxide by living systems can produce biomolecules enriched in ^{12}C carbon isotopes at the expense of ^{13}C isotopes. For example, on Earth, over 1 600 samples of fossil kerogen (a complex organic macromolecule

produced from the debris of biological matter) have been compared with carbonates in the same sedimentary rocks. The organic matter is enriched in ^{12}C by about 25‰. This offset is now taken to be one of the most powerful indications that life on Earth was active nearly 3.9 billion years ago, because the sample suite encompasses specimens right across the geologic timescale.

1.1.5
Clays as Possible Primitive Robots

Any scientist who has observed the crystallization of minerals initiated by the addition of seeds to a supersaturated solution is tempted to associate life with mineral crystals. Jean Schneider, for example, suggested that complex dislocation networks encountered in crystals may, in some cases, follow the criteria of living units and lead to a crystalline physiology. He also discussed the places of possible occurrence in nature of this kind of physiology, such as terrestrial and extraterrestrial rocks, interplanetary dust, white dwarfs, and neutron stars.

According to Cairns-Smith, there is no compelling reason to necessarily relate the last common ancestor made of organic molecules with first life. Although the easy accessibility of numerous organic building blocks of life has been demonstrated experimentally, the dominant use of these molecules in living organisms can be seen as a result of evolution rather than a prerequisite for its initiation. Cairns-Smith proposed that the first living systems, and the chemical evolution preceding it, might have been based on a chemistry different from that which we know. The structurally and functionally complex genetic system of modern life arose subsequently in a living organism using a less efficient primary system with a much higher probability of spontaneous assembly. As genetic candidates, he advocated crystalline inorganic materials presenting suitable properties, such as the ability to store and replicate information in the form of defaults, dislocations, and substitutions. Clay minerals, such as kaolinite, are particularly attractive because they form at ambient temperatures from aqueous weathering of silicate rock.

The following "genetic takeover" scenario was proposed by Cairns-Smith as a mineral origin of life. Certain clays having properties that favor their synthesis proliferated, and their replication defects, likewise, became more common. In certain clay lineages, the development of crude photochemical machinery favored the synthesis of some non-clay species, such as polyphosphates and small organic compounds. Natural selection favored these lineages of clays because the organic compounds they produce catalyzed the clay formation. Multiple-step pathways of high specificity, including chiral stereoselection, arose through specific adsorption, followed by the appearance of polymers of specified sequence, at first serving only structural roles. Base-paired polynucleotides replicated, giving rise to secondary and minor genetic material. This secondary material proved to be useful in the alignment of amino acids for polymerization. The ability to produce specific enzymes came concomitantly with the ability to produce sequence-specified polypeptides and proteins. More-efficient pathways of organic synthesis ensued, and

finally the clay machinery was dispensed with in favor of a polynucleotide-based replication–translation system. Although each step of the hypothetical sequence of events was developed in detail, the scenario has not been supported by experimental facts.

1.2
Reconstructing Life in a Test Tube

It is now a generally accepted conception that life emerged in water and that the first self-reproducing molecules and their precursors were probably organic molecules built up with carbon atom skeletons. Organic molecules were formed from gaseous molecules containing carbon atoms (methane, carbon dioxide, carbon monoxide), nitrogen atoms (nitrogen, ammonia), or sulfur atoms (hydrogen sulfide, sulfur oxide). The energy for these reactions came from electric discharges, cosmic and UV radiation, or heat.

1.2.1
The Quest for Organic Molecules

1.2.1.1   Terrestrial Production

In 1953, Stanley Miller exposed a mixture of methane, ammonia, hydrogen, and water to electric discharges to mimic the effects of lightning. Among the compounds formed, he identified 4 of the 20 naturally occurring amino acids, the building blocks of proteins. Since this historic experiment, 17 natural amino acids have been obtained via the intermediate formation of simple precursors, such as hydrogen cyanide and formaldehyde. It has been shown that spark discharge synthesis of amino acids occurs efficiently when a reducing gas mixture containing significant amounts of hydrogen is used (see Chapter 3). However, the true composition of the primitive Earth atmosphere remains unknown. Today, geochemists favor a non-reducing atmosphere dominated by carbon dioxide. Under such conditions, the production of amino acids appears to be very limited. Strongly reducing environments capable of reducing carbon dioxide were necessary for the synthesis of amino acids.

Deep-sea hydrothermal systems may represent suitable reducing environments for the synthesis of prebiotic organic molecules. The ejected gases contain carbon dioxide, carbon monoxide, sulfur dioxide, nitrogen, and hydrogen sulfide. For instance, high concentrations of hydrogen (more than 40% of the total gas) and methane have been detected in the fluids of the Rainbow ultramafic hydrothermal system of the Mid-Atlantic Ridge. The production of hydrogen, a highly reducing agent favoring prebiotic syntheses, is associated with the hydrous alteration of olivine into serpentine and magnetite, a reaction known as "serpentinization." Indeed, hydrocarbons containing 16 to 29 carbon atoms have been detected in these hydrothermal fluids. Amino acids have been obtained, although in low yields, under conditions simulating these hydrothermal vents.

