INTERNATIONAL SPACE SCIENCE INSTITUTE

# SPATIUM

Published by the Association Pro ISSI

No. 30, October 2012

## Planets And Life

# Editorial

The present issue of Spatium addresses a field *at the very frontier of science where knowledge ends and ignorance begins.* This is as true today as it was 150 years ago when the British scientist William Whewell* made this incisive characterization of astrobiology.

Still, science and technology have made tremendous progress since Whewell's days. Much is known regarding the evolution of life on Earth of which the oldest traces date back as far as 3.8 billion years. It seems that our planet became inhabited as soon as it was habitable, that is when the relevant physical and chemical parameters allowed life as we know it to emerge. If this is the case, then life should (or even must) emerge on other planets as well provided again that some general conditions are met. This is good news for all scientists engaged in searching for life in the universe. The bad news, however, is that the evolution of a species that is able to give signs of life to interstellar counterparts seems very unlikely in view of the sequence of improbable events that made this possible on Earth. Think only of the about three billion years when life on our planet rested on microbes, which did not communicate beyond their habitat, while such a species on Earth only gained the required capability 30 years ago. Or remember the dinosaurs that for more than 100 million years ruled the Earth without developing any means for interstellar communication, and without their extinction by a meteorite hitting Earth 65 million years ago, history would have taken quite a different path. The evolution of what we call intelligent life on Earth has rested on a number of such chance events, at least some of which had a very low probability.

So, the search for extraterrestrial life is basically the hunt for micrometer sized microbes on a planet that may be some hundred billion kilometres away. Surprisingly, this is not an impossible mission. Science has gained enough insight in how life may have evolved on Earth and how it interfered with the planet's evolution changing its signature so deeply that it may be witnessed from light years away.

Professor Tilman Spohn, Director of the Institute of Planetary Research of the German Aerospace Center (DLR), presented the current status of our knowledge of what is required for a planet to eventually allowing life to emerge and the fascinating interplay between life and its host planet. We thank Prof. Spohn and his collaborators for their valuable support in publishing herewith a summary of his talk and wish our readers enlightening moments when tagging along his lines of thought.

***Hansjörg Schlaepfer***
*Brissago,* October *2012*


## *Impressum*

SPATIUM
Published by the
Association Pro ISSI

INTERNATIONAL SPACE SCIENCE INSTITUTE

Association Pro ISSI
Hallerstrasse 6, CH-3012 Bern
Phone +41 (0)31 631 48 96
see
www.issibern.ch/pro-issi.html
for the whole Spatium series

***President***
Prof. Nicolas Thomas,
University of Bern

***Layout and Publisher***
Dr. Hansjörg Schlaepfer
CH-6614 Brissago

***Printing***
Stämpfli Publikationen AG
CH-3001 Bern


* William Whewell, 1794, Lancaster, England – 1866, Cambridge, England, English scientist, Anglican priest, philosopher, theologian, and historian of science.

# Planets and Life[1]

*Professor Tilman Spohn, Deutsches Zentrum für Luft- und Raumfahrt (DLR), Berlin*

## *Introduction*

Seven gruelling years in clammy dungeons were behind him, and the burning on the stake before him, when the heavy doors of Castel Sant'Angelo in Rome opened for Giordano Bruno[2] on 17 February 1600. The Roman inquisition had found him guilty of propagating heretical ideas, such as the Copernican heliocentric world model, or about worlds beyond ours inhabited by intelligent beings: such devious thoughts needed to be purged by fire.

Four hundred years have passed, and progress has been made since. Speculating about extraterrestrial life is no more considered an act of heresy, but rather a challenging scientific and philosophical undertaking, and searching for life beyond Earth provides us a deepened understanding of our home planet and its eventful past. Yet, just like Giordano Bruno, we still lack any tangible proof of alien life.

The following pages attempt to summarize the present state of knowledge regarding the assets that make a planet habitable and speculate about the interplay between the evolution of a planet and life.

Habitability is defined in a seminal NASA document (1)[3] as the potential of a planet to host life of any kind. In order to remain on safe ground we will focus – as most researchers do when discussing habitability – on life as we find it on our planet clearly bearing in mind, however, that quite different forms of life may exist elsewhere.

Even worse, we do not even have a universally accepted scientific definition of life although we know elements that such a definition should encompass. Amongst these are metabolism, reproduction, passage of genetic information between generations, and adaption to the environment. Nevertheless, inquiring about the ingredients that made and make life possible on Earth provides us with most fascinating insights into our own planet, and hopefully the will to keep this wonderful planet alive. This is the mission of the present *Spatium*.

***Fig. 1: The statue honouring Giordano Bruno on the Campo dei Fiori square in Rome.*** Created in 1889 by the Roman sculptor Ettore Ferrari it was placed at the very location where in February 1600 Giordano Bruno died on the stake. In our days, the square hosts the colourful weekly flower market.

---

1 The present text reports on a lecture by Prof. Spohn for the Pro ISSI Association on 8 November 2011.
2 Giordano (Filippo) Bruno, 1548, Nola, Italy –1600, Rome, Italian priest, philosopher, mathematician and astronomer.
3 See references at the end of the text.

# The Cosmic Environment

Safely sheltered by a benevolent atmosphere, one tends to underrate the importance of the cosmic environment for the emergence and subsistence of life. While the Sun, venerated since the dawn of mankind, is easily appreciated as the major source of energy for life at present, the ephemeral nightly appearance of meteors reminds us of the cosmic pieces of debris that several times in its history caused chaos and death on Earth. Let us, therefore, start by elaborating on a planet's cosmic environment before addressing the properties a planet itself must possess to eventually serve as a cradle for life.

