Workshop on "Geoscience for understanding habitability in the solar system and beyond" in Furnas, São Miguel, Azores, Portugal, 25–29 September 2017

This workshop gathered 68 participants and was organized in terms of review talks, key notes, oral and poster presentations, and discussions, for a total of 38 oral presentations and 10 posters. It addresses the fundamental understanding of habitability in terms of geophysics of planets.

1. Introduction

This conference deals with fundamental issues of planetary habitability, i.e. the environmental conditions capable of sustaining life, and how interactions between the interior of a planet or a moon and its atmosphere and surface (including hydrosphere and biosphere) affect the habitability of the celestial body.

It addresses some hotly debated questions in the field including the following:

- What effects do core and mantle have on evolution and habitability of planets?
- What is the relation between (plate) tectonics and atmospheric evolution?
- What role does the mantle overturn play in the evolution of the interior and atmosphere?
- What is the role of the global carbon and water cycles herein?
- What influence do comet and asteroid impacts exert on the evolution of the planet?
- How does life interact with the evolution of Earth's geosphere and atmosphere?
- How can we use our knowledge of the solar system geophysics and habitability for exoplanets?

2. General aim

The evolution of planets (including the Earth) is driven by its internal energy sources (radiogenic sources and energy stored during accretion) and depends on the composition, structure, and thermal state of their core, mantle, lithosphere, crust, and on interactions with a possible ocean and atmosphere and – in case of the Earth – with a biosphere. This conference addresses the fundamental understanding of the concept of habitability, i.e. the environmental conditions capable of sustaining life, and how interactions between the interior of a planet or a moon and its atmosphere and surface (including hydrosphere and biosphere) affect the habitability of the celestial body.

3. Scope

The interdisciplinary workshop goes beyond that of current studies in Earth-System and Planetary Sciences and/or Astronomy by encompassing the entire planets from the upper atmosphere to the deep interior in the frame of the study of its habitability. It addressed questions within four main themes: (1) the interaction between the interior, the atmosphere and space in the framework of planetary and Earth evolutions (including the possibility of very early mantle overturn and its consequences), (2) the identification of preserved life tracers and interaction of life with planetary evolution, (3) the definition of the habitable zone considering the geophysical interplays and integrating comparative histories of terrestrial planets, and (4) the contribution of geophysics in the search for habitable exoplanets. While the workshop was more focused on the Earth, Venus, and Mars, the answers to the questions that have been addressed are also relevant to the other terrestrial planets or moons of the solar system and to exoplanets.

It was fruitfully built on initially collaborating institutions/groups (presented below) and was sponsored by different organisms (EGU Galileo, COST, EuroPlaNet...) enabling the necessary critical mass and excellence.

4. Sponsoring

Here is the list of our sponsors:

- European COST (Cooperation in Science & Technology) Action "ORIGINS" (Origins and evolution of life on Earth and in the Universe)
- EGU (European Geophysical Union) Galileo conferences
- EuroPlaNet (European Planetology Network) 2020 RI (Research Infrastructure)
- German TRR 170 (TransRegio collaborative research) network
- Planet TOPERS (Planets: Tracing the Transfer, Origin, Preservation, and Evolution of their ReservoirS) Belgian IAP (Inter-university Attraction Pole)

Thanks to our sponsors and our networks, we could build up a program as proposed previously and aggregate excellent speakers and participants. We could also invite young career scientists, which provided very interesting fresh mind views. We have reached the critical mass for excellent fruitful discussions and could reach our aims. The presentations were all high level. The main results are summarized here below (see next points) as well as in a power point presentation available.

Furnas offered the possibility to organize excursions that did not only hold a recreational, but also a scientific value. Being in a place where everything is close together also fosters interaction between participants.

The infrastructure of the site (lecture room, technical equipment) was adequate for the group and the format (session organization, time for discussions, general schedule etc.) was adequate for the objectives of the meeting. Interesting open discussions at the end of each session were mostly quite useful.

The discussions and the warm atmosphere that was created by the infrastructure, excursions, program, and organization have leaded to new collaborations. The group wishes to continue to work together and has discussed at the end of the workshop the necessary actions towards a new COST Action and the EAI (European Astrobiology Institute).

We are deeply thankful to all our sponsors!