According to Wächtershäuser (1994), primordial organic molecules formed near the hydrothermal systems; the energy source required to reduce the carbon dioxide might have been provided by the oxidative formation of pyrite (FeS_2), from iron sulfide (FeS) and hydrogen sulfide (H_2S). Pyrite has positive surface charges and bonds the products of carbon dioxide reduction, giving rise to a two-dimensional reaction system, a "surface metabolism." Laboratory work has provided support for this promising new "metabolism-first" approach. Iron sulfide, hydrogen sulfide, and carbon dioxide react under anaerobic conditions to produce hydrogen and a series of thiols, including methanethiol. Methanethiol and acetic acid have also been obtained from carbon monoxide, hydrogen sulfide, iron and nickel sulfides, and catalytic amounts of selenium. Under specific conditions, thioesters are formed that might have been the metabolic driving force of a "thioester world," according to de Duve (1998). Thioesters are sulfur-bearing organic compounds that presumably would have been present in a sulfur-rich, volcanic environment on the early Earth.

Hydrothermal vents are often disqualified as efficient reactors for the synthesis of bioorganic molecules because of their high temperature. However, the products that are synthesized in hot vents are rapidly quenched in the surrounding cold water, which may preserve those organics formed.

1.2.1.2 Delivery of Extraterrestrial Organic Molecules

Comets and meteorites may have delivered important amounts of organic molecules to the primitive Earth (see Chapter 3). Nucleic acid bases, purines, and pyrimidines have been found in the Murchison meteorite. One sugar (dihydroxyacetone), sugar alcohols (erythritol, ribitol), and sugar acids (ribonic acid, gluconic acid) have been detected in the Murchison meteorite, but ribose, the sugar moiety of ribonucleotides, themselves the building blocks of RNAs (see Chapter 4), has not been detected.

Eight proteinaceous amino acids have been identified in one such meteorite, among more than 70 amino acids found therein. Cronin and Pizzarello (1997) found an excess of about 9 % of L-enantiomers for some non-protein amino acids detected in the Murchison meteorite. The presence of L-enantiomeric excesses in these meteorites points towards an extraterrestrial process of asymmetric synthesis of amino acids asymmetry that is preserved inside the meteorite. These excesses may help us to understand the emergence of biological asymmetry or one-handedness. The excess of one-handed amino acids found in the meteorites may result from the processing of the organic mantles of the interstellar grains from which the meteorite was originally formed. That processing could occur, for example, by the effects of circularly polarized synchrotron radiation from a neutron star, a remnant of a supernova. On the other hand, strong infrared circular polarization, resulting from dust scattering in reflection nebulae in the Orion OMC-1 star formation region, has been observed by Bailey. Circular polarization at shorter wavelengths might have been important in inducing this chiral asymmetry in interstellar organic molecules that could be subsequently delivered to the early Earth.

Dust collection in the Greenland and Antarctic ice sheets and its analysis by Maurette show that the Earth captures interplanetary dust as micrometeorites at a rate of about 20 000 tons per year. About 99 % of this mass is carried by micrometeorites in the 50–500 μm size range. This value is much higher than the most reliable estimate of the normal meteorite flux, which is about 10 tons per year. A high percentage of micrometeorites in the 50–100 μm size range have been observed to be unmelted, indicating that a significant fraction traversed the terrestrial atmosphere without drastic heating. In this size range, the carbonaceous micrometeorites represent 20 % of the incoming micrometeorites, and they contain 2.5 % carbon on average. This flux of incoming micrometeorites might have brought to the Earth about 2.5×10^{22} g carbon over the period corresponding to the late heavy bombardment. As inferred from the lunar craters, during this period planetesimals, asteroids, and comets impacted the Earth until about 3.85 billion years ago (see Chapter 2). For comparison, this delivery represents more carbon than is in the present surficial biomass, which amounts to about 10^{18} g. In addition to organic compounds, these grains contain a high proportion of metallic sulfides, oxides, and clay minerals that belong to various classes of catalysts. In addition to the carbonaceous matter, micrometeorites might also have delivered a rich variety of catalysts. These may have functioned as tiny chemical reactors when reaching oceanic water.

On 15 January 2006, the *Stardust* reentry probe brought cometary grains to the Earth for the first time. The preliminary analyses of these grains from comet Wild-2 confirmed that micrometeorites are probably witnesses of a chemical continuum – via the cometary grains – from the interstellar medium, where they form, to terrestrial oceans. Comets are the richest planetary objects in organic compounds known so far. Ground-based observations have detected hydrogen cyanide and formaldehyde in the coma of comets.

In 1986, onboard analyses performed by the two Russian missions *Vega 1* and *Vega 2*, as well as observations obtained by the European mission *Giotto* and the two Japanese missions *Suisei* and *Sakigake*, demonstrated that Halley's Comet shows substantial amounts of organic material. On average, dust particles ejected from Halley's nucleus contain 14 % organic carbon by mass. About 30 % of cometary grains were dominated by the light elements C, H, O, and N, and 35 % are close in composition to the carbon-rich meteorites. The presence of organic molecules, such as purines, pyrimidines, and formaldehyde polymers, has been inferred from the fragments analyzed by the *Giotto* PICCA and *Vega* PUMA mass spectrometers. However, there was no direct identification of the complex organic molecules probably present in the cosmic dust grains and in the cometary nucleus.

