Search for Life in the Universe – What can we Learn from our own Biosphere?

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Abstract

Space exploration has extended the boundaries of biological investigations beyond the Earth to other planets, moons, comets, meteorites, and space at large. This field is covered by the new multidiscipline of astrobiology which has focused on the different steps of evolutionary pathways through cosmic history that are related to the origin, evolution and distribution of life on Earth, or elsewhere in the universe. The over-riding objective of astrobiological research has been to attain a better understanding of the principles leading to the emergence of life from inanimate matter, its evolution, and its distribution, thereby building the foundations for the construction and testing of meaningful axioms to support a theory of life. In the endeavor to quest for life on other celestial bodies of our solar system or beyond, clues can be gained from the history of our own biosphere and its strategies to adapt to changing and even "extreme" environmental conditions. Assuming water in liquid phase as universal prerequisite for habitability, the neighbor planet Mars and Jupiter's moon Europa are now favored targets of astrobiological research.

1 Astrobiology, a Multidisciplinary Approach

Astrobiology is a relatively new research area that addresses questions that have intrigued humans for a long time: "How did life originate?", "Are we alone in the Universe?", and "What is the future of life on Earth and in the Universe ?" They are jointly tackled by scientists converging from widely different fields, reaching from astrophysics to molecular biology and from planetology to ecology, among others.

Whereas classical biological research has concentrated on the only example of "life" so far known, i.e. life on Earth, astrobiology extends the boundaries of biological investigations beyond the Earth, to other planets, comets, meteorites, and space at large. Focal points are the different steps of the evolutionary pathways through cosmic history that may be related to the origin, evolution and distribution of life. In the interstellar medium, as well as in comets and meteorites, complex organics in huge reservoirs are detected that eventually may provide the chemical ingredients

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for life. More and more data on the existence of planetary systems in our Galaxy are being acquired which support the assumption that habitable zones are frequent and are not restricted to our own solar system. From the extraordinary capabilities of life to adapt to environmental extremes, the boundary conditions for the habitability of other bodies within our solar system and beyond can be assessed. This spilling beyond the boundaries of classical sciences opens completely new opportunities for research, a state described by some contemporaries as the "Astrobiology Revolution of the Sciences" (Ward & Brownlee 2000). Hence, astrobiology has the potential to give new impulses to biology much as the development of astronomy has broadened our understanding of the physical world and the spectral analysis of the stars has proven the universality of the concepts of chemistry (Lederberg 1960).

The final goal of astrobiology is to reveal the origin, evolution and distribution of life on Earth and throughout the Universe in the context of cosmic evolution and thereby build the foundations for the construction and testing of meaningful axioms to support a theory of life. Several books deal with the fascinating world of this newly emerging science of astrobiology (e.g., Brack 1998; Lunine 1999; Horneck & Baumstark-Khan 2002; Clancy et al. 2005; Gargaud et al. 2005; Rauchfuß 2005).

2 The Early Biosphere

Astrobiology concepts generally assume that life emerges at a certain stage of either cosmic or planetary evolution, if the right environmental physical and chemical requirements are provided (de Duve 1994). On Earth, most of the early geological record has been erased by later events so that we remain ignorant of the true historical facts concerning the origin of life on this planet. However, already the oldest sedimentary rocks show signatures of fossil microorganisms (Westall et al. 2001), indicating that the history of life on Earth goes back over at least 3.5 billion years (Figure 1). Therefore, events leading to the origin of life must have predated this time.

2.1 Model scenarios for the origin of life

With regard to the chemical prerequisites for the origin of life, the availability of the so-called "biogenic" elements CHONSP and relevant "biogenic" organic compounds are considered to be indispensable, as well as the presence of liquid H_2O (e.g., Oro et al. 1982). The biogenic elements, which make up the bulk of terrestrial biomass, are among the most abundant elements in the Universe. Whether the organic starting material relevant to the origin of life came from *in-situ* production on our planet or from delivery by extraterrestrial sources is still an open question.

In laboratory experiments, simulating the conditions of the primitive Earth, it was possible to form amino acids, the building blocks of the proteins, from methane (Miller 1953). However, these pioneering experiments succeeded only when a reducing gas mixture containing significant amounts of hydrogen was used. Although the true composition of the early terrestrial atmosphere remains unknown, geochemists

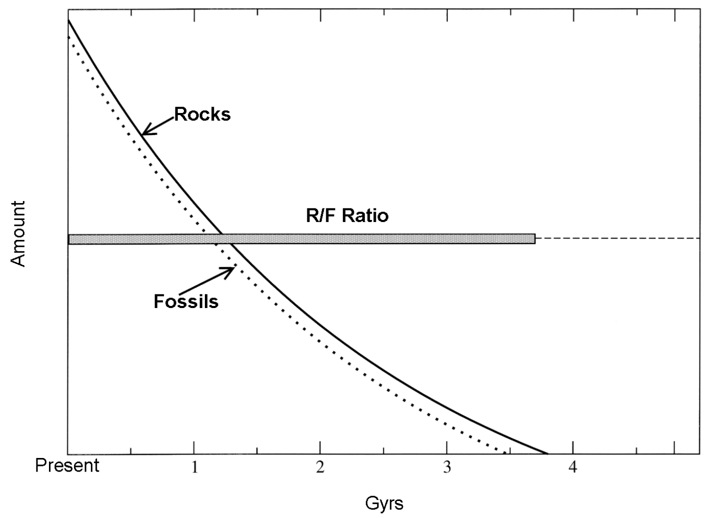

Figure 1: Occurrence of sedimentary rocks and fossils over the history of the Earth (after a sketch provided by the late Mayo Greenberg)

now favor a non-reducing primitive atmosphere, dominated by CO_2; these conditions would allow only limited *in-situ* production of the essential precursors of life.