5. Session summary

5.1. Formation of habitable planets

Dust grows to pebbles by coagulation and deposition of volatile ices, but the continued growth to planetesimals is hampered by the poor sticking of mm-cm-sized pebbles. Planetesimals can nevertheless form by gravitational collapse of pebble clumps concentrated in the turbulent gas through the streaming instability. The subsequent growth initially occurs by planetesimal-planetesimal collisions, but the accretion rate of pebbles dominates the growth from 1000-km-sized protoplanets to form terrestrial planets and the solid cores of gas giants, ice giants and super-Earths. The case of super-Earths formation was discussed and showed to be different from terrestrial planets.

5.2. Sessions on mantle overturn and their role in the formation of habitable planets, the evolution of their interiors (core and mantle) and atmospheres, and relation between them

Convection of the rocky mantle is the key process that drives the evolution of the interior: it causes plate tectonics, controls heat loss from the metallic core (which generates the magnetic field) and drives long-term volatile cycling between the atmosphere/ocean and interior. Cycling of water and carbon dioxide between the atmosphere/ocean and interior is a key process that is thought to regulate habitability because the more CO_2 we have in the atmosphere, the higher is the temperature, and the more weathering we have. Plate tectonic induces larger outgassing and is therefore a key factor for atmosphere generation. At the same time, the volatile content of the surface environment, particularly the presence or not of liquid water, is thought to have a large feedback on the interior, for example by influencing of the existence or not of plate tectonics. Partial melting and mantle depletion extract water from the interior to the surface. Outgassing and volcanism are also related to that. It is necessary to consider a coupled atmosphere-interior evolution for the understanding of habitability.

Additionally, mantle convection controls heat fluxes in the core, which determines magnetism.

The comparison between Earth, Mars and Venus shows that the rocky mantle of terrestrial planets can shape their possible surface habitability via different internal processes like plate tectonics and volcanic activity. Similar feedback mechanisms between interior and surface are thought to exist on rocky exoplanets, even if they may have different chemical compositions (correlated with the mother star). The dimension of the planet and of the core are important, in particular for the formation of a secondary atmosphere through outgassing that would be needed to preserve surface water. Volcanic activity and associated outgassing in one-plate planets is strongly reduced after the magma ocean outgassing phase, if their mass and/or core-mass fraction exceeds a critical value (which depends on the mantle composition), which changes the HZ outer boundary. While the outer edge of the HZ is mostly influenced by the amount of outgassed CO_2, the inner edge presents a more complex behavior dependent on the partial pressures of H_2O and CO_2 gases.

The activity of the star is also important. The induction heating has different influence on the temperature profile in the planet.

Terrestrial exoplanets are now observed, around different stars (including white dwarf). Terrestrial planets can have deep ocean or shallow ocean, they can be H-rich or completely rocky planet. From phase curves (ground observation of a planet crossing the disc of its star) and spectrum, we can characterize the atmosphere of exoplanets, identify presence of oceans and lands, as well as characterize the interaction between surface and interior.

The recent discovery of seven roughly Earth-sized planets orbiting the low-mass star TRAPPIST-1 has vaulted this system to the forefront of exoplanetary characterization. The planets orbit the star with semi-major axes < 0.1 AU, and orbital periods of a few Earth days. Given their proximity to the star, and the star's low mass and low luminosity, the surface of each planet has a moderate temperature (from ~160 to 400 K), consistent with solid surfaces composed of water ice and/or rock. The planets' orbits are in a near mean motion resonance, which maintains their eccentricities, raising tidal forces in the bodies that heat their interiors by tidal dissipation. Tidal heating may be an important energy source that can significantly increase the temperature of planets and satellites.

Magmatism plays a major role in planetary evolution and habitability and it is twofold, the emerged and immersed parts.

The emerged magmatism constitutes the volatile pipelines connecting the mantle to the planetary surface (upwelling, melting, diking, and degassing). C-O-H-S-N species can be delivered to the surface if the P-T-redox conditions of mantle melting make it possible.

The immersed magmatism involves stagnant melt in the mantle that most likely induces of rheological weakening. The melting regime that produces stagnant melt is related to mantle volatiles producing minute amount of melts. The stagnant melting regime may play a critical role in the establishment of a low viscosity layer enabling the shifting of plates.