Many chemical species of interest for exobiology were detected in Comet Hyakutake in 1996, including ammonia, methane, acetylene (ethyne), acetonitrile (methyl cyanide), and hydrogen isocyanide. The study of the Hale-Bopp Comet in 1997 led to the detection of methane, acetylene, formic acid, acetonitrile, hydrogen isocyanide, isocyanic acid, cyanoacetylene, formamide, and thioformaldehyde.

It is possible, therefore, that cometary grains might have been an important source of organic molecules delivered to the primitive Earth. Comets orbit on unstable trajectories and sometimes collide with planets. The collision of Comet

Shoemaker-Levy 9 with Jupiter in July 1994 is a recent example of such an event. Such collisions were probably more frequent 4 billion years ago, when the comets orbiting around the Sun were more numerous than today. By impacting the Earth, comets probably delivered a substantial fraction of the terrestrial water (about 35 % according to the estimation of Owen based on the relative contents in hydrogen and deuterium) in addition to organic molecules. The chemistry that is active at the surface of a comet is still poorly understood. The European mission *Rosetta*, launched in 2004, will analyze the nucleus of the comet 67 P/Churyumov-Gerasimenko. The spacecraft will first study the environment of the comet during a flyby over several months, and then a probe will land to analyze the surface and the subsurface ice sampled by drilling.

1.2.2
Space Experiments

Ultraviolet (UV) irradiation of dust grains in the interstellar medium may result in the formation of complex organic molecules. The interstellar dust particles are assumed to be composed of silicate grains surrounded by ices of different molecules, including carbon-containing molecules (see Chapter 3). In a laboratory experiment, ices of H_2O, CO_2, CO, CH_3OH, and NH_3 were deposited at 12 K under a pressure of 10^{-5} Pa (10^{-7} mbar) and were then irradiated by electromagnetic radiation representative of that in the interstellar medium. The solid layer that developed on the solid surface was analyzed by enantioselective gas chromatography coupled with mass spectrometry (GC-MS). After the analytical steps of extraction, hydrolysis, and derivatization, 16 amino acids were identified in the simulated ice mantle of interstellar dust particles. These experiments confirmed the preliminary amino acid formation obtained first by Greenberg. The chiral amino acids were identified as being totally racemic (consisting of equal amounts of D- and L-enantiomers). Parallel experiments performed with ^{13}C-containing substitutes definitely excluded contamination by biological amino acids. The results strongly suggest that amino acids are readily formed in interstellar space.

Before reaching the Earth, organic molecules are exposed to UV radiation, both in interstellar space and in the Solar System. Amino acids have been exposed in Earth orbit to study their survival in space. The UV flux of wavelengths <206 nm in the diffuse interstellar medium is about 10^8 photons cm^{-2} s^{-1}. In Earth orbit, the corresponding solar flux is in the range of 10^{16} photons cm^{-2} s^{-1}. This means that an irradiation over one week in Earth orbit corresponds to that over 275 000 years in the interstellar medium. Thin films of amino acids, like those detected in the Murchison meteorite, have been exposed to space conditions in Earth orbit within the BIOPAN facility of the European Space Agency (ESA) onboard the unmanned Russian satellites *Foton 8* and *Foton 11* (see Chapter 11). Aspartic acid and glutamic acid were partially destroyed during exposure to solar UV. However, decomposition was prevented when the amino acids were embedded in clays.

Amino acids and peptides have also been subjected to solar radiation outside the MIR station for 97 days. After three months of exposure, about 50 % of the amino

acids were destroyed in the absence of mineral shielding. Peptides exhibited a noticeable sensitivity to space vacuum, and sublimation effects were detected. Decarboxylation was found to be the main effect of photolysis. No polymerization occurred and no racemization (the conversion of L- or D-amino acids into a racemic mixture) was observed. Some samples were embedded into mineral material (montmorillonite clay, basalt, or Allende meteorite) when exposed to space. Among the different minerals, the meteoritic powder offered the best protection, whereas the clay montmorillonite was the least efficient. Different thicknesses of meteorite powder films were used to estimate the shielding threshold. Significant protection from solar UV radiation was observed when the thickness of the meteorite mineral was 5 µm or greater.

1.2.3
Attempts to Recreate Life in a Test Tube

By analogy with contemporary living systems, it was long considered that primitive life emerged as cellular entities, requiring boundary molecules able to isolate the system from the aqueous environment (membrane). Further, catalytic molecules would be needed to provide the basic chemical work of the cell (enzymes), as well as information-retaining molecules that allow the storage and transfer of the information needed for replication (RNA).

Fatty acids are known to form vesicles when the hydrocarbon chains contain more than 10 carbon atoms. Such vesicle-forming fatty acids have been identified in the Murchison meteorite by Deamer (1985). However, the membranes obtained with these simple amphiphiles are not stable over a broad range of conditions. Stable neutral lipids can be obtained by condensing fatty acids with glycerol or with glycerol phosphate, thus mimicking the stable contemporary phospholipid. Primitive membranes also could initially have been formed by simple isoprene derivatives.

