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Editorial

Editorial: Special issue "Planetary evolution and life"

Given the enormous number of stars in the universe and the number of confirmed and postulated planets in our galaxy, it is generally agreed that our home planet Earth is not likely to be unique (e.g., Sagan, 1980; Bignami et al., 2005; Hawking and Mlodinow, 2010). But is it? Although the number of known extrasolar planets grows almost by the day, observational bias caused by the technological challenges of finding Earth-size, rocky extrasolar planets and determining their masses and sizes have thus far prohibited the detection of a second Earth. But even if a second Earth were to be found—located in what is termed the habitable zone (e.g., Kasting et al., 1993)—can we expect that life would have originated there and have evolved beyond the most primitive forms? Is the universe "bio-friendly" as Paul Davies said (cited after Sullivan and Baross, 2007) using the Anthropic Principle (Barrow and Tipler, 1986) or is the origin of life so complex and our home planet so peculiar (Ward and Brownlee, 2000) that we are the unlikely product of a chain of unlikely events (Gould, 1989)? And if life existed on a second Earth or on many other planets, would we be able to detect it? Would life have shaped these planets such as life has shaped the Earth?

Looking at our neighborhood—the solar system—it is clearly recognized that the Earth stands out. Not only does it have an atmosphere at the triple point of water allowing the three phases of the substance to coexist (a fundamental requirement of surface habitability) and abundant life, it is also the only planet of which we know that it has plate tectonics operating. Plate tectonics is considered an important element of habitability (e.g., Lammer et al., 2010). First, it is a vital element of the carbon–silicate cycle that stabilizes the Earth‘s climate (e.g., Kasting and Catling, 2003). It is also instrumental in cooling the core and keeping the geodynamo process alive that produces the magnetic field (e.g., Breuer et al., 2010). The latter helps to protect the atmosphere against erosion and life on Earth against harmful radiation. Plate tectonics also provides diversity and thermodynamic disequilibrium by e.g., generating continental crust and shelf areas and by powering mid-oceanic ridge volcanism. Mid-oceanic ridge volcanoes and continental shelves have been identified as the most likely regions on Earth where life could have originated. There may still be other places in the solar system that may be habitable to at least primitive life forms. The most prominent example, of course, being Mars but Europa, Enceladus and even Titan being candidates. The Martian surface shows evidence for water having shaped the surface in its early history (the Noachian, more specifically) with lacustrine and fluvial land forms. Europa and Enceladus are speculated to have oceans in contact with rock (e.g., Iess et al., 2014 for a most recent study) providing water and nutrients. (The energy source for life still posing problems, though.) Titan, finally, has been repeatedly speculated to be a habitat for life that may use other solvents than water (e.g., Bains, 2004; Benner et al., 2004)

On Earth we know from extremophiles that life adapts to varying environments on a time scale of a few generations. But is the complimentary true? If life adapts to a planet, will a planet adapt to life? Can life stabilize the environment and even the tectonic mechanism? Will it influence the plate tectonics engine and perhaps even stabilize this tectonic mechanism?

In 2008, the Helmholtz Association began funding a research Alliance that studies the habitability of planets such as Mars but also of satellites and of extrasolar planets. Moreover, it considers the interactions between the evolution of a planet and its habitability as well as the interactions between a planet and life. About one hundred scientists were involved in the Alliance up to the end of 2013 and 630 peer reviewed papers have been published between 2008 and now. This special issue collects 21 papers, some of which review the progress of the Alliance (e.g., Jaumann et al., 2014; Fritz et al., 2014) while others are research papers in their own right. The subjects of the papers range from mantle dynamics and plate tectonics to atmosphere studies and surface geology. Other studies consider the physics, chemistry and biology of primitive life on present Mars and the formation of habitable planetary systems, that is of planetary systems that have rocky planets (or satellites) at an orbital distance from the central star where liquid water on the surface is possible and where the available insolation could power a biosphere.

The subject of the first in this collection of papers (Höning et al., 2014) is the interaction between life and plate tectonics. The authors argue that life through its effect on erosion and sedimentation and water cycling between the interior and the surface reservoirs will buffer the mantle water content and the surface area of the continents. An abiotic Earth after reaching an equilibrium state of balance between continental crust production and destruction and mantle water degassing and regassing would differ significantly from the present biotic Earth in the surface area of continents and mantle water content. The authors speculate that their abiotic Earth with a much smaller continental coverage and much drier mantle would probably not be able to sustain plate tectonics.

If plate tectonics is an important element of habitability, then it will be important to see how likely plate tectonics would be on rocky planets bigger or smaller than Earth. We would conclude from the few examples of the solar system that there is no compelling evidence for plate tectonics on planets smaller than Earth. The problem of plate tectonics on super-Earths (up to 10 Earth radii) has been widely discussed in the literature

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following the pioneering paper of Valencia et al. (2006) and Noack and Breuer (2014) are adding their results to the debate. Extending earlier studies by Stamenkovic et al. (2011, 2012) they find that the propensity for plate tectonics of a planet should vary with planetary mass and should peak at about the mass of the Earth making super-Earth‘s intrinsically less habitable than Earth size rocky planets.