The incorporation of interstellar matter in meteorites and comets in the presolar nebula provides a basis for a cosmic dust connection. Comets are of special interest to astrobiology, because – among all celestial bodies – they contain the largest amount of organic molecules (Kissel et al. 1986). They are considered the most pristine celestial bodies bearing witness to the existence of a dynamic organic chemistry from the earliest stages of our solar system. Comets have been suggested to be the major source of the hydrosphere, the atmosphere, and probably also of the organic compounds of the early Earth (Oro et al. 1992).

Support for a scenario of an extraterrestrial import of organics can be found in the meteorites collected on the Earth's surface, micrometeorites found embedded deep within ice and cosmic dust sampled at stratospheric and Earth-orbit level. Particularly carbonaceous chondrites contain up to 5% by weight of organic matter. Carbonaceous micrometeorites show a high percentage (30%) of unmelted chondrites from 0.1 to 1 mm in diameter. This observation indicates that many particles cross the terrestrial atmosphere without drastic modification by thermal treatment. It has been estimated that during the early terrestrial bombardment, about 10^{17} tons of carbon have been brought to the early Earth by micrometeorites. This number is 5 orders of magnitude larger than that of the present surface biomass's carbon (Maurette et al. 2000).

The detection of hydrothermal vents in the late seventies of the last century surrounded by a rich ecosystem well adapted to this submarine hot environment has supported the hypothesis of a hot origin of life (Pace 1991, critically reviewed by

Gribaldo and Forterre in Gargaud et al. 2005). The ocean floor at a submarine alkaline hot spring has been suggested to provide all prerequisites for the emergence of life on the early Earth about 4 billion years ago. Deep-sea hydrothermal systems are producing sites of hydrocarbons, even today. As energy source for the reduction of CO_2, the oxidative formation of pyrite from FeS and H_2S has been postulated. Pyrite provides an active surface binding for the organic molecules formed and has been proposed as the site of a chemolithoautothrophic origin of life (Wächtershäuser in Brack 1998). Support to a hot origin of life comes also from the universal phylogenetic tree of life, based on molecular biology analysis (see part 2.3) where microorganisms that are adapted to extremely high temperatures (hyperthermophiles) cluster around the "root" of this tree (Stetter in Horneck and Baumstark-Khan 2002).

Alternatively, a cold scenario has been proposed for the origin of life. According to Trinks et al. (2005) a sea ice reactor would consist of a dynamic three phase system of ice crystals, brine channels and gas bubbles with dynamic temperature gradients and energy transport. In laboratory experiments simulating the dynamic variability of real sea ice, the abiotic synthesis of long chain biomolecules (polynucleotides) was achieved. Hence sea ice occurring abundantly at the polar ice caps could provide optimal conditions for the early replication of nucleic acids and the RNA world, a suggested precursor of the first cellular system.

Saturn's moon Titan has been considered as a natural laboratory for studying the formation of complex organic molecules on a planetary scale and over geological times. The Huygens probe that descended on Titan on January 14, 2005 has provided further insight into the chemistry of Titan's atmosphere where complex organic matter is photochemically produced (Owen 2005). Titan's extremely low temperature of 94 K keeps its water frozen and methane is the dominant carbon carrying gas and liquid. Photochemical reactions in the atmosphere produce nitrogen-containing organic compounds that form a thick layer of smog and "rain" steadily on Titan's surface. Hence, the study of Titan's organic chemistry allows understanding the process of chemical evolution under anhydrous conditions.

2.2 The fossil record

Paleobiology has traced back the history of life on Earth to its very early stages in a chronological manner. The search for fossils spans over a time-period of 3.8 billion years, up to the first evidence of sedimentary rocks. However, as one goes back in time more than 2.5 billion years to the Archean, only few sedimentary rocks have survived without alteration. Therefore, it is sometimes difficult, to establish the authenticity of Archean microfossils. The oldest bona fide evidence for life on the early Earth comes from the 3.3 to 3.5 billion years old sediments found in South Africa and Australia (Westall et al. 2001). In these formations well preserved micron-sized fossils of microorganisms and biofilms were discovered which once flourished in hydrothermal shallow ponds.

Because all common biological pathways of autotrophic carbon fixation discriminate against the heavy isotope of carbon ^{13}C, the measurement of the $^{13}C/^{12}C$ fractionation has been used as a means to discriminate between biogenic (organic) carbon and sedimentary carbonate in the deposits. Figure 2 shows that this depletion

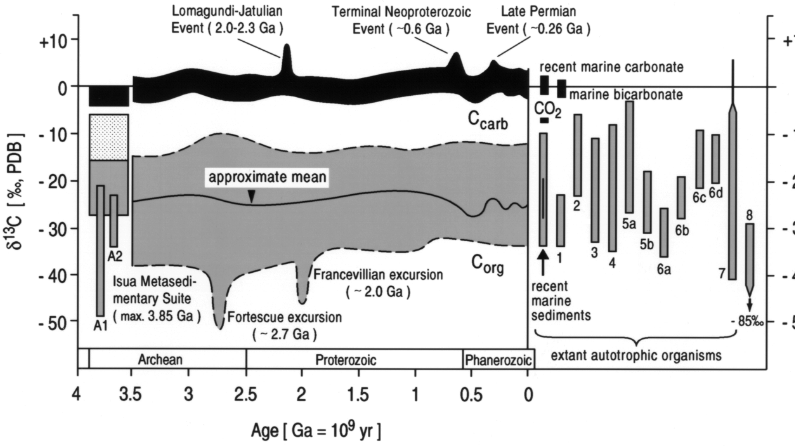

Figure 2: Isotopic fractionation of carbon in contemporary organisms and fossils, given as $\delta^{13}C$ values, indicating either an increase (+) or a decrease (-) in the $^{13}C/^{12}C$ ratio of the respective substance compared to a carbonate standard (from Schidlowski in Horneck and Baumstark-Khan 2002)

of ^{13}C is quite conservatively transcribed from the extant biomass through recent marine sediments over billions of years into the Archean period, and with a slight modification even back to the 3.8 billion years old Isua formation.