## A Source of Energy

Energy is a critical resource for life in any form, and nuclear fusion processes in the cores of stars are the most relevant sources of energy in the universe. Yet, while there are innumerable stars of all sizes, not all may be equally well qualified to foster the emergence of life on their planets, if they have such. For instance, a star may be too massive, that is many times the mass of the Sun. Such a star is short-lived, shining for maybe 10 million years only, that is about one thousandth of the Sun's lifetime, which could be much too short for allowing life to appear on its planets. Even worse: massive stars tend to have high radiation temperatures, which is equivalent to emitting strongly in the blue and ultraviolet wavelength regions of the electromagnetic spectrum. These parts are detrimental for living cells as we know them since the radiation would destroy their genetic information. In contrast, a smaller star, an M-star say, of only a fraction of the solar mass, tends to be long-lived. Its radiation, however, is shifted more to the red and infrared side of the spectrum where the photons may not carry enough energy to support photosynthesis, the process allowing plants to exploit the sunlight to build up their structures. Moreover, the observed emissions from M-stars suggest strong magnetic activity, much stronger than that of G-stars like our Sun. As a consequence, there may be very strong flares with radiation in the ultraviolet and high-energy particles. Thus, planets orbiting close enough to receive enough insolation from the M-star may be subject to intense radiation that could render the planet inhabitable for life as we know it. Hence, a star may be required to have about the

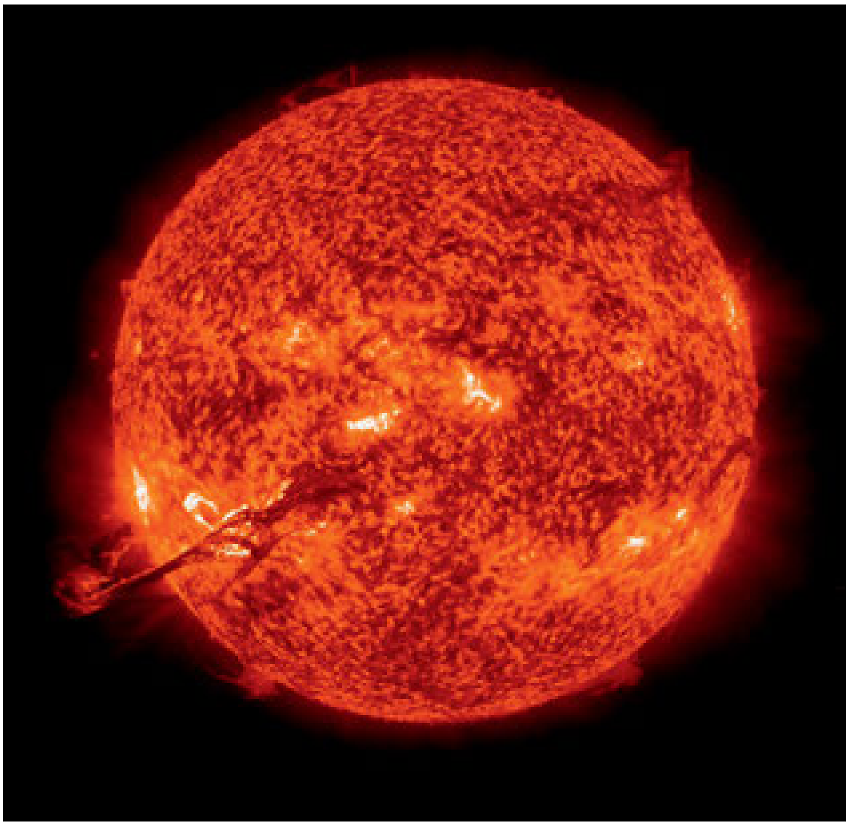

**Fig. 2: A busy star:** At the time of writing, the Sun is heading towards the next solar maximum foreseen to occur in early 2013 when the number of sunspots on its surface will reach its maximum again. Sunspots are visible signs of intense magnetic activity within the Sun. This image was taken at the hydrogen wavelength $h_\alpha$, a specific red visible spectral line created by the hot hydrogen on the solar surface with a wavelength of 656.28 nm. (Courtesy of NASA/SDO and the AIA, EVBE, and HMI science team)

size of the Sun **(Fig. 2)**, in order to allow life as we know it to emerge on one or more of its planets.

While the Sun is the most important source of energy for life on Earth today, it is agreed that life did not start out by using photosynthesis, which was likely invented by microorganisms after about one billion years of evolution only. There are important alternative sources of energy such as subaquatic volcanoes where hydrothermal vents bring up heat from deeper strata, and materials that serve as nutrients. In fact, one of the theories explaining the emergence of life on Earth – the iron-sulphur world model of G. Wächtershäuser (2) – focuses on underwater volcanoes and associated hydro-thermal vents. Here, life exploits the internal energy of a planet acquired during accretion and supplemented continuously by the decay of radiogenic elements.

Another source of energy may come from tidal forces acting on a planet, or a moon circling a large planet, respectively. Tidal energy may be dissipated as heat and transferred through e.g., volcanic activity into the subsurface ocean on Jupiter's moon Europa. A similar mechanism may be at work in a distant ocean planet circling another star.

## *Cosmic Impacts*

The genesis of a planetary system starts with a collapsing cloud of dust and gas producing a proto-star surrounded by a disk of surplus material (3). In that disk, material accretes first to planetesimals, then to proto-planets and finally to planets over some millions of years. Gas giants like Jupiter and Saturn are believed to form first as cores of heavy elements onto which gas gravitationally collapses once the core has reached a sufficient mass. Rocky planets are believed to form in a cascading process from many small planetesimals to few planets. The term accretion, however, is a nice euphemism for what in reality is a fierce process including violent collisions of smaller and larger bodies at cosmic speeds. The Moon's large basins may give an impression of those powerful impacts **(Fig. 3)**.

The frequency of collisions will decline when most of the matter on neighbouring orbits has been incorporated in planets, or when it has been removed from the disk by gravitational interaction with the growing planets. Thanks to their enormous gravity fields, the giant planets Jupiter and Saturn have been most effective in moving ma-

***Fig. 3: The Moon's cratered surface*** bears witness to cosmic impacts during the Last Heavy Bombardment, 4.1 to 3.8 billion years ago. While on Earth such traces have been eroded since, on Mars and on the Moon they are still visible. The Moon itself is likely the result of a Mars-size body having impacted on Earth, vaporizing its outer layers. The Moon then formed from the vapour and the remnants of the impactor. (Credit: NASA)

terial in the growing solar system as new model calculations[4] suggest. In the early phase of the solar system they migrated towards the Sun focussing the region of the disk from which the terrestrial planets formed. The inward migration is a natural consequence of the giant planets' interaction with the disk from which they grew. In many exoplanetary systems giant planets are found at distances from the star where in the solar system the terrestrial planets are located, some circling their star at even closer distances than Mercury orbits the Sun. Now, surprisingly, Jupiter and Saturn eventually reversed their course to move out again, leaving the space where the terrestrial planets now could evolve. The reversal of their motion is a possible albeit rather unlikely process as the accretion model of Walsh et al. has shown. This observation causes one to wonder whether or not the formation of Earth and its siblings Mars and Venus at a comfortable distance from the Sun is an unlikely outcome of the process of planet formation. Almost certainly, the terrestrial planets would not have formed if Jupiter and Saturn would have continued their inward migration!