Most of the catalytic chemical reactions in a living cell are achieved by proteinaceous enzymes made of 20 different homochiral L-amino acids. Amino acids were most likely available on the primitive Earth as complex mixtures, but the formation of mini-proteins from the monomers in water is not energetically favored. Because the peptide bond of proteins is thermodynamically unstable in water, it requires an energy source, such as heat or condensing chemicals, to link two amino acids together in an aqueous milieu. Oligoglycines up to the octamer have been obtained from glycine in a flow reactor simulating hydrothermal circulation. These compounds were formed by repeatedly circulating solutions of glycine and $CuCl_2$ from a high-pressure, high-temperature chamber to a high-pressure, low-temperature chamber, simulating conditions in a hydrothermal vent. Clays and salts may also be used to condense free amino acids in water. When subjecting mixtures of glycine and kaolinite to wet–dry cycles and 25–94 °C temperature fluctuations, the formation of oligopeptides up to five glycines long has been observed.

Bulk thermal condensation of amino acids has been described by Fox, who has shown that dry mixtures of amino acids polymerize when heated to 130 °C to give "proteinoids." In the presence of polyphosphates, the temperature can be decreased

to 60 °C. High molecular weights were obtained when an excess of acidic or basic amino acids was present. In aqueous solutions, the proteinoids aggregated spontaneously to form microspheres of 1–2 μm, presenting an interface resembling the lipid bilayers of living cells. The microspheres increased slowly in size from dissolved proteinoids and were sometimes able to bud and to divide. These microspheres were described as catalyzing the decomposition of glucose and were able to work as esterases and peroxidases. The main advantage of proteinoids is their organization into particles, but they also represent a dramatic increase in complexity.

The number of condensing agents capable of assembling amino acids into peptides in water is limited, especially when looking for prebiotically plausible compounds. Carbodiimides, having a general formula R-N=C=N-R', power the ligation of both glutamic and aspartic acids on hydroxyapatite. The simplest carbodiimide, H-N=C=N-H, can be considered a transposed form of cyanamide (NH_2-CN), which is present in the interstellar medium. In water, cyanamide forms a dimer, dicyandiamide, which is as active as carbodiimides in forming peptides. However, the reactions are very slow and do not proceed beyond the tetrapeptide.

Oligomers of glutamic acid greater than 45 amino acids in length were formed on hydroxyapatite and illite after 50 feedings with glutamic acid and the condensing agent carbonyldiimidazole (Im-CO-Im). Amino acid adenylate anhydrides have been reported to condense readily in the presence of montmorillonite. According to de Duve (1998), the first peptides may have appeared via thioesters, which generate short peptides in the presence of mineral surfaces. Among the most effective activated amino acid derivatives for the formation of oligopeptides in aqueous solution are the *N*-carboxyanhydrides.

Chemical reactions capable of selectively condensing protein amino acids more readily than non-protein ones have been described. Helical and sheet structures may be modeled with the aid of only two different amino acids, the first one being hydrophobic and the second hydrophilic. Polypeptides with alternating hydrophobic and hydrophilic residues adopt a water-soluble β-sheet geometry because of hydrophobic side-chain clustering. Because of the formation of β-sheets, alternating sequences display a good resistance toward chemical degradation. Aggregation of alternating sequences into β-sheets is possible only with homochiral (all L or all D) polypeptides, as demonstrated by this author at the Centre de Biophysique Moléculaire in Orléans, France. Short peptides have also been found to exhibit catalytic properties.

In contemporary living systems, the hereditary memory is stored in nucleic acids built up with bases (purine and pyrimidine), sugars (ribose for RNA, deoxyribose for DNA), and phosphate groups. The accumulation of significant quantities of natural RNA nucleotides does not appear to be a plausible chemical event on the primitive Earth. Purines are easily obtained from hydrogen cyanide or by subjecting reduced gas mixtures to electric discharges. No successful pyrimidine synthesis from electrical discharges has been published so far, whereas hydrogen cyanide affords only very small amounts of these bases. Condensation of formaldehyde leads to ribose as well as a large number of other sugars. Although the synthesis of purine nucleosides (the combination of purine and ribose) and of nucleotides has

been achieved by heating the components in the solid state, the yields are very low and the reactions are not regioselective. Interestingly, very effective montmorillonite-catalyzed condensation of nucleotides into oligomers up to 55 monomers long has been reported by Ferris from nucleoside phosphorimidazolides.

The synthesis of oligonucleotides is much more efficient in the presence of a preformed, pyrimidine-rich polynucleotide acting as a template. Non-enzymatic replication has been demonstrated by Orgel. The preformed chains align the nucleotides by base-pairing to form helical structures that bring the reacting groups into close proximity. However, the prebiotic synthesis of the first oligonucleotide chains remains an unsolved challenge.