Carbon and degassing under reduced conditions can build the first atmospheres. During the harsh conditions of the Hadean and early Archean Eons, a nitrogen-dominated atmosphere was not able to survive as it has been eroded within a few million years due to the high EUV flux and the strong solar wind of the early Sun (atmosphere extended above the magnetopause and strong atmospheric escape). This suggests that a CO_2-dominated atmosphere during the late Hadean eon and a later outgassing of the nitrogen atmosphere and that the present-day nitrogen-dominated atmosphere has its origin during later stages of the geological history of the Earth. Mainly CO and H_2 survive for high temperature in the condition of the reduced magma ocean. CO_2 degassing is much more efficient on Earth than on Mars due to much more oxidizing assumed conditions in the Earth's mantle. The redox parameter, oxygen fugacity, is the most important of the parameter spaces, as it rules both melting and degassing. Degassing pressure is also critical as degassing may occur under the sea, i.e. submarine volcanism, or as subaerial processes leading to very different compositions of volcanic gases. There is a coupling between melting-diking-degassing, with feedbacks due to the atmospheric pressures and sub-aerial/marine situation (seafloor weathering), which shows the important role of magmatic processes in the development of habitable worlds.

The present-day terrestrial atmosphere, as dominated by the volatile elements nitrogen and oxygen, is providing a habitable environment for a diverse range of lifeforms.

Earth has undergone a great oxidation event: this event involved the shift in redox conditions from very reducing (stable metal iron) to moderately oxidizing conditions.

The biosphere on its own cannot change Earth’s net global oxidation state because every biologically generated oxidant is accompanied by a mole-equivalent reductant. Instead, a net atmospheric redox shift requires that these redox products couple differentially to geologic fluxes.

Plate tectonics also has a strong influence on the continuous existence of volcanism. Changes in the organic and inorganic components of the carbon cycle would have affected key gases in Earth’s early atmosphere (O_2, CO_2, CH_4 and N_2), and are linked to the evolution of life. Evolving O_2, CH_4 and N_2 levels can be understood by considering global redox conservation.

CO_2 cycle on Earth influenced by both continental weathering (carbon-silicate cycle) and (to a smaller extend) seafloor weathering, instead on early Earth seafloor weathering was very efficient. Early Earth (here before ~2.3 Gyr) atmosphere of Earth was likely anoxic and methane-rich (would help with faint young sun problem).

Understanding our Solar System Planetary Atmospheres is a significant step forward for paving the way for future studies of atmospheres of Extrasolar Planets. Notably, Venus and Mars are natural comparative laboratories to investigate diversity of circulation regimes of terrestrial planets' atmospheres. In this context, comparative studies are essentials to understand the evolution of climate of our Earth, both in the past and in the future. Notably, Venus and Mars are natural comparative laboratories to investigate diversity of circulation regimes of atmosphere of terrestrial planets involving large scale and small-scale processes.

5.3. Session on Interaction of life with the atmosphere, geosphere and interior of planets

Major shifts in Earth's evolution led to progressive adaptations of the biosphere. Particularly the emergence of continents permitted efficient use of solar energy. In contrast, effects of the emergence and evolution of life on the Earth's system are much less certain. A link is provided by biologically enhanced weathering rates of silicate rock. Weathering rates are crucial to the evolution of plate tectonics planets in various respects. On one hand, weathering is an important component in the long-term silicate-carbonate cycle, which stabilizes Earth's climate. In this context, the biologically enhancement of weathering rates has been argued to extend the lifespan of the biosphere. In addition, the dissolution of rock enhances the rate of surface erosion and thus the flux of sediments into subduction zones. This establishes a potential link to the deep interior. Stably bound water within subducting sediments not only enhances partial melting but also further affects the mantle rheology. The mantle responds by enhancing its rates of convection, water outgassing, and subduction. Subduction of water is crucial for the production of continents (in relation with volcanism event enhancement). Altogether, to understand how surface life feeds back on the interior evolution of Earth requires the investigation of the intertwined feedback cycles including the growth of continental crust and the hydration of Earth's mantle.

