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.

Contents

1. Introduction

This workshop is a joint effort of several groups. The starting point was some enthusiasm from young scientists working on mantle convection and planetary evolution to make the last final workshop of the Planet TOPERS (see below) group on a volcano.

The Azores belong to the geologically most interesting places in Europe. The geothermal area at Furnas on the Island of São Miguel on the Azores is one of the most interesting features in the Azores. There are hot springs at the village and studies of extremophiles are conducted at the Furnas Microbiological Observatory. Furthermore, there is a very interesting crater close to the venue, where the Centre of Monitoring and Research of seismic and volcanic activity is located, which also hosts an interesting exhibition. All these places are in walking distance from Furnas and can be visited without huge demand of time.

Therefore came the idea to go in the Azores, also convenient to invite US colleagues. Starting from that idea, we have built on and contacted several organizations to get sponsors for young scientists mainly. Naturally, the COST action (European Cooperation in Science & Technology) ORIGINS (TD1308) to which most of us belong was the first, and then the EGU, EuroPlaNet, and the Planet TOPERS group as well.

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?

This report has been built, on the one hand from the abstracts, and on the other hand by notes taken during the presentations and the discussions. I have also tried to capture the main ideas in a short summary and a power-point presentation.

1.1. 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.

1.2. Focused aim

Within this thematic framework, there are several hotly debated questions in the community of scientists working on the relations and interactions between planetary reservoirs and their evolution through time. A particular important issue is the difference between the evolutions of Earth and Mars. While the processes responsible for this are mostly identified, several fundamental questions remain: (1) What is the relation between (plate) tectonics and atmospheric evolution? What is the role of the global carbon and water cycles herein? How to export our knowledge on the solar system geophysics and habitability to exoplanets? (2) What is the influence of comet and asteroid impacts on the evolution of the interior and the atmosphere? (3) How does life interact with the evolution of these two reservoirs (interior and atmosphere)? How to link the identification of preserved life tracers in the context of its interaction of life with planetary evolution? (4) What is the role of an early mantle overturn after fractional crystallization of a magma ocean for convection and thermal evolution? What is the role of mantle overturn in evolution of the interior and atmosphere? (5) What are the effects of the core and mantle composition on their evolution and on habitability? These questions do not have a simple answer and scientists must discuss the pros and cons of different hypotheses. In the coming years a lot of efforts in this direction have been made and the workshop helped in assessing the answers to these questions in a constructive critical way.

1.3. 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.

1.4. COST ORIGINS

First this workshop is part of the COST Action “ORIGINS” (Origins and evolution of life on Earth and in the Universe) coordinated by Muriel Gargaud. This COST action has 5 Working Groups (WGs) and 2 teams on Education/Training and Dissemination/Outreach:

- WG1: Understanding the formation of planetary systems
- WG2: Searching for the origin of the building blocks of Life
- WG3: Tracing the origin and evolution of life and finding its limits
- WG4: Detecting life on other planets and satellites
- WG5: Philosophy, History of sciences and ethics

It is engaging (future) researchers and the public. This workshop is trans-domains as it is addressing all the themes of the WGs. It is the sixth Conference of COST action. Previous conference information is available on the COST website (http://www.life-origins.com). It also paths the way to the next conference that will be held in April 2018. Maybe on Habitability and sustainability of life in the Solar system and beyond.

1.5. EGU Galileo Workshop

EGU (European Geophysical Union) Galileo conferences are named in honor of Galileo Galilei, the famous Italian physicist, philosopher, astronomer and mathematician, universally recognized as the founder of modern science.

The EGU Galileo conferences address well-focused cutting-edge topics at the frontier of geosciences research. The conferences are informal: the state-of-the-art is outlined in keynote presentations designed to trigger in-depth discussion of important aspects of the conference topic.

This was typically our case! We have thus sent in a proposal, which was accepted!

1.6. EuroPlaNet

EuroPlaNet (European Planetology Network) 2020 Research Infrastructure (RI) is a €9.95 million project to address key scientific and technological challenges facing modern planetary science by providing open access to state-of-the-art data, models and facilities across the European Research Area. The project was launched on 1st September 2015 and is funded under the European Commission's Horizon 2020 programme. It is led by Nigel Mason from the Open University in the UK. EuroPlaNet 2020 RI has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 654208. Among its activities, EuroPlaNet has networking activities, including meetings, workshops and personnel exchanges, to strengthen the community, develop industry-academic collaboration, discuss latest scientific results, and set the strategy and goals for planetary science in Europe for decades to come in cutting-edge planetary science and exploration. We did send an application for sponsoring our workshop, which was accepted!

1.7. German TRR 170

In order to cover a maximum of young scientists we also applied for sponsoring from the German TRR 170 (TransRegio collaborative research) network on "Late Accretion onto Terrestrial Planets" funded by the German Research Foundation (DFG), which was accepted as well!

1.8. Planet TOPERS

Planet TOPERS stands for Planets: Tracing the Transfer, Origin, Preservation, and Evolution of their ReservoirS. It is a Belgian Inter-university attraction pole addressing the question of habitability in our Solar System. The IAP Planet TOPERS (IAP – Interuniversity Attraction Pole) field of research supports a broad community in an interdisciplinary approach to understand habitability. The Pole focusses its contribution on the full integration of the themes in the following Work Packages (WP) in order to better demonstrate how life can be sustained and to characterize the existence and persistence of life through the development of potential habitats:

- Internal Geophysics and Interaction with Atmosphere
- Atmosphere and interaction with surface, hydrosphere, cryosphere, and space
- Identification of life tracers, and interactions with planetary evolution
- Accretion and evolution of planetary systems
- Integration of information into "Global System dynamics": Case study and comparisons of evolution pathways; definition of habitability conditions and its sustainability on different bodies

The Planet TOPERS group is at the end of its existence and wanted a last workshop to address the roadmaps for their future, developing, in a holistic approach, an integrated model of planetary thermodynamic engine that includes mass, energy, and entropy balances into a “Global System dynamics” considering the role of feedback cycles to stabilize habitable conditions.

Each partner of this IAP coming to the workshop has been financed either by the project or by own funds.

1.9. Last comment

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!

1.10. Towards the sessions

Veronique Dehant and Tilman Spohn presented their view on the habitability of planets with a geoscience perspective in a talk entitled “General overview talk on planetary habitability and geophysical interactions”.

Extraterrestrial life would probably be based on organic chemistry in a water solvent. The stability of liquid water at the surface of a planet defines a habitable zone (HZ) around a star. In the Solar System, it stretches between Venus and Mars. Depending on details of the models, Venus may have been in the habitable zone in the early solar system when the Sun was less luminous. Geological evidence suggests water on early Mars but whether Mars has been habitable is still debated.

We believe that the presence of water at a planet surface is strongly influenced by the planetary interior and atmosphere evolution. In order to understand more deeply habitability, we study planetary evolution and dynamic processes, e.g. internal dynamo, magnetic field, deep interior evolution, atmosphere, plate tectonics, mantle convection, volcanism, thermal evolution, meteorite impacts and erosion etc. These dynamic processes modify the planetary surface conditions, the possibility to have liquid water, the thermal state, the energy budget and the availability of nutrients. We show that the dynamics and the interrelation between interior and atmosphere is very important for understanding habitability.

The discussions that have followed the talk were mainly dedicated to the importance of a magnetic field for habitability. While the magnetic field definitely acts as a shield against cosmic radiation that protects life itself, its precise effects on the evolution of atmospheres is still debated. The traditional view holds it as a shield that prevents or limits atmospheric escape by non-thermal processes. However, the observation of terrestrial planets from the Solar system indicates similar escape rates for Earth, Mars and Venus. Thus, it has been proposed that magnetic fields would not be as effective as previously thought to avoid volatile losses. The proposed reason for this is that the magnetic field extends very far outside the solid planet and thus intercepts much more solar energy than a planet without any magnetic field (just solid planet plus atmosphere). As escape processes are usually seen as energy limited, the larger amount of energy available for escape balances out the shielding effect afforded by the field (see work by Barabash et al.). This theory is still disputed, though (Tarduno et al., 2014), mentioning that not all species that escape are lost, since some can fall back into the atmosphere at a different location after being excited by solar radiation. Measurements depend massively on the condensation rate of ions in the atmosphere, which is still poorly constrained. Discussions also noted that other cases could lead to limitations of the shielding properties of the magnetic field, like a thick expended (possibly hot) atmosphere whose upper layers would reach so far from the ground that species would not be protected. In the end, it is assured that the magnetic field affects escape rates, but we are still unsure about the specific mechanisms.

Other mechanisms that deplete or replenish the atmosphere were discussed such as atmospheric hydrodynamic or non-thermal escape to space and volcanic degassing of the mantle. Atmospheric escape (hydrodynamic) was only relevant during the early evolution (0-500 Ma), when Extreme UV flux leads to massive loss of hydrogen and oxygen. It is not affected by the magnetic field. Noble gases are fractionated during that time. Non-thermal atmospheric escape was the main escape-mean during the bulk of the evolution (the last 4 Ga).

2. Session on Formation of habitable planets

2.1. Terrestrial planets and Super-Earths: similar bodies? An origin perspective (Review talk) by Alessandro Morbidelli, University of Nice, FR

Super-Earths, particularly those with a bulk density similar to that of our planet, are often considered as scaled-up versions of our Earth.

However, our planet is not just characterized by a mass and a radius. A specificity of our planet is that it formed slowly, over tens of millions of years. Thus, it formed mostly after the disappearance of the protoplanetary disk of gas, via a sequence of giant impacts. The precursors of the Earth, the planetary embryos, which formed within the disk lifetime, were small. They had a mass presumably smaller than that of Mars. Thus, they did not migrate significantly while in the protoplanetary disk. In addition, they did not build a primitive atmosphere, while their atmosphere was mainly formed by degassing presumably.

The super-Earths are more massive than our planet and they are much closer to the central star. Some of them may have migrated from the outer parts of the disk and thus they are probably more similar to Neptune than the Earth. But also the rocky super-Earths may have formed differently from our planet. In fact, if more mass is available in the system to form more massive planets in the end, the planetary embryos grow faster and bigger as well. Thus, they start to be affected by orbital migration. Migration in turns affects strongly the accretion process. We predict that close-in super-Earths formed mostly within the proto-planetary disk lifetime. Their growth was dominated by the accretion of small particles, and giant impacts have been rare. Primitive atmospheres are likely. Higher radioactivity is expected and the water fraction is presumably larger.

It is unclear whether this different accretion path leads to chemical and geophysical properties different from those of our Earth, affecting their capability to sustain life even if they are emplaced in the end in the so-called “habitable zone”.