At the time of writing, the NASA Kepler mission is exploring part of our Milky Way for planets at unprecedented sensitivity. Extrapolations by David Latham and colleagues (5) based on these observations suggest that at distances to the star resembling those of the inner solar system, planets of sizes between one to two times the Earth should be abundant[5]. It is not clear, however, whether in these planetary systems there are any Jupiter-size planets that would regulate the smaller planets' orbits so that they would be of low eccentricity and inclination. Observation rather shows that many exoplanets have substantial eccentricities and inclinations which may severely hamper the development of life as we will see later.

The inner solar system eventually got largely discarded from debris, granting the terrestrial planets and the Moon a comparatively quiet further evolution. Yet, enough debris was left in the asteroid belt and in the inner solar system so that every now and then some remains cross the Earth's orbit. If their size is small, say up to ten metres, they are mostly harmless as they burn in the atmosphere or break up to fall as meteorites (6). The impact of bodies of larger size will be increasingly catastrophic both through the immediate energy released by the impact and through the debris stirred up causing a global climate catastrophe: the dust in the atmosphere blocks the sunlight preventing it from reaching the surface, disrupting the energy input for life. Mass extinctions may be the consequence (7). The last major such extinction event – the Cretaceous-Tertiary event that exterminated about half of all animal species on Earth – took place 65 million years ago and was likely caused by an object some tens of kilometres in size. Amongst other genera, it wiped out the dinosaurs paving the way for the dominance of mammals. Hence, a planet must be spared from too large and too frequent impacts for the emergence and subsistence of life. On the other hand, impacts can also foster the evolution of new species as the Cretaceous-Tertiary event shows. It has been speculated that human beings would not rule the Earth had the impact not eliminated the dinosaurs!

The lunar cratering record **(Fig. 3)** suggests that up to about the time when life is thought to have emerged on Earth a number of violent impacts should have occurred that may have even sterilized our planet. This raises the possibility that what we see today is only the result of the latest of possibly more than one Genesis on Earth. Unfortunately, that life may end one of these days in a similar catastrophe cannot be excluded. How the threat from impacts could be mitigated is the subject of ongoing research and should be enough motivation for humankind to advance space technology further.

---

[4] Kevin Walsh, Allesandro Morbidelli and their colleagues (4) from the Observatoire de Nice recently developed a computer model simulating the first few tens of million years providing new insights in the earliest phase of evolution of the solar system.

[5] Due to technical limitations the Kepler mission cannot easily detect planets as small as the Earth and smaller.

## *Planetary Orbits*

The orbit around the central star is a further important parameter regarding the habitability of a planet. A popular criterion for locating potential life in a planetary system is the concept of the circumstellar habitable zone that goes back to the 1950's. The concept has evolved over the years but is now mostly used to define the range in orbital distance at which the surface of a planet with an atmosphere just like the Earth's would be at a temperature allowing for liquid water. While this definition does not imply any specific form of life, it still assumes that water is the solvent on which life is based. If the planet happens to circle too close to the star, the planet's surface temperature will increase in a runaway process and any ocean will evaporate. If, on the other hand, the planet is too far away from the star, surface water will freeze. Between these two boundaries lies the habitable zone for water-based life, see **Fig. 4.**

The location of the habitable zone depends on the brightness and thus the radiative power of the central star, the distance of the planet to the star and the composition and mass of the planet's atmosphere, the latter obviously depending on the planet's overall mass and, hence, gravity. Yet, the star's brightness is not constant over its lifetime. Rather, stellar evolution starts with a lower energy output that tends to increase over time. Hence, the distance to the habitable zone evolves with time, and one planet may move into and another may move out of the habitable zone with time. Venus for instance, the second planet in the solar system, may well have been within the habitable zone in the early days of the solar system. This observation poses a problem for early Mars, however. There is enough evidence in its geological record that rivers and lakes existed on Mars at least for some periods of time about four billion years ago, **Fig. 5.** These, of course, permit us to speculate that life may have emerged on the Red Planet. How Mars could have been warmer and wetter than today at a time of a fainter Sun is still a matter of scientific debate.

