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Astrobiology

Editorial

Are we the proud subjects of our will or the wretched victims of our drives? Charles Darwin, the British clergyman and naturalist, found the origin of the species – including men – in the continued natural selection process ruling the randomly mutating gene pools of living systems. In other words, the variety of species – including men – is seen as the result of a simple albeit very efficient trial and error process adapting the species to different and ever changing environmental conditions. Are we nothing else than the output of a soulless evolution machinery?

Sigmund Freud, the Austrian psychiatrist, identified in us an ego struggling for a niche between the super-ego coined by the authorities we experienced in our youth and the id, the instinctual heritage from our distant ancestors. This is good news, as the ego is, at least in principle, able to anticipate the future and to act responsibly in the here and now, while the evolution process is strictly governed by the conditions prevailing in the past. If we take, however, the number of species living on this planet as the measure of success, then we find no much remains of the proud responsible ego: the rate of extinction caused by human activities is estimated to be similar that of the major mass extinctions in the Earth's long history.

Sometimes we have to go far to come close. Astrobiology tells us what an isolated and outstanding value life represents in the universe: against all efforts so far, no traces of life have been found beyond the Earth. Oliver Botta, the young scientist at ISSI, presented the fascinating quest for life in the universe in the frame of the Pro ISSI lecture on 25 October 2005. We are indebted for his kind permission to submit our readers herewith a revised version of his talk. May the present issue of Spatium on astrobiology enhance our awareness of the unique value of life here on Earth!

Hansjörg Schlaepfer
Zürich, June 2005

Impressum

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Front Cover: An image of the Eagle nebula (Credit: NASA) is combined in this artist's impression with a colony of bacteria.

Astrobiology[1]

Dr. Oliver Botta, NASA Goddard Space Flight Center and International Space Science Institute

Introduction

Natural science has made overwhelming progress in the past few centuries: Galilei, Newton, Einstein are among the names standing for quantum leaps in our knowledge of the physical world. Yet, we are far from understanding one of the most common phenomena here on Earth: life. Charles Darwin's[2] concept of evolution based on random mutation of genetic properties and selection by the environment was a major leap forward **(Fig. 1)**. Watson[3] and Crick[4] found the double helix structure of the deoxyribonucleic acid (DNA) helping to understand these processes on the molecular level. But despite all this progress, the most fundamental questions remain unanswered: What is life? How did life emerge on Earth? What are the conditions for life to emerge? How did the environment influence the evolution of life on Earth and how did life in turn influence the environment? These and many other questions are open: the stage is set for astrobiology. It requires an interdisciplinary approach with contributions from all branches of science to unravel the answers to these questions. Astrobiology (sometimes also called xenobiology or exobiology) is the attempt to bring together scientists to combine their knowledge with a twofold goal: to understand the origin of life on Earth and to search for life outside of the Earth.

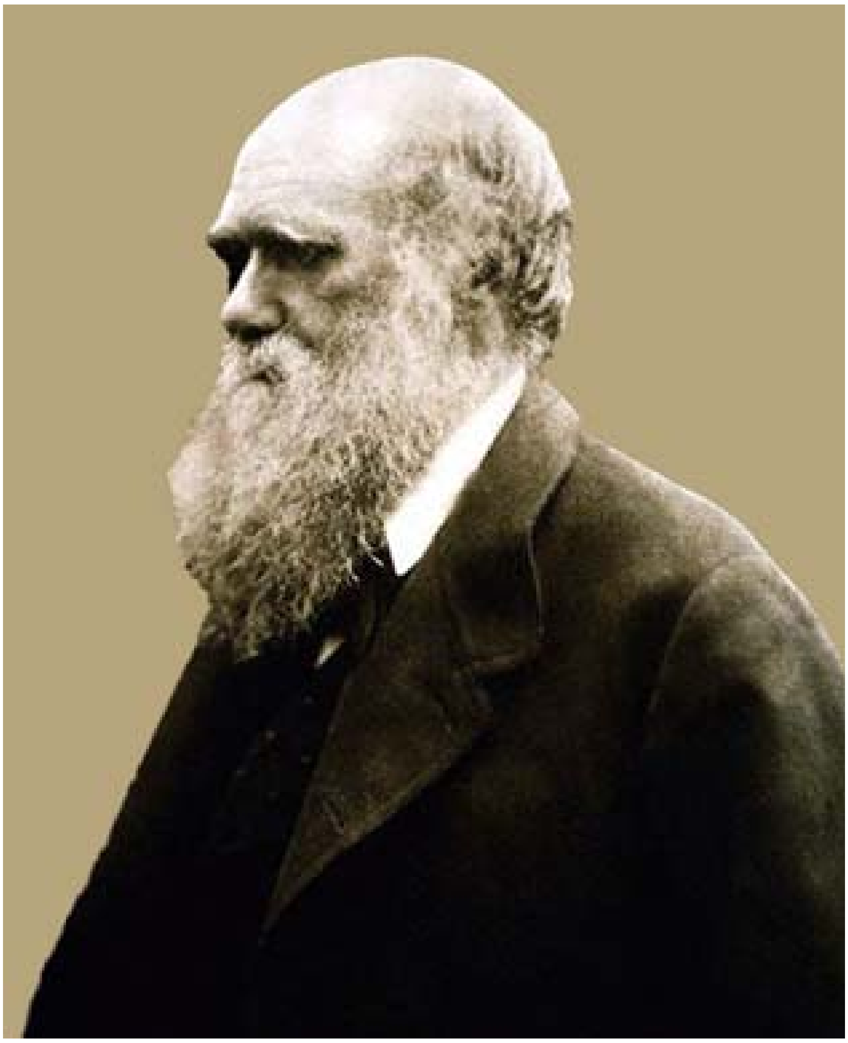


Fig. 1: Charles Darwin (1868)

[1] This article is based on a Pro ISSI lecture by Dr. Oliver Botta on 25 October 2005. In addition, we owe Dr. Frank Rutschmann, University of Zurich, significant contributions regarding biology.
[2] Charles Darwin, 1809 Shrewsbury–1882 London, clergyman and natural scientist
[3] James Dewey Watson, 1928 Chicago, biochemist, Nobel laureate 1962
[4] Francis Harry Compton Crick, 1916 Northampton–2004 San Diego, physicist, Nobel laureate 1962

What is Life?

Life is everywhere on Earth: heat-loving micro-organisms (called hyperthermophiles) populate hot springs with temperatures of more than 100 °C, alkaliphiles (alkalic-environment-preferring organisms) are found in soda lakes, piezophiles (pressure-resistant organisms) have been reported from the Mariana Trench, the deepest sea floor on Earth, some 10'000 metres below sea level. Life is everywhere, yet the most fundamental problem is our current inability to provide an all-encompassing definition, which we could use to direct the search for life elsewhere. In this situation, NASA adopted for its current roadmap for astrobiology the formulation of life as *a self-sustained chemical system capable of undergoing Darwinian evolution.* In the following chapters, we will adhere to this definition.

There are two basically different approaches to the understanding of the origin of life on Earth. The "top-down" approach looks at the current organisms, in particular in extreme environments, and also at the fossil record, to understand the molecular and phenological history of life and to attempt to extrapolate this knowledge towards the earliest forms of life on this planet. The "bottom-up" approach tries to understand how the planetary system, including the Earth, has formed and what the conditions on the surface were in the first billion years of its history. One also tries to understand which molecular building blocks of life could have been present on the early Earth, and how and where they were formed. From that knowledge one attempts to extrapolate towards the earliest traces of life which can be observed today.

