Orig Life Evol Biosph
DOI 10.1007/s11084-016-9488-z

ASTROBIOLOGY

PLANET TOPERS: Planets, Tracing the Transfer, Origin, Preservation, and Evolution of their ReservoirS

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Received: 15 September 2015 / Accepted: 21 January 2016

Abstract The Interuniversity Attraction Pole (IAP) 'PLANET TOPERS' (Planets: Tracing the Transfer, Origin, Preservation, and Evolution of their Reservoirs) addresses the fundamental understanding of the thermal and compositional evolution of the different reservoirs of planetary bodies (core, mantle, crust, atmosphere, hydrosphere, cryosphere, and space)

Paper presented at the conference: Habitability in the Universe: From the Early Earth to Exoplanets 22–27 March 2015, Porto, Portugal

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Published online: 23 June 2016

considering interactions and feedback mechanisms. Here we present the first results after 2 years of project work.

Keywords Habitability · Planet evolution · Impacts · Mantle overturn · Atmosphere evolution · Interior evolution

Objectives of Planet TOPERS

The evolution of planets is driven by the composition, structure, and thermal state of their internal core, mantle, lithosphere, crust, and by interactions with a possible ocean and atmosphere. The Interuniversity Attraction Pole (IAP) 'PLANET TOPERS' (Planets: Tracing the Transfer, Origin, Preservation, and Evolution of their ReservoirS) addresses the fundamental understanding of the relationships and interactions between those different planetary reservoirs and their evolution through time. It aims at bringing further insight into the origin and sustainability of life on planets, including Earth. See Fig. 1.

The proposed interdisciplinary approach applied in this project goes beyond that of current studies in Earth-System and Planetary Sciences and/or Astronomy by encompassing the entire planet from the upper atmosphere to the deep interior in the frame of the study of its habitability. The planetary bodies that are studied include, beside the Earth, a whole range of rocky bodies in the Solar System (and beyond): such as Earth-like planets, natural satellites, and undifferentiated asteroids.

Particular attention is devoted to Mars, but also to planets and satellites possessing an atmosphere (Earth, Mars, Venus, and Titan) or a subsurface ocean (e.g., Europa, Ganymede), as they are the best candidates for hosting life. The IAP 'PLANET TOPERS' addresses four main themes: (1) the interaction between the interior and the atmosphere, (2) the interaction between the atmosphere and space, (3) the identification of preserved life tracers and interaction of life with planetary evolution, and (4) the accretion and evolution of planets. The four themes are integrated into a comparative history of habitability conditions for Mars, Earth, and Venus.

The research program builds on, refines, and couples models of the individual reservoirs developed by the different authors of the paper. It also integrates new results of planetary geodesy – probing the deep interior, of atmosphere remote sensing, laboratory studies of meteorite samples, and observations of traces of life in past and present extreme conditions. The search for biomarkers and traces of life on early Earth serves as a case study to refine techniques allowing to detect potential habitats and possible life on other planets. A strong emphasis is also placed on impact processes, an obvious shaper of planetary evolution, and on meteorites that document the early Solar System evolution and bear witness to the geological

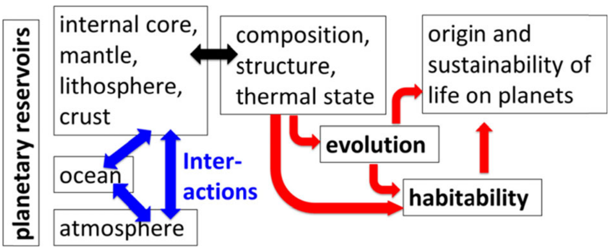

Fig. 1 Sketch on the themes involved in Planet TOPERS. Note that this sketch is done for all terrestrial planets including the Earth

processes taking place on other planetary bodies. The proposed research also relies on spectroscopic and isotopic laboratory measurements, geochemical analytical developments, and theoretical calculations to determine reference parameters and to unravel reaction mechanisms, allowing the optimal retrieval of information from observation data, and providing a deeper insight into the chemistry, physics, and dynamics of atmospheres and rocky materials.

The research carried out by the IAP is organized around 7 institutes (see authorship) with the following objectives:

- To improve our understanding of the thermal and compositional evolution of the different reservoirs (core, mantle, crust, hydrosphere, cryosphere, atmosphere, (and space)) considering interactions and feedback mechanisms;
- To investigate the chronology of differentiation processes, the onset conditions of plate tectonics and the recycling of the crust and their implications for the early thermal and compositional evolution of a planet;
- To examine the role of the impacts of meteorites and comets in the atmospheric evolution of planets, leading to the depletion and replenishment of the atmosphere or possibly even changing the magnetic field;
- To determine the observational constraints related to meteorites, in order to better understand the impact processes and impact fluxes as a function of time;
- To identify preserved signatures of early life and to understand the interactions through time between life and geochemical reservoirs; to search for traces of life, with early Earth as a case study;
- To perform a detailed comparison of the habitability of Mars, Earth, and Venus, based on the integrated analysis of interacting reservoirs;
- To develop a more general understanding of how geophysical factors influence the habitability of planets and moons, including exoplanets.

The IAP network involves teams combining different but highly complementary expertise. The partners belong to two Belgian federal institutions and four Belgian universities, and the project networks with the "Planetary Evolution and Life" programme of the German Aerospace Center DLR and the Priority Programme "The first ten million years of the Solar System" of the Deutsche Forschungsgemeinschaft DFG, some results of which are included in this report (e.g., 1, 2, 5, and 12 below). The Interuniversity Attraction Pole (IAP) 'PLANET TOPERS' gathers existing and internationally recognized expertise in planetary sciences, geobiology, cosmo/geochemistry, and analytical and physical chemistry, with the aim of establishing a solid interdisciplinary network infrastructure in Belgium.

Of prime interest in terms of global system evolution are the early state of Mars, Venus, and Earth. Though the conditions on these planets were likely similar soon after their formation, their histories have diverged about 4 billion years ago. The reason for these differences is addressed through comparative studies with other rocky bodies that from the start followed a different evolutionary pathway, such as Mercury, the moons or the small rocky bodies in the asteroid belt.

As the research strategy mainly focuses on unraveling and understanding the mechanisms and exchanges between the various planetary reservoirs, specific methods will be developed to boost internal collaborations, e.g. by putting the emphasis, through PhD and Postdoctoral research topics, on the interaction between reservoirs, in a trans-disciplinary approach between teams. In cooperation and full synergy with the foreign partner, the goal is to evolve into an excellence center in planetology, astrobiology and habitability at the international level. Determining the possibility and limitations of extraterrestrial life is of fundamental importance to mankind with profound implications, both practical and philosophical. By evaluating the interactions between planetary evolution and life on such a large scale, the PLANET TOPERS project puts the evolution of our home planet (even the current anthropogenic effects) into perspective.

Main Results

Accretion Phase, Planetary Embryos, Volatiles, Meteorites

Compositions of meteorites and morphological features of asteroid surfaces indicate that partial melting and differentiation were common processes in the early Solar System planetesimals, a particular focus of work in the DFG programme. Although it is suggested that differentiated planetesimals are the building blocks of planets, the differentiation of such small bodies is poorly understood. Numerical simulations have been conducted to investigate the differentiation and core formation processes in accreting planetesimals when considering the contribution of short-lived nuclides like ^{26}Al and ^{60}Fe, effects of sintering, melt transport via porous flow and radiogenic heat source redistribution due to melting and differentiation (Neumann et al. 2012). Our results show that differentiation of planetesimals cannot be assumed instantaneously but strongly depends on the formation time, accretion duration and accretion law. Thus the interior of rocky planetesimals varies from the most evolved structure, in which an iron core exists below a silicate mantle covered by a basaltic crust, through a structure in which a small iron core and a thin silicate mantle are covered by undifferentiated and sintered material to a structure consisting only of undifferentiated and unsintered regolith. While an evolved interior structure, with an iron rich core, a silicate mantle and a basaltic crust, is the most likely scenario for the asteroid 4Vesta (Neumann et al. 2014a), 21Lutetia instead, has potentially experienced little differentiation with an interior compacted by sintering below a porous layer (Neumann et al. 2013), and for smaller km-size asteroids even wide-spread sintering is less likely (Neumann et al. 2014b). In addition, planetesimals consisting of ice and rock could have undergone water-rock differentiation as it is suggested by the observations of 4 Ceres as well as by numerical studies (Neumann et al. 2015).

Mantle Overturn, Stagnant Lid, Early Dynamics, Volatiles, Meteorites

The various and intense energy sources involved in the early stages of planetary formation, such as kinetic energy of accretion, decay of short-lived radiogenics, release of gravitational potential energy upon core formation, and tidal effects, are thought to have caused partial or possibly entire melting of the mantle of terrestrial planets and moons (see Plesa et al. 2013; Plesa and Breuer 2014; Tosi et al. 2013). Global or local liquid magma oceans could thus have formed, whose solidification upon