Particularly important are self-reinforcing mechanisms associated with continental growth that can cause a non-linear behavior in Earth's evolution. A temperature rise below insulating continents and an increased subduction rate of sediments with the emergence of continents cause an increasing continental production rate with an increasing volume of continental crust. Analyzing the strengths of positive and negative feedbacks show that positive feedbacks are sufficiently strong to cause a bifurcation in the continental growth system.

In a phase plane spanned by continental coverage and (upper) mantle water concentration, three fixed points emerge of which two are stable and an intermediate point is unstable with respect to continental coverage and located at present-day Earth values. In other words, the present-day Earth fraction of emerged continents is not a necessary result for Earth-sized plate tectonic planets in general. Rather, the fraction of emerged continents depends on initial conditions (e.g., initial mantle water budget, initial mantle temperature, initiation time of plate tectonics) as well as on the weathering rate. Reducing the weathering rate, i.e. simulating the evolution of the Earth without its biosphere, enlarges the zone of attraction of the stable fixed point with small continents and a dry mantle. Photosynthetic life enhances continental production via water-carrying sediments. It thus becomes increasingly likely for the planet to evolve into a water-world scenario with hardly emerged continents.

Since the Early Earth until modern time, the deep ocean chemistry had changed, in particularly in term of iron (Fe) and sulfur (S) species and concentrations. The Fe and S biogeochemical cycles have been strongly associated, since the Early Earth. Three main periods corresponding to their respective change in concentrations and speciation have been described. Thus the ocean was assumed to be anoxic and ferruginous during Archean; to be anoxic and sulfidic during the Proterozoic and to be oxic with sulfates since the Phanerozoic. Work on the role of the biotic and/or abiotic processes, involved in the evolution and shaping of these two elements cycles indicates that entire S and Fe cycles can function at high temperature and under anaerobic conditions. These biogeochemical cycles are linked, via both microbial metabolisms and/or chemical reactions between sulfide and iron compounds.

Nano-crystals were directly formed or induced by microbial activities while micro-crystals were solely the result from inorganic processes.

5.4. Session on Role of cometary, meteorite and asteroid impacts on planetary evolution

The evolution of planets and life has been influenced by collisions throughout the history of our planetary system. The violent bombardment of the primordial planets affected their thermal evolution, which is crucial for the formation of habitable worlds. Comets and carbonaceous chondrites may have been important sources of water and pre-biotic molecules delivering key ingredients for the formation of an atmosphere and biosphere. However, the delivery of volatiles by impacts that may have significantly contributed to the growth of atmospheres is counteracted by impact-induced atmospheric erosion. The current state of research to quantify the source and loss processes due to impacts is mostly based on numerical modelling.

In addition to the fact that impacts shaped the evolution of planets and how Earth evolved into a habitable world, the origin of life on Earth may be also a consequence of impact: the “Lithopanspermia” hypothesis considers the transfer of life-seeded rock fragments ejected from one planetary body by impact and then delivered through space to another planetary body as meteorites.

Brecciation and impact melting of the target may have led to long-term surface and subsurface hydrothermal activity and may have provided a perfect habitat for the origin of life and its continued evolution, in particular during the early Achaean time. However, large impacts also pose a significant threat for developed biospheres through catastrophic environmental consequences. For example, the 65 Ma Chicxulub impact event caused one of the most pronounced mass extinctions in Earth history.

Both the positive and negative consequences of impacts on the evolution of life have been explored by laboratory analogue experiments and numerical models. Brecciation and impact melting depend on the initial material and its porosity. The shock wave attenuation depends on impact velocity. Strength causes a significantly faster decay of the shock pressure. The presence of a core is also important. Heating of interior depends as well on impact angle. Now we need to understand how much of shock-heated material gets molten, which depends on both temperature/heat and pressure. The simulations can be done for small bodies and impact-induced melting in giant collision events is computed from a parameter scale law, accounting for the fact that the material involved in small impact is from the crust while the material involved for large impacts is from the mantle and a little bit of material of the core can be involved. We can start from different temperature profiles. The critical velocity is 12km/s for the impactor. There might be some stretching of the particles inside down to the core or not. One impact does not change too much to the heat inside the planet; however, when we accumulate the impacts, we have a sort of “impact heating regime”.

During the end of the accretion, the so-called Late Veneer phase, while the bulk of the mass of terrestrial planets is already in place, a substantial number of large collisions can still occur. Those impacts are thought to be responsible for the repartition of the Highly Siderophile Elements. They are also susceptible to have a strong effect on volatile repartition and mantle convection.