The Building Blocks of Life

From atoms and molecules…

On the level of atoms, life is nothing else than a complex arrangement of a very limited set of chemical elements. This set comprises the biogenic elements carbon C, hydrogen H, nitrogen N, oxygen O, phosphorus P and sulphur S. Of every 200 atoms in our body, for example, 126 are hydrogen, 51 oxygen, 19 carbon, three are nitrogen and the remaining atom is one of all other elements. We have inherited all the hydrogen atoms, 63% of the material constituting our body, directly from the Big Bang fourteen billion years ago. The other elements up to iron have been synthesized by the main sequence stars burning hydrogen to helium and helium to carbon, etc., while the heaviest elements were created and expelled into space during supernova explosions[5]. As the first supernovae probably occurred just 500 million years after the Big Bang, life has had, at least in principle, plenty of time and space to evolve since then.

Amongst the six biogenic elements, carbon plays a central role thanks to its outstanding ability to form complex macromolecules containing thousands of atoms, which are stable in the temperature range where water is a liquid. On the other hand, the energy content of the carbon-carbon bond is low enough allowing water to dissolve and rearrange the carbon compounds.

Two other biogenic elements, namely hydrogen and oxygen, are important when combined to the water molecule H_2O. Water is a key ingredient for life as we know it as a solvent allowing molecules to be transported and chemical reactions to take place. Water has some unique properties including the fact that its solid form (ice) is lighter than its liquid state. In addition, water is very common in the universe: water is produced in the cold molecular clouds of the interstellar medium, where the oxygen atoms freeze on the surface of silica dust grains and eventually capture two hydrogen atoms to form the water molecules. Comets consist of a mixture of dust grains embedded in water ice. As they are the most pristine objects in the solar system, they testify that water has been present in remarkable quantities in the early solar system already.

In addition to water, a variety of other solvents, such as formamide ($CHONH_2$) or ammonia (NH_3), have similar solubility properties under certain conditions, but as

[5] See Spatium 13: Woher kommen Kohlenstoff, Eisen und Uran, Ruedi von Steiger, November 2004

Fig. 2: The original laboratory equipment used by Stanley Miller (1953).

they are less abundant in the universe than water, they did not play a role for the emergence of life on Earth.

In search for experimental evidence that the elements and simple compounds present on the early Earth can form complex organic molecules, Miller and Urey (1953) conceived an experiment **(Fig. 2)** which produced a wealth of complex organic molecules from water, methane, ammonia and hydrogen. In his apparatus, Miller boiled water and circulated the vapour through a glass vial, past an electric spark, then through a cooling jacket that condensed the vapour and directed it back into the boiling flask. This process yielded for the most part black, tarry organic residue, which was difficult to characterize back in these days. Most surprisingly, however, Miller was able to identify in this mixture the presence of amino acids, which are the very basic building blocks of proteins. This was the first experimental evidence that biologically relevant molecules could be synthesized from simple gases under conditions as they were thought to have occurred on the early Earth.

Later, it was found that the early atmosphere of the Earth was probably composed of other gases, from which under the same conditions significantly lower amounts of amino acids and other organic molecules are formed. This finding led to an increased interest among astrobiologists in the possibility that extraterrestrial organic matter could have been delivered to the early Earth by impacts of comets, asteroids, meteorites and interplanetary dust particles to contribute the first prebiotic building blocks of life.

…over macromolecules…

The next major step consists of combining many relatively simple molecules, such as for example amino acids, to complex macromolecules. In modern biology, the formation of macromolecules, which involves many individual steps, requires a sophisticated biochemical machinery. The synthesis of these molecules under prebiotic conditions has turned out to be one of the biggest challenges in the understanding of the origin of life. Biological macromolecules in all forms of life on Earth come in the following classes:

- The *carbohydrates* are macromolecules based on a carbon structure with many hydroxyl groups (–OH) attached. Large carbohydrate structures are used for energy storage (for example sugar or starch) as well as providing structural support in living systems (for example cellulose in the cell wall of plants).

- The *proteins* are the most diverse and functionally versatile biological macromolecules. The proteins consist of a chain of amino acids. Every amino acid is connected to one of 20 different residues, small compounds such as for example CH_3 or CH_2OH. Most proteins of living systems on Earth are composed of the same 20 different amino acids. Proteins are either important structural molecules of cells or possess catalytic properties. In the latter case they are called enzymes.

- The *nucleic acids* are the largest macromolecules existing in living organisms. They consist of individual nucleotides linked together to form long linear polymers. A nucleotide is a chemical compound that consists of a heterocyclic base, a sugar, and one or more phosphate groups. The nucleic acids come in two flavours, the deoxyribonucleic acid (DNA, **see Figure 3)** and the ribonucleic acid (RNA) discussed below.

Both the DNA and the RNA consist of two complementary strands that coil about each other like a spiral staircase to form a double

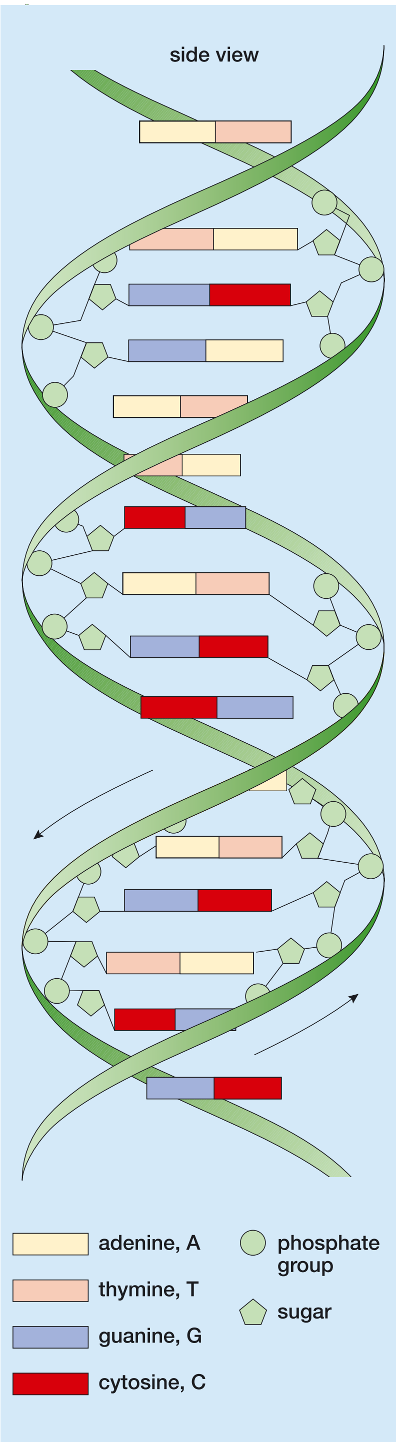


Fig. 3: The structure of the DNA double helix. (Credit: I. Gilmour, M. A. Sephton, Editors: An Introduction to Astrobiology, Cambridge University Press, 2003)