Summing up, from the currently available paleobiological and geochemical data, there is evidence that life has emerged very early on the juvenile Earth – with a degree of certainty earlier than 3.5 billion years ago and probably earlier than 3.8 billion years ago. Autotrophic carbon fixation has been extant since at least 3.8 billion years and therefore must have evolved in much older times than are covered by terrestrial rock record.

2.3 The molecular biology record

Molecular biology reveals a fundamental unity of modern life. All extant organisms are cellular; the genetic information is stored in the DNA, transcribed into RNA, and translated into proteins. This communality of the basic biochemical features to all known forms of life on Earth suggests their descent from a universal ancestor.

In order to trace the history of life back from extant forms to the universal ancestor, molecular phylogeny makes use of the fact that at the level of the genotype, i.e. DNA, changes constantly occur which are fixed randomly in time. By comparing the genotypic information stored in the sequence of e.g., nucleic acids, a universal phylogenetic tree can be constructed that groups all known organisms in three domains: Bacteria, Archaea and Eukarya (Woese et al. 1990) (Figure 3).

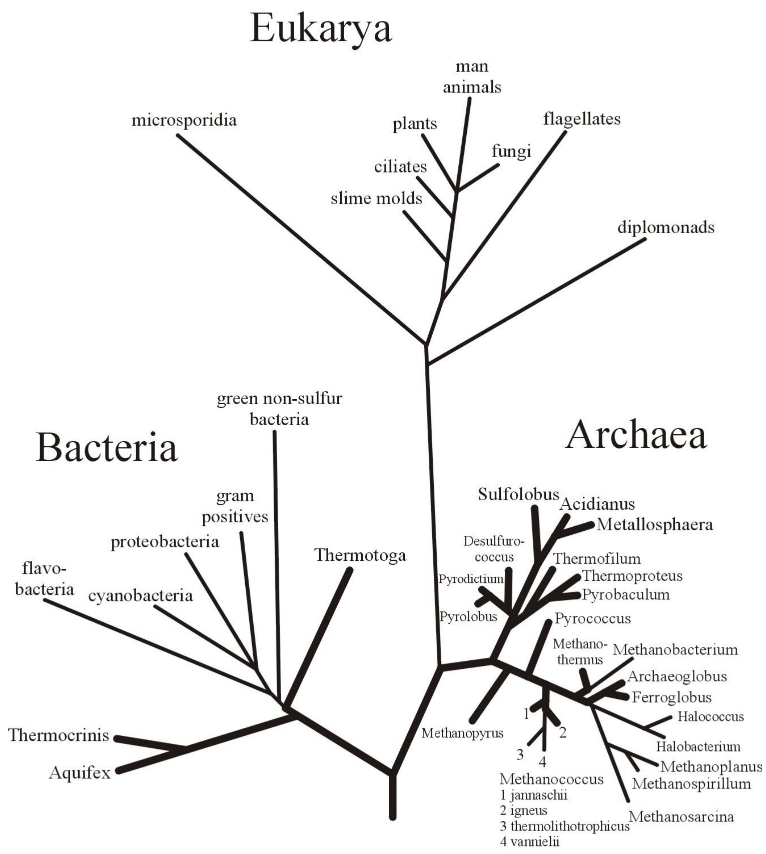

Figure 3: Phylogenetic tree of life, based on the sequence analysis of ribonucleic acid (16S rRNA) of a variety of organisms. Bold lines represent hyperthermophiles (from Stetter in Horneck and Baumstark-Khan 2002)

The molecular record allows also for inferences on the metabolic characteristics of the common ancestor. In Figure 3, hyperthermophilic microorganisms of both, Archaea and Bacteria, are among members forming the deepest branching. These observations support the assumption of a chemolithoautotrophic hyperthermophilic nature of the common ancestor (Stetter in Horneck and Baumstark-Khan 2002).

2.4 Impact scenario

The fossil record reveals that microbial autotrophic ecosystems existed on the early Earth already by 3.5 billion years or even 3.8 billion years ago. Before this date, during the Hadean period (before 3.8 billion years ago) the Earth was struck several times by gigantic impacts sufficient to vaporize the entire terrestrial ocean, as has been extrapolated from lunar crater records (Oberbeck and Fogleman 1990). As a result of a runaway greenhouse effect, surface temperatures up to 2000 K have been suggested which would have certainly sterilized the Earth. This impact catastrophe scenario implies that, if life did already exist in the Hadean, it may have been extinguished several times, until the end of the heavy bombardment.

Impactors of sizes larger than 1 km lead to the ejection of a considerable amount of soil and rocks that are thrown up at high velocities, some fraction reaching escape velocity. Meteorites of lunar and some of Martian origin detected within in the last decades are witnesses of these processes. The question arises, whether such rock or soil ejecta could also be the vehicle for life to leave its planet of origin, or, in other words, whether spreading of life in the solar system via natural transfer of viable microbes is a feasible process. Simulation experiments have shown that some rock populating microorganisms would survive all different steps of such an interplanetary transfer of life, including the escape from the planet, the long journey in space and the entry process on another planet (Mileikowsky et al. 2000).

3 History of Life on Earth

Although the surface of the Earth went through dramatic changes since the beginnings of life, examples are the formation and drift of the continents, periodic global glaciations and the oxygenation of the atmosphere, life has persisted and evolved through more than 3.5 billion years until today (Rothschild and Lister 2003). The history of life can be best reconstructed from fossil relics imprinted in sedimentary rocks. Recently, the evolution of life through time has been correlated with the rise in atmospheric oxygen generated by oxygenic photosynthesis (Catling et al. 2005). This hypothesis is based on the fact that aerobic metabolism, i.e. respiration, provide about an order of magnitude more energy for a given intake of food, e.g. 1 mol of glucose, than anaerobic metabolism, i.e. fermentation. Consequently, the accessibility of oxygen to the organisms, either by diffusion or by blood circulation, determines their growth and complexity.