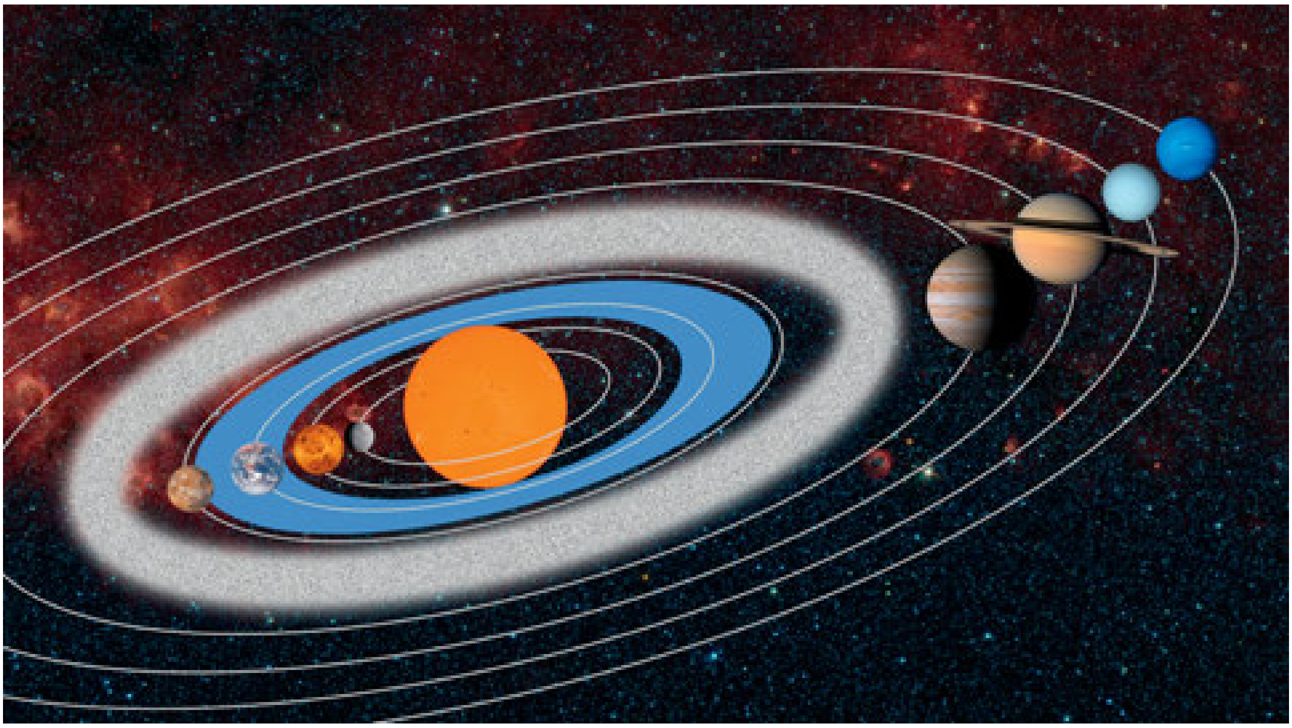

***Fig. 4: The solar system and its habitable zone.*** This figure shows the eight planets circling the Sun, together with the asteroid belt marked in light grey. The habitable zone for water-based life is shaded in blue. It is the region around the Sun where a planet with sufficient atmospheric pressure can maintain liquid water on its surface. As can be seen Earth is the only planet solidly within the habitable zone. (Credit: DLR)

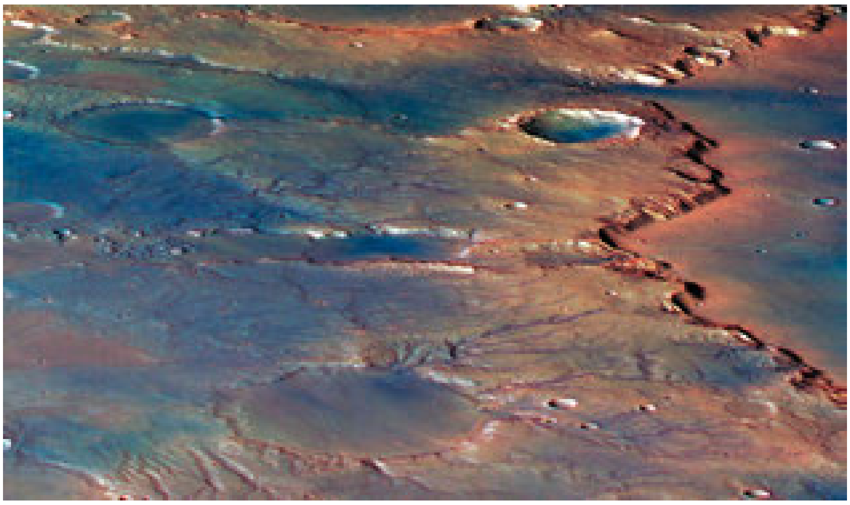

***Fig. 5: The early Mars paradox.*** The Martian surface bears convincing witness to the presence of liquid water in its early history: Yet, at that time the Sun produced less radiative power leading to an even colder temperature regime than today. (Credit: ESA/DLR/FU Berlin, G. Neukum)

Planetary orbits are governed by the laws found by Johannes Kepler[6] in the early 1600's. In general, they are elliptical in shape. This means that the planet's distance from the central star oscillates continuously, and only in the special case of a truly circular orbit remains constant over time. Yet, a highly elliptical orbit might bring the planet temporarily outside the habitable zone leading to climate variations that could place severe restrictions on the emergence of life, **Fig. 6**.

Research on exoplanetary systems in the past 15 years suggests that the low eccentricities of the Sun's eight companions may not be typical. Rather, many known exoplanets exhibit orbits with large eccentricities that may prevent them from having a sufficiently balanced climate, and most probably life to emerge assuming that they would otherwise be habitable.

***Fig. 6: A highly eccentric orbit around the central star*** may temporarily bring a planet outside the habitable zone, here shaded in green. Such orbital characteristics lead to strong climate variations that may prevent life from emerging even though the planet meets the requirements for habitability from time to time. (Credit: NASA/JPL-Caltech)

Finally, the angle between a planet's rotational axis and the plane of its orbit around the central star (the axial tilt or obliquity, **Fig. 7**) is a further criterion that may hamper the evolution of life. The axial tilt is responsible for seasonal changes particularly in the high latitudes, which in winter receive less insolation than in summer. If the obliquity is relatively small, and constant, then the global climate remains more or less stable over time. In the case of Earth, the Moon helps stabilize the Earth's rotational axis to currently 23.4°. Nevertheless, the Earth's tilt angle is slowly changing with a periodicity of some 41,000 years, which is a major driving factor for the current glacial/interglacial fluctuations as shown by Milutin Milanković[7] (7).

Up to now we have assumed water is the solvent for living systems. If, however, we consider other solvents, a habitable zone could extend between different orbital distances. For instance, scientists speculate that methane may do well as a solvent in very cold environments, as it possesses a freezing point of –182°C, and a boiling point of –162°C at a pressure of one atmosphere. The habitable zone for methane-based life in the solar system would lie far outward covering Saturn and its moon Titan (8, 9).

The concept of the habitable zone has obviously several shortcomings. For instance, it fails to explain early

[6] Johannes Kepler, 1571, Weil der Stadt (near Stuttgart), Germany – 1630, Regensburg, German philosopher, theologian, mathematician, and astronomer.

[7] Milutin Milanković, 1879, Dalj, then Austria-Hungary – 1958, Belgrade, Yugoslavia, Yugoslavian geophysicist and mathematician.

Mars, but it also misses a possibly habitable world in an ocean covered by a protective shell of ice. The Jovian moon Europa and other Jovian and Saturnian satellites located far out of the Sun's habitable zone are examples. By reducing itself to the temperature range for liquid water, it will not account for other elements of habitability such as the problem of the star's radiative environment, or whether life could use the particular stellar spectrum for photosynthesis. It also does not account for the supply of nutrients and the required stability of climatic conditions. More sophisticated concepts of habitability and even indexes of habitability have been proposed that attempt to account for the shortcomings of the original concept, but owing to its simplicity the latter is still the one most often used.

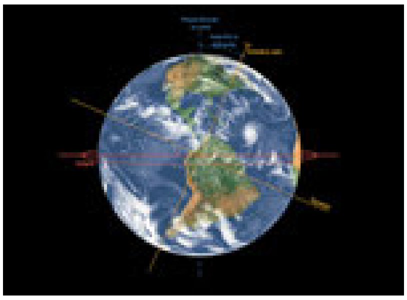

**Fig. 7: Obliquity is a measure of the axial tilt of a planet's rotational axis** with reference to its orbital plane. As the axis remains tilted in the same direction throughout a year, a hemisphere is pointing away from the central star in winter, then half an orbit later in summer this hemisphere will be pointing towards the star thereby receiving more insolation. This effect is the main cause of the seasons on Earth. (Credit: NASA, DLR)

# Planetary Assets

So far we have focussed on a planet's cosmic environment that must satisfy some criteria for allowing life to emerge. In a next step, we are going to elaborate on the assets a planet itself must possess to be habitable for life as we know it.