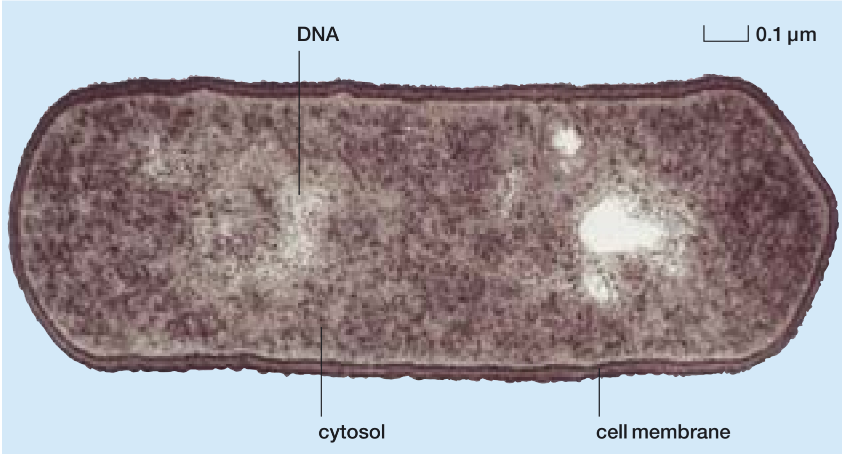


Fig. 4: The basic building blocks of a simple cell. (Credit: I. Gilmour, M. A. Sephton, Editors: An Introduction to Astrobiology, Cambridge University Press, 2003)

helix. Hydrogen bonds between the nucleotides form the steps of the staircase **(Fig. 3)**. They consist always of pairs: adenine in one strand is always linked to thymine in the other, and guanine in one strand is always paired with cytosine in the other. The bases are attached to a backbone made out of sugar molecules, which in turn are connected together along the exterior of the helix by phosphate groups.

Intriguingly, the DNA of all known forms of living systems is based on only these four bases constituting the universal genetic code. The code is expressed in the form of the specific sequence of the base molecules. The genetic code directs the production of proteins needed for the structure and the functions of the cell and for its own replication machinery. It represents the entire construction plan of a living organism.

…to self-replication…

Replication is one of the core principles of life. It allows overcoming the limited lifetime of all material entities. In addition, replication is central for evolution by providing a set of similar copies of an original on which the process of selection can act.

Under the effect of a large number of enzymes, the DNA can replicate in a very complicated process. In the vast majority of cases, the replication process yields an exact copy of the original DNA, so the replica is identical to the original. Sometimes, however, the sequence of the nucleotides of the copy is different from the original. It is this accidental change which is the underlying mechanism for the Darwinian evolution. A sequence of such random mutations may become prevalent in the gene pool of a population, if it is favoured by the natural selection process.

In contrast to the DNA, some RNA molecules were found to possess catalytic properties enabling to replicate themselves (self-replication). In a complicated laboratory procedure called *in-vitro selection,* some RNA molecules were found that showed the unique capacity to catalyze their own replication. It is thought that a selection process favoured RNA thanks to its replication potential. This led to the "RNA World Hypthesis", stating that on the early Earth the first replicating systems were RNA molecules. Based on its replication and evolution capacity, the RNA is seen as the most basic living system as per the definition above. That system did not contain a cell, but solely existed in suitable media providing the necessary supply of organic matter. Eventually, according to the RNA World Hypthesis, the genetic storage functionality of RNA was taken over by the more stable DNA, and the catalytic activity by the proteins, which have a wider range of functionalities. However, there still remain (major) problems even in this relatively straightforward scenario, for example how the building blocks of RNA, the ribonucleotides, were synthesized under prebiotic conditions. Another unsolved question is how the very reactive ribonucleotides were protected from simply being hydrolyzed in water thereby losing their reactivity.

… to living systems …

While the DNA in modern organisms stores its genetic information, it cannot self-replicate without being provided with monomeric building blocks to construct a second copy. These building blocks have to be synthesized by the organism or supplied by the surrounding medium. It is the cell, which provides the DNA the required infrastructure for its replication. The next giant step forward in the history of life was the encapsulation of bio-molecules inside compartments, where they are protected and concentrated **(Fig. 4).**

The function of the cell can be compared with a factory, in which the DNA acts as the construction plan contained in the DNA and the necessary raw material. The DNA acts as the factory's master plan storing the genetic code and controlling the processes in the cell. The DNA is surrounded by the cytosol, a liquid containing thousands of different types of proteins constituting the raw material. The cytosol acts as the factory's assembly line allowing the raw material to be transported to the places where it is needed. The cell volume finally is enclosed by a cell membrane made from lipids and proteins.

To replicate, the cell goes through a process called mitosis. First, the entire DNA of the cell is replicated. Then, the original and its copy move to different parts of the cytosol. Then, the cell begins to divide, separating properly the two DNA-containing regions. The result of this process are two identical daughter cells.

… to Darwinian evolution

If the replication process would work perfectly and would produce identical replicas exclusively, no evolution would be possible. The term evolution designates random mutation of the genetic properties of the individuals coupled with natural selection. In order to be selected by the environment, the genetic mutation must translate into a phenological advantage of the individual. In his epochal oeuvre "On the Origin of Species by Means of Natural Selection, or the Preservation of Favoured Races in the Struggle for Life" Charles Darwin saw the natural selection process driven for example by climate change or by competition with other species for limited resources. As a further important selection mechanism he identified the sexual selection: Failing to mate prevents the individual to contribute to the evolution of the population's gene pool which is equivalent to eliminating its genetic properties from the gene pool. While these selection processes act on the level of the individual, they cause the population's collective gene pool to drift continuously beyond the lifetime of the single individual.

The Evolution of Life on Earth

The Sun and its planets are the result of the gravitational collapse of an interstellar cloud some 4'600 million years ago. The planets were formed from a debris disk that circulated the early Sun through accretion of dust grains on relatively short time scales of some tens of million years. The exact environmental conditions on the early Earth at that time, called the Hadean, are not known, but it is thought that the surface of the Earth cooled down to a level where water is liquid after about 200 million years. The heavily cratered surface of the Moon, lunar samples and meteorites have provided evidence for the early impact history of the Earth–Moon system. While impacts of comets and asteroids may have brought water and organic compounds to the early Earth, these impacts were devastating events that may have sterilized the whole surface of the planet and even boiled away the water on Earth. Eventually, though, the inventory of large bodies crossing the Earth's orbit declined, so that the frequency of these impacts decreased paving the way for the evolution of life on Earth.

Fig. 5: These living stromatolites have an age of around 3'500 years. The warm, shallow waters of Western Australian's Shark Bay favour the growth of micro-organisms, particularly cyano-bacteria. Fossil stromatolites – literally layered rocks – also represent the oldest evidence for life on Earth. (Credit: University of South Carolina, Geology Department)

The conditions under which prebiotic chemistry on the early Earth occurred that would have eventually led to the first self-replicating organisms are not known. It is assumed that sandy beaches and volcanic mud pools may have provided the required milieu that protected prebiotically synthesized organic compounds from ultraviolet radiation and oxidation. Superheated columns of mineral-rich water that gush from vents in the seafloor, the so-called black smokers, may have been another potential environment for life to emerge.

The oldest traces of life on Earth are fossil cyano-bacteria that were found in 3.5 billion years old rocks in Western Australia, although there is a strong controversy about this topic in the scientific community. More secure morphological traces appear in the form of stromatolites in around 2.5 billion years old rocks. Stromatolites are the solidified ("lithified") remnants of microbial mats, in particular of cyano-bacteria. Active stromatolites can be found today in hyper-saline lakes and marine lagoons **(Fig. 5)**. It can be said that these modern forms of cyano-bacteria constitute the most ancient organisms of life on Earth.