The terrestrial atmosphere started with virtually no oxygen and remained anoxic until about 2.4 billion years ago. For this period, fossils give evidence of micron-sized, single cellular organisms, only. Two stepwise increases in atmospheric oxygen occurred, one around 2.4 to 2.3 billion years ago and the next 1.0 to 0.5 billion years ago. Both oxygen increases appear to have been followed by substantial changes in the climate, e.g., built up of an ozone shield, and biota: First larger fossils, visible to the naked eye, are dated for 1.89 billion years ago, animal fossils date back to 600 million years ago.

3.1 Adaptation of microorganisms to extreme environments

Paleobiology has demonstrated the persistence of prokaryotic microorganisms: they have flourished on Earth for more than 3.5 billion years and dominated the Earth's biosphere during the first 2 billion years of its history before the first unicellular mitotic eukaryotes (cells with a nucleus and other organelles) appeared.

Microorganisms have invented several strategies to cope with and adapt to environments of a wide range of physical and chemical parameters (reviewed by Horneck 2000). Examples are microbial ecosystems in deep crystalline rock aquifers several hundreds of meters below the surface, in the interior of ice-cores from drillings in the Antarctic ice down to a depth of several km and in cores from drillings in permafrost regions in Siberia at similar depths. It was found that the interior of rocks in cold and hot deserts provides ecological niches for endolithic microbial communities just as crystalline salts from evaporite deposits. Microorganisms have been isolated from extremely cold environments, such as the Antarctic soils as well as from hot environments at temperatures in the range of 80°C to 113°C which are usually associated with active volcanism as hot springs, solfataric fields, shallow submarine hydrothermal vents, abyssal hot vent systems ("black smokers") as well as oil-bearing deep geothermally heated soils. Microbial communities are also found buried in groundwater sediments, in marine sediments several 100 m below the sea floor, as well as in the atmosphere where viable microorganisms were collected from altitudes up to 77 km. These examples demonstrate that nearly all sites on Earth are inhabited by microbial communities, where an energy source is available and which are compatible with the chemistry of carbon-carbon bonds. Table 1 gives the environmental range allowing growth of at least one microbial representative.

Table 1: Environmental range allowing growth or survival of microorganisms

Parameter	Growth	Survival
Temperature (°C)	$-20 - +113$	$-262 - +150$
Pressure (Pa)	$10^5 - 10^8$	$10^{-7} - \geq 10^8$
Ionizing radiation (Gy)	≈ 50	≤ 5000
UV radiation (nm)	terrestrial (≥ 290)	$\approx$ terrestrial (≥ 290)
Water stress (a_w)	≥ 0.7	$0 - 1.0$
Salinity	$\leq 30\%$	salt crystals
pH	$1 - 11$	$0 - 12.5$
Nutrients	high metabolic versatility, high starvation tolerance	not required, better without
Gas composition	different requirements (oxic or anoxic)	better without oxygen
Time (a)	≤ 0.5[1)]	$\leq (25 - 40) \times 10^6$

[1)] generation time

Metabolic diversity is one of the approaches microorganisms use for adapting to extreme environments. Whereas photosynthesis is the most common autotrophic pathway (and the only one used by eukaryotes), prokaryotes have invented a variety of autotrophic pathways, which either use an energy source different from sunlight (e.g., H_2, Fe^{2+}, Mn^{2+}, reduced or oxidized sulfur or nitrogen compounds) or use an electron donor different from water (e.g., H_2, Fe^{2+}, or H_2S and S°). This metabolic versatility enables prokaryotic microorganisms to colonize even deep subsurface sites which cannot be reached by sunlight.

Special challenges to microorganisms are environments with fluctuations among extreme conditions, as they are experienced in deserts or on alpine rock surfaces (e.g., rapid changes in temperature and water activity). Other oscillations may concern salinity, pH, redox potential or radiation stress. Microbial mats are especially adapted to cope with these changing environments. They dwell on and inside rocks, in air and under water where energy sources, nutrients or water are only occasionally available. These mats, which are sometimes covered by protective layers of slime, sugars and pigments, are composed of so-called poikilotrophic microbial communities, a mixture of microorganisms capable of outlasting long periods of unfavorable conditions at a reduced metabolic rate.

Several prokaryotes as well as a few eukaryotes possess strategies of surviving unfavorable conditions in a kind of dormant state and are capable of regaining full metabolic activity if conditions change to less hostile ones again. Hence, the limits for microbial survival extend much further than those for growth (Table 1). Temporary transition of microbial cells to the dormant, so-called anabiotic state, which involves biochemical, physiological and ultrastructural changes, is a widespread mechanism developed by organisms to promote survival of interim hostile conditions.

Under certain conditions, bacterial cells produce a dormant spore. In these spores, the DNA is extremely well protected against environmental stressors, such as desiccation, oxidizing agents, UV and ionizing radiation, low and high pH as well as temperature extremes. The high resistance of bacterial spores is mainly due to a dehydrated core (cellular interior) enclosed in a thick protective envelop, the cortex and the spore coat layers, and the saturation of their DNA with small, acid-soluble proteins whose binding greatly alters the chemical and enzymatic reactivity of the DNA. Bacterial spores have survived for extended periods in space (so far maximum duration tested was 6 years) which is governed by a high vacuum, temperature extremes and an intense radiation of solar and galactic origin. Isolates from Dominican amber suggest that *Bacillus* spores remain viable for several millions of years.

3.2 Properties common to all life forms

All life on Earth, despite of its enormous genotypic and phenotypic variation, is based on the same basic principle, if we consider the microscopic blueprint or the molecular biology processes running the system. One of the basic characteristics of life is its compartmentalization. All life forms are composed of cells as self-reproducing building blocks and sites of the basic functions of life. All cells use lipid membranes to separate their protoplasm from the environment or from the cell wall. In unicellular organisms, like Bacteria and Archaea, the cell autonomously takes charge of all functions sustaining life. In multicellular organism, such as Eukarya which comprise all plants and animals, cells in tissues and organs are specialized for defined functions.