The take away message was:

- Earth formation occurred for the most part after the removal if the protoplanetary disc (of gas).
- The formation of planet above some threshold mass requires/implies more rapid growth and therefore the interaction of the planets with the gas; there is a substantial role of migration in that case; super Earth share that accretion mode.
- One can pass from the first to the second formation mode by increasing the surface density of available solids.
- Earth-like planets probably have masses ≤ 2-3 M_E.
- Super-Earth can also be Uranus-Neptune like planets that migrated into the inner system; this did not happen to the Solar system thanks to the presence of Jupiter and Saturn.
- There is no direct evidence for Earth-like planets so far; basically, all planets either have H/He envelopes or are likely to have lost them by irradiation.
- The observed distribution of radii and measured bulk densities for atmosphere-less planets seem to imply the rocky nature (no ice) of Super-Earths.
- The apparent absence of ice-rich Super-Earths is puzzling.
- What is the habitability potential of Super-Earths from the geophysical point of view? (Large mass, huge radioactive heating, primitive atmosphere, water fraction).

2.2. Formation of habitable planets (Keynote talk) by Anders Johansen, Lund University, SE

Planets form in protoplanetary discs around young stars as dust and ice particles collide to form larger and larger bodies. A coherent theory framework for the formation of planetary systems was presented, which includes 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.

So the take-away message was:

- Protoplanetary discs are really food pebble factories.
- Streaming instability concentrates particles down to chondrule sizes at elevated metallicities.
- Chondrules likely represent pebbles from the terrestrial planet formation zone, although their formation is not understood.
- Chondrule accretion explains well the size distribution of asteroids and drives the growth of Protoplanets.
- Chondrules may have contributed the dominant mass to terrestrial Protoplanets and planets.

2.3. Habitable planets in multi-planet systems by Ewa Szuszkiewicz, from University of Szczecin, PL

There are more than 600 known multiple planet systems. They are characterized by a remarkable variety of structures and dynamical behaviors. This gives a real possibility of studying life-bearing planets. Habitable conditions have been investigated for some of the most interesting systems taking into account not only the requirement of the existence of liquid water on the planet surface, but also for an internal heat that is sufficient to drive plate tectonics.

Mainly the TRAPPIST-1 system was presented and analyzed in terms of the HZ as well as tidal heating possibilities. The rates of internal heat generation by the tidal forces have been evaluated consistently with the current orbital configuration of the system, its orbital evolution and formation scenario. It was concluded that only one of the seven planets (planet e) was at the intersection of the tidal and conservative insolation zones for a dissipation factor at the level of 10^3, while in a more optimistic case also planet d remained in both habitable zones. The dissipation factor depends on the present age of TRAPPIST-1, which is still poorly constrained. If one can adopt the lower bound of 0.5 Ga for its age than planets d, e and f are potentially habitable.

2.4. Discussion

The discussion was mainly related to the definition of the habitable zone. There are different definitions of habitable zones, the Earth-like definition takes into account a N_2-H_2O-CO_2 atmosphere because if Earth would be pushed closer to the Sun, water would lead to a runaway greenhouse effect, and at outer boundary of HZ the non-condensable greenhouse gas (here CO_2) starts to condense → maximum greenhouse effect for CO_2-dominated atmosphere.
This is different for other atmospheres, e.g. H-He atmospheres, but one can argue that it is better to concentrate on atmospheres where Earth-like life could exist, whereas another argument would be that we should look for all possible habitability zones / atmosphere possibilities, to widen the amount of possible biosignature detections in exoplanets, but then the problem arises what are clear biosignatures, especially for non-Earth-like life.

3. Session on Core and mantle evolution, mantle overturn and their role in the formation of habitable planets and the evolution of their interiors and atmospheres

3.1. Coupled evolution of the core, mantle and lithosphere over billions of years: Our current state of understanding (Review talk) by Paul Tackley, ETH Zürich, CH

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. Thus, plate tectonics is often considered necessary for planetary habitability. 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. Thus, long-term effects of water cycle and carbonate cycle must be considered together with their mutual relation. In this frame, we need to consider a coupled atmosphere-interior evolution.

Unfortunately, plate tectonics is still not well understood; other terrestrial planets like Venus and Mars instead have a stagnant lithosphere. Furthermore, Earth may not have had plate tectonics early on. Thus, one key topic of investigation is the possible tectonic modes of terrestrial planets and how their appearance depends on planet size, surface environment, internal temperature, internal heating rate, history, etc. The heat loss through the surface comes from a combination of cooling from a hot primordial state and radioactivity.

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

For example, our recent models indicate that variations in crustal thickness caused by partial melting are important in facilitating plate tectonics, and have been ignored in previous analyses.

Numerical simulations of mantle convection, plate tectonics and volcanism help to understand what process generates plate tectonics, which is related to viscous, brittle, plastic, elastic deformations, non linearity, grain size, composition, and occurs over multi-scales. Low/high yield stress lead to diffuse deformation, plate tectonics, or stagnant lid convection. Simulations help to develop understanding of the scaling of tectonic modes with Rayleigh number, internal heating rate, yield stress etc. As planet cools, this scaling predicts a transition from stagnant lid to plate tectonics.

There is much debate about whether super-Earth have plate tectonics. According to our analysis, larger planets are more likely to have plate tectonics. However, it is complicated due to dependence of the physical properties on pressure and other things.

Did the Earth have always plate tectonics? Probably not, because simulations predict that when the mantle temperature was higher there was no subduction. Partial melting was more widespread.

Precambrian times the mantle was hot and melting and crustal production were more vigorous. It is important to take these into account in models. There were several effects melting, crustal production help plate tectonic to operate and may also result in a new tectonic mode, the plutonic squishy lid mode. This allows volatiles to be recycle without plate subduction, instead by delamination. This mode may be relevant to Venus on which the stagnant lid could be non-rigid, with magma injections.

The mantle determines the CMB heat flux. A layer of denser material above the core acts as a thermal blanket allowing correct core cooling history.

Water has also much influence on convection. In addition, water favors plate tectonics. Models are very complicated as the minerals take water differently. Complexity arises in subduction zones. Global models do not represent well the detailed pressure and temperature path in subduction zones.

3.2. The link between mantle convection, atmosphere evolution and surface habitability - from the Solar System to exoplanets (Keynote talk) by Lena Noack, FU Berlin, DE

The Earth is only one out of three planets in the HZ of the Solar System - with Mars and Venus at the boundaries. Both planets lack active plate tectonics, a global magnetic field and (at least in the case of Mars) active volcanism.

Planets like Mars without plate tectonics and no or only limited volcanic events (and thus limited outgassing potential of greenhouse gases) are not able to build up a dense CO_2 atmosphere. At the outer boundary of the HZ, the greenhouse effect would not be strong enough to ensure liquid surface water and the planets may not be considered as habitable at their surface.

Venus, lying at the inner boundary of the HZ, has a dense CO_2 atmosphere and is not habitable. If the planet were to be at the outer boundary of the habitable zone or if some of the CO_2 from the atmosphere would have been extracted by weathering and carbonate formation (for example via a global plate-tectonics-driven carbon cycle similar to Earth), Venus might have been a habitable planet - at least in its past.

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.

Here we study the effect of the planet interior of stagnant-lid planets in the habitable zone on the formation of a secondary atmosphere through outgassing that would be needed to preserve surface water. In general, we find that 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). As a consequence, the effective outer boundary of the habitable zone is then closer to the host star than suggested by the classical habitable zone definition, setting an important restriction to the possible surface habitability of massive rocky exoplanets, assuming that they did not keep a substantial amount of their primary atmosphere and that they are not in the plate tectonics regime.

Models with partial melting and mantle depletion extract water from the interior to the surface.

Correlation exist between iron fraction and water fraction and the type of star. From star composition, on can evaluate several possible planet interior composition.

It is easier to produce melt when the percentage of Fe is high. The percentage of melt increase with increasing the percentage of Fe. There is a cross point where densities of melt material and solid material crosses. However, there are regions where one and the other are higher or lower. Water outgassing, oxygen fugacity changes with pressure and temperature; one can compute CO_2 in melt and it changes a lot.

One can look how much mantle depletion, a lot of volcanic activity and outgassing. This percentage changes with core size; the larger the core, the less depletion we have. It also depends on the mass of the planet. There is an optimum between 2-3 M_E, where we have large outgassed CO_2.

How does this change for plate tectonics planet? Plate tectonic induces larger outgassing. Therefore, it is a key factor for atmosphere generation. The influence of the mass on plate tectonics is difficult to evaluate. It depends on so many factors that it is impossible to conclude.

The influence of composition for different cores on the outgassing is very high. There is a specific range of planets where the outgassing is particularly high. Something like $2M_E$. Now we must vary all the parameters systematically to have conclusions. In the different models with different rheology is very important for the outgassing (of CO_2 and H_2O). The mass is the most important factor for a stagnant lid planet.

The activity of the star is also important. The induction heating has different influence on the temperature profile in the planet and is different for the Trapist-1 planets. Local magma oceans can be expected on Trappist-1b and -1c. Strong outgassing is expected on Trappist-1d planet.

3.3. Global Archean geodynamics and onset of plate tectonics evidenced by 142^{Nd} by Vinciane Debaille, ULB, BE

Short-lived chronometers record very ancient differentiation events that can later only be modified by subsequent re-mixing. As such, 142Nd signatures observed in Archean rocks can be related to ancient differentiation events within the first 500 Myr of Earth history, and have been subsequently re-mixed by mantle convection in modern-day samples (e.g. [1]). So far, present-day samples display no 142Nd anomaly (e.g. [2]). As such, it is supposed that the homogenization of the mantle has been achieved regarding that isotope. The discovery of a 7-ppm anomaly in 2.7 Gyr old rocks from the Abitibi greenstone belt also indicates that the homogenization of the mantle was not fast, despite intense mantle convection when the Earth was hotter in the Archean [3]. This paradox has been interpreted as relating to a stagnant-lid tectonic regime with only scarce and short episodes of subduction [3].

When observing the record of 142Nd in the most ancient samples, large disparities exist with geographic locations. The largest positive variations are found in the Isua Greenstone Belt (e.g. [1, 4]), while at the same period, very small positive variations are recorded in the Yilgarn craton, Australia [1] and negative ones in the Nuvvuagittuq Greentsone Belt, Canada [5]. Of a similar age, the Barberton Greenstone Belt, South Africa [6], has no 142Nd anomaly while small negative anomalies are also found in Isua [7]. Finally, our recent results in the West African Craton, Mauritania, also find no 142Nd anomaly, hence suggesting the African continent does not sample any ancient event. Such a geographic diversity is intriguing and could be interpreted in terms of the onset of plate tectonics at the global scale or not, on Earth. Indeed, because of the geographic scale, it could mean either that the Earth did not differentiate homogeneously, or that the terrestrial mantle did not remix homogeneously [1]. The second case could be related to localized conditions for plate tectonics. By investigating other cratons, we distinguish between the two scenarios, and their implications.

Fully mixing the terrestrial mantle was not that rapid, it took at least 1.8 Gyr, despite mantle convection. Role of plate tectonics on the mixing mantle: even on Archean conditions, we have even with plate tectonic very long mixing times. However, the planet existence with/without plate tectonic have very different mixing times.

Inefficient mixing in Mars. Efficient for Earth but Archean Earth observation need stagnant lid with previous data.

Magmatic events are analyzed in terms of the 142Nd. What do we see? Theo flow (sample at 2.7 Ga) needs both large chemical anomaly and low mixing. In the literature, one sees a large bias in North Atlantic. There is no anomaly in 142^{Nd} elsewhere on Earth. Is this bias real? Is it something real? Still debated. This needs more samples. Either the Earth differentiated homogeneously or it did not. In that last case, we have different 142Nd ratio.

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3.4. On the habitability of a stagnant-lid Earth by Barbara Stracke, from German Aerospace Centre, DE

Plate tectonics is considered a fundamental component for the habitability of the Earth. Yet whether it is a recurrent feature of terrestrial bodies orbiting other stars or unique to the Earth is unknown. The stagnant lid may rather be the most common tectonic expression on such bodies. To understand whether a stagnant-lid planet can be habitable (i.e., host liquid water at its surface), we model the thermal evolution of the mantle, the volcanic outgassing of H_2O and CO_2, and the resulting climate of an Earth-like planet lacking plate tectonics. We use a 1D model of parameterized convection to simulate the evolution of melt generation and the build-up of an atmosphere of H_2O and CO_2 over 4.5 Gyr. We then employ a 1D radiative-convective atmosphere model to calculate the global mean atmospheric temperature and the boundaries of the Habitable Zone (HZ).

The evolution of the interior is characterized by the initial production of a large amount of partial melt accompanied by a rapid outgassing of H_2O and CO_2. The maximal partial pressure of H_2O is limited to a few tens of bars by the high solubility of water in basaltic melts. The low solubility of CO_2 causes instead most of the carbon to be outgassed, with partial pressures that vary from 1 bar or less if reducing conditions are assumed for the mantle, to 100–200 bar for oxidizing conditions. At 1 AU, the obtained temperatures generally allow for liquid water on the surface nearly over the entire evolution. 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 both gases.

At 1 AU, the stagnant-lid planet considered would be regarded as habitable. The width of the HZ at the end of the evolution, albeit influenced by the amount of outgassed CO_2, can vary in a non-monotonic way depending on the extent of the outgassed H_2O reservoir. Our results suggest that stagnant-lid planets can be habitable over geological timescales and that Joint modelling of interior evolution, volcanic outgassing, and accompanying climate is necessary to robustly characterize planetary habitability.

The concluding remarks are:

- Outgassing of H_2O is limited to 9 bar for the reference case due to the increasing atmospheric pressure and high solubility of H_2O in surface magmas.
- Outgassing of CO_2 is much less soluble than water and can be outgassed throughout the evolution and is controlled by redox state of the mantle. For the reference case with an assumed oxygen fugacity at the iron wuestite buffer around 2 bar of CO_2 can be outgassed.
- At 1 AU, a stagnant lid Earth could be “habitable” throughout its evolution with a global ocean of around 80 m, which corresponds to around 3% of Earth ocean.
- At this step, they do not have feedback of the atmosphere into the interior (no sinks).

3.5. Characterizing terrestrial exoplanets – the present and the future, by Renyo Hu, from JPL

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. When the planet is larger than Earth, it becomes more difficult to lose the primordial atmosphere. How to detect rocky exoplanet surfaces? How to detect atmospheres of rocky exoplanets? What atmospheric pressure are we probing? In particular when they are completely rocky, can we say something from the observation?

Spectral features of rocky planetary surface are multiple as seen from the Moon where lunar mare and highland have completely different spectra. We can have metal-rich (primary crust), ultramafic, feldspathic, basaltic, granitoid, clay, ice-rich silicate, Fe-oxidized surfaces.

When there is an ocean, from phase curves (ground observation of a planet crossing the disc of its star) we can identify presence of oceans and lands. It constrains the thermal redistribution efficiency. One can then study the planetary flux considering that it is the sum of thermal emission + gas reflection + cloud reflection.

Characterizing the atmosphere of exoplanets (phase curve and spectrum) allows characterizing the interaction between surface and interior as well.

3.6. New evidence for recent geologic activity on the surface of the Moon by Adomas Valantinas, from University of Copenhagen, DK

The conventional understanding of the Moon states that it is a differentiated but currently a geologically ‘dead’ body. Most of the lunar mare volcanism took place ~4-3 Ga ago and basin related extensional tectonics ended 3.6 Ga ago with some degree of contractional tectonics up to 1.2 Ga [1-

4]. However, with the help of high resolution images provided by NASA's Lunar Reconnaissance Orbiter a number of geologically young structures have been recently identified by various workers. Evidence for basaltic volcanism in the past 100 Ma has been proposed from the observations of so-called Irregular Mare Patches (IMPs) [5]. A number of surface tectonic expressions such as small graben and lobate scarps were found to be also <~100 Ma [6-8]. In our work, we analyze several contractional lunar wrinkle ridge systems that are thought to be manifestations of global stress fields along nearside maria edges [9]. Results from stratigraphic relationships and the lack of large superimposing craters suggests that all wrinkle ridges in our study regions are at least Copernican (i.e. <1.1 Ga in age). We derive model ages from crater size frequency distributions that result in ages all below 30 Ma. Analyzed lunar wrinkle ridges appear morphologically crisp and include various degrees of pristine rocky outcrops. The latter supports the evidence that they are geologically young because estimates of lunar surface boulder obliteration rates imply that rock populations are fully destroyed in 300-1500 Ma [10-13]. These results suggest that there might be active and long lasting crustal weakness in the lunar nearside due to antipodal impact at the South Pole Aitken basin [14].

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3.7. The obliquity of icy satellites with internal global oceans by Rose-Marie Baland, from Royal Observatory of Belgium, BE

Much progress has been made in recent years in modeling the obliquity of synchronous icy satellites with an internal global ocean sandwiched between a solid interior and an icy shell. Obliquity depends sensitively on the interior of the satellites, notably the properties of the ocean, and obliquity measurements are important to assess the habitability of bodies like Titan or Ganymede, as they help to constrain the satellite's interior and ocean.

The obliquity is the angle between the rotation axis and the normal to the orbital plane. In the same way as for the Moon, synchronous satellites are expected to be in a Cassini state, an equilibrium rotation state. If there were no internal ocean, the external torque exerted by the parent planet on the oblate figure of the satellite would lead to a fixed obliquity in the case of an orbital ascending node uniformly precessing in space.

Because of the internal ocean, the internal layers are differently affected by the external torque, so that their spin axes can have different obliquities. This misalignment gives rise to internal gravitational and pressure couplings that tend to restore, but without achieving, the alignment. The measured obliquity of Titan is not consistent with the predicted solid body obliquity and is evidence of a subsurface ocean. It moreover requires the ocean density to be at least about 20% above that of pure water, indicating a high level of enrichment in salts. Future obliquity measurements (e.g. with JUICE) for Europa, Ganymede, and Callisto can provide independent evidence of the existence of internal oceans and help constrain them.

Additional physical processes affecting the obliquity include the variations of the orbital precession rate, which leads to a time-variable obliquity, the tidal deformations induced by the parent planet and the flow inside the internal ocean. We include all these elements in a new obliquity model to improve the interpretation of obliquity measurements in terms of the interior and possible habitability.

Application to Titan with an internal global ocean allows to retrieve the measured obliquity and tide values (the Love number k_2) and to characterize the thicknesses and densities of the internal layers. Few density profiles are consistent with both obliquity and tides. Elasticity is then considered. Adding elasticity and Poincaré flow in the ocean leads to the conclusion that there could be larger tidal deformation and this jeopardize the previous conclusion on interior. Further refinements (dissipation + nutations) of the models could lead to a better understanding of the density of the ocean, ocean properties.

Similarly for Enceladus, the use of tide and obliquity would lead to information on interior. However, the obliquity is too small to be detectable.

3.8. Interior structures and tidal heating in the Trappist-1 planets by Vera Dobos, from Konkoly Observatory, HU

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.

We use a model that balances heat production by tides with heat loss by conduction and convection to constrain tidal heating rates for each of the Trappist-1 exoplanets. We construct simple interior models for each planet based on its mean density, and knowledge of the physical properties of ice, rock, and metal. We determine how the interior of the planet responds to tidal forcing, by calculating the Love number k_2, which describes how a planet gravitational potential changes in response to tidal forces. We calculate the expected tidal heat flux on each planet, and discuss the consequences on habitability and the geophysical state of the planet (e.g., potential for volcanism).

The interior structure of the planets are based on a choice for interior (rock, iron, high-pressure ice, ice and water).

3.9. Discussion

How the outgassing changes the early Earth to present day: The great oxidation event on Earth may have been triggered by a change of volcanic degassing pressure (from volcanism at the bottom of the ocean to surface volcanism) following Gaillard et al. (2011, Gaillard, F., Scaillet, B., Arndt, N.T. Atmospheric oxygenation caused by a change in volcanic degassing pressure. Nature 478, 229–232). Plate tectonics also has a strong influence on the continuous existence of volcanism (e.g. Noack et al., 2014, Noack L., Godolt M., von Paris P., Plesa A.-C., Stracke B., Breuer D., and Rauer H., Can the interior structure influence the habitability of a rocky planet? Planetary and Space Science, special issue ‘Planetary evolution and life’, 98, pp. 14-29, DOI: 10.1016/j.pss.2014.01.003.).

In a simplified approach, the evolving surface temperature can be calculated from the amount of CO2 and water in the atmosphere using a radiative-convective atmosphere model (e.g. for Venus see Gillmann and Tackley, 2014, Atmosphere/mantle coupling and feedbacks on Venus. Journal of Geophysical Research: Planets, 119(6), pp. 1189-1217, DOI: 10.1002/2013JE004505). This is mostly true for Venus-type planets, where surface temperature is mainly uniform due to the thick atmosphere and varies vertically. Surface temperature in turn acts as a boundary condition for the mantle convection model.

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 (Krissansen-Totton and Catling, 2017, Nature Communications, 15423, DOI: 10.1038/ncomms15423). Zahnle et al. (2006, Geobiology, 4, 271-283, DOI: 10.1111/j.1472-4669.2006.00085) showed that early Earth (here before ~2.3 Gyr) atmosphere of Earth was likely anoxic and methane-rich (would help with faint young sun problem).

4. Session on Relation between interiors, plate tectonics and atmospheres, and their evolutions

4.1. The magmatic processes making habitable worlds (Keynote talk) by Fabrice Gaillard, from University of Orléans, FR

Capturing the chain of processes making habitable worlds is a requirement to resolve the fascinating issue of the Earth’s unicity. Observing exoplanets strikes the imagination by reasoning on the size and the stellar endowment of the planets and information on the atmospheric signature of exoplanets have become a groundbreaking field. The terrestrial planets of our solar system also constitute valuable and observable benchmarks and, as such, they display a great diversity in surface chemistry telling us that size and solar endowment must be considered together with a variety of other processes. These processes are mostly ancient, telluric phenomena that erected the initial status of the planets and triggered subtle changes producing the bifurcation toward sterile, episodically habitable or definitively habitable worlds. Among these telluric phenomena, magmatism is one of the most important 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. Several melting routes that have been reviewed here can prevent degassing of C or S.

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

An analysis of these magmatic processes has been reviewed and whether they can account for the diversity of surficial conditions found in terrestrial planets.

Carbon and degassing under reduced conditions can build the first atmospheres. 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. For example, degassing at a 90 bar surface pressure can cut the amount of volatiles going into the atmosphere by more than 80%. Finally, the pressure of melting, that is to say the depth of melting, is controlled by the temperature of the mantle. It has a major effect of the fate of mantle volatile during partial melting: The deeper, the less volatile species enter the magma.

Our ability to calculate the outgassing of planetary mantles depends on our understanding of potential secular evolutions of the condition of melting. Core-mantle formation, then core separation occurred within less than 100 Million of years, immediately followed by a great mantle oxidation event: this event involved the shift in redox conditions from very reducing, that is to say metal iron is stable, to moderately oxidizing conditions, that is to say similar to the modern Earth's mantle; much later (2 Gyr after the solar system formation, the atmosphere became oxidized. Why is there a gap between the oxidation of the mantle and the atmosphere? The oxygen fugacity of volcanic gases is fundamental for this.

Stagnant melt versus diking depends on permeability, buoyancy, melt overpressure and gravity. The Earth's LVZ (a broad layer observed below the lithosphere) indicate a particular regime of melting where the melt is stagnant. These stagnant melts remain there for > 1 million of years without producing volcanoes and the associated degassing in the atmosphere. It remains unclear why this occurs and how the planetary degassing of the mantle is impacted by those stagnant melts; furthermore, what is there role of stagnant melts on the process allowing the shifting of plate remains a first order unknown.

There is a coupling between melting-diking-degassing, with feedbacks due to the atmospheric pressures and sub-aerial/marine situation. We need a new generation of models linking deep melting, melt extraction and melt degassing allowing us to connect the planetary interiors to their surficial conditions, in order to address to the role of magmatic processes in the development of habitable worlds.

4.2. Origin and evolution of the terrestrial nitrogen atmosphere by Manuel Scherf, from Austrian Academy of Sciences, AT

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. However, simulations of the terrestrial paleo-magnetosphere as well as of the solar wind induced atmospheric ion-pickup escape ~4 billion years ago (Scherf et al. 2017, Lichtenegger et al. 2010) are indicating that during the harsh conditions of the Hadean and early Archean eons a nitrogen-dominated atmosphere would not have been able to survive, but would have been eroded within a few million years due to the high EUV flux and the strong solar wind of the early Sun (Tu et al. 2015, Johnstone et al. 2015). In addition, these results are suggesting that the present-day nitrogen-dominated atmosphere has its origin during later stages of the geological history of the Earth, whereas for the late Hadean and early Archean, CO_2 can be considered as the dominating atmospheric constituent. Supported by several different studies of the ancient atmospheric composition and pressure, as well as of the different $^{14}N/^{15}N$ isotope fractionations of the terrestrial mantle and atmosphere, we are proposing that the nitrogen-dominated atmosphere started to build up during the Archean eon and slowly evolved from a low-pressure atmosphere via outgassing of N_2 into the present-day habitable environment. Important environmental conditions for this evolution and its interconnections have been discussed within this presentation. This includes the role of the paleo-magnetosphere and of plate tectonics; the evolution of the solar EUV flux, as well as the essential role of lifeforms on the sustainability of a nitrogen-dominated atmosphere.

Take away message:

- Simulations of the paleo-magnetosphere show a significantly smaller magnetosphere during the late Hadean than today.
- Due to the high EUV flux, a nitrogen-dominated atmosphere would have been extended above the magnetopause during that time, being susceptible to strong atmospheric escape (loss of the atmosphere within a few million years).
- This suggests a CO_2-dominated atmosphere during the late Hadean eon and a later outgassing of the nitrogen atmosphere.
- A slow built-up of the nitrogen atmosphere could have started during the early Archean (-3.5 -4 Ga ago), however a small fractionation of $^{14}N/^{15}N$ in the atmosphere suggest some atmospheric escape in the past.
- Importance of the evolution of the oxidation state and of plate tectonics.
- Role of life for the built-up and maintenance of the nitrogen-dominated atmosphere; importance of denitrification, which started ~2.7 Ga ago.
- Slow rotating Sun favorable against a moderate or even fast rotating Sun.

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4.3. Possible methane outgassing scenarios from clathrates on Mars and atmospheric transport modelling by Özgur Karatekin, from Royal Observatory of Belgium, BE

Methane has been shown to vary with location and time in the Martian atmosphere, with abundances of up to tens of parts-per-billion by volume (ppbv). Since methane is short-lived on geological time scales, its presence implies the existence of an active, current source of methane that is yet to be understood.

The destabilization of subsurface reservoirs of clathrate hydrate as a possible geological source of methane is investigated. Present-day maps of clathrate stability zone variations have been shown for clathrates trapping different fractions of methane. Then, a gas transport model is used to determine the CH_4 flux at the surface due to the diffusion of different plausible methane volumes released by clathrate hydrates at variable depths under the Martian surface. Finally, the transport of the released methane spike into the atmosphere is simulated using the PlanetWRF model with thermophysical properties of the soil with diffusion and advection kinds of fluxes. Observation show sudden flux of methane (impact, diffusion in fracture zones?). GCMs (General Circulation Model) have been used to model methane transport within the Martian atmosphere, considering different release locations, with different concentrations. From the observation, we can see that there are some regions matching the observations. They also looked at fluctuation over diurnal timescale. After a few days, the methane is completely diffused in the equatorial region. Compared to MSL measurements, short timescale release inside the Gale crater, we see that sometime the methane get high and then disappear. As a result, it is important to look at with time of the day we are looking, also the location where it is measured. The methane even released elsewhere can be observed. Mixing time in the atmosphere is pretty short. It is more specific for the Gale region.

Summary and conclusions:

- CH_4-rich clathrates are stable close to the surface.
- The beginning of HSZ (clathrate stable zone) is closer to the surface for high altitudes. At the equator, the HSZ is closer to the surface where Gamma Ray Spectrometer (MGS) data show higher hydrogen content near surface.
- The abundance of methane in clathrates and type of soil (geothermal conditions) control the depth of clathrate formation.
- Methane storage capacity of the early Martian cryosphere is sufficient to have stored large amount of methane. While the stability of such reservoirs depends on many factors that are poorly constrained, it is possible that such reservoirs have remained trapped at depth until the present day.
- The methane release from these reservoirs could explain transient CH_4 plumes that have been observed on the surface during the past years.
- By making use of a realistic emission scenario based on a subsurface methane transport model, we have been able to reproduce the observations acquired by Mumma et al. (2009). Unlike previous studies, we have tested different locations and performed simulations with point type transient emissions instead of a large source region.
- Methane behavior in the Martian atmosphere 14 sols after emission is on agreement with the observations (Mumma et al. 2009, Webster et al. 2015).
- Timing is very important for measurements from SAM (Sample Analysis at Mars) on MSL at Gale crater (daily variability with peaks).
- The source location does not need to match with the observation location; if CH_4 exists on Mars, SAM/MSL should be capable to detect; it does not matter where it comes from.
- TGO (The ExoMars Trace Gas Orbiter) will provide valuable measurements to understand the volatile reservoirs on Mars and particularly the sources and the sinks of methane.

4.4. The evolution of atmospheric composition on the early Earth (Review talk) by David Catling, from University of Washington, US

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. Atmospheric O_2 is tied to burial of organic carbon in the context of evolving global redox fluxes. Atmospheric oxidation rapidly removes CH_4, so pCH_4 inversely correlates with pO_2. Precambrian pN_2 would have also been affected by pO_2 because oxidative weathering of continental organics releases nitrate, which denitrifiers use to make N_2. In contrast, pCO_2 is more closely tied to climate and weathering.

Evolving O2, CH_4 and N_2 levels can be understood by considering global redox conservation. 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. Four key global redox fluxes describe the system and oxidized the surface environment by removing reductants: (1) an oxidizing flux caused by escape of hydrogen to space; (2) an oxidizing flux of O_2 associated with the long-term burial of organic carbon (or sulfide derived from sulfate); (3) the efficient consumption of O_2 by reducing gases and aqueous cations (combining subaerial volcanic and metamorphic gases, seafloor volcanism, and seafloor oxidation); and (4) an O_2 consumption flux in oxidative continental weathering. A model using these fluxes plausibly explains three states: anoxia with high CH_4 and low pN_2 before 2.4 Ga; an oxic but low- O_2 middle Proterozoic; and a high O_2, high pN_2 state in the Phanerozoic. Results indicate that mid-Proterozoic O_2 should have been buffered by geologic emissions of (seafloor) reductants, while a dominant O_2 sink from continental weathering characterizes only the Phanerozoic. Increasing Precambrian O_2 levels can also be linked to growth in pN_2.

The history of pCO_2 is constrained by the carbonate-silicate cycle including seafloor weathering (see abstract by Krissansen-Totton et al.). But pCO_2 is linked to redox evolution through global mean temperatures and thus CH_4 (greenhouse) levels.

The extent to which such atmospheric evolution applies to Earth-like exoplanets remains to be determined. But the key principles of redox conservation and crustal weathering sink for CO_2 ought to be universal, and so studying a different planet - the early Earth – provides some insight.

4.5. Comparative study of circulation regimes of terrestrial planets' atmospheres by Pedro Machado, from Institute for Space Sciences, PT

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.

Venus for example, is Earth's closest sibling but it has ended up with a radically different climate. Venus atmospheric science is thus increasingly important in an era in which we are trying to understand the divergent evolutionary outcomes for terrestrial planets, whether we are considering the future of our Earth or the habitability in other planetary systems.

A study based on large scale and small-scale processes going on the middle/upper atmosphere of Venus and Mars combining wind measurements and 3D model simulations has been shown.

Venus is a slowly rotating planet with a dense atmosphere. The mechanisms for the generation and maintenance of super-rotation are still unclear and no model has been able to successfully reproduce its circulation in decades (Lebonnois 2013). A proper monitoring of Venus winds is crucial towards a full understanding of this phenomenon. With this aim, we intend to conduct a synthesis effort that could provide important constraints on atmospheric models. In Venus's mesosphere (65-85 km), visible observations of Doppler shifts in solar Fraunhofer lines have provided the only Doppler wind measurements near the cloud tops in recent years (Machado et al. 2014, 2017). The atmosphere is studied using wind measurements based on VLT/UVES and CFHT/ESPaDOnS observations (around 70 km), wind measurements based on Akatsuki space probe data (and ESA's Venus Express archive data) with cloud tracking methods (from 48 km till 70 km), using an improved version of a cloud tracking tool based on phase-correlation between images. Venus lose its water in any case. There is a Y-shape feature in the atmosphere interpreted to be a wave. There is a new type of wave distorted by the winds in Venus' atmosphere. The atmosphere is so warm that we can see the clouds. Features change from one day to the other. Zonal and meridional winds can be determined using these observations.

This technique can be used on Mars when there is dust storm and the circulation can be followed. Of course, Jupiter and Saturn are also a target for these kinds of measurements from the ground.

The objective of this work is to help constrain the planetary atmospheric characterization, and to take a step forward in the comparative studies of terrestrial planets.

4.6. Robust constraints on the climate and ocean pH of the early Earth using a geological carbon cycle model from Joshua Krissansen-Totton, from University of Washington, US

Constraining surface conditions on the early Earth is an important prerequisite to understanding the long-term habitability of Earth-like planets. The geological carbon cycle must play a role in controlling Earth's climate and ocean pH on long timescales. Generally, a thermostat based on weathering of continental silicates is thought to buffer Earth's climate against changes in insolation. However, there is considerable uncertainty over the efficiency of this feedback, and so debate remains over the climate and ocean pH of the early Earth. Estimates of average Archean temperatures vary widely from below freezing to over 350 K. Ocean pH estimates similarly range from highly acidic to highly alkaline. Finally, there is uncertainty over the extent to which seafloor weathering acts as a carbon sink, moderating climate and buffering ocean pH. Previously, some authors have suggested that early seafloor weathering was so efficient that the Hadean and early Archean climates were characterized by widespread glaciation.

To better constrain surface conditions and the operation of these feedbacks, we applied a new geological carbon cycle model to all of Earth history. Our model tracks continental and seafloor weathering, outgassing, carbonate burial, and ocean chemistry. The latter enables the parameterization of seafloor weathering kinetics. The model has been validated over the Cenozoic and Mesozoic where abundant proxy data are available. To extend the model to the Precambrian we took a conservative approach by iterating over a broad range of assumptions about Earth's internal evolution, continental growth, biogenic enhancement of weathering, and the temperature/CO_2-sensitivity of weathering. Consequently, the uncertainties in our final model outputs are large, but they likely bound the true evolution of Earth's carbon cycle.

We find that the early Earth was probably temperate (270-310 K). The combined buffering effects of continental and seafloor weathering preclude hot Archean temperatures. This is true even for extreme scenarios with no Archean land because temperature-dependent seafloor weathering still buffers climate to temperate values. We also find that ocean pH evolved monotonically from 6.4-7.5 at 4.0 Ga to moderately alkaline modern values. Seafloor weathering is an important feedback, but not as efficient as previously assumed, and so it does not cause a Snowball early Earth. Our conclusions are robust to uncertainties in model parameters.

Take away message:

In terms of modeling of Cenozoic and Mesozoic:

- Long term climate sensitivity greater than last feedback estimates.
- Temperature dependence silicate weathering weaker than commonly supposed.
- Tectonic forcing important driver of C cycle.

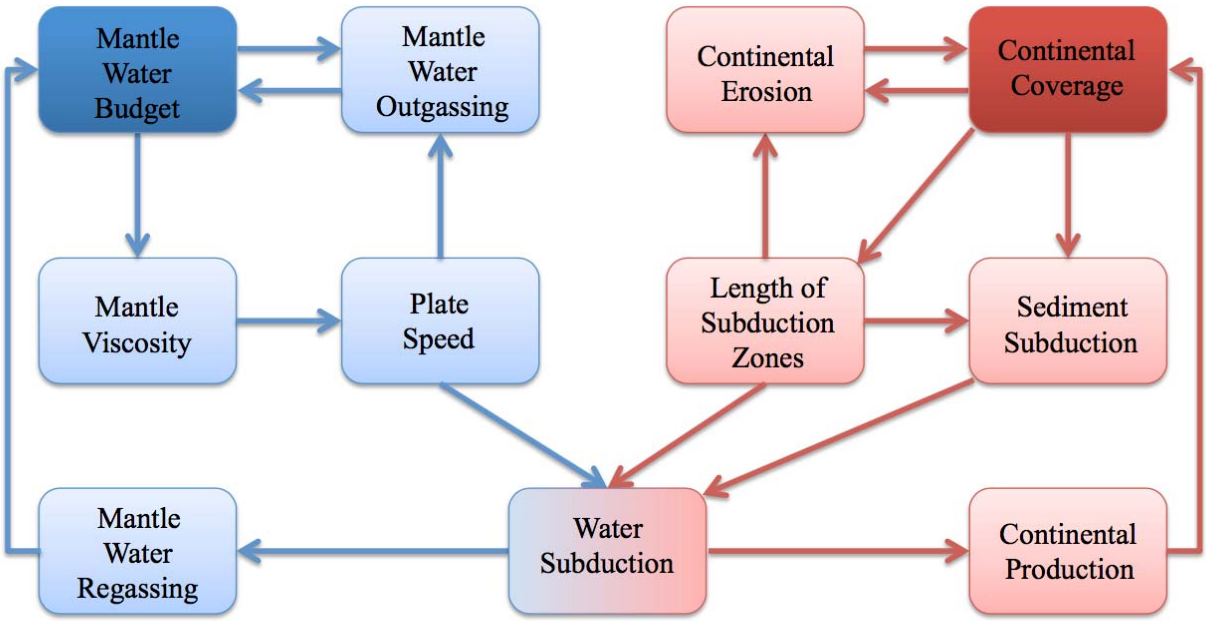
In terms of modeling of the entire Earth history:

- Archean seafloor C sink was important but less efficient than previously assumed; less methane required to keep early Earth warm.
- Early Earth was probably temperate (0°-50°).
- Ocean pH evolved from 6.4-7.1 at 4.0 Ga, to 6.6-7.6 at the GOE (Great Oxygenation Event, around 2.45 Ga ago), to slightly alkaline modern value.

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

5.1. Impact of life on feedbacks cycles in Earth's evolution (Keynote talk) by Dennis Höning, from German Aerospace Centre, DE

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 (Schwartzman and Volk, 1989). 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 (Lenton, 2002). 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 (see figure).



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. It thus becomes increasingly likely for the planet to evolve into a water-world scenario with hardly emerged continents (Höning and Spohn, 2016).

Long-term Earth system feedback cycles are considered from the surface to the deep interior where life acts as an important component in creating and sustaining a habitable environment. In addition, we discuss whether this concept could be used to search for life on planets beyond our solar system.

Take away message:

- Biological weathering contributes to stabilizing Earth's climate via the long-term carbonate-silicate cycle;
- Water subduction in sediments provides a link to Earth's interior evolution;
- Continental cycle and mantle water cycle can be described as a coupled system;
- Positive feedbacks in continental growth may cause bifurcation;
- Is the Earth at an unstable equilibrium point? This scenario could explain a small present-day rate of net continental growth
- Photosynthetic life enhances continental production via water-carrying sediments → effect on the fixed points!
- Rapid evolution of early life could have been crucial to keep Earth habitable (Gaian bottleneck) – but later evolutionary steps as well if bifurcation occurred in the more recent past!

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5.2. Microbial isotopic biosignatures and biomineralization to unveil biosphere-hydrosphere-geosphere interactions by Nolwenn Callac, from Stockholm University, SE

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. However, the role of the biotic and/or abiotic processes, involved in the evolution and shaping of these two elements cycle remains quite unexplored, as well through the geological time that in the various reservoirs, i.e. the hydrosphere and the geosphere. In order to investigate the biosphere-hydrosphere-geosphere interactions during the Early Earth, we have explored both the Fe and S chemistry, isotopic fractionation and mineral alterations in modern deep-sea hydrothermal systems that are considered as analogue of the Early Earth environments. Thus, we highlighted that entire S and Fe cycles can function at high temperature and under anaerobic conditions. We demonstrated that these biogeochemical cycles are linked, via both microbial metabolisms and/or chemical reactions between sulfide and iron compounds. Regarding the Fe isotopic signature, we have shown that it is quite difficult to distinguish the biotic Fe isotopic signature, linked to hydrothermal endemic thermophilic iron-reducer microorganisms, from the abiotic one. Consequently, the Fe isotopic signature as a proof of biosignature should be used with caution and other proxies has to be associated. Ours in situ colonization experiments, through colonization modules deployed in hydrothermal sediments, have revealed the presence of nano-crystals of pyrite and barite only in the biotic colonizers and associated to organic maters, while micro-crystals of pyrite and barite were observed in biotic and abiotic colonizers. These observations suggest that nano-crystals were directly formed or induced by microbial activities while micro-crystals were solely the result from inorganic processes. Consequently, the study of Early Earth analogues, might give some insights about how life had interacted with the geosphere and its evolution through geological time.

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

6.1. Seeding Life, Punctuating Evolution – How impact processes affected planetary evolution (Review talk) by Kai Wünnemann, from Museum of Natural History, DE

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 and will be summarized in the presentation.

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". There is a lot of works linking impacts and internal heating, either based on shock effects on material or heating scaling laws.

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 a fourth (4) 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.

By means of computer simulations of the Chicxulub impact event it will be discuss how these simulations constrain the ensuing catastrophic environmental effects of the KPg impact. Laboratory experiments and complementary numerical models provide constraints on the conditions required for the survival of bacteria during interplanetary transfer.

The presentation has summarized the current understanding how the planet's collision history affected the evolution of lithospheres, atmospheres, and biospheres.

6.2. Studying the extraterrestrial flux to Earth: what can we learn from the terrestrial impact cratering record? (Keynote talk), by Steven Goderis, from Vrije Universiteit Brussel, BE

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 [1]. Currently, approximately 190 terrestrial impact craters are known, ranging from 13.5 m to 160 km for the collapsed transient crater [2]. 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. There are about 200 large events identified on Earth. The rule of thumb concerning the dimension is the following: The size of the object → 20 x larger impact crater size.

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.

The crater on the Moon and Mars can also be used to further improve crater formation models. The destructive consequences of high-velocity impacts on the terrestrial ecosystem became apparent through the work of [3], who linked the Cretaceous-Paleogene (K-Pg) mass extinction event 66 million years ago to the impact of an asteroid larger than 10 km in diameter (cf. summary in [4]). To date, the K-Pg boundary event remains the only recognized mass extinction that coincides with a large impact event. Many more impacts of similar or larger size have occurred during Earth's history without a substantial influence on life, and often also without dramatic changes in the global geological record, or such links remain the subject of debate. The environmental outcome of impact events resulting from asteroid break-up events punctuating Earth's geologic past range from local to global scales. 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 [6]. At present, there is a project of drilling in the Chicxulub crater to better constrain all this. Anhydrite evaporated, 100000 megatons of sulfur were degassed and injected in the atmosphere as aerosol! A lot of dust in the atmosphere! Both induce darkness and inhibit the photosynthesis. Then cooling of the climate for decades! And of course extinction of a lot of species of animals.

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 [5].

Terrestrial impact record is very poor but they have punctuated Earth's geological past, with a link with extinction or other important changes. There has been periods of higher bombardments with respect to what we know today.

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6.3. Early large impacts and the evolution of Venus by Cedric Gillmann, from Royal Observatory of Belgium, BE

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.

We study how Late Veneer impacts modify the evolution of Venus and its atmosphere, using a coupled numerical simulation. We focus on volatile exchanges and their effects on surface conditions.

Mantle dynamics, volcanism and degassing processes lead to an input of gases in the atmosphere and are modeled using the StagYY mantle convection code. 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.

Large impacts are capable of contributing to (i) atmospheric escape, (ii) volatile replenishment and (iii) energy transfer to the mantle. We test various impactor compositions, impact parameters (velocity, location, size, and timing) and eroding power. Scenarios we tested are adapted from numerical stochastic simulations (Raymond et al., 2013). Impactor sizes are dominated by large bodies (R>500 km).

Erosion of the atmosphere by a few large impacts appears limited. Swarms of smaller more mass-effective impactors seem required for this effect to be significant. Large impactors have two main effects on the atmosphere. They can (i) create a large input of volatile from the melting they cause during the impact and through the volatiles they carry. This leads to an increase in atmosphere density and surface temperatures. However, early impacts can also (ii) deplete the mantle of Venus and (assuming strong early escape) ultimately remove volatiles from the system, leading to lower late degassing and lower surface temperatures. The competition between those effects depends on the time of the impact, which directly governs the strength of atmospheric losses.

The take away messages are:

- Erosion by large impacts do not seem to do much;
- The impact can bring a lot of volatile but wet projectiles seem too efficient;
- The solid planet is heavily affected by large impacts;
- Large impacts can efficiently deplete planetary mantles and make a planet dry;
- Important effects still needing to be incorporated: (i) swarms of small impacts (erosion dominates), (ii) rehydration of the mantle (tracking the volatiles).

6.4. Discussion

Discussion revolved around some specific consequences of impacts on the solid planet.

First came the question of the importance of ejectas that can wrap a large part of a planet in a warm insulating layer and affect the long-term thermal evolution of the mantle. It is however still unresolved what precise effect ejectas from large impacts could have: the mass of ejecta means compaction would occur and lead to a diminished porosity and lower insulating effect.

Next point discussed was the question of the origin of the Martian dichotomy. It was mentioned that at the current level of our knowledge, it is still unknown how it formed. Simple mantle dynamics can cause such a specific feature by single ridge convection for example (Keller et al., 2009). However, an early large impact, followed by magmatism near the impact location due to the crustal material emplaced by melting, has been shown to produce features comparable to those observed on Mars (Golabek et al., 2011). Both cited studies use the StagYY code to account for mantle dynamics in widely different setups.

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

7.1. Early Life Traces and Evolution, & Implications for Astrobiology (Keynote talk) by Emmanuelle Javaux, from University of Liège, BE

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, 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. This research also documents steps in biological and biochemical innovations, the emergence and rise of biological complexity, and their possible environmental and or ecological causes. Combining minimum ages of fossil biosignatures with molecular phylogeny 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 or metabolisms.

This keynote talk has presented examples from the Archean through the Proterozoic recording crucial steps in the evolution of life to illustrate the results and challenges of this multidisciplinary approach, and discuss implications for the search of extraterrestrial life. Cyanobacteria are important, as they have changed the atmosphere and the ocean chemistry. GEO occurred around 2.4 Ga ago and possibly some local effects already at around 3 Ga. We have fossils at 1.1 Ga and before. Other microbial mats in the muddy rock record at around 3.2 and 3.4 Ga old. Mud preserves them very 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. Favor preservation environment is mud.

Resolving the issues of signs and preservation is critical if we want to understand in which conditions life may originate (habitability), evolve, and what are the interactions between planet and life. These interactions leave traces or biosignatures that provide a rationale to tentatively define ways to look for life on Earth or in extraterrestrial environments. The future missions ESA EXOMARS 2020 and NASA MARS 2020 are now developed based on these early Earth approaches. On Mars, preservation in mud is possible but we need to have this mud rapidly preserved deep in the terrain in order to avoid the radiation effects.

7.2. Photodegradation of selected organics on Mars, by Inge Loes ten Kate, from Utrecht University, NL

At least as much as 2.4 10^6 kg of unaltered organic material is estimated to be delivered to the Martian surface each year. However, intense UV irradiation and the highly oxidizing and acidic nature of Martian soil cause degradation of organic compounds. First results were obtained with the recently developed PALLAS facility at Utrecht University. PALLAS, the Planetary Analogues Laboratory for Light, Atmosphere, and Surface Simulations, is a 50x50x50 cm stainless steel vacuum chamber, equipped with a turbo pump to create and maintain atmospheric pressure. This facility is specifically designed to simulate planetary and asteroid surface conditions to study the photocatalytic properties of relevant planetary minerals. Samples were placed on a cooling table in the beam spot of a solar simulator equipped with a water filter to remove residual heat (LOT-Oriel, 450 W UV enhanced Xe, 180-900 nm). Experiments were carried out at 20°C and -55°C in vacuum (10^{-7} mbar) and Mars-like atmospheric conditions (10 mbar CO_2) for 24-48 hours. Before and after exposure the samples were analyzed with Diffuse Reflectance Infrared Fourier Transform Spectroscopy (DRIFTS) and Raman Spectroscopy, enabling direct probing of the effects of the exposure to the Martian conditions, as the samples holders can be placed directly in the DRIFTS and the Raman. Our results tentatively show degradation of several compounds and preservation of others. Photocatalysis is a process known to effectively degrade organic compounds. Previous work has shown that several organic species can be photo-oxidized on very common minerals, such as olivine. Our results indicate that some minerals are more effective catalysts whereas others aid in the preservation of organic compounds. Furthermore, some of the compounds tested appear to be more stable than others. Further studies are underway to better understand the chemistry underlying these results.

7.3. Habitability of hyper-arid Atacama Desert soils as an analog for the search of life on Mars, by Alesandro Airo, from TU Berlin, DE

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. Can these limits be expanded on other solar system bodies such as Mars or Titan? 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 with respect to the adaptability of life as we know it. In a next step, we outline the range of possible environments for a diverse set of alien planets and moons, which we categorize according to Planetary Environment Types (PETs) to inform us about their potential habitability. Some of these types are present in our Solar System, others are thought to exist beyond our Solar System. At this time, our results are limited to Earth-type life, particularly with respect to the use of solvent (water) and energy source (light and chemical compounds).

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

8.1. The impact of the host star and of geophysical processes on the habitability of exoplanets (Review talk) by Lee Grenfell, from German Aerospace Centre, DE

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. 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. We review recent results of model simulations studying the atmosphere-interior-biosphere interaction as well as the planet-star interaction and their impact on habitability of exoplanets orbiting different types of stars (solar-like and cool M dwarf stars).

In particular, 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 is interesting to see what kind of spectrum we can get. It can show e.g. Ozone, OH, CH_4 evolutions, with their feedbacks, considering UV effects etc. It goes with the evolution of the star. The faint young Sun case is also considered in these simulations.

The author also discussed habitability indicators in the atmosphere of extrasolar planets and their detectability with future instruments.

8.2. Interpreting Spectra of Exoplanetary Atmospheres: A Review of Atmospheric Retrieval (Keynote talk), by Kevin Heng, from University of Bern, CH

The study of the atmospheres of exoplanets has come of age in the past decade. Astronomers have progressed rapidly from measuring the transit depths of close-in (fractions of an AU) gas giants (hot Jupiters) in broad wavebands to establishing spectrophotometry as a robust technique for inferring the presence of molecules in the atmospheres of transiting exoplanets with sizes down to that of Neptune’s. 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 devised techniques to direct image (i.e., photometrically separate the exoplanet from its star) the thermal emission from gas giants on orbits of tens to hundreds of AU, 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.

On the theoretical front, astrophysicists are borrowing and generalizing a technique from the Earth remote sensing and Solar System communities known as atmospheric retrieval: inferring the atmospheric chemistry and temperature-pressure profile from inverting the measured spectra. A key challenge is that we do not have in-situ measurements or high-resolution imaging for exoplanets, which necessitates that we invest our efforts into carefully understanding the physics and chemistry we are inserting into our retrieval models.

The author reviewed the progress of this subfield of exoplanetary science, starting from the first introduction of retrieval into our literature in 2009. He discussed a set of challenges associated, separately, with applying atmospheric retrieval to transiting and directly imaged exoplanets.

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.

First we need to retrieve the atmosphere given some spectra, how can we find parameters like chemistry of the atmosphere. The retrieve relies on opacities of molecules and chemistry and radiative transfer models. This is a successful technique applied in the solar system.

Even if you get precise data, you need to understand chemical abundances and degeneracies, which depend on the spectra (transmission, emission, imaged). With have degeneracies related to a lack of absolute normalization, some prior-dominated effects, and some unknowns like radius and gravity. Solutions can be found in e.g. the use of Gaussian priors. Also priors on radius and surface gravity are needed.

The author also used the HR 8799 system, which hosts four directly imaged gas giants with measured spectra, as a “real life” case study where atmospheric retrieval is applied to real data. Specifically, the elemental abundances of carbon and oxygen may be extracted from the measured spectra, which in turn allows us to infer the posterior distributions of the carbon-to-oxygen ratio and set constraints on the formation history of these exoplanets.

Finally, a look to the future was presented and the state of the art for identifying and detecting biosignature gases were discussed.

8.3. Habitability of Many Worlds and the Adaptability of Life on Earth, by Dirk Schulze-Makuch, from TU Berlin, DE

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. 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. Can these limits be expanded on other solar system bodies such as Mars or Titan? 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. In a next step, we outline the range of possible environments for a diverse set of alien planets and moons, which we categorize according to Planetary Environment Types (PETs) to inform us about their potential habitability. Some of these types are present in our Solar System, others are thought to exist beyond our Solar System. At this time, our results are limited to Earth-type life, particularly with respect to the use of solvent (water) and energy source (light and chemical compounds).

The landscape of life is very broad with temperature and water activity being the most restrictive parameters; the landscape of life as we do not know it may even be much broader.

8.4. Apatite geochemistry coming to the rescue for evaluation of Martian abiotic environment composition, by Ewa Slaby, from Polish Academy of Sciences, PL

Apatite from Martian meteorites is frequently used to show volatiles/fluid content in Martian mantle and crust. This mineral has structurally bonded OH, F and Cl. As a behavior of all of them is predictable during magma evolution, degassing, and partitioning into fluid, the data on apatite geochemistry may allow us to assign precisely its crystallization to particular environment and at the same time to recognize the environment chemistry. Especially the information about composition of crustal fluids circulating in Martian crust is important to diagnose the abiotic environment and the possibility of its transition to conditions conducive to life. To get relevant data on crystal structure and geochemistry each apatite domain needs careful examination. F-rich, however containing Cl and OH groups, apatite is consistent with crystallization from mafic magma. During degassing, Cl strongly partitions into the exsolved fluid, whereas F remains in the melt. Thus, apatite crystallizing from degassed melt is pure fluorapatite. Cl and OH rich apatite crystals are results of post-crystallization reaction with fluids. We present apatite case study from NWA 2975 Shergottite. Three types of apatite have been recognized: magmatic, crystallizing after degassing and apatite indicating influence of Cl-rich crust assimilation. The possibility of using data to show mantle/crust volatiles/fluid composition is shown. Magmatic apatite brought data on degree of Martian mantle hydration. The obtained data also allow us to verify the suitability of apatite in reconstruction of abiotic crustal environment.

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.

Other questions concerned the methodology, the ability to quantify water in the environment of Mars (mantle/crust).

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

9.1. The need for an ethics of planetary sustainability, by Andreas Losch, from University of Bern, CH

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 and I will extend it here, elaborating on a similar NASA initiative. This presentation (1) sketched the contemporary economic-political initiatives, which call for a special reflection of Earth's location in space, and then (2) discussed the meaning of the concept of sustainability in this context. Next, (3) related the discussion to the issue of planetary protection, (4) finally, presented a philosophical and theological perspective that seems particularly able to broach the issue of the multiple dimensions of sustainability in this context. This is the concept of constructive-critical realism.

See www.planetarysustainability.unibe.ch

All these questions are important when considering the Moon village or the Mars-One project. Maybe less Moon village as we know Moon cannot sustain life and there is no life.

9.2. Astrobiology and Society in Europe Today, by Klára Anna Čapová, from University of Durham, UK

There is a White Paper with the aim to explain the challenges and benefit of logy to the wider society in Europe with the purpose of paving the way for an EAI (European Astrobiology Institute).

This is written by lead authors on behalf of the WG5 on History and Philosophy of Astrobiology; the pre-final version of the joint Astrobiology and Society in Europe Today has been introduced. The talk gave a brief overview of the structure and contents of the latest version of the white paper, i.e. Version 5. During the talk, the societal implications of astrobiology research in the European context and the timely role of an organized initiative in astrobiology policy as well as astrobiology communication have been discussed.

This paper is also an advisement of astrobiology in Europe.

In December, they will have to have the final version. They need to have feedbacks from WG leaders and scientists as soon as we can.

If we would like to contribute, we can send an email. (k.a.capova@durham.ac.uk)

There are plans to publish it in a shorter version, but the white paper will be open access on line on a website later (the website of the COST action).

9.3. The role of communication in science and astrobiology, by Arianna Ricchiuti, from University of Bari, IT

"A good communication is made of 20% of what you know and 80% of what you feel about what you know."

Misinformation is the activity of spreading misleading and non-objective information in order to deceive someone's opinion about a person, a situation or a fact. Misinformation can be particularly dangerous in science. A great effort has been done and it is still going on by Italian scientists and communicators in order to suffocate the movement who states that vaccines cause autism. A lack of scientific education and false but easy-to-believe stories lead many parents not to vaccinate their children and exposing them to terrible diseases. That is why it is necessary to give people correct and reliable information about every field of science. Science communication plays a key role in order to fight against misinformation, but it can have other important roles.

First, to point out how useful scientific research can be even when it seems useless (like space exploration). Second, to make science something interesting, friendly and suitable for everyone; third, to make people understand scientists are firstly moved by passion, curiosity and the desire of knowledge. Not every single thing a scientist does is necessarily "useful" to someone or something. As astrobiologists, we want to study the origin and evolution of life in the universe and we want to find extra-terrestrial life. That is just because we are passionate, because we feel a connection with the universe.

The language used in science communication is essential and it must vary respect to the type of audience (children, public, and specialists) and event (birthday, conference, entertainment show). A communicator or a researcher should carefully choose the strategies to make his activity charming, so he can plan a power point presentation or take advantage of the full-dome technology of planetariums, which allows people to feel involved and carried away by the images. A Planetarium can be particularly suitable to talk about astrobiology, for example to represent how the Earth was when the first form of life emerged or to picture molecules and chemical reactions. In order to stay in close contact with people, a science communicator can use simple and common objects to represent difficult issues: a stone can become a meteorite and a little ball can become bacteria. This is very successful especially when we are dealing with kids. On the other side, some specific occasions require professional instruments like telescopes for astronomical observations.

Strategies for science communication: (1) pay attention to the language, (2) take care of the occasion, (3) you can use instrument, (4) you can run experiments in your presentation, (5) you should use common object in order to be close to your audience, also the people can picture what you show, (6) you are welcome to use a planetarium as the people are capture by the large images, (7) if you can do it, you can make joke, (8) use body language, even use sounds.

There are always three talks: (1) the one you prepare, (2) the one you give, and (3) the one you wish you had given.

How to deal with miscommunication: be really sure about what you say and be short and essential.

How can we describe the HZ, “surfable zone” (where you can do surf) and not where you have life. Rely on possible liquid water.

The issue of how we justify science is on the base of progress. Some do science for the results and discover the principle, some for the intellectual interest. One can point to many of these things to the public.

It is important as well to point out what we do not know and show how we can reach the knowledge.

General discussion

General discussions have led to discuss about the different themes and the group also discussed the future proposal for COST action.

To build the community is no more a target for future actions as we have already aggregated a lot of scientists interested; so we need to find a final “product(s)” which would be the point to target.

Five themes of large interest have been identified:

- Evolution of life and environment
- How does environment (star/planet) affect habitability
- Uninhabited habitable planets/moons/niches
- Preservation and evolution of tracers over time,
- Instrumentation for remote/in situ search for tracers

We will continue to use sessions of EGU etc. for inducing disciplinary meetings.

10. Posters

10.1. EMPA and LA ICP-MS studies of apatite crystals from Archean Barberton Greenstone Belt, by Łukasz Birski

The studies of Archean abiotic environments are crucial for understanding the origin of Life. The examinations of Archean apatite $Ca_{10}(PO_4)_6(OH,Cl,F)_2$, investigated as a source of information on volatiles on Early Earth, may help us understand how it happened. Unfortunately, since analyzed apatites are very old, with a long history of secondary alterations and transformations it is crucial to point out which of investigated apatite crystals preserved primordial signature of the environment of their origin.

Analyzed by LA ICP-MS and EMP samples from Barberton Greenstone Belt (3.5 – 3.2 Ga) can be divided into 3 groups. The first group is represented by unaltered apatite crystals of ultramafic origin. Predominantly these are Cl-enriched hydroxyapatites with Cl concentration of about 1 wt%. Normalized to chondrite profiles of REEs concentrations are relatively flat with slightly increasing concentrations of LREEs. The second group is represented by apatite crystals of sedimentary origin. EMP analyses revealed that these crystals are Cl-depleted hydroxy-fluorapatie with variable F:OH ratio. Their REEs profiles, normalized to chondrite, are flat with positive Eu anomaly. Last group is represented by hydrothermally altered apatite. It has to be noticed that apatite crystals from both sedimentary and ultramafic environments can be found in this group. EMP analyses show that they are definitely fluorapatite. Their REEs profiles present a wide range of shapes. Some are only LREEs depleted whereas others depleted in both, LREEs and HREEs. Moreover, in some cases crystals from a single sample can be divided into two populations basing on REE profiles.

Future research of apatite crystals of first group can give us information about the concentration and evolution of volatiles in Archean mantle. Investigations of second group can be used to examine to what extend apatite preserve primordial sedimentary signature of its origin and signature of secondary alterations.

10.2. Oxygen isotope composition of apatite as a tool for paleoenvironmental and astrobiological studies, by Alicja Giera, from Institute of Geological Sciences, Polish Academy of Sciences, Warsaw, Poland, and GFZ German Research Centre for Geosciences, Potsdam, Germany

Apatite $Ca_{10}(PO_4)_6(F,Cl,OH)_2$ is the most common phosphate mineral in geological environments and it is also the main component of bones and tooth enamel. The oxygen isotopic composition of biogenic apatite has been widely used for reconstructing marine paleotemperatures via measurements of the 18O/16O ratio in fossils (e.g. Joachimski et al. 2009). Even apatite reaching back to the ancient Barberton Greenstone Belt (3.2-3.5 Ga) in South Africa has proved useful for estimating the temperature of the Archaean ocean (Blake et al. 2010). Moreover, the 18O/16O ratio in apatite has been proposed as a potential biomarker for life on Mars (Greenwood et al. 2003). The determination of 18O/16O is commonly conducted using gas source mass spectrometry, which requires up to a few milligrams of sample material. In the case of very small samples, the in situ analysis by secondary ion mass spectrometry (SIMS) is a more suitable analytical tool, requiring under a nanogram of total sample mass. However, SIMS is hampered by the lack of homogeneous reference materials (RMs) required for quantitative measurements. Durango apatite from Mexico has been commonly used as a RM, but recent research has shown that it can have significant intra- and inter-crystalline variations in $\delta^{18}O$ up to 2 permil (Sun et al. 2016), rendering Durango of little use for SIMS calibration. The aim of the research we report here is to develop a suite of well-characterized, homogeneous reference materials for the measurements of $\delta^{18}O$ in apatite. We have tested 32 samples acquired from mineral collections using both isotopic (SIMS, GS-IRMS) and chemical methods (EPMA, SEM-EDS). Our goal is to characterize a set of apatite crystals with 0.1 permil repeatability of $^{18}O/^{16}O$ measurements that are available in quantities allowing us to provide this material to all laboratories, making the data they generate traceable.

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10.3. Ground and space based cloud-top wind velocities using CFHT/ESPaDOnS (Doppler velocimetry) and VEx/VIRTIS (cloud tracking) coordinated measurements, by Ruben Gonçalves, from Institute of Astrophysics and Space Sciences, Portugal

We present wind velocity results based in the measurements of the horizontal wind field at the cloud top level of the atmosphere of Venus, near 70 km altitude in the visible range on the dayside. The purpose is to characterize the zonal and meridional wind latitudinal behavior and profiles on hour and day timescales. The technique developed over the last decade [Machado et al. 2017] is based on solar lines Doppler velocity in the light scattered by cloud top particles in motion. The study was undergone in coordination with ESA's Venus Express cloud tracking measurements. Our 2014 observations focused on the wind field at latitudes 60°S-60°N, while VEx/VIRTIS privileged southern latitudes poleward of 45°S in search for zonal and meridional wind circulation patterns.

ESPaDOnS and the sequential technique of visible Doppler velocimetry has proven a reference technique to measure instantaneous winds. These measurements are necessary to help validating Global Circulation Models (GCMs), and to extend the temporal coverage of available datasets. The ground-based observations in the base of this project are critical in their complementarity with Venus Express data, which was recently decommissioned, and they are expected to play the same role during the ongoing Akatsuki mission.

Our analysis technique shows unambiguous characterization of the zonal wind latitudinal, local time profile and its temporal variability. We will also present a latitudinal profile of the meridional wind measured along both hemispheres, in the mid-latitudes range.

10.4. An analysis of the stationary points of the [C_6, H_4, N]- anionic potential energy surface, from Jan Hrušák, from Institute of Physical Chemistry, Academy of Sciences of the Czech Republic

The electron spectrometer (ELS) part of the Cassini plasma spectrometer (CAPS) on board the Cassini spacecraft detected heavy negative ions, long chained N containing hydrocarbons, in the deep (<1400 km) ionosphere of Titan [1,2]. An unexpected feature of the negative ions was their notably high mass (up to ~ 14 000 amu/q), while the positive ions were detected up to 350 amu/q. Vuitton et al. [3] have theoretically investigated the formation mechanisms for negative ions at Titan based on laboratory studies. They conclude that dissociative electron attachment to neutral molecules (mainly HCN) leads to the formation of negative ions with the main ions being CN- and C_3N-. Further, it is proposed that these negative ions are precursors to the aerosols observed at lower altitudes in Titan's atmosphere. In the present study we aim on the description of all the relevant stationary points of the [C6, H4, N]- anionic potential energy surface (PES) with the ultimate goal to understand the entire

CC-CN- + CH_3-CC-H → [C_6, H_4, N - intermediates]- → fragments / products reaction.

The relative stabilities were calculated at the CCSD(T)/aug-cc-PVQZ//MP2/aug-cc- PVTZ level of theory using the GAUSSIAN09 program package. MP2/aug-cc-PVTZ calculated harmonic frequencies were used for characterization of the minima, the corresponding transition states, and the reaction products. In order to maintain the immense complexity of these calculations the [C6, H4, N]- PES, which is very rich on stationary points (416 identified and characterized so far), was divided into subsections of chemically reasonable molecular patterns. The starting addition reactions are

CC-CN- + CH_3-CC-H → NC-CC-C(CH)CH_3- → CC-CN-C(CH)CH_3- → HC-C_4-CH_3-

These pathways were investigated separately including all the possible fragmentation channels. The sizable electron affinity of [C_6, H_4, N]- allows very rich anionic chemistry. Surprisingly, the cyclic CH_3-C_4H–CN- and CH_2-C_4H_2-CN- intermediates were found to play a key role in the reactions. The overall energetics will be rationalized in terms of these different molecular families and compared with the results of energy resolved mass spectrometry experiments.

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10.5. Cold and thin but liquid - microscopic water and its habitability aspects on Mars, by Akos Kereszturi, from Research Centre for Astronomy and Earth Sciences, Budapest, Hungary

Based on theoretical argumentation and some observations, microscopic liquid brines could be present on Mars. The candidate minerals (like perchlorates and chlorides) might produce liquid by deliquescence during nighttime hours. Based on climate model computations and orbital humidity observations at most (but not all) past missions' landing sites, microscopic brine could have emerged ephemerally. Analyzing the conditions by climate model at ExoMars rover's primary landing site at Oxia Planum, the best annual period based is found to be between Ls 115–225, and (in) at Local Time 2–5, after midnight; while using REMS data (meteorology station onboard Curiosity) two short periods centered at Ls 20 and 270 are plausible candidates as RH maximizes that time.

Although such liquid has extreme characteristics, its relevance for astrobiology should be evaluated, especially regarding water trapping issues, and its emergence under past climates that differ from the current one because of the tilt of the rotational axis. The existence of such liquid will be detected for the first time by the HABIT instrument, which is located onboard the ExoMars rover. This instrument will analyze several habitability related issues, including humidity, the potential role of regolith on daily and annual H2O migration, the emergence of liquid water on hygroscopic minerals and UV radiation. Among these issues, the characteristics of nighttime liquid water will be overviewed and presented, supported by the COOP-NN-116927 project of NKFIH.

10.6. Cycles of the landscape genesis on Moon and the evolution of crater landscapes, by Serhii Kyryliuk, from Yuriy Fedkovych Chernivtsi National University, Ukraine

The study deals with the exploration of landscape structure of the lunar impact-explosion craters and its evolution using a morphometric analysis. The scheme of cycles of landscape genesis on Moon in response to the main geological periods (Pre-Nectarian, Nectarian, Imbrian, Eratosthenian, and Copernican) is suggested. The scheme has two levels: (1) morphostructural level reflects the formation of global holistic parts of the Moon landscape sphere formed in the result of the complex and continuous interaction of the landscape factors: bombarding of lunar surface by small bodies together with supplementary geodynamical processes that played a key role in the mega-relief structures; (2) morphostructural level concerns the establishment of the characteristic landscape features within the structural elements of Moon under the influence of weathering processes.

The obtained landscape and morphometric models of lunar craters of basic Moon geologic periods (Pomortsev (Dubiago P), Yerkes, Picard and Menelaus) demonstrate the level of evolution of the main Moon landscape types. To get the comparative morphometric indices determinative of the evolution moment, standard deviation is applied. The original axiomatic concept was used to build landscape models. The concept is aimed at the generation of the unified scheme of search for the surface elementary units and the following classification and interpretation. The application of axiomatic concept in such a way contributes to the classic landscape theory while enables landscape modeling without the contact with the natural body. The concept is significant for the case taking into account the simplicity of the Moon surface. The model contains three positions: 1) the surface image is stable or invariant with stable peculiarities of geometric figures and the formed knots on the surface; 2) landscape properties are seen separately from the geometric form of the surface that involves transition from specific to abstract; 3) elementary form is identified with elementary geometric figures (circle, square, and triangle) that leads to distinguishing invariants and its knots. The holistic images – geosystems are possible to reproduce while moving the figures in the space. According to the theory of symmetry, the number of such movements is rather limited that contributes to the rapid detection of all the groups of movements and formation of its combinations. Accordingly, the scheme of the impact-explosion craters' landscape structure and its evolution on the basis of landscape models is produced.

10.7. Earth and Venus: Planetary evolution and habitability, by Pauli Laine, from University of Jyvaskyla

In our Solar System Earth and Venus are very similar at planetary level. Venus has sometimes even named Earth's twin because they both have similar size, density, surface composition and have cloudy atmosphere. There are also some differences between these planets. Venus is about 30% closer the Sun than Earth. Venus has retrograde rotation (opposite to Earth's) of 243 days, longer than its's orbital period, 225 days. The most striking difference is the atmosphere, 90 times denser than Earth, and it contains 96.5% CO_2, compared to 0.04% on Earth. These planets' orbits are within the habitable zone (for the existence of liquid water). What caused these two planets to evolve very differently? Could Venus have evolved to more Earth-like state? Could Earth end up to similar state that Venus is today? This presentation will review these important questions in the light of astrobiology and Earth's future.

10.8. Exo-Kuiper belts and water deliverable to planets, by Jean-Francois Lestrade, from Observatoire de Paris - CNRS

The Far-IR Observatories Herschel and Spitzer have discovered a few hundreds exo-Kuiper belts around main sequence stars in the solar neighborhood and the total masses of their icy planetesimals have been modelled. A few have been angularly resolved and their radii directly measured. In addition, a few exo-asteroidal belts are known. The ice and hydrated minerals of the planetesimals provide a reservoir of water deliverable to the inner planetary of the system. We study how star encounters, in the early evolution phase of these systems when they are still embedded in the open cluster of their birth, can trigger comet showers to deliver water to the planets.

10.9. Learning the limits of Earth life, by Julie Nekola Novakova, from Department of Geophysics, Faculty of Mathematics and Physics, Charles University

Extremophile organisms provide a valuable insight into life's adaptations on various conditions, indispensable for evolutionary biology, biotechnology, astrobiology and many other fields. They provide us with the only reasonable anchor of how to assess habitability of other celestial objects. However, for many of them, we only know their limits in a few dimensions of all the possibilities within environmental conditions, which could cloud our judgment in estimating that a given environment is habitable. For example, we know of several hundred halophiles from various taxa, but for most of them, we do not possess the knowledge of their tolerance toward radiation (let alone different types of radiation) and temperature changes (while many halophiles are tolerant either toward cold, or hot conditions, less is known about the full range of most of them). These would be of great benefit e.g. for estimating the habitability of environments on Mars (where low water availability, high salt activity, radiation, low temperatures and substantial temperature changes play a role), or the risks of its contamination by our spacefaring activities.

For all fields connected to extremophiles, but astrobiology in particular, it would be desirable to know various extremophiles' limits in terms of all dimensions of the "environmental space" (e.g. temperature, salinity, acidity/alkalinity, metal content, biogenic elements' availability, pressure, radiation tolerance, desiccation tolerance). Most environments outside of Earth considered as potentially habitable (some areas of Mars, subsurface oceans of icy moons, cloud deck of Venus, "deep hot biosphere" of Earth and perhaps other objects) would require polyextremophile life from our point of view. For most tested species, however, we know limits only in one or two dimensions.

We are working on an educational brochure that could be used in schools or children's science courses. It will introduce the topic of extremophiles in general and specific examples, accompanied by colored ink illustrations, and highlight the question of search for life in space and its challenges. A draft of the brochure will be available by the poster. It will be prepared in English and Czech. If successful, it could be accompanied by more educational materials including interactive ones. By learning the limits of Earth life, we can promote more in-depth knowledge about Earth's environments and history and other celestial bodies' geology, and we can also make more educated guesses about the chances of life elsewhere, which is important for both research and outreach.

10.10. Young Enceladus: Implications for Habitability, by Tomas Petrasek, from Charles University, Prague

Studies of the Saturn system have recently suggested a tantalizing possibility that some of its moons, including the ocean-bearing Enceladus, are not primordial (4.6 Ga old), but formed much later (Asphaug and Reufer, 2013). They probably post-date the Late Heavy Bombardment (Movshovitz et al., 2015), and perhaps accreted as late as 0.1 - 1 Ga ago (Ćuk et al., 2016). This scenario perhaps makes it easier to explain the amount of energy released by the South Polar Terrain on Enceladus, but also has consequences for astrobiological potential of this body.

In our poster, we will estimate the consequences of recent formation in several domains, including the availability of energy from accretion, tides, radioactivity and chemical reactions, the challenge of fast origin of life and stability of the environment.

We suggest that the recent formation of Enceladus should not make it less promising for astrobiological exploration - even if life did not arise there (yet), it may offer us a glimpse into the very process of biogenesis. In the future, exploration of Enceladus (as well as the other, presumably older ocean worlds) may put meaningful constraints on the theories of life origin and the timing of the process.

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11. Additional information

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11.2. Further information

- Number of participants: 68
- Number of participants of Inclusiveness states: 25
- Number of female participants: 23
- Number of male participants: 45
- Number of early career scientists: 18
- Participants from Industry: 0
- Amateur Participants: 0
- Participants from outside Europe: 3