The history of life on Earth is also a history of mass extinctions. Life has been endangered or even nearly extinct many times since it emerged by massive climate changes, cosmic impacts or major volcanism events. It is estimated that more than 99.9% of all species that have ever lived are now extinct. An especially critical phase seems to have been the period between 750 and 580 million years ago when the Earth was completely covered by heavy ice sheets with surface temperatures as low as −50 °C according to the "Snowball Earth Theory". Such environmental conditions would have erased all but a small fraction of existing life deep on the floors of the oceans. Because the ice cover could not stop the continued output of the greenhouse gases by volcanoes, the Earth regained a moderate climate in a very short timeframe leading to hot environments according to the "Hot House Theory", now endangering the existing living systems which had successfully adapted to low temperature climates before. However, the subsequent phase of a warm, relatively stable climate allowed virtually every major phylum of animals to evolve within a relatively short time period of some 40 million years (the Cambrian explosion).

Mass extinctions have led to the loss of many species, but they stimulated also the evolution of life by creating unoccupied ecological niches where the remaining organisms could proliferate. The last known mass extinction occurred some 65 million years ago. It is thought to be caused by the impact of an asteroid of the size of 10 kilometres near what is now the north-western part of Mexico's Yucatan peninsula. This impact and the subsequent dust in the atmosphere led to a decade-long winter and to the extinction of 60 to 80% of all then living species, including the dinosaurs. Interestingly, some animal classes were less affected, like for example the amphibians and the mammals. The latter were present in the form of rat-like animals. After the cease of the dinosaurs' dominance, they were able to proliferate and to develop into the most complex animals on this planet, including men.

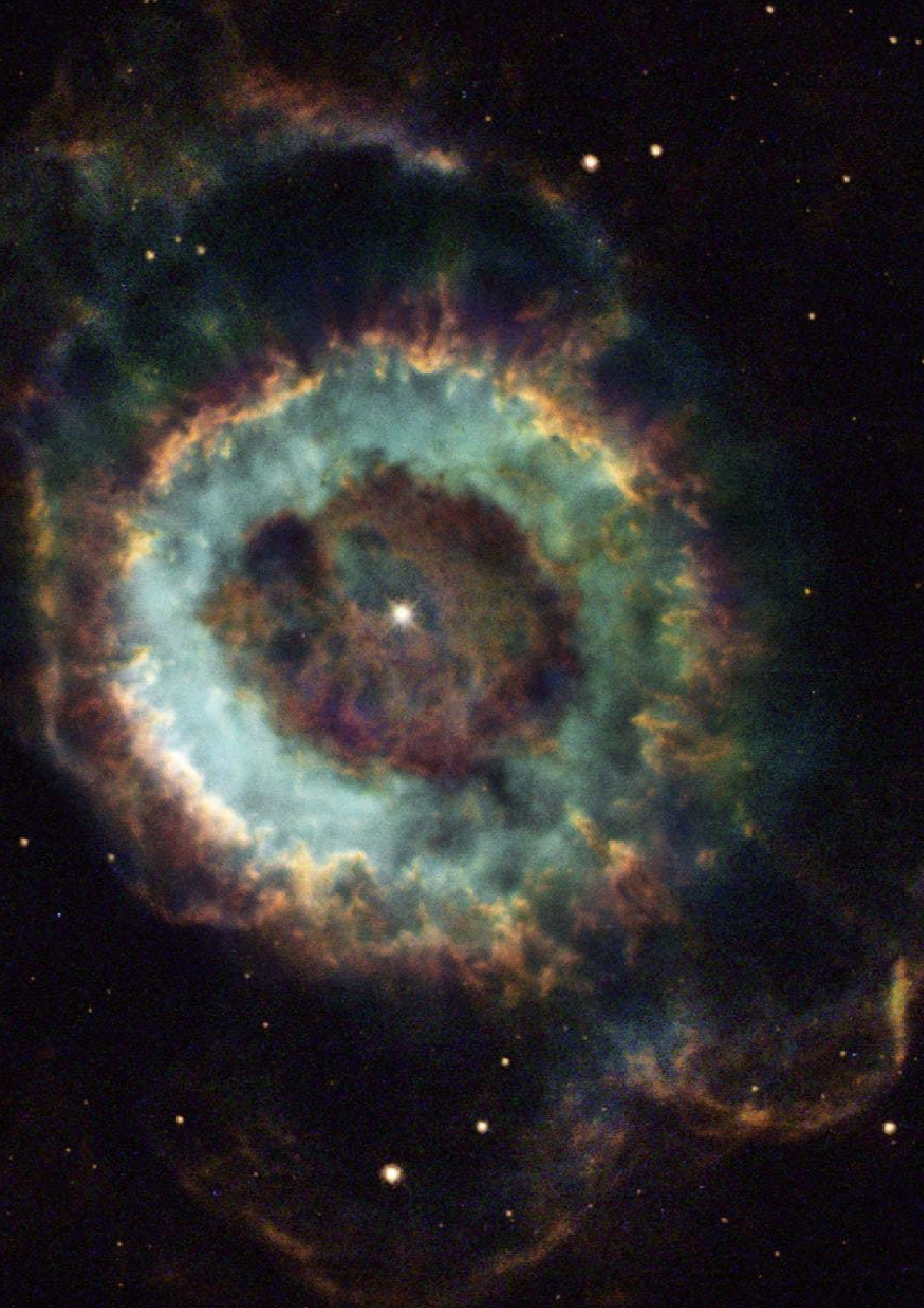
Co-evolution of Life and its Environment

According to the operational definition cited above, life is characterized as a self-sustaining chemical system with the ability to undergo Darwinian evolution. Through its chemical processes life is in constant exchange of matter and energy with its environment causing life to alter the environmental conditions leading to a co-evolution with its environment. This aspect is gaining central importance when it comes to searching for life in the universe as specific atmospheric biosignatures can be used as a proxy for biological activities on a planet.

The Earth's early atmosphere is supposed to have been dominated by carbon dioxide, nitrogen and water vapour. At that time, oxygen was present in the atmosphere only in trace amounts namely as a product of the breakdown of water vapour by the Sun's ultraviolet radiation or out-gassing from the interior. Therefore, no ozone layer was there to shield the surface of the Earth against incoming high energy radiation. This is one of the arguments in support of the hypothesis that the first living systems evolved in more sheltered environments such as sediments or deep waters.

The atmospheric concentration of oxygen rose to modern levels only about 2 billion years ago. However, oxygen was produced by cyanobacteria on the Earth through photosynthesis supposedly since 3.5 billion years. This leaves about 1.5 billion years of time on the Earth (the Archean epoch) when life was present, but the atmosphere was still anoxic. In fact, one of the key questions associated with the evolution of life on Earth is why it took so long for oxygen to reach these higher levels. Only this rise of oxygen in the atmosphere provided enough harvestable energy required by multicellular organisms.