1.2.4
A Primitive Life Simpler than a Cell?

Thomas Cech found that some RNAs, the ribozymes, have catalytic properties (see Chapter 4). For example, they increase the rate of hydrolysis of oligoribonucleotides. They also act as polymerization templates, because chains up to 30 monomers long can be obtained starting from a pentanucleotide. Since this primary discovery, the catalytic spectrum of these ribozymes has been considerably enlarged by the directed test tube molecular evolution experiments initiated in the laboratories of Gerald Joyce and Jack Szostak. Since RNA was shown to be able to act simultaneously as genetic material and as a catalyst, RNA has been considered the first living system on the primitive Earth (the "RNA world"). This is because it can simultaneously be the genotype and the phenotype and can fulfill the basic cycle of life consisting of self-replication, mutation, and selection. Strong evidence for this proposal has been obtained from the discovery that modern protein synthesis in the ribosome is catalyzed by RNA. One should, however, remember that RNAs synthesis under prebiotic conditions remains an unsolved challenge. It seems unlikely that life started with RNA molecules, because these molecules are not simple enough. The RNA world appears to have been an episode in the evolution of life before the appearance of cellular microbes rather than the spontaneous birth of life.

RNA analogues and surrogates have been studied. The initial proposal was that the first RNA was a flexible, achiral derivative in which ribose was replaced by glycerol, but these derivatives did not polymerize under prebiotic conditions. The ease of forming pyrophosphate (double phosphate) bonds prompted investigation of linking nucleotides by pyrophosphate groups. This proposal was tested using the reactions of the diphosphorimidazolides of deoxynucleotides. Their reaction in the presence of magnesium or manganese ions resulted in the formation of 10–20 mers of the oligomers.

Considering the ease of formation of hexose-2,4,6-triphosphates from glycolaldehyde phosphate in a process analogous to the formose reaction, Eschenmoser and coworkers chemically synthesized polynucleotides containing hexopyranose ribose (pyranosyl-RNA or p-RNA) in place of the usual "natural" pentofuranose ribose found in RNA. p-RNAs form Watson-Crick-paired double helices that are more stable than RNA. Furthermore, the helices have only a weak twist, which

should make it easier to separate strands during replication. Replication experiments have had marked success in terms of sequence copying but have failed to demonstrate template-catalysis turnover numbers greater than 1. The chemical synthesis of threo furanosyl nucleic acid (TNA), an RNA analogue built on the furanosyl form of the tetrose sugar threose, was also reported by the Eschenmoser group. TNA strands are much more stable in aqueous solution than RNA and are resistant to hydrolysis. They form complementary duplexes between complementary strands. Moreover, of even greater potential importance, they form complementary strands with RNA. This raises the possibility that TNAs could have served as templates for the formation of complementary RNAs by template-directed synthesis. TNA is a more promising precursor to RNA than p-RNA, because tetroses have the potential to be synthesized from glycolaldehyde phosphate and two other carbon precursors, which may have been present in quantities greater than those of ribose on the primitive Earth.

Peptide nucleic acids (PNA), first synthesized by Nielsen and coworkers, consist of a peptide-like backbone to which nucleic acid bases are attached. PNAs form very stable double-helical structures with complementary strands of PNA (PNA-PNA), DNA (PNA-DNA), RNA (PNA-RNA), and even stable PNA_2-DNA triple helices. Information can be transferred from PNA to RNA, and vice versa, in template-directed reactions. Although PNA hydrolyzes rather rapidly, thus considerably restricting the chances of PNA ever having accumulated in the primitive terrestrial oceans, the PNA-PNA double helix illustrates that genetic information can be stored in a broad range of double-helical structures.

Chemists are also tempted to consider that primitive self-replicating systems must have used simpler informational molecules than biological nucleic acids or their analogues. Because self-replication is, by definition, autocatalysis, they are searching for simple autocatalytic molecules capable of mutation and selection. Reza Ghadiri tested peptides as possible templates, and non-biological organic molecules have been screened by Günter von Kiedrowski. In most cases, the rate of the autocatalytic growth was not linear. The initial rate of autocatalytic synthesis was found to be proportional to the square root of the template concentration: the reaction order in these autocatalytic self-replicating systems was found to be 1/2 rather than 1, a limiting factor as compared to most autocatalytic reactions known so far. Autocatalytic reactions are particularly attractive because they might amplify small enantiomeric excesses, eventually extraterrestrial, to homochirality.

1.3
The Search for Traces of Primitive Life

1.3.1
Microfossils

The first descriptions of fossil microorganisms in the oldest, well-preserved sediments (3.5–3.3 billion years old) from Australia and South Africa were made by

William Schopf and Elso Barghoorn. Although their observations have been called into question, Westall and others have more recently established that life was abundant in these rocks. From a theoretical point of view, the earliest forms of life would most likely have had a chemolithoautotrophic metabolism, using inorganic materials as a source of both carbon and energy. Evidence for the presence of chemolithotrophs in the hydrothermal deposits from Barberton and the Pilbara comes from the N and C isotopic data. Considering the high temperatures on the early Earth, it is probable that the earliest microorganisms were thermophilic. Structures resembling oxygenic photosynthetic microorganisms such as cyanobacteria have been described, and carbon isotope data have been interpreted as evidence for their presence. However, these interpretations are strongly disputed. Nevertheless, the fact that the microorganisms inhabiting the early Archean environments of Barberton (South Africa) and Pilbara (Australia) formed mats in the photic zone suggests that some of them may already have developed anoxygenic photosynthesis.