## The Planet's Size and Mass

The most fundamental set of planetary parameters is size and mass. A planet may not be massive enough to hold an atmosphere, a key element of habitability even though the lack of an atmosphere, for instance on a much smaller planetary body or a moon, would not necessarily preclude life as the speculations about life in the ocean of Jupiter's moon Europa suggest. But if access to solar radiation and photosynthesis are important for the evolution of life, then an atmosphere will be needed both to form an environment in which life can evolve as well as to secure an adequate surface temperature. In addition, the planet must be large enough in order to produce and keep its internal heat for a sufficient period of time to maintain it tectonically active. This is important as an active geology is rated as a basic precondition for life to emerge as we are going to show later. On the other hand, if a planet is too massive, its geologic activities could be suppressed, as the rock's viscosity depends on pressure: the higher the pressure, the less ductile the rock becomes. It may well be that Earth happens to possess the ideal mass and size for an active geology and hence for life.

## The Atmosphere

Space is not a friendly environment for life as we know it[8]. Cosmic rays, stellar wind, high energy radiation from the central star are all lethal threats to living cells if not properly shielded. This sheltering is achieved by the atmosphere and by the magnetic field. Not only though: the atmosphere serves to reduce surface temperature variations by transporting heat from the regions of high insolation to those of low insolation and provides for the greenhouse effect. The solar flux peaks in the wavelength of visible light to which the atmosphere is largely transparent. Some of the radiation is reflected and radiated from the atmosphere back into space. Another part of the energy is absorbed at the surface and is re-emitted in the infrared to which the atmosphere is much less transparent. This infrared re-radiation gets absorbed in the atmosphere thereby raising the global temperature. This is the essence of the greenhouse effect. While in the absence of the atmosphere, the mean Earth surface temperature would amount to a mere –18 °C, it is a comfortable 15 °C (7).

8 This is true even though certain types of extremophile bacteria have been shown to withstand the harsh environment of space. Yet it is not known whether they could emerge under such hostile conditions.

A further important role assumed by the atmosphere is the distribution of vital elements all over the globe: water for instance would be concentrated in ice-covered oceans were it not for the atmosphere, which continuously recycles water by evaporation from the sea, transport over the globe by winds, and precipitation. Carbon, a further important element for living systems, is recycled in the frame of the carbon-silicate cycle (12) that also acts to stabilize the climate on time scales much longer than anthropogenic effects on the climate by burning fossil carbon[9]. In the long-term carbon-silicate cycle, carbon dioxide is released into the atmosphere through volcanic activity from the Earth's interior. In the atmosphere, carbon dioxide acts as a powerful greenhouse gas contributing to raising the surface temperature. A rise in atmospheric temperature will cause an increase in humidity and rain fall. Weathering of rocks by carbonic acid contained in the rain binds atmospheric carbon, which is then washed out to eventually reach the oceans. As we will outline below, dissolved carbon in ocean water is bound into rocks which eventually are subducted down to deeper strata of the Earth's mantle, from where it escapes again in volcanic eruptions into the atmosphere. The climate can be stabilized in the long-term by this interaction between the atmosphere and the interior. The biosphere participates in the cycle by increasing the weathering rate through microbial activity and the rate at which carbon is bound in the sediments. There are other important chemical cycles in the atmosphere in shorter time scales that include the biosphere e.g., the nitrogen cycle where microorganisms play an important role by fixing atmospheric nitrogen thereby making it available for plants. In any case, the dynamic atmosphere is of primordial importance for the global distribution of the substances required by life.

***Fig. 8: Colourful atmosphere.*** Here, the photographer stands on the top of Mauna Kea, Hawaii, USA, 4,205 m above sea level. His image shows the Moon rise through the shadow of Mauna Kea while the Sun has just set in the opposite direction, behind the camera. The various atmospheric layers scatter the sunlight in a intriguing variety of colours. (Credit: Michael Connelley, University of Hawaii)

## A Cocktail of Elements

Life as we know it has use for almost every element that can be found on Earth. However, there are six chemical elements that play a major role in living systems, the biogenic elements. These are: carbon, hydrogen, oxygen, nitrogen, phosphorus, and sulphur. They are all readily available on Earth which underlines the principle that life uses what is available in its environment. Of these, hydrogen and oxygen, bound to $H_2O$, play a key role serving as a solvent for all forms of life on Earth. Carbon is an essential building block as it is able to build up long molecular chains, which are at the root of the chemical complexity of life. It is interesting to note that water and carbon dioxide are important albeit minor constituents in the interior of the Earth essential for the tectonic engine and for interactions between the atmosphere and the Earth's interior.

[9] Fossil carbon is carbon stored by trees and other green plants that lived millions of years ago and converted to coal and oil upon burial in sedimentary basins.

Mostly water, and to a lesser degree carbon dioxide, make the mantle rock more ductile and reduce its melting temperature, and both are cycled between the interior and the atmosphere as described above. To say these two molecules serve as a kind of lubricant for the gigantic conveyor belt-like mechanism of plate tectonics and continental drift seems not to be exaggerated.

## *Geologic Activity*

The term plate tectonics is used to characterize the global tectonic style of the Earth whose crust is made of seven major plates that move relative to each other across the surface. The movement is driven by forces from the convective flow in the mantle below and by the plate's own local negative buoyancy varying laterally across the plate. There are plate margins where the plates move apart and magma intrudes from the mantle below to add new crust. A prominent example of these ridges is the Mid-Atlantic Ridge extending almost from the North to the South pole. At other margins – called subduction zones, **Fig. 9** – one heavier plate made of iron-rich oceanic crust slides underneath its lighter aluminium- and silica-rich neighbouring plate of continental crust and is thereby forced back into the mantle down to some 700 km. There, it is dissolved by the heat of the Earth's mantle.