Fig. 6: The white dwarf star in the centre of the planetary nebula NGC 6369 radiates strongly at ultraviolet wavelengths and powers the expanding nebula's glow. The nebula's main ring structure is about a light-year across. It contains the three biogenic elements oxygen, hydrogen, and nitrogen, which are coloured blue, green, and red respectively. In a remote future some of these elements eventually may help to constitute a living system. (Credits: Hubble Heritage Team, NASA)



Life from Space, Life into Space

The possibility that the emergence of life on Earth was based on organic molecules delivered to the Earth from space has become a subject of increasing interest. The analysis of carbonaceous meteorites has demonstrated that organic molecules, including amino acids, are formed in extraterrestrial environments. Astronomical observations have also shown that some of these molecules were formed already before the sun even started to form, and were incorporated into planets and smaller solar system objects such as comets and asteroids. Due to the extremely high temperatures on the planets during their formation, no organic molecules survived this epoch. The organic compounds necessary for the origin of life were formed either later in the atmosphere (e.g. through Miller-Urey-type reactions), or were delivered to the early Earth by large asteroid and comet impacts (as discussed above) or by their fragments, the meteorites and interplanetary dust particles. The study of meteorites, particularly the carbonaceous chondrites that contain organic matter up to 5% by weight, has allowed close examination of extraterrestrial organic material. One of the most famous sources of extraterrestrial material is the Murchison meteorite named after the Australian town where it reached the Earth in 1969 **(Fig. 8)**. Among other classes of organic compounds, more than eighty different amino acids have been identified in the Murchison meteorite at abundances of more than 1 part-per-million (ppm), eight of which are identical to those used in life on Earth as building blocks of proteins and enzymes. Also, the presence of sugar-related molecules and nucleobases was confirmed. Another source of information is the collection of micrometeorites that have been extracted from Antarctic ice. Many of these tiny objects in the 50–100 µm size

Fig. 8: The Murchison meteorite. This is the most intensively investigated carbonaceous chondrite. It fell near the town of Murchison in Australia on 28 September 1969, only three months after the first lunar landing of Apollo 11. Fortunately, all the techniques that were developed at NASA to investigate the lunar samples for organic compounds could be applied to the meteorite as well. This allowed publishing the first report about the extraterrestrial amino acids in this meteorite shortly after its impact.

Fig. 7: This chicken embryo has been bred for seven days. Like its remote ancestors and like the majority of fossil and living tetrapodes, it will develop feet with five digits in the next few days, of which one however will disappear again to produce an individual with only four digits on its feet like all the currently living birds. This is an example of a vestigial trait, showing that the evolution of this individual (its ontogeny) mirrors the evolution of the birds in general (its phylogeny). (Credit: Hansjörg Schlaepfer)

are unmelted chondritic micrometeorites, indicating that they had crossed the terrestrial atmosphere without suffering drastic thermal shock. In February 2006, the NASA Stardust spacecraft has returned, for the first time, samples from beyond the Earth-Moon system in the form of cometary dust particles, which will give scientists a new window on the composition of comets.

It is thought that the various extraterrestrial sources may have delivered about 10^{20} g of carbon to the Earth during the first 600 million years (the Hadean period). This delivery represents more carbon than the amount engaged in the current biomass, which is estimated at 10^{18} g. Whether or not these extraterrestrial compounds were the major source of organic molecules on the early Earth cannot be established even qualitatively since there are currently no estimates of the contributions from the other, indigenous sources.

If meteorites can transport organic matter to the Earth, the next logical question relates to whether living systems could have been delivered to the Earth. Of course, such specimens would experience the severe environmental conditions of space. Still, understanding survival in extreme conditions is essential for evaluating the potential for the interplanetary transfer of viable micro-organisms, and thus the potential that any life elsewhere in the solar system might share a common origin with life on Earth (or vice versa). Conditions in space and on other worlds are much more extreme than those encountered by any of the habitable extreme environments on Earth. Therefore, studies of survivorship beyond the Earth belong to the important tests of the resilience of Earth-originated life towards extreme conditions and its potential for dissemination in space.

Another option for life to leave its home planet is that of a civilized society using advanced technology to travel into space. This is what we call manned spaceflight **(Fig. 9)**. The fact that all the niches on Earth are occupied by some forms of life suggests that it might be the ultimate destiny of life to leave its cradle and to proliferate into space.

Fig. 9: Launch of the NASA Space Shuttle Columbia on STS-109 on 1 March 2002. Currently, rockets with their inefficient chemical fuels are our only way to leave the Earth and to travel into space. If this journey is the destiny of mankind, we have only achieved the very first steps so far. A major leap forward, comparable with the introduction of jet engines in aeronautics that revolutionized air-travel, is required to travel anywhere beyond Mars. (Credit: NASA)

Strategies for Life Detection

When it comes to finding strategies for the detection of extraterrestrial life, two cases have to be distinguished depending on where the target is located:

- *Within the solar system,* detection of living systems may be done by sending a spacecraft there with instruments to take *in-situ* measurements. Another option is remote sensing like for instance mapping the methane distribution in the Martian atmosphere from an orbiting spacecraft. The remote sensing approach allows only the detection of an active biosphere by finding gases in the atmosphere in concentrations that are beyond any abiotic processes. In contrast, the *in-situ* strategy allows the search for biosignatures that are either based on morphological, molecular or isotopic patterns from not necessarily currently living systems. There is not one single biomarker that can be used to unambiguously identify a signature of life. Therefore, the recognition of patterns, for example in the form of an overabundant presence of a certain group of molecules, becomes the favourite approach since life as we know it makes use of building blocks that are used repetitively to form larger structures. This approach is attractive also because it allows the recognition of patterns that do not necessarily have to be similar to terrestrial life.

- *Beyond the solar system,* the distances are by far beyond the reach of any spacecraft. The quest for life, therefore, must be based on remote sensing techniques exclusively. Of primary interest are exosolar planets. So far, over 200 extrasolar planets have been found, but most of them are very different from what we expect to be a habitable planet. The test whether such a planet may harbour life will be based on so-called atmospheric biosignatures, similar to the spectroscopic approach mentioned above.

The European Space Agency (ESA) is currently planning a mission called Darwin **(Fig. 10)** to search for gases in the atmosphere of exosolar planets such as ozone, a proxy for the presence of large amounts of molecular oxygen, ozone, water, carbon dioxide, and methane. This approach, however, is extremely challenging since the luminosity of the star is orders of magnitudes higher than that of the planet. The analyses can be done by means of very sensitive long based spectrometers, which split the light reflected by a planet's atmosphere into its spectrum, where the content of these trace gases can be observed. The important clue here would come from the fact that some of these gases can be present in detectable amounts in the atmosphere of an exosolar planet only if there is a constant re-supply maintained by living systems. Any gas mixture that is in disequilibrium in an atmosphere to such an extent that it can not be explained by abiotic reactions would indicate biological activity on the planet.