Noack et al. (2014) pose the question whether or not the bulk properties of a rocky planet mass, radius, and moment-of-inertia factor would allow conclusions on its habitability. Assuming a rocky planet consisting of a mantle and a core, they vary the core radius (at constant planetary radius). They then calculate the melting and outgassing rates of single-plate and plate tectonics planets. (A single-plate planet being one with a closed outer shell that may be pierced by volcanic vents but has no plates with lateral relative movement and subduction.) The authors conclude that for single-plate planets the outgassing rate should be inversely proportional to the core radius while for plate-tectonics planets the effect would be small. A single plate planet with a large core would then tend to be less habitable than a planet with a small core or planets with plate tectonics.

Although extremophiles may very well strive on a planet even without the protection of a magnetic field (e.g., Southam and Westall, 2007), a magnetic field is generally held to add to the habitability of a planet (e.g., Lammer et al., 2010). The conditions for magnetic field generation are therefore important considerations in the present context. The surface magnetization of Mars (see Connerney et al. (2004) for a review) is generally interpreted as being due to an early dynamo but the magnetization geometry suggests asymmetry either in the distribution of magnetizable crustal rock or the dynamo. Hori et al. (2014) numerically model the early Martian dynamo considering thermally and chemically driven dynamos with and without inner cores and asymmetric cooling of the core by mantle heat transfer. Building on the observation that Mars had an asymmetric early magnetic field, they find that in the absence of an inner core a purely thermally driven dynamo would be more susceptible to symmetry breaking than a chemical dynamo driven by inner core growth. It should be noted that the absence of an inner core has been postulated as a cause for the lack of a present-day magnetic field on Mars (see e.g., Connerney et al., 2004).

With Mars in mind but with a general model still, Plesa and Breuer (2014) discuss partial melting, differentiation by crust formation and outgassing of one-plate planets and provide a bridge for a collection of papers on the evolution of the Martian atmosphere. They find that the most important parameter determining the thermo-chemical evolution of a differentiating planet is the difference in density between fertile mantle rock and mantle rock chemically depleted by partial melting and basalt extraction. Their evolution scenario leads to the formation of distinct geochemical reservoirs as have been concluded to exist on Mars based on the isotopic record in SNC meteorites (e.g., Jagoutz, 1991; Debaille et al., 2009)

The early evolution of the Martian atmosphere is intensely debated (e.g., Tian et al., 2010). Geological evidence for water on the surface is abundant but a warm and wet climate during the first billion or so years is not easy to explain. And even if the early atmosphere was more massive, how does one loose enough atmosphere to explain the present atmosphere pressure and climate? The present mass loss rates as measured by spacecraft provide an important boundary condition for the modeling. Gröller et al. (2014) contribute to the debate by calculating mass loss rates due to the escape of O and C from the modern atmosphere using a Monte-Carlo model and assuming conditions of low and high solar activity. They compare these values with CO_2^+ escape rates measured by the ASPERA-3 experiment on Mars Express and find up to 40 times higher values. The total loss rate of carbon—as the authors conclude—is mostly due to photodissociation of CO.

Erkaev et al. (2014) model the formation of the early Martian atmosphere and hydrosphere while considering accretionary processes and the variation of the solar XUV flux. They find that the proto-atmosphere was lost within a few million years and that sufficient outgassing is required to explain the geological evidence for water on the surface. They speculate that there may have been sporadically periods of water on the surface. A warmer and wetter climate then today could have been the consequence of outgassing and impacts delivering volatiles. However, impacts may be constructive and destructive depending on parameter values. Shuvalov et al. (2014) show that impacts may significantly erode an atmosphere and provide a scaling law that relates impactor and target parameters to the amount of atmospheric erosion.

Still early on, but with a focus on the Earth is a modeling study of the evolution of the early Earth atmosphere considering the faint young sun (Kunze et al., 2014). The authors find that Earth could still have been habitable under these conditions with liquid water on the surface if the concentration of CO_2 in the atmosphere was ten times larger than today. Farther from home is an atmospheric modeling study of Grenfell et al. (2014) who consider the spectral emissions of planets orbiting cool M-stars. Assuming a biosphere and varying the UV emissions of the star they consider the detectability of ozone and nitrous oxide spectral signatures. This paper thus addresses the fundamental question of identifying unique biosignatures with which life could be found on extrasolar planets, planets too far away to be visited by spacecraft, at least in the foreseeable future.

In the solar system, Mars is still the most likely place for the detection of extraterrestrial life. Much of the discussion of the habitability of Mars centers on the availability of liquid water on the surface both in space and time. Jaumann et al. (2014) review a substantial bulk of work that they have accumulated and published during the course of the Alliance funding. They report on geomorphological and mineralogical evidence—mostly from Mars Express—for the existence of water and nutrients in ecological niches over extended periods of time. Bamberg et al. (2014) use Mars Express HRSC data to investigate floor-fractured craters on Mars. They find evidence for ground water in the formation of these geological features.