The subduction zones are the loci of most earthquakes on Earth and are caused by the friction between the plates. A prominent example of

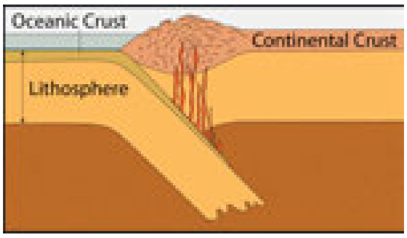


***Fig. 9: Subduction is the process that takes place at convergent boundaries of tectonic plates*** by which one plate moves under another plate, sinking into the Earth's mantle, as the plates converge. Mountains build up as the overriding plate is compressed and as melt from the subducting slab intrudes from below. These areas are subject to earthquakes and volcanoes. (Credit: DLR)

this type of plate margin is traced by the Andes in South America. Another example are the Himalayas where the Indian plate collides with and slides underneath the Eurasian plate. Here, two continental plates are colliding, compressing and uplifting the crust. Still another example are the Alps, where a slab of the African plate collides with and slides underneath the Eurasian plate. At a third type of margin plates move past each other, again causing surface faults and earthquakes. A prominent example is the San Andreas Fault in California where the Pacific plate slides past the North American plate.

Volcanic chains usually characterize subduction zones. These are fed by a partial melt zone immediately above the subducting slab at depths between 100 and 200 km. It is commonly held that water stored in water-rich minerals in the subducted crust is released as these minerals break down due to the high pressure and temperature. The water then causes the melting tempera-

***Fig. 10: Volcanoes are important players influencing the environment for life on Earth.*** By feeding carbon from the Earth's interior into the atmosphere they contribute to stabilizing the atmospheric $CO_2$ content in the long term which in turn is important for controlling the global climate. Huge amounts of ash and dust jettisoned in the atmosphere tend to reduce the solar flux reaching the surface and hence the global temperature in the short term. This image shows Mount Cleveland on one of the Aleutian islands erupting on 23 May 2006 as seen from the International Space Station. (Credit: NASA)

ture of the adjacent rock to be reduced. The melt moves upwards due to its buoyancy feeding the volcanoes. The process is of utmost importance because it adds rock to the continents and makes continents grow.

How exactly plate tectonics works is still a strongly debated issue. With some unanimity, however, it is accepted that water plays a key role. Water changes the rock's viscosity thereby rendering it more ductile, and water reduces the mantle melting temperature thereby enabling volcanism. One popular theory holds that near-surface rock being relatively cold and stiff would naturally form a plate on top of the mantle. At greater depths of about 100 km – depending to some extent on the size of the planet and the rates of increase of temperature and pressure with depth – the rock becomes ductile enough to allow for albeit very slow mantle flow. This flow transfers the heat from the interior of the planet to the base of the plate and is termed mantle convection. Now, if the flow is vigorous enough such that the stresses of the flow on the near surface plate exceed the failure strength of the plate, the latter may break apart locally and participate in the flow. The strength of the plates decreases with the water content and with temperature. In the Martian mantle, the flow would not be vigorous enough to break the plate owing to its smaller size and lower heat content. On Venus, the lack of water may have prevented the surface plate from breaking. However, the high temperature at the surface (about 460 °C) may cause some local deformation and – together with volcanic activity – some surface recycling.

Plate tectonics are thought to play a complex and multifaceted role for the subsistence of life on a planet. As outlined above, plate tectonics help stabilize the atmospheric carbon dioxide concentration in the self-regulatory carbon-silicate cycle, and hence the global climate. Plate tectonics permit volatile components to be recycled, with water and carbon dioxide encapsulated in sedimentary rock re-entering the interior in the subduction zones. Microorganisms play a catalytic role in this process by effectively capturing and bonding carbon dioxide and water in the sedimentary rock. Moreover and most importantly, plate tectonics efficiently cool the Earth's interior. This drives the Earth's dynamo, which in turn creates the magnetosphere that shields the atmosphere from erosion by the solar wind, and the surface from energetic cosmic radiation. **Figure 11** summarizes how these processes combine to set up the complex machinery of a planet as a system.

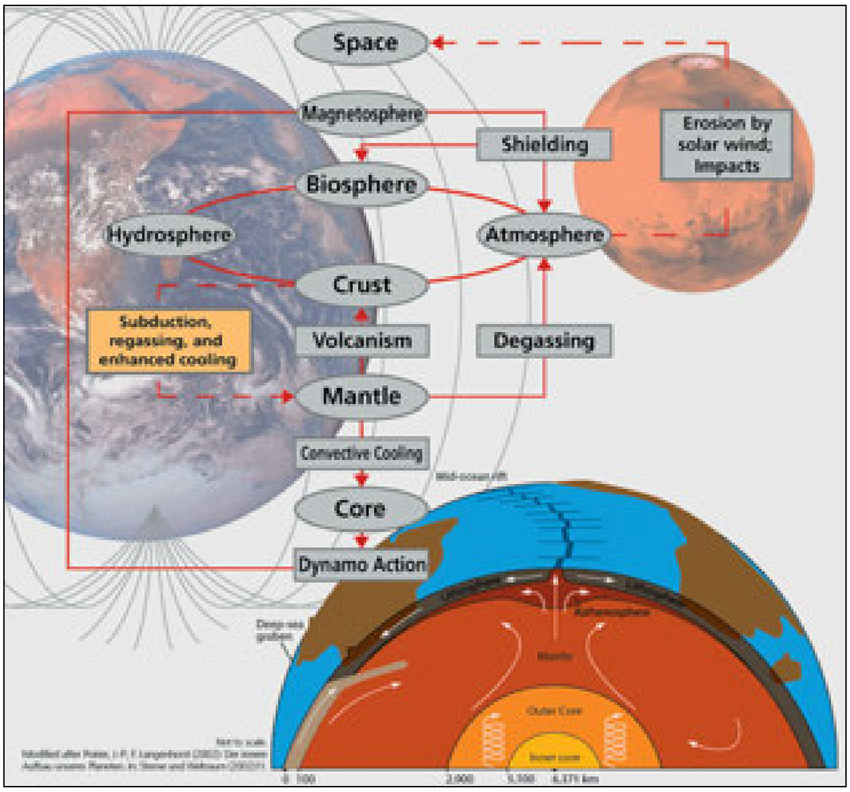


***Fig. 11: A simplified flow diagram of the processes on planet Earth:*** Plate tectonics provide a mechanism to inject material from near surface reservoirs into the deep interior. The enhanced cooling of the deep interior that goes along with subduction of cold lithosphere helps drive the core dynamo which in turn generates the Earth's magnetic field. Thanks to its still active plate tectonics the Earth's surface continues to be shielded against lethal cosmic high energy radiation whereas Mars's magnetic field died about 3.5 billion years ago. (Credit: DLR)

# Co-evolution of Planets and Life

As inferred from Earth's history, the advent of life changed the planet's evolution profoundly, as biological processes add to ongoing chemical and physical weathering. This is so because the metabolism of living systems generates characteristic waste products that interact with the planetary environment.