In the cells, the genetic information is stored in the DNA, transcribed into RNA, and translated into proteins. All organisms use the same or a very similar genetic code and they use the same amino acids in their proteins. Although there are some differences in the transcription and translation machinery, the basic process is very similar in all organisms. Further, all cells use the same energy-rich metabolites as well as homologous enzymes to run the basic functions and to energize their cell membranes.

The basic functions of life are threefold (Figure 4):

- Identical self-replication: Storage and replication of the information is located in the DNA.
- Evolution through mutation: Errors, occasionally occurring during replication, lead to mutations, i.e. changes in the genetic information. As a consequence new species may arise being better adapted to the environment, a step that promotes biological evolution. The concept of evolution implies that by these errors the systems reach higher complexity and possibly a better adaptation to environmental constraints.
- Metabolism: The proteins – enzymes – maintain the metabolism within the cell. They also catalyze the replication of the DNA and the translation of its information into proteins.

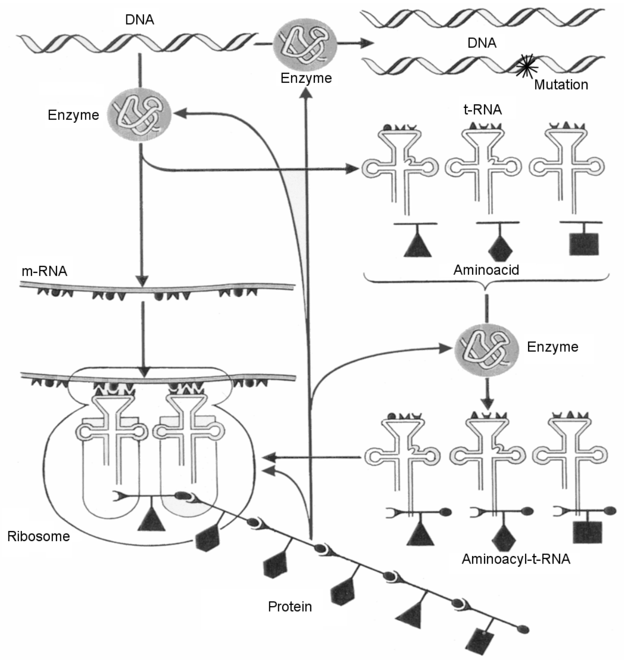

Figure 4: Basic functions of life: identical replication of the information stored in the DNA, evolution through mutations, and metabolism (modified from Eigen, 1992).

In a very abstract view, one can consider "life" as an open chemical system able to transfer its molecular information via self-replication and to evolve via mutations (Clancy et al. 2005). However, one has to bear in mind that our biosphere is the only example of life known. This makes it difficult to determine whether properties that are peculiar to terrestrial life are also valid throughout the universe.

4 Search for Life in the Solar System

Within the on-going and planned ventures to explore the planets, moons and other bodies of our solar system by orbiters and robotic landing missions, the search for signatures of life beyond the Earth is one of the major drivers. In the selection of candidate targets for this enterprise, the overarching argument is the putative habitability of the planet or moon under consideration.

4.1 Prerequisites for habitability

On the basis of the general properties of terrestrial life, Oro et al. (1982) postulated criteria for the emergence and evolution of life in a universal context with reference to stellar, planetary, chemical and biological requirements as follows:

- Star: single star, availability of heavy elements, mass, lifetime, planetary system;
- Planet: mass, orbit, atmosphere, discrete liquid sphere, surface;
- Chemistry: solvents, element composition and concentration, energy source, redox potential, pH range;
- Biology: replication of informational molecules, stereospecific catalytic molecules, information transfer molecules, polymerizing molecular assembly, interphasic molecular assembly.

These criteria, mentioned above, come from the notification of at least three basic prerequisite for a planet or moon to be habitable (see also Schulze-Makuch and Irwin 2004 for a critical interpretation):

- A carbon based chemistry,
- An energy source, and
- Water in liquid phase.

Carbon based molecules are the universal building blocks of life as we know it. The ability of carbon to form complex, stable molecules with itself and with other elements, e.g., hydrogen, oxygen, or nitrogen, is unique and is attributed to at least three factors:

- The stability of carbon molecules due to the high carbon-carbon bond energy
- The capability to form double and triple bonds in addition covalent bonds
- The high activation energy for substitutions and bond cleavage reactions which support the stability of the molecules to water and oxygen.

Although a wealth of complex organic molecules has been detected at many extraterrestrial places, such as the interstellar medium, comets, meteorites and planetary atmospheres (Ehrenfreund and Menten in Horneck and Baumstark-Khan 2002), they have not been found at the surface of Mars, so far (reviewed in Horneck 1995). The most plausible explanation for the absence of organics on the surface of Mars is an active surface photochemistry from the energetic solar UV radiation, where peroxides are produced by UV-irradiation of hematite in the presence of traces of water.

Life requires a flow of energy to organize its material, perform the work, and maintain a low state of entropy. The energy sources, used by life on Earth, are a narrow band of visible light, redox reactions or organic molecules. Solar light is the energy source for photosynthesis. Subsurface organisms use the oxidation of inorganic electron donors, such as hydrogen, sulphur, sulphide, ammonia, nitrite, or iron. However, there seems to be no limitation on which redox reactions are used, even relatively rare elements, such as arsenic, selenium, copper, lead, and uranium serve the purpose.