The next group of articles considers the habitability of present Mars for microorganisms using mineralogical and biological arguments. While early Mars is widely considered to have likely been habitable, at least for primitive organisms, present Mars is much more debated. Still, the habitability of present Mars is an important issue not only for missions like ExoMars that will search for extinct and extant life but also as an observable that may constrain models of early Mars. One problem is, of course, the average pressure and temperature on Mars that will mostly forbid liquid water to be present. The question is then how the stability field of liquid water can be extended into the ice region.

The series starts off with a discussion of the extension of the stability field of liquid water into the ice region by various biological and mineralogical mechanisms (Hansen-Goos et al., 2014). This paper is followed by an empirical study by Jänchen et al. (2014) on the liquid water storage capacities of selected extremophiles and minerals at Martian surface pressure and temperatures. The then following two papers are studies of terrestrial extremophiles under present day Martian surface conditions. In general, the conclusion is that some protection against environmental stresses is required. The studies would still suggest that extant life might there to be found on Mars provided one would e.g., be able to drill to a few meters depth. First, de Vera et al. (2014) describe how Antarctic lichen adapted to Martian niche conditions within about a month time if protected against high UV doses—an order of magnitude less than on the planet. The experimental study was performed in a Mars simulation chamber with a careful simulation of Martian surface conditions including UV radiation, atmosphere composition, pressure and temperature, and water activity. Bauermeister et al. (2014) use the *Acidithiobacillus ferrooxidans* bacterium as a model organism to see whether or not acidophilic iron bacteria could grow in the geochemical environment of the Martian surface. They speculate that microhabitats may exist at shallow depth underneath the surface of the planet.

Among the problems facing any settling of the question of life on Mars is the problem of finding the most suitable tool to detect biological activity. Schirmack et al. (2014) present a method to measure the methane production rate of methanogens with high precision and time resolution and use the method to measure the production rate for terrestrial methanogens at Martian surface pressure and temperature. Their results support the conjecture that methanogenic archaea could metabolize on Mars. Serrano et al. (2014) use Raman spectroscopy to study methanogenic archae at different stages of their growth. They propose Raman spectroscopy as an analytical tool for in-situ biosignature detection but caution against neglecting the effects of heterogeneity between cells of individual cultures.

The final group of papers in the special issue concerns itself with the formation of the solar system and planetary systems that have habitable planets—termed habitable planetary systems. The relevance of the latter question stems from the observation that in many exoplanetary systems the habitable zone is occupied by giant gaseous planets rather than rocky planets. Tornow et al. link the formation of water in the early solar nebula to the composition of the parental cloud and to processes that occur in the core of the nebula and the dust to gas ratio in the nebula. In the first paper (Tornow et al., 2014a) they consider a quasi-stationary cloud core and model the thermal and chemical evolution of the nebula. In the second paper (Tornow et al., 2014b) they study the evolution of the nebula when the core collapses. They find that the water on Earth may have had two sources, one of which formed before the nebula collapse and a second after the collapse.

Fritz et al. (2014) finally discuss the formation of an Earth-like habitable planet in the context of formation models of planetary systems (based on the Nice model of Gomes et al. (2005), Tsiganis et al. (2005) and Morbidelli et al. (2005)) and the impact record of the Moon (e.g., Stöffler and Ryder, 2001). They find that migrating giant planets in planetary systems may work in two ways: they may jeopardize the formation of terrestrial planets in the habitable zone but may also be instrumental in delivering water that condensed in the outer planetary system to the inner part of the system. In the solar system the reversal of the inward migration of Jupiter and Saturn in what the authors term the “Grand Tack Scenario” both kept the rocky planets and also provided volatile-rich planetesimals from the outer solar system. The record of that transfer being the so called Late-Heavy-Bombardement.

This special issue spans a range of subjects representative of the work of the Helmholtz Alliance “Planetary Evolution and Life” between 2008 and 2013. The work reaches from models to explain the formation of the terrestrial planets in the solar system—successful because they arrive at a Mars-size body at the right distance for the first time (see Fritz et al., 2014) to the experimental verification of the viability of terrestrial extremophiles under Martian conditions. The research findings include atmospheric investigations of potentially habitable super-Earths and calculations of theoretical atmospheric spectra for a range of planetary scenarios including Earth-like exoplanets and early Earth. Models of the interior structure and dynamics of Earth-size and super-Earth-size planets have been calculated that suggest that plate tectonics and magnetic field generation may be more likely for Earth-size planets and that the propensity for these features may decrease with increasing planetary mass beyond Earth‘s mass. Geological mappings of Mars reveal the (paleo)-habitable environments of this planet and mappings of Titan show lakes and rivers of carbon-hydrates. Finally, a study linked life to the plate tectonic engine.

Funding by the Helmholtz Association regularly terminated by the end of 2013. The Alliance, however, continues operating albeit with smaller funding, size and scope. More in depth information on the Alliance including a list of published work is available at http://www.dlr.de/pf/desktopdefault.aspx/tabid-4843/

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