1.3.2
Oldest Sedimentary Rocks

The oldest sedimentary rocks occur in southwest Greenland and have been dated at 3.8–3.85 billion years by Manfred Schidlowski and Stephen Mozsis. The old sediments testify to the presence of permanent liquid water on the surface of the Earth and to the presence of carbon dioxide in the atmosphere. They contain organic carbon. Minik Rosing found that the isotopic signatures of the organic carbon found in Greenland meta-sediments provide indirect evidence that life may be 3.85 billion years old. Taking the age of the Earth as about 4.6 billion years, this means that life must have begun quite early in Earth's history. Although there are serious reservations concerning these studies (contamination by more recent fossilized endoliths, ^{12}C enrichment produced by thermal decomposition of siderite and metamorphic processes), stepped combustion analysis by Mark von Zuilen has verified the existence of the ^{12}C enrichment in these sediments.

1.4
The Search for Life in the Solar System

1.4.1
Planet Mars and the SNC Meteorites

The mapping of Mars by the spacecrafts *Mariner 9*, *Viking 1* and *Viking 2, Mars Global Surveyor*, and *Mars Express* revealed channels and canyons resembling dry riverbeds (see Chapter 8). The gamma-ray spectrometer instrument onboard the Mars orbiter *Odyssey* detected hydrogen, which indicates the presence of water ice in the upper meter of soil in a large region surrounding the planet's south pole, where ice is expected to be stable. The amount of hydrogen detected indicates 20–

50 % ice by mass in the lower layer beneath the topmost surface. The ice-rich layer is about 60 cm beneath the surface at latitude 60 °S and approaches 30 cm of the surface at latitude 75 °S. The ancient presence of liquid water on the surface of Mars was confirmed by the two American Mars Exploration Rovers (MER A and B), *Spirit* and *Opportunity*, and by the presence of sulfates and clays revealed by the infrared spectrometer OMEGA onboard the European Mars orbiter *Mars Express*. However, Martian oceans were probably restricted to the very early stages of Martian history. Mars therefore possessed an atmosphere capable of decelerating carbonaceous micrometeorites, and chemical evolution may have been possible on the planet.

The *Viking 1* and *Viking 2* lander missions were designed to address the question of extant (rather than extinct) life on Mars (see Chapter 5). Three experiments were selected to detect metabolic activity, such as photosynthesis, nutrition, and respiration of potential microbial soil communities. The results were ambiguous, because although "positive" results were obtained, no organic carbon was found in the Martian soil by gas chromatography–mass spectrometry (GC-MS). It was concluded that the most plausible explanation for these results was the presence at the Martian surface of highly reactive oxidants, such as hydrogen peroxide, which would have been photochemically produced in the atmosphere. Direct photolytic processes were suggested to be responsible for the degradation of organics at the Martian surface. Because the *Viking* landers could not sample soils below 6 cm, the depth of this apparently organic-free and oxidizing layer is still unknown. More information is expected from the upcoming lander missions to Mars: the U. S. *Mars Science Laboratory* (MSL) to be launched in 2009 and the European *ExoMars* mission to be launched in 2013 (see Chapter 12).

There are Martian rocks on Earth represented by a small group of meteorites of igneous (volcanic) origin, known as the SNC meteorites (after their type specimens Shergotty, Nakhla, and Chassigny), that had comparatively young crystallization ages, equal to or less than 1.3 billion years (see Chapter 8). One of these meteorites, designated EETA79001, was found in Antarctica in 1979. It had gas inclusions trapped within a glassy component. Both compositionally and isotopically, this gas matched the makeup of the Martian atmosphere, as measured by the *Viking* mass spectrometer. The data provide a very strong argument that at least that particular SNC meteorite came from Mars, representing the product of a high-energy impact that ejected material into space. There are now 34 SNC meteorites known in total.

Two of the SNC meteorites, EETA79001 and ALH84001, supply new and highly interesting information. A subsample of EETA79001, excavated from deep within the meteorite, has been subjected to stepped combustion. The CO_2 release from 200–400 °C suggested the presence of organic molecules. The carbon is enriched in ^{12}C, and the carbon isotope difference between the organic matter and the carbonates in Martian meteorites is greater than that observed on Earth. This could be indicative of biosynthesis, although some as yet unknown abiotic processes could perhaps explain this enrichment. David McKay has reported the presence of other features in ALH84001 that may represent a signature of relic biogenic activity on Mars, but this biological interpretation is strongly questioned.