## The Emerging Atmosphere

The most popular and obvious example for the co-evolution of life and the planet is the Earth's atmosphere. Initially, it consisted mostly of carbon dioxide, see **Fig. 12.** As $CO_2$ is an efficient greenhouse gas, the Earth's surface temperature is thought to have reached some 80 °C even though the young Sun was significantly less bright than it is today. Microbial life – methanogenic cyanobacteria – emerging some 3.6 billion years ago bound parts of the atmospheric $CO_2$ into the living biomass, producing methane instead. The early microorganisms were chemotroph, that is gaining their energy from chemical reactions with surface rock. Since the energy sources need to be replenished by replenishing rock and since the replenishment depends on the dynamic activity of the planet fed by its internal energy, life fundamentally lived off the thermal energy of the planet. A measure for the flow of this energy is the overall geothermal flux of the Earth which was likely larger, but no more than twice as large than today, where it amounts to 80 mW/m$^2$. As the solar flux reaching the surface today amounts to some 350 W/m$^2$, the global biomass must have been significantly smaller than today. About 3 billion years ago, life on Earth invented photosynthesis. With this new process, life began to tap the rich energy flux from the Sun that is about 4,000 times larger than the geothermal flux. Land surfaces, which at the time were not as abundant as today, offer easy access to the solar flux and – at the same time – to the fundamental nutrients provided by rock.

## The Evolving Atmosphere

Photosynthesizing life produces oxygen that is used by oxygen-consuming life forms. Today, oxygen production is balanced by oxygen consumption, and therefore the oxygen concentration in the atmosphere remains constant. The rapid growth of the continents that ensued at the Archean-Proterozoic boundary about three billion years ago, **Fig. 12,** may have caused the oxygen producers to outweigh the oxygen consumers for some period of time. As a consequence, the oxygen concentration in the atmosphere grew rapidly after 2.3 billion years ago. This in turn allowed for one of the most fundamental environmental changes in Earth's history paving the way for higher forms of life: the atmospheric oxygen became abundant enough to allow the ultraviolet part of the sunlight to build up the ozone layer (10), an efficient shield against the harmful short-wavelength part of the solar radiation. The advent of the ozone layer gave an important thrust for life to conquer the land surfaces, and allowed it to build ever more complex organisms.

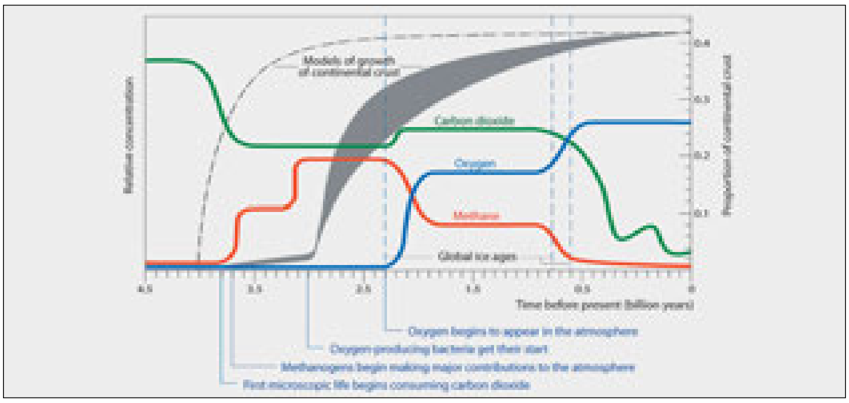


***Fig. 12: The evolution of Earth's atmosphere is a prime example for the interplay between life and the planet.*** In the frame of a long co-evolution, the initially oxygen-free atmosphere has been given the chemical composition we have today. It is thought that around 3 billion years ago a rapid increase of the solid surface coincided with the advent of photosynthesis, a chemical process that uses carbon dioxide to build up organic compounds, especially sugars, using the energy from sunlight and producing oxygen as a waste product. This made the concentration of oxygen rise globally. A next important step took place some 500 million years ago when rooted plants conquered the land surface giving rise to a further increase in atmospheric oxygen to the levels we see today. (Credit: DLR, modified after [12])

As oxygen does not act as a greenhouse gas – in contrast to carbon dioxide and methane that formerly constituted the atmosphere to a large extent – Earth's global surface temperature declined drastically leading to a period called the global ice age, between 750 and 580 million years ago. It is thought that at that time the entire Earth, or at least most of its surface area, was covered by sheets of ice forcing life to retreat to sub-aquatic shelters. The ice sheet interrupted the water cycle leading to an atmosphere deprived of water. The lack of atmospheric moisture prevented the withdrawal of $CO_2$ by rain; so also the carbon cycle was suspended. On the other hand, volcanic activity continued, leading to an increase of atmospheric carbon dioxide, and other greenhouse gases, making the surface temperature rise again. This caused the ice to melt, first in the tropics, later on most of the surface thereby setting an end to the "Snowball Earth" period. The now globally improved conditions for life prompted a rapid evolution, first in the form of the Ediacara[10] biota, and later to the Cambrian[11] explosion, when most of the genera present today appeared in a relatively short period of time. About 500 million years ago, rooted plants conquered the land surface giving rise to a further increase in atmospheric oxygen to the levels we see today.

## *Microorganism and the Plate Tectonics Engine*

While the atmosphere is a well known example for life-planet interaction, the catalytic activity of micro-biota in the sedimentary basins of continents is much less popular, but possibly no less important. The distribution of the biomass living on Earth today between animals, plants, and micro-organisms is debated but it is widely held that a majority of microbes live in the shallow sedimentary basins in front of continents. That these sedimentary basins are so well populated is not the least a consequence of the wealth of microorganisms living on land.

The biota in the sedimentary basins act as catalysts in metamorphic reactions that bind atmospheric carbon dioxide and water. Examples are the formation of calcium carbonate ($CaCO_3$), found in rocks in all parts of the world, binding atmospheric $CO_2$, and the illite-smectite transition[12] that occurs at moderate temperatures and pressures in deep sedimentary basins. Both of the minerals bind water between their silicate layers but illite – although it contains less water per unit mass of rock – is much more stable at elevated temperatures than smectite and can carry water to greater depth in the subduction zone. Illite is also less permeable to water than smectite and will more efficiently block water to escape in the subducting crust as the pressure rises.