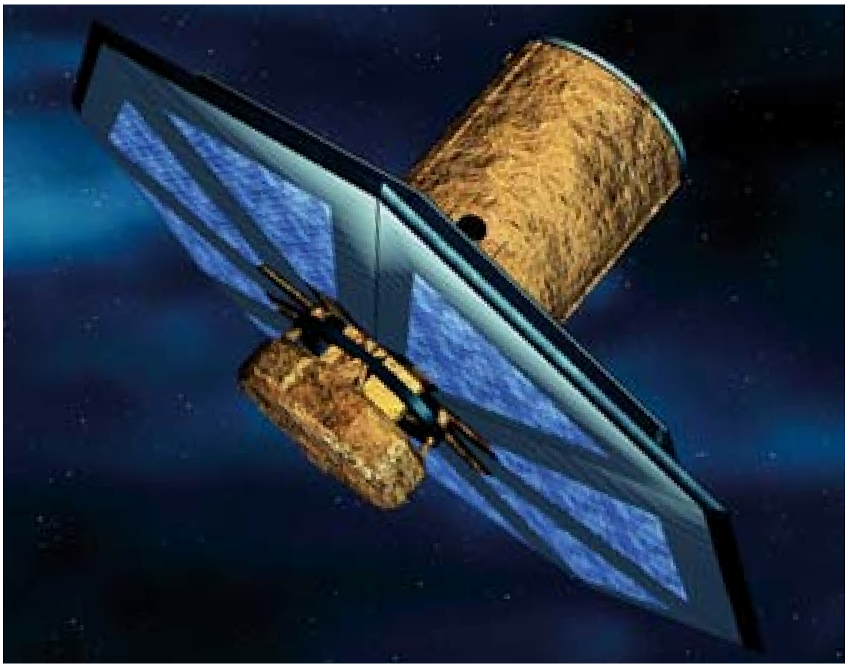


Fig. 10: One of the three space telescopes of the European Space Agency's Darwin mission. (Credit: ESA)

Life in the Universe

So far we have discussed the properties of life, how life evolved on Earth and how we can maximize the chance to detect life in the universe. Now, we address the question where we should search for life.

The Prerequisites for Life

Although no convincing signs of life have been found outside the Earth so far, a set of conditions can be compiled which must be fulfilled by a star and its planetary system in order to allow the development of life as we know it:

- The central star must not be too massive (no more than about 1.5 times the mass of the Sun). More massive stars burn their hydrogen faster, and the time span in which the star is in a stable state is probably too short for life to originate and evolve on its planets. On the other hand, stars with less than about 10% of the solar mass will tidally lock planets into synchronous orbits. Such a planet would have a very hot side towards the star and a very cold side in the opposite direction, similar to Mercury in our own solar system. Provided the planet does not have the mass range of Jupiter-type planets, it will probably not be able to keep an atmosphere over periods of hundreds of millions of years. It is also highly unlikely that such a planet contains liquid water. In addition, the planet would be exposed to high energy solar flares providing a deadly environment for prebiotic chemistry and life.

- For each star it is possible to determine the so-called habitable zone, which depends of course on how one defines the term "habitable". For example one could correlate "habitability" with the presence of liquid water on the surface of a planet with an appreciable atmosphere. If such an atmosphere contains a certain amount of greenhouse gases, such as methane or carbon dioxide, the habitable zone is widened towards the outer range of the stellar system. Since the luminosity of a star tends to increase during its lifetime, the habitable zone is being shifted outwards slowly.

- Finally, the size of the planet is critical as well. The mass of a potentially habitable planet should not be too small; otherwise its gravitational field would be too weak to maintain a dense atmosphere over hundreds of millions of years. Also the planet should be massive enough to maintain active plate tectonics or at least some form of volcanism throughout its lifetime. Plate tectonics continually recycle oceanic crust back into the mantle at subduction zones and continually regenerate it at ocean ridges by the solidification of fresh magma. Without such a process, the planet does not have a feedback mechanism that would allow it to stabilize its climate and the physical conditions on the surface.

While these prerequisites apply to planets on which life could potentially develop, there are places in our solar system that are considered as potential habitats for some forms of life, but do not fulfil all these criteria. Of particular interest are the moons of the giant planets Jupiter and Saturn, where the lack of solar irradiation may be compensated by other mechanisms such as tidal heating to provide the required energy. Spacecraft data from the Galileo and Cassini missions have supported the notion that liquid water, and perhaps oceans, could be present under the icy surfaces of these objects.

Astrobiological Exploration of the Solar System

The solar system is of principle interest in the quest for extraterrestrial life. Most importantly, the distances to the other planets are such that, with our current technology, we have the capability to explore these worlds with robotic missions to perform *in-situ* measurements and eventually bring samples back for analysis here on Earth. Although we have set foot on the moon almost 40 years ago, we have not yet made the next step, which is the manned mission to Mars. And it seems that it will take at least another 30 years for this to happen. Of all the planets and small objects in our solar system, most are outside the habitable zone (as defined above). For example, Mercury, the innermost planet in the solar system, is far too close to the Sun and therefore too hot to harbour life. The surface temperatures on Mercury range from about –180 °C at the bottom of craters near the poles to about 400 °C at the sub-solar point. In combination with the absence of a dense atmosphere on Mercury, life as we know it could not develop there.

Venus

Venus is the most similar planet to the Earth in the solar system. It is often called the Earth's sister, since it has almost identical diameter and mass. Very early in its history, its environmental conditions may have also been similar to those of the Earth, and perhaps favourable for the emergence of life. However, due to its closer distance to the Sun, Venus has developed surface conditions, including temperatures of around 460 °C and permanent thick clouds of H_2SO_4 droplets, which make the current presence of any form of life highly unlikely.

The Earth's Moon

The Moon is thought to have been formed as a result of a collision between a very early, semi-molten Earth and a planet-like object with the size of Mars. The samples returned from the Apollo and Luna missions have shown that there are no signs of life and not even organic compounds present on the Moon's surface. The sterilizing UV and particle radiation it is exposed to would prevent any organic molecule to build up. However, the Moon may have been a crucial element in the development of life on the Earth. With the exception of Pluto and its moon Charon, Earth is the only planet in the solar system that has such a massive satellite relative to its own mass (the mass of the Moon is