Because Mars had a presumably "warm" and wet past climate, it should have sedimentary rocks deposited by running and/or still water on its surface as well as layers of regolith generated by impacts. Such consolidated sedimentary rocks therefore ought to be found among the Martian meteorites. However, no such sedimentary material has been found in any SNC meteorite. It is possible that they did survive the effects of the escape acceleration from the Martian surface but did not survive terrestrial atmospheric entry because of decrepitation of the cementing mineral. The "STONE" experiment, flown by ESA, was designed to study precisely such physical and chemical modifications to sedimentary rocks during atmospheric entry from space (see Chapter 11). A piece of basalt (representing a standard meteoritic material), a piece of dolomite (sedimentary rock), and an artificial Martian regolith material (80% crushed basalt and 20% gypsum) were embedded into the ablative heat shield of the satellite *Foton 12*, which was launched on 9 September 1999 and landed on 24 September 1999. Such an experiment had never been performed before, and the samples, after their return, were analyzed for their chemistry, mineralogy, and isotopic compositions by a European consortium. Atmospheric entry modifications are made visible by reference to the untreated samples. The results suggest that some Martian sedimentary rocks might, in part, survive terrestrial atmospheric entry from space.

Even if convincing evidence for ancient life in ALH84001 has not been established, the two SNC meteorites (EETA79001 and ALH84001) do show the presence of organic molecules. This suggests that the ingredients required for the emergence of primitive life were present on the surface of Mars. Therefore, it is tempting to consider that microorganisms may have developed on Mars and lived at the surface until liquid water disappeared. Because Mars probably had no plate tectonics, and because liquid water seems to have disappeared from Mars' surface very early, the Martian subsurface perhaps keeps a frozen record of very early forms of life.

Currently, a very intensive exploration of Mars is planned, and U. S., European, Russian, and Japanese missions to Mars are taking place or are in the planning. Exobiology interests are included, especially in the analysis of samples from sites where the environmental conditions may have been favorable for the preservation of evidence of possible prebiotic or biotic processes. The European Space Agency (ESA) convened an Exobiology Science Team chaired by this author to design an integrated suite of instruments to search for evidence of life on Mars. Priority was given to the *in situ* organic and isotopic analysis of samples obtained by subsurface drilling. The basic recommendations of the Exobiology Science Team are presently serving as guidelines for the elaboration of the Pasteur exobiology payload of the ESA *ExoMars* mission scheduled for 2013 (see Chapter 12).

1.4.2
Jupiter's Moon Europa

The Jovian moon Europa appears as one of the most enigmatic of the Galilean satellites. With a mean density of about 3.0 g cm^{-3}, the Jovian satellite should be

dominated by rocks. Ground-based spectroscopy, combined with gravity data, suggests that the satellite has an icy crust, which is kilometers thick, and a rocky interior. The images obtained by the *Voyager* spacecraft in 1979 showed very few impact craters on Europa's surface, indicating recent, and probably continuing, resurfacing by cryovolcanic and tectonic processes. Recent images of Europa's surface, taken by the *Galileo* spacecraft over 14 months (from December 1997 to December 1999), show surface features – iceberg-like rafted blocks, cracks, ridges, and dark bands – that are consistent with the presence of liquid water beneath the icy crust. Data from *Galileo*'s near-infrared mapping spectrometer show hydrated salts that could be evaporites. The most convincing argument for the presence of an ocean of liquid water comes from *Galileo*'s magnetometer. The instrument detected an induced magnetic field within Jupiter's strong magnetic field. The strength and response of the induced field require a near-surface, global conducting layer, most likely a layer of salty water (see Chapter 10).

If liquid water is present within Jupiter's moon Europa, it is quite possible that it includes organic matter derived from thermal vents. Terrestrial-like prebiotic organic chemistry and primitive life may therefore have developed in Europa's ocean. If Europa maintained tidal and/or hydrothermal activity in its subsurface until now, it is possible that microbial activity is still present. Thus, the possibility of extraterrestrial life present in a subsurface ocean of Europa must seriously be considered. The most likely sites for extant life would be at hydrothermal vents below the most recently resurfaced area. To study this directly would require making a borehole through the ice in order to deploy a robotic submersible. On the other hand, biological processes in and around hydrothermal vents could produce biomarkers that would be pushed up as traces in cryovolcanic eruptions and thereby be available at the surface for *in situ* analysis or sample return. Mineral nutrients delivered through cryovolcanic eruption would make the same locations the best candidates for autotrophic life.

1.4.3
Saturn's Moon Titan

Titan's atmosphere was revealed mainly by the *Voyager 1* mission in 1980, which yielded the bulk composition (90% molecular nitrogen and about 1–8% methane). Also, a great number of trace constituents were observed in the form of hydrocarbons, nitriles, and oxygen-containing compounds, mostly CO and CO_2. Titan is the only other object in our Solar System bearing any resemblance to our own planet in terms of atmospheric pressure, which amounts to 1.5×10^5 Pa (1.5 bar), and carbon/nitrogen chemistry. It therefore represents a natural laboratory for studying the formation of complex organic molecules on a planetary scale and over geological times (see Chapter 9). The European Space Agency's Infrared Space Observatory (ISO) has detected tiny amounts of water vapor in the higher atmosphere, but Titan's surface temperature (94 K) is much too low to allow the presence of liquid water. Although liquid water is totally absent at the surface, the satellite provides a unique milieu to study, *in situ*, the products of the fundamental physical and chemical

interactions driving a planetary organic chemistry. Herewith, Titan serves as a reference laboratory to study, by default, the role of liquid water in exobiology.