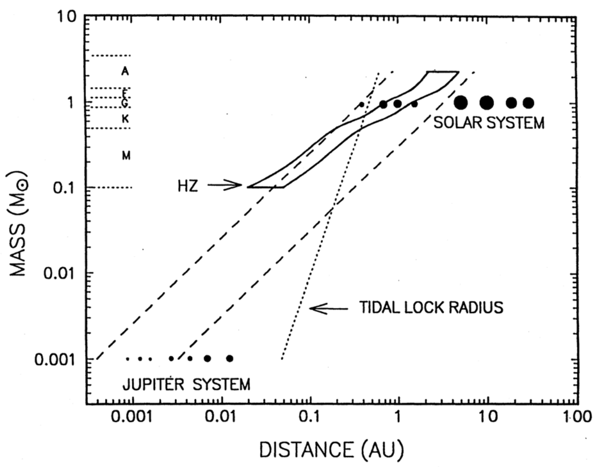

Figure 5: Habitable zone as a function of the distance from the star and its mass (from Franck et al. in Horneck and Baumstark-Khan 2002).

Water has been called "the spring of life" (Brack in Horneck and Baumstark-Khan 2002). In the liquid phase water exhibits several peculiarities that make it indispensable for life. Water serves as

- A diffusion milieu,
- A selective solvent,
- A heat dissipater,
- A stabilizer of biopolymer structure,
- A reaction partner in essential biological processes, e.g., in photosynthesis.

On the assumption that liquid water is essential for life, the common definition of a "habitable planet" has been one that can sustain substantial liquid water on its surface. Assuming a tolerable temperature range between 0°C and +100°C at the surface of a planet, our solar system would provide a habitable zone in an orbit between 0.7 and 2.0 AU, or in more conservative estimate the width of the habitable zone is restricted to the range of 0.95 to 1.37 AU (Figure 5). Venus, Earth and Mars are situated in this habitable zone or in close neighborhood. However, in view of the adaptability of microorganisms to extreme environments and the detection of rich submarine and subsurface microbial ecosystems on Earth, liquid water does not necessarily need to exist at the surface to sustain a biosphere. Therefore, the definition of a "habitable planet" may require revision.

4.2 Signatures of life

On Earth, the most commonly used direct methods to detect and analyze microbial communities in extreme environments include the following:

- Direct observations of structural characteristics in the micro- and macroscale;
- Culture techniques for isolating microorganisms in pure culture and then analyzing these cultures for their biochemical properties;
- Activity measurements in microcosms which focus on the net effects of microbial processes in the community;
- Chemical marker techniques to record characteristic biochemical primary substances or chemical secondary products (Table 2).

Based on the fact that during its more than 3.5 billion years old history life on Earth has substantially modified the terrestrial lithosphere, hydrosphere and atmosphere, indirect proofs of life are also valid (reviewed in Horneck 2000, Clancy et al. 2005).

4.3 Mars

Mars with a mean distance to the sun of 1.52 AU is located at the outer border of the habitable zone around the sun which is estimated under the premise of the presence of liquid water on the planet's surface at some time during its 4.5 billion years lasting history. With the exception of the Earth, Mars is by far the most intensively studied of the planets of our solar system. In 1972, for the first time a spacecraft, Mariner 9, passed over the younger parts of Mars revealing a wide variety of geological processes, indicated by volcanoes, canyons, and channels that resemble dry river beds (Carr 1981). These extensive fluvial features confirmed during several follow-on missions to Mars were difficult to reconcile with any origin other than liquid water. They attest to a stable flow of water on Mars at some time in the past, and sporadically even in more recent times.

Understanding the history of water on Mars appears to be one of the clues to the puzzle on the probability of life on Mars. The estimates of the total amount of water

Table 2: Methods to detect and analyze microbial communities in extreme environments.

Method	Approach	Information
Direct observation of structural indications of life	Optical microscopy	Dividing cells
	Phase-contrast microscopy	
	Epifluorescence microscopy	Differentiation between cellular structures and similar structures of abiotic origin
	Confocal laser scanning microscopy	Three-dimensional visualization of microbial communities
	Scanning electron microscopy	Subcellular structures
Detection of microbial activity	Cultivation	Biochemical and phylogenic analysis of isolates
	DNA probes and biomarker chips	Not yet culturable microorganisms
	In situ biochemical analysis	Metabolically active communities
	Microelectrodes for *in situ* measurements of natural gradients of gas, pH, minerals etc.	Metabolic activity, e.g. photosynthesis, respiration
	Combination of epifluorescence microscopy and television image analysis	Metabolic activity
Detection of chemical signature and biomarkers	Determination of total biomass, biomolecule contents	Major contribution species; physiological stage, e.g. active, dormant, extinct
	Determination of isotopic ratios	Biogenic origin
	Determination of optical handedness	Biogenic origin
	Fourier transform Raman spectroscopy	Distribution of organic and inorganic components
Indirect fingerprints of life	Macroscopical deposits	Biomineralization, bioweathering, indication of extinct life
	Mineral analyis	Biogenic minerals
	Detection of dynamic cycles of hydrosphere or atmosphere	Indication of extant life

that may have existed at the surface of Mars range over two orders of magnitude. A low amount of water ranging from 3.6 to 133 m is suggested from the composition of the contemporary atmosphere, e.g. the D/H ratio. On the other hand, the geological flow features, provide evidence of abundant water at the surface of Mars, at least at some time in the past, assuming a global inventory of water of at least 440 m. From the global neutron mapping of the Mars Odyssey mission, the present distribution of water in the shallow subsurface was divided in 4 types of regions (reviewed in Tokano 2005):

- Regions with dry soil with a water content of about 2 wt%
- Northern permafrost regions with a high content of water ice (up to 53 wt% of water)
- Southern permafrost regions with high content of water ice (> 60 wt% of water) covered by a dry layer of regolith.
- Regions with water-rich soil at moderate latitudes (about 10 wt% of water) covered by a dry layer of soil. These water-rich regions are well separated from the Martian atmosphere by the rather thick layer of desiccated regolith. Therefore, it was supposed that they were formed long time ago, when the climate allowed liquid water at the surface.