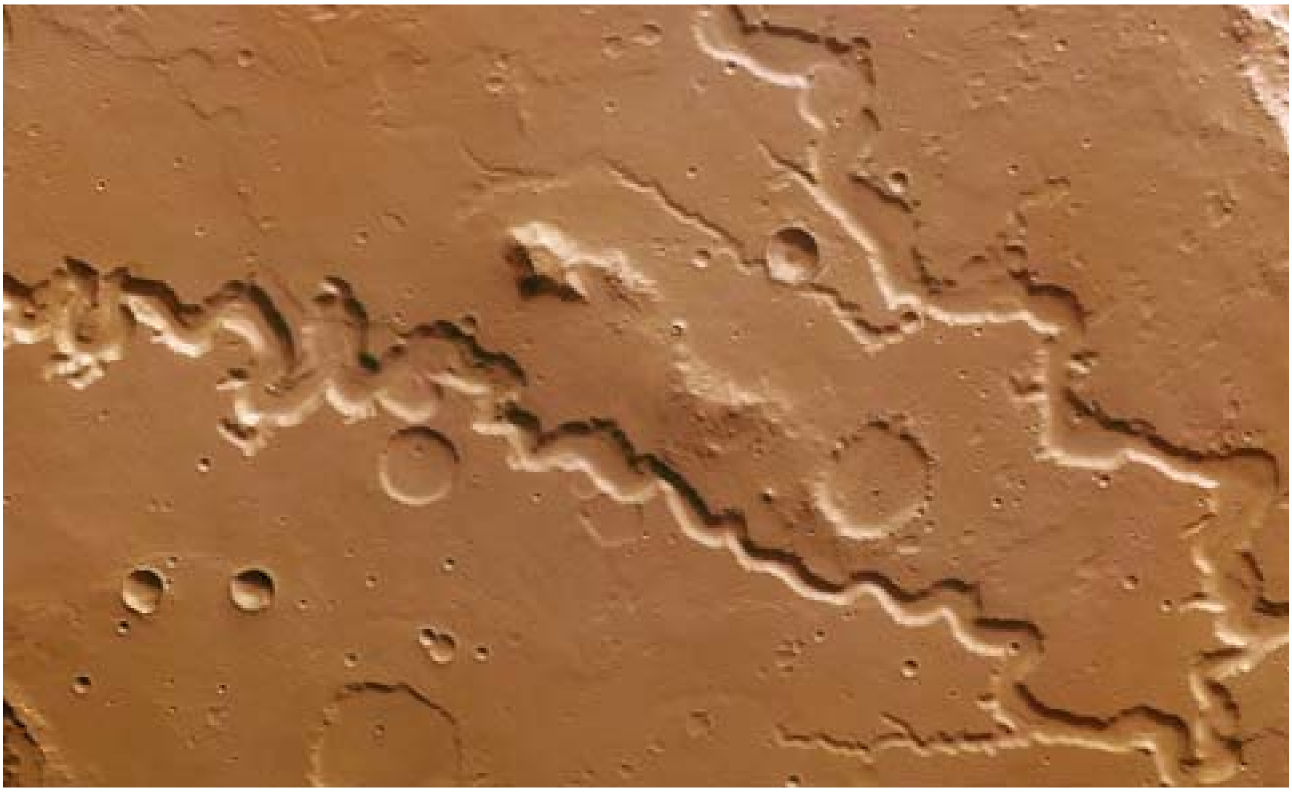


Fig. 11: Nanedi Valles, a roughly 800-kilometre valley extending southwest–northeast and lying in the region of Xanthe Terra, southwest of Chryse Planitia of Mars. In this view, Nanedi Valles ranges from approximately 0.8- to 5.0-kilometre wide and extends to a maximum of about 500 metres below the surrounding plains. The valley's origins remain unclear, with scientists debating whether erosion caused by ground-water outflow, flow of liquid beneath an ice cover or collapse of the surface in association with liquid flow is the responsible mechanism. This image was captured by the High-Resolution Stereo Camera (HRSC) onboard ESA's Mars Express. (Credit: ESA).

about $^1/_7$ of the Earth's mass). This high mass ratio has the effect that the Earth's rotation axis has always been relatively stable at its current inclination of 23.5°, which in turn provided a stabilized climate on the surface over billions of years.

Mars

Mars is the primary target for the search of traces of past or present life in the solar system. From the many Mars exploring spacecrafts and rovers there is convincing evidence that water existed in substantial quantities on its surface at some earlier epoch. We do not know, however, whether it was present on the surface for a sufficiently long period of time and if it is perhaps still present in subsurface aquifers. Based on the morphological evidence for the presence of surface water in the earliest epochs, including large outflow regions **(Fig. 11)** and layered sedimentary records, Mars initially had a dense atmosphere. However, due to the smaller mass of Mars as compared to the Earth, it lost its atmospheric gases to space, leaving it with the current thin CO_2-rich atmosphere.

The two Viking landers, which touched down on the Martian surface in 1976, carried biological life detection instruments as well as a gas chromatograph-mass spectrometer. These instruments were used to analyze soil samples in the immediate vicinity of the landers **(Fig. 12)**, but they failed to detect organic molecules in any of these samples. This finding is the primary evidence that points to an absence of life on the surface and immediate subsurface of Mars today. However, given the recent discovery of flourishing biospheres at 1'000 metres below the Earth's surface in South African gold mines, it is conceivable that a similar microbial community might be present in the deeper subsurface of Mars.

The Giant Planets Jupiter and Saturn

The atmospheres of Jupiter and Saturn (as well as Uranus) are mainly composed of hydrogen and helium, with a noticeable fraction of methane and a lower contribution of ammonia. The astrobiological interest of these planets is limited as they have no solid surface. In contrast, the interest in the giant planets' satellites is rapidly growing currently.

The Jovian Moons

The Galilean moons of Jupiter were visited several times by the Galileo spacecraft while orbiting Jupiter for almost 10 years. Magnetometer data have provided evidence for an ocean of liquid water beneath the icy crust of Europa, **Fig. 13.** Similar conditions may also exist on Ganymede and Callisto. While their distances from the Sun prevents these objects to receive sufficient solar radiation to maintain liquid water on their surfaces, their orbital geometries give rise to tidal forcing of their interior that provides a heat source which is probably sufficient to melt some of the subsurface ice layers. Although liquid water is supposed to be present on Europa, the chances for life to have originated and de-

Fig. 12: A Martian landscape acquired by the Viking 2 camera in 1976. While some parts of the lander are visible in the foreground, a rocky environment is seen in the background. (Credit: Edward A. Guinness, Washington University, St. Louis, USA)

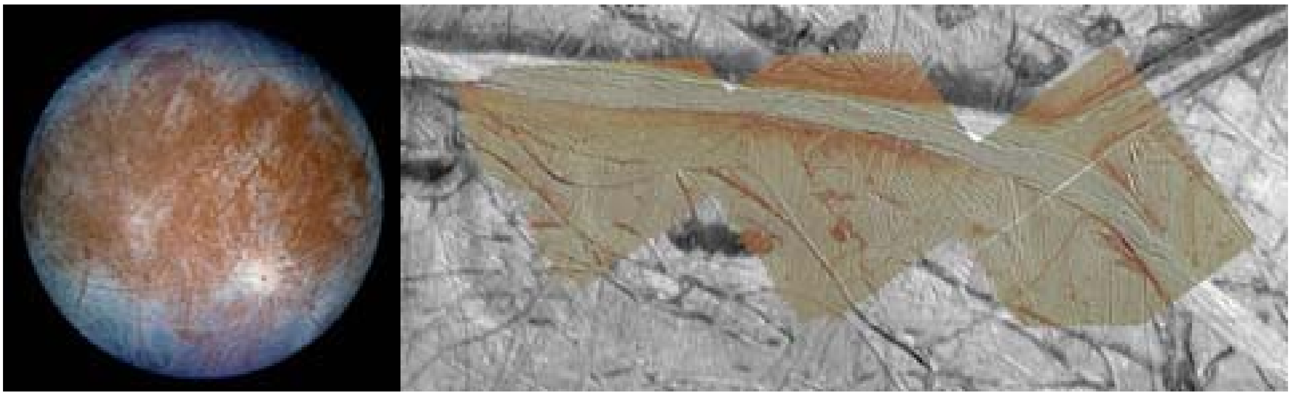


Fig. 13: Jupiter's icy moon Europa (left) and Agenor Linea (right), a bright white band on its surface obtained by NASA's Galileo spacecraft. Along this portion of Agenor is a "triple band," flanked by dark, reddish material of uncertain origin. On the right side of this image, Agenor splits into two sections. While these and other details of Europa's surface formations remain mysterious, the general results of Galileo's exploration of Europa have supported the idea that an ocean of liquid water lies beneath the cracked and frozen crust. (Credit: NASA).

veloped in this subsurface ocean are remote because it is not clear where organic compounds would have come from. Although some organics may have survived an impact on Europa, the transport of this material through the ice shell is not at all understood. Because of these uncertainties, Europa is still a prime target for future missions, which could include a ground penetrating radar instrument or even a sample return mission.

The Saturnian Moons

Since 1944, when Gerhard Kuiper detected methane in Titan's atmosphere, this moon was suspected to harbour life, as on Earth methane is a product of organic metabolism. Titan has a dense N_2 atmosphere rich in organics in both gas and aerosol phases. It represents, therefore, a natural laboratory for studying the formation of complex organic molecules on a planetary scale and over geological times. Despite the fact that Titan's surface temperatures are much lower than those found at the Earth's surface and that liquid water is totally absent therefore, the satellite provides a unique milieu to study the products of the fundamental physical and chemical interactions driving a planetary organic chemistry. However, neither the Cassini orbiter nor the Huygens lander have found any sign of life so far.