The NASA–ESA *Cassini–Huygens* spacecraft launched in October 1997 arrived in the vicinity of Saturn in 2004 and performed several flybys of Titan, making spectroscopic, imaging, radar, and other measurements. On 14 January 2005, an instrumented descent probe managed by European scientists penetrated the atmosphere and systematically studied the organic chemistry in Titan's geofluid. For 150 min, *in situ* measurements provided analyses of the organics present in the air, in the aerosols, and at the surface. The GC-MS of the *Huygens* probe measured the chemical composition and the isotopic abundances, from an altitude of 140 km down to the surface. The main findings are as follows:

- nitrogen and methane are the main constituents of the atmosphere;
- the isotopic ratio $^{12}C/^{13}C$ suggests a permanent supply of methane in the atmosphere;
- the surface is "wetted" by liquid methane and rich in organics (cyanogen, ethane);
- the presence of ^{40}Ar suggests the existence of internal geological activity.

1.5
The Search for Life Beyond the Solar System

1.5.1
The Search for Rocky Earthlike Exoplanets

Apart from abundant hydrogen and helium, 114 interstellar and circumstellar gaseous molecules have been identified in the interstellar medium (see Chapter 2). It is commonly agreed that the catalog of interstellar molecules represents only a fraction of the total spectrum of molecules present in space, the spectral detection being biased by the fact that only those molecules possessing a strong electric dipole can be observed. Among these molecules, 83 contain carbon, whereas only 7 contain silicon. Silicon has been proposed as an alternative to carbon as the basis of life. However, silicon chemistry is apparently less inventive and does not seem to be able to generate any life as sophisticated as the terrestrial carbon-based one. May these molecules survive the violent accretion phase generating a planetary system?

The origin and distribution of the molecules from the interstellar medium to the planets, asteroids, and comets of the Solar System are presently at the center of a debate based on isotope ratios. Some molecules might have survived in cold regions of the outer Solar System, whereas others would have been totally reprocessed during accretion. Whatever the case, the interstellar medium tells us that organic chemistry is universal.

What about liquid water? New planets have been discovered beyond the Solar System. On 6 October 1995, the discovery of an extrasolar planet, i.e., a planet

outside our Solar System, was announced by Michel Mayor and Didier Queloz. The planet orbits an 8 billion year old star called 51 Pegasus, 42 light years away within the Milky Way. The suspected planet takes just four days to orbit 51 Pegasus. It has a surface temperature around 1 000 °C and a mass about 0.5 the mass of Jupiter. One year later, seven other extrasolar planets were identified. Among them, 47 Ursa Major has a planet with a surface temperature estimated to be around that of Mars (–90 to –20 °C), and the 70 Virginis planet has a surface temperature estimated at about 70–160 °C. The latter is the first known extrasolar planet whose temperature might allow the presence of liquid water. As of May 2006, 193 exoplanets had been observed.

1.5.2
Detecting Extrasolar Life

Extrasolar life, i.e., life on a planet of a solar system other than our own, will not be accessible to space missions in the foreseeable future. The formidable challenge of detecting distant life must therefore be tackled by astronomers and radio astronomers. The simultaneous detection of water, carbon dioxide, and ozone (an easily detectable telltale signature of oxygen) in the atmosphere would constitute the most convincing biomarker but not absolute proof. Other anomalies in the atmospheres of telluric exoplanets (i.e., rocky Earthlike planets), such as the presence of methane, might be the signature of an extrasolar life. European astrophysicists are proposing the construction of a flotilla of four free-flying spacecrafts, each containing an infrared telescope of 3 m in diameter, to search for signs of life on terrestrial-like planets. The mission, called *Darwin-IRSI*, is presently under study at ESA. Finally, the detection of an unambiguous electromagnetic signal (via the Search for Extraterrestrial Intelligence program) would obviously be an exciting event.

1.6
Conclusions

On Earth, life probably appeared about 4 billion years ago, when some assemblages of organic molecules in a liquid water medium began to transfer their chemical information and to evolve by making a few accidental transfer errors. The number of molecules required for those first assemblages is still unknown. The problem is that on Earth, those molecules have been erased. If life started on Earth with the self-organization of a relatively small number of molecules, its emergence must have been fast; therefore, the chance of the appearance of life on any appropriate celestial bodies might be real. On the other hand, if the process required thousands of different molecules, the event risks being unique and restricted to the Earth.

The discovery of a second independent genesis of life on a body presenting environmental conditions similar to those prevailing on the primitive Earth would strongly support the idea of a rather simple genesis of terrestrial life. More than

just a societal wish, the discovery of a second genesis of life is a scientific need for the study of the origin of life. It will demonstrate that life is not a magic, one-shot process but a rather common phenomenon. Many scientists are convinced that microbial life is not restricted to the Earth, but such conviction now needs to be supported by facts.

1.7
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1.7.1
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1.7.3
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