Atmosphere lost for giant impacts is at the level of 20% of the mass of the impactor. There are several effects: (1) direct burst and ejection (quite substantial) of the atmosphere (related to the shock wave); (2) plume effect involving the vaporized projectile and sediments, (3) basement clasts particle ejections; the particles ejected in the atmosphere accelerate and heat the atmosphere; here the impact angle is important for the amount of particles. Most of the 20% are however due to (4) a fourth mechanism: the ground motion of the planet caused by the impact that can accelerate particles of the atmosphere above escape velocities. It is possible to compute the net balance of erosion and retention assuming a given impactor flux/different scenarios.

Although micrometeorites (<2 mm) dominate the extra-terrestrial flux to Earth (40,000 tons/year), impacts of km-sized objects affect Earth's evolution much stronger. Impactors with diameter in between ~600 m and 5 km that are thought to cause global catastrophes, still occur once every 0.1 to 1 million years. Currently, approximately 190 terrestrial impact craters are known, ranging from 13.5 m to 160 km for the collapsed transient crater. This number reflects the geological activity on our planet and correlates regionally to the available geological knowledge. As terrestrial impact structures are often modified by erosion, their identification primarily relies on the occurrence of shock metamorphic effects or geochemical and isotopic anomalies induced by the contamination of impact melt rocks and ejecta material with meteoritic matter.

These terrestrial structures provide ground truth data on the geologic effects of impacts and the subsurface structure of impact craters on other terrestrial planetary bodies (e.g., the Moon or Mars). The bombardment history of the inner solar system is uniquely revealed on the Moon. Whatever happened on the moon between 3.7 and 1.7 Ga could have happened on the Earth by 17 times more, with 15 basins on Earth between 2.5 and 3.7 Ga ago as well as 70 Chicxulub size events… Spherule existence indicate these impacts. Short-term effects include thermal radiation, blast-wave propagation in the atmosphere, crater excavation, earthquakes, and tsunamis, while long-term consequences comprise the ejection of dust and climate-active gases into the atmosphere.

Impact cratering may not only be destructive in nature, as impact cratering may have created hydrothermal systems in the Archean (or even before) crust inducing environmental conditions (H_2O, heat, metals) favorable for prebiotic synthesis and perhaps organism diversification.

Mantle dynamics, volcanism and degassing processes lead to an input of gases in the atmosphere and are related to mantle convection. Volatile losses are estimated through atmospheric escape modeling. It involves two different aspects: hydrodynamic escape (0-500 Myr) and non-thermal escape. Hydrodynamic escape is massive but occurs only when the solar energy input is strong. Post 4 Ga escape from non-thermal processes is comparatively low but long-lived. The resulting state of the atmosphere is used to the calculate greenhouse effect and surface temperature, through a one-dimensional gray radiative-convective model.

5.5. Session on Identification of preserved life tracers in the context of the interaction of life with planetary evolution

The search for life on the early Earth or beyond Earth requires the characterization of biosignatures, or "indices of life". These traditionally include fossil chemicals produced only by biological activity, isotopic fractionations of elements indicative of biological cycling, biosedimentary structures induced by microbial mats such as stromatolites, and microstructures interpreted as morphological fossils. However, these traces can in some cases also be produced by abiotic processes or later contamination, leaving a controversy surrounding the earliest record of life on Earth. Looking for life beyond Earth is even more challenging, in situ on other rocky bodies, or by remote sensing in exoplanet atmospheres.

Geobiological studies can improve our understanding of preservational environments and taphonomic processes (how organisms decay and become fossilized), abiotic processes and products, and help us to develop a multidisciplinary approach to establish the biogenicity (biological origin), endogenicity (the fact that the microfossil is in the rock and not a contamination), and syngenicity (the fact that the fossils has the same age of the host rock) of these in situ biosignatures or the possible biogenicity of atmospheric signatures. Combining minimum ages of fossil biosignatures with molecular phylogeny (hereditary molecular differences, mainly in DNA sequences, to gain information on an organism's evolution) permits to produce molecular clocks, that provide dating of branching events and important biological innovations, and allow predictions for the evolution of former and later clades (group of organisms having a common ancestor) or metabolisms.