Recently, another moon of Saturn, the tiny Enceladus, has made scientific headlines when NASA announced the detection of huge water geysers on Enceladus by the Cassini orbiter **(Fig. 14)**. Plumes of icy material extend far above its southern polar region. It is believed that the plumes stem from geysers erupting from pressurized subsurface reservoirs, potentially containing liquid water, while the surface cover is ice at a temperature of around –200 °C.

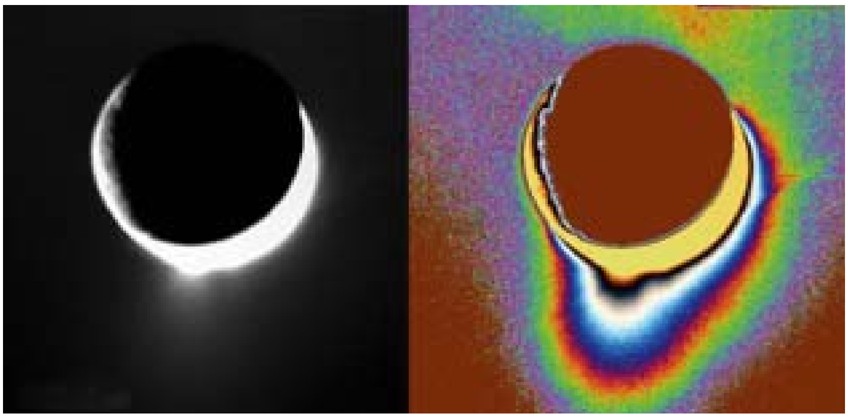


Fig. 14: Plumes of icy material extend above the southern polar region of Enceladus. (Credit: NASA/JPL/Space Science Institute)

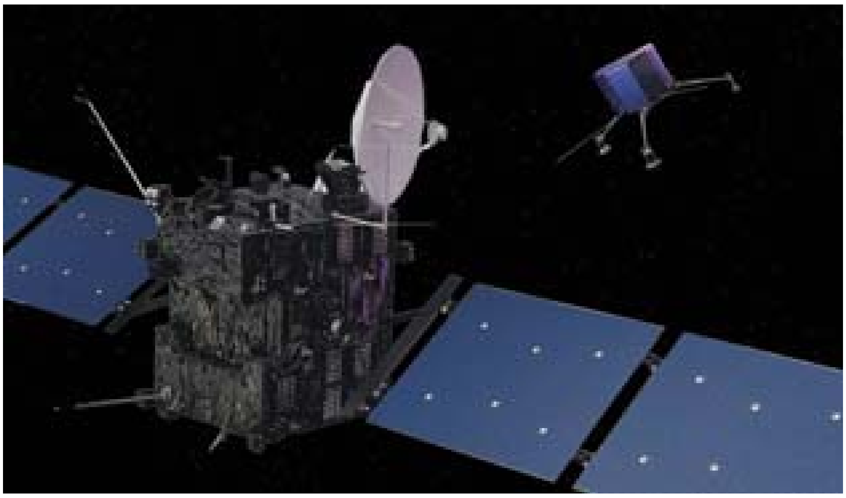


Fig. 15: An artist's view of the Rosetta mission and its lander Philae heading for the comet 67 P/Churyumov-Gerasimenko. Rosetta is under way since spring 2004 and will reach the orbit of its target comet in spring 2014. After close inspection of the comet, the probe will deliver the vehicle Philae, which is to touch down on the comet some days later. The probe itself will continue to circle around the comet for another year during its closes approach to the Sun. (Credit: ESA)

Objects on the Outer Rim of the Solar System

The icy giants Uranus and Neptune as well as Pluto and the Kuiper belt objects are too far away from the Sun to have liquid water on their surface; however, the exploration of these planets is immensely important to our general understanding of the formation of planetary systems.

Comets

Comets are believed to be Kuiper belt or Oort cloud objects whose orbit has been changed by gravitational pull from the outer planets bringing them into the inner solar system. As stated above, comets contain large amounts of water[6]. For example, two thirds of the material in Comet Halley's nucleus are water ice, and the rest is made out of silicate grains and organic particles. Substantial amounts of organic molecules including for example formaldehyde, methanol, etc. were detected in the comas of several comets. Improving detection capabilities of scientific probes allowed for the identification of many more organic substances in cometary comas, like for example ammonia, methane and acetylene, up to more complex molecules like cyano-acetylene. Unfortunately, we have no direct measurements about the composition of the nucleus yet. The European Space Agency's Rosetta mission with its lander Philae is on its way to comet 67 P/Churyumov-Gerasimenko and will address this question with its scientific payload **(Fig. 15).**

Outlook

Searching for new worlds has been one of mankind's very basic endeavours since its earliest days. Astrobiology is nothing else than the continuation of this effort into new dimensions. But at the same time it provides us with a deepened knowledge of the conditions of life on our own planet. In that sense, astrobiology may help us also to become aware of the unique value of life prompting us to safeguard the richness of species on our Earth.

[6] Spatium 4: Kometen by Kathrin Altwegg, October 1999

The Author

Oliver Botta was born in Liestal, Kanton Baselland, where he visited the elementary and secondary schools. Fascinated by the overwhelming wealth of molecules that can be composed from a limited set of atoms he decided to study chemistry at the University of Basel. He concluded the studies with the Ph.D. degree in organic chemistry in 1999. Then he moved to the Scripps Institution of Oceanography at the University of California at San Diego, USA, where he was engaged in organic trace analysis. This activity brought him in contact with the analysis of meteorites, thus combining his chemical background with his fascination of space. He also was involved in the early development of an analytical instrument for the robotic exploration of solar system bodies and that is now part of the science package of the European ExoMars mission.

From 2002 to 2004 Oliver Botta was engaged by the European Space Agency ESA as an external Post Doctoral Fellow at the University of Leiden in the Netherlands, where he not only continued his activities in the area of organic trace analysis of meteorites, but was also involved in astronomical observations of organic molecules in space. From April 1st 2004 onwards he was engaged at the International Space Science Institute with the primary task to organize an international forum on Astrobiology, leading the way for the Institute to increase its activities in this interdisciplinary scientific field. Last year, Oliver Botta then moved to the United States again, where he was engaged at the NASA Goddard Space Flight Center in Maryland to support the development of the Sample Analysis at Mars (SAM) instrument, a gas chromatograph-mass spectrometer for the future NASA Mars Science Laboratory rover mission. On July 1st 2006 he returned to ISSI to lead the Institute's future activities in Astrobiology.

Astrobiology is not really a new scientific field, but more a rigorous attempt to combine the knowledge and the methodologies of the classical branches of science with the goal to lead to answers to some of mankind's most fundamental questions relating to the emergence of life on the Earth and the possibilities for life at other places in the solar system and beyond. This interdisciplinary approach requires scientists to communicate in a common language, and that is where Oliver Botta sees his role in his future engagement at ISSI. Together with his wife, Oliver Botta has two sons and a daughter, with whom he likes to play Lego, a concept that is comparable to nature's to build up complex systems by repeating and re-arranging (relatively) simple building blocks.