The illite-smectite transition rate depends on the concentration of a particular stochiometric form of iron in the smectite. Iron may occur as a positively charged ion with two positive charges and with three positive charges, or, as it is termed, two-valued versus three-valued iron. The smectite-illite transition occurs with a rate increasing with the concentration of two-valued iron in the smectite. Microbes in the sedimentary basin will feed on the three-valued iron in the smectite gaining energy by removing oxygen and reducing three valued iron to its two-valued form. Thus, in the presence of microbes – and depending on their concentration – more smectite is transferred to illite and, at the same rate of subduction, more water is carried to the Earth's deeper interior. Model calculations suggest that in a biotic world about twice as much water is subducted per unit area and time than in a putative abiotic world. The increased flux of water will lubricate the plate tectonics engine and increase the rate of continental growth. Thus, observing that the geologic record suggests a balance between continental erosion and continental growth, that balance occurs at a larger rate than if there was no life on Earth.

---

[10] Called after the Edicara hills to the north of Adelaide in Australia, where the first specimens were found. The Edicaran period ranges from 635 to 542 million years before the present.

[11] The Cambrian is a period in Earth's history lasting from 542 to 490 million years ago.

[12] Illite and smectite are both ultrafine-grained clay minerals ubiquitous in sedimentary basins and capable of taking up substantial amounts of water.

# Summary and Outlook

Summarizing these observations we come to the question of whether Earth is an ordinary or rather an extraordinary planet. Two contradicting theories speculate about the commonness of Earth-like planets in the universe. The *Rare Earth* hypothesis argues that the emergence of complex life on Earth required a rather improbable combination of astrophysical and geological events and circumstances. If the Rare Earth hypothesis is correct, then the search for extraterrestrial life – at least for evolved or even intelligent life – is most probably bound to fail, as any other planet hosting life must be expected to be so far away that we can never get in contact with it or even explore it.

The Rare Earth concept contrasts with the *principle of mediocrity* stipulating that Earth is a typical rocky planet in a typical planetary system, located in an unexceptional region of a common spiral galaxy. This would make the universe teem with life, and the search for extraterrestrial life promising if we succeed in developing the tools of remote sensing to detect it. Even though much effort has been spent searching for extraterrestrial life in the last say 50 years, the issue is still open, and the question continues to challenge scientists and the public alike. The discovery of large numbers of extrasolar planets in particular by the missions Corot by ESA and Kepler by NASA, but also from terrestrial observatories, suggest that some tens of per cent of all stars are likely to have planets. This means nothing less than there must exist billions of planets a significant number of which could be Earth-like.

As so often, the truth may lie somewhere between these extremes. Considering that most of the biomass on Earth is plants and microbes, and that the latter dominate the evolution of life in time during the Earth's evolution, and that these tolerate much more extreme conditions than mammals, we may very well look at a universe in which life may be commonplace while complex, evolved, and intelligent life may be rare. But how could we detect microbial life on an exoplanet some hundred light years away?

The search for and the understanding of life in the universe encompass fundamental questions in the natural sciences but also in philosophy and may have psychological, social and theological implications. The discovery of extraterrestrial life would complete the revolutions brought about by Copernicus and Darwin and give the geocentric world the final blow. So far, however, there is no solid, undebated scientific evidence for or against the existence of life beyond Earth. All arguments about whether life is common and universal or whether we live in a unique place in the cosmos are rather based on philosophical beliefs and assumptions. This brings us back to Giordano Bruno and one of his most prominent coevals, Galileo Galiei, who accomplished the irrevocable methodical separation between science and both philosophy and religion by requiring a hypothesis to be verifiable in order to become a truth. Thus, before becoming an accepted fact, empirical proof is required for the existence of alien life. This is the major driver for scientists searching for life beyond Earth. Mars should be our best bet. It is reachable and could have been (marginally) habitable in the past.


**References**

(1) A. Steele et al. (2005). The Astrobiology Field Laboratory. White paper. http://mepag.jpl.nasa.gov/index.html
(2) Wächtershäuser, G. (1992): Groundworks for an evolutionary biochemistry: the iron-sulphur world. Progress in Biophysics and Molecular Biology, 58, 85–201.
(3) Spatium no. 6: From Dust to Planets by Willy Benz, October 2000.
(4) K. Walsh, A. Morbidelli, S. Raymond, D. P. O'Brien and A. M. Mandell (2011): A low mass for Mars from Jupiter's early gas-driven migration, Nature, 475, 206-209.
(5) D. Latham and 32 co-authors (2011): A first comparison of Kepler planet candidates in single and multiple systems. The Astrophysical Journal Letters, 732: L24 (4pp)
(6) Spatium no. 7: Meteorites by Beda Hofmann, February 2009.
(7) Spatium no. 28: Spaceship Earth, by Roger M. Bonnet, May 2011.
(8) Spatium no. 15: Titan and the Huygens Mission by Nicolas Thomas, November 2005.
(9) Spatium no. 16: Astrobiology by Oliver Botta, July 2006.
(10) Spatium no. 21: The Earth's Ozone Layer by Yasmine Calisesi, February 2008.
(11) Spatium no. 8: Sun and Climate by Jürg Beer, November 2001.
(12) J. Kasting and D. Catling (2003): Evolution of a habitable planet. Annu. Rev. Astron. Astrophys. 41, 429–463.

SPATIUM

## The Author

Prof. Tilman Spohn is the Director of the Institute of Planetary Research of the German Aerospace Center (DLR) and a Professor of Planetary Physics at the Westfälische Wilhelms Universität Münster. He specializes in the thermodynamics of planetary interiors using modelling and space instrumentation, the habitability of planets and the role of life in their geologic evolution. He is the Principal Investigator of the MUPUS (MUlti PUrpose Sensors for surface and subsurface science) experiment on the ESA Rosetta lander planned to visit Comet 67P/Churyumov-Gerasimenko from 2014 onwards and of the HP3 package on the NASA InSight mission intended to analyze the interior of Mars in 2016. Together with Prof. Thomas of the University of Bern, he serves as Principal Investigator of the ESA BepiColombo Laser Altimeter (BELA) instrument scheduled to probe Mercury's surface topography in 2022. Prof Spohn is engaged in a broad variety of editorial, publishing and advisory activities, and not least he serves as the chairman of the ISSI science committee from 2012 on.