Cyanobacteria are important, as they have changed the atmosphere and the ocean chemistry.

Mud preserves very old fossils well and even more evolved life like eukaryotes. Archean life was preserved in mud at 3.2 Ga. This allows reconstructing the co-evolution of Earth and life. Habitable early Earth > 3.8 Ga.

All life on Earth uses the same fundamental biochemistry, but even within that constrain the adaptability of life to a versatility of environments is enormous. The adaptability results from the coevolution of the biosphere and the geosphere during the natural history of our planet and seems to require an active recycling mechanism such as plate tectonics.

Some of the physicochemical parameters encountered on Earth exceed the ability of life to adapt, but most lie within the adaptability range of Earth's biota. Certain parameters such as water activity seem to be close to the limit of biological activity, which is readily observable in hyper-arid deserts on Earth. A large range of environmental parameters exists on Earth and on other planetary bodies that can be potential habitats.

Organisms outside Earth atmosphere are subject to intense UV irradiation like on Mars where they also encounter a highly oxidizing and acidic soil. Their degradation can be measured in laboratory experiment designed to simulate planetary and asteroid surface conditions.

The temperature ranges is important for organism but the extreme are large (+122°); pressure ranges do not seem to play a role. There seems to be a salinity limit of life or in fact, the limit may not yet be reached on Earth. Certain parameters such as water activity seem to be close to the limit of biological activity, which is readily observable in hyper-arid deserts on Earth. There is a need of protection from radiation by an atmosphere, as well as a need of transport of nutrients. A much wider range of environmental parameters certainly exists on planetary bodies within and beyond our Solar System and the question arises which set of environmental parameters would still allow the origin and persistence of life. In a first analysis we identify some of the critical parameters such as temperature, pressure, and water availability, which are relatively well constrained in regard to the adaptability of life as we know it.

The discussion highlighted the importance of the presence of phosphorus in the environment, as a mineral forming factor, and as a participant in the formation of relationships related to the formation of life.

5.6. Session on Habitability and planet formation in a broader context

The search for Earth-like planets in the habitable zone of stars has become a central focus of research. However, understanding whether a planet could indeed be potentially habitable requires a deep knowledge of the geophysical processes driving the key elements for habitability (as seen in the previous Sessions). To gain a better understanding of these processes, the evolution of Earth is often taken as a reference case for the interaction of atmosphere, geology and biological processes. Such processes will also take place on terrestrial exoplanets, but are much harder to constrain without in situ information. Furthermore, terrestrial planets around other types of stars, or young planetary systems, may experience much harsher space weather conditions that can affect habitability as well as the presence of biosignatures.

If one takes the Earth and put it in the HZ of an M-dwarf start, we see that the atmosphere is changing due to the interaction with the star emissions (done with a chemical-climate model). Also coupling with a biogeochemistry model allows determining what kind of spectrum we can get. It can show e.g. Ozone, OH, CH_4 evolutions, with their feedbacks, considering UV effects etc.

Measuring the transit depths of close-in (fractions of an AU) gas giants (hot Jupiters) in broad wavebands to establishing spectrophotometry is a robust technique for inferring the presence of molecules in the atmospheres of transiting exoplanets. The Wide Field Camera 3 (WFC3) onboard the Hubble Space Telescope is now routinely used to detect the presence of water in transiting exoplanets. In parallel, astronomers have designed techniques to direct image (i.e., photometrically separate the exoplanet from its star) the thermal emission and take their spectra. In principle, both techniques may be eventually applied to Earth-sized exoplanets to remotely infer the chemical inventory of their atmospheres. The promise of exoplanetary atmospheres relies on the fact that they are a window into probing the chemistry, surface conditions, biosignatures, and formation history of an exoplanet.

5.7. Session on Planetary research: Ethical, philosophical and societal issues

The concept of sustainability is widely acknowledged as a political guideline. Economic, ecological, social and cultural aspects of sustainability are already under discussion. Current space mining efforts demand that the discussion become a broader one about "planetary sustainability", including the space surrounding Earth. To date, planetary sustainability has mainly been used with reference to Earth only. It is necessary to broach the issue of the multiple dimensions of sustainability in this context. This is the concept of constructive-critical realism.