The history of water on Mars suggests a dramatic change in the climate about 3.8 billion years ago. Based on a model by McKay and Davis (1991) 4 different epochs can be distinguished for the history of water on Mars, starting with a wet water-rich planet before 3.8 billion years ago, and becoming gradually more and more dry. For each of these epochs, the probability for indigenous life is discussed taking into consideration the requirements for the emergence of life and current knowledge of terrestrial ecosystems as model systems for Martian habitats (Horneck 1995).

In the first epoch, reaching up to the end of the heavy bombardment about 3.8 billion years ago with warm surface and liquid water, it has been suggested that the main putative prerequisites for life to arise did exist. Therefore, by analogy to the early Archean biosphere on Earth, an early Martian biosphere could be postulated with habitats and microenvironments similar to those on the early Earth. The major uncertainty seems to be whether liquid water was available long and abundantly enough for life to arise.

Finally, atmospheric CO_2 was irreversibly lost due to carbonate formation, and the pressure and temperature then declined. However, ice-covered lakes could have persisted over a period of 700 ± 300 million years which provided liquid water habitats on early Mars, analogous to ice-covered lakes in Antarctica or cryoconite holes on glaciers. These terrestrial analogues contain plankton organisms as well as an abundant benthic community forming microbial mats. Such ice-covered lakes might have served as niches for putative life on Mars to retreat by providing both thermal stability against a cooling external environment and enhanced concentrations of CO_2 and N_2 against a thinning atmosphere.

With gradually decreasing pressure and temperature the ice-covered lakes would eventually have dried out due to lack of melt water supply thereby initiating the next epoch where liquid water would be restricted to porous rocks and to the subsurface. In order to cope with these dramatic environmental changes, adaptive steps of a putative Martian biota could have been to withdraw into protected niches, e.g. inside rocks or in the subsurface. Such endolithic habitats exist on Earth in areas of extreme aridity and frigidity, e.g. dry valleys of Antarctica. The cryptoendolithic microbial communities form lichen-dominated ecosystems with cold-adapted nearly exclusively eukaryotic algae and less commonly cyanobacteria as primary producers and fungi as consumers. Other potential biotic oases, to which the putative life on Mars might have withdrawn, are the polar ice caps and permafrost regions, or hydrothermal areas in connection with volcanic activities.

The present atmosphere is too cold to support liquid water on the surface for long and too thin to support ice – any ice that does form will quickly sublimate into water vapor. The life-threatening surface conditions of Mars were clearly shown by the 2 Viking landing missions, which searched for indications of microbial activity on Mars. Based on the assumption that

- Martian life, if it exists, will be carbonaceous,
- its chemical composition is similar to that of terrestrial life, and
- it most likely metabolizes simple organic compounds,

a life detection instrument package was installed to detect metabolic activity of potential microbial soil communities. All three Viking biology experiments gave positive results indicative of active chemical processes when samples of Martian soil were subjected to incubation under the conditions that were imposed to them. However, no organic carbon was found in the Martian soil by the GCMS experiment. So far, the mechanisms underlying the results of the Viking biology experiments are not known. A number of hypotheses have been forwarded in order to explain the enigma of an active chemistry in the absence of organics. The most plausible one is based on photochemical surface processes where the energetic solar UV-irradiation forms peroxides in the regolith when impinging on the hematite in the presence of traces of H_2O.

Considering the open questions with regard to the habitability of Mars, the in situ search for signatures indicative for putative extant or extinct life on Mars can only be one of the final steps in the quest for extraterrestrial life. Much information can be obtained from remotely sensed global measurements, such as the seasonal atmospheric and surface water distribution, the mineralogical inventory and distribution, geomorphologic features obtained with high spatial resolution, thermal mapping of potential volcanic regions to determine possible geothermally active sites, and trace gases like H_2, H_2S, CH_4, SO_x, and NO_x. The on-board measurements on current and planned missions to Mars, such as Mars Global Surveyor, Mars Express and Mars Odyssey efficiently serve these needs. The recent detection of traces of methane in the Martian atmosphere, hints of the presence of deep underground water-ice, and indications of relatively young volcanic activities in the north polar regions are prominent results of the current Mars Express mission (see also: http://www.esa.int/SPECIALS/Mars Express/). The search for possible biological oases will be connected with the detection of areas where liquid water still exists under the current conditions on that planet.

With the Mars Exploration Rover mission NASA intends to unravel the story of water on the red planet. Especially in the Meridiani Planum, the landing site of the rover Opportunity, they detected distinct layering in some rocks which showed that water once flowed there on the surface of Mars, leaving ripple-like curves in the outcrop rocks. Bead-like objects, the so-called "blueberries", turned out to be rich in hematite, a mineral that requires water to form. The detection of sodium chloride which only forms when water has been present is another indication of liquid surface water in the past of Mars (see also: http://marsrovers.jpl.nasa.gov/home/index.html)

ESA's exploration program foresees as the next step the ExoMars mission that uses a rover with high autonomy and equipped with the analytical capacity to select suitable drilling site or exposed vertical stratigraphy to find signs of extinct or extant life. To do this requires the development of an efficient Mars drilling system and the correspondent sample analysis suite to be used in the underground exploration of selected sites. In addition, the habitability of these regions will be explored by *in-situ* measurements of the climate, radiation environment and surface and subsurface chemistry in dry and wet state. It is important to understand the mechanisms of the strong oxidative processes present on the surface of Mars which have been identified by the Viking experiments.

4.4 Jupiter's moon Europa

Europa, a satellite of Jupiter, is another focus for astrobiology. More than 95% of the spectroscopically detectable material on its surface is H_2O (Greenberg in Horneck and Baumstark-Khan 2002, Greenberg 2005). It has been established with high probability that this moon of Jupiter harbors an ocean of liquid water, beneath a thick ice crust. In addition to liquid water, carbon and energy sources are requested to support life as we know on Earth. If carbon might have been delivered by impacts of various bodies (although crust resurfacing does not show so many impact craters), the question of energy sources is still open. The existence of liquid water beneath the ice crust might be the result of a deep hydrothermal activity, radioactive decay and/or tidal heating. In this case, conditions allowing prokaryotic-like life as we know on Earth would have been gathered.

4.5 Planetary Protection

The introduction and possible proliferation of terrestrial life forms on other planets by means of orbiters, entry probes or landers could entirely destroy the opportunity to examine the planets in pristine condition. From this concern by the scientific community, the concept of planetary protection has evolved. Its intent is twofold:

- to protect the planet being explored and to prevent jeopardizing search for life studies, including precursors and remnants, and
- to protect the Earth from the potential hazards posed by extraterrestrial matter carried on a spacecraft returning from another celestial body (Rummel 1989).

Planetary protection issues are bound by an international treaty (UN Doc. A/6621, Dec. 17, 1966) and agreement (UN Gen. Ass. Resol. A/34/68, Dec. 5, 1979). Since 1959, COSPAR has developed planetary protection guidelines that originally were based on relevant information about the probability of survival and release of organisms contained either in or on exposed surfaces of spacecraft, about the surface and atmosphere characteristics of the planet under consideration, and about the probable distribution and growth of types of organisms involved. This concept of probability of contamination of a planet of biological interest was replaced by a concept of contamination control to be elaborated specifically for certain space-mission/target-planet combinations, such as orbiters, landers, or sample return missions (Rummel 1989). In view of the current and planned landing activities on Mars, with robotic and finally human visits, the planetary protection guidelines are currently under review within ESA and NASA.

5 Search for Life Beyond the Solar System

Estimates of the occurrence and frequency of habitable zones outside our solar system were first mainly based on astronomical concepts of the structure and dynamics of our Galaxy, on planetary atmosphere models and on biological interpretations of the requirements for the emergence and evolution of life. For solar type stars, a habitable belt, ranging from about 0.95 to about 1.5 AU has been suggested (Figure 5). In addition to single main-sequence stars, variable stars, giant stars and binary systems have been examined for supporting a habitable zone. Within our Galaxy, the orbit of our Sun was suggested as especially favorable for supporting life forms mainly due to the availability of heavier elements.

An important step in the search for habitable zones outside of our solar system was achieved in 1995 with the discovery of the first extrasolar planet orbiting a star similar to our sun, 51 Pegasi (Udry and Mayor in Horneck and Baumstark-Khan 2002). Its presence was inferred from the induced modulation of the observed stellar radial velocity. In the following years, this field has rapidly evolved and more than 100 extrasolar planets have been detected so far, using different approaches. All planets so far detected are massive, most are Jupiter-class planets, considered unlikely to harbor life as we know it. Many have short orbital periods. If planets like Earth exist, with smaller masses and longer orbital periods, their discovery will require more sensitive instruments and years of precise, sustained observations. The ESA project Darwin is intended to look for spectral signatures of atmosphere constituents, such as CH_4 and O_3 in order to identify Earth-like planets capable of sustaining life (Foing in Horneck and Baumstark-Khan 2002). Another ambitious mission searching for Earth-like planets is NASA's Terrestrial Planet Finder (TPF) as a suite of two complementary observatories, a visible-light coronagraph and a mid-infrared formation-flying interferometer. They will detect and characterize Earth-like planets around as many as 150 stars up to 45 light-years away.

For estimations of the expected number of habitable planets in our Galaxy, a formula, known as the Drake equation has been developed which takes into consideration (1) the rate of star formation, (2) the fraction of stars which have planetary systems, (3) the average number of planets per planetary system which fall in a habitable zone, and (4) the fraction of habitable planets on which life arises (Drake 1974). Since interstellar distances are so vast, radio-communication has been deemed the only way of detecting life beyond our solar system. This requires that additional terms be included in the Drake formula, namely (5) the fraction of planets with life on which intelligence arises, (6) the fraction of intelligent species that evolve a technological state that enables interplanetary communication, and (7) the lifetime of such technological civilization. Estimates made on the number of habitable planets in our galaxy range between 2×10^6 and 1×10^{11} (reviewed in Ulmschneider 2005). However, so far, radio-astronomical search for extraterrestrial intelligence has not given any positive indications.

6 Conclusions

It is owing to astrobiology, that the question on the origins and distribution of life in the universe is now tackled in a multidisciplinary scientific approach. Major research activities pertain to

- comparing the overall pattern of chemical evolution of potential precursors of life, in the interstellar medium, and on the planets and small bodies of our solar system;
- tracing the history of life on Earth back to its roots;
- deciphering the environments of the planets in our solar system and of their satellites, throughout their history, with regard to their habitability;
- testing the impact of space environment and simulated planetary environments on survivability of resistant life forms;
- searching for other planetary systems in our Galaxy and for their habitability.

It is important to note the multidisciplinary character of astrobiological research which involves scientists from a wide variety of disciplines, such as astronomy, planetary research, organic chemistry, paleontology and the various subdisciplines of biology including microbial ecology and molecular biology. Pieces of information provided by each discipline have contributed to the conception of the phenomenon of life within the process of cosmic evolution. New techniques that have been developed within the various disciplines are now accessible. Besides space technology and various remote sensing techniques, they include among others radioastronomical molecular spectroscopy, isotope fractionation analysis, nucleic acid and protein sequencing technology, immunofluorescence approach for the detection of hitherto uncultured microorganisms, and sensitive assays in organic chemistry and radiation biochemistry. Their application has already led to several conceptional breakthroughs, especially in the field of early biological evolution and in the detection of extrasolar planetary systems.

As mentioned above, the final goal of astrobiology is building the foundations for the construction and testing of meaningful axioms to support a theory of life. The discovery of a second genesis of life, either directly from planetary missions within our solar system, e.g., to Mars or Europa, or indirectly by radioastromony, would provide clues necessary to reach a universal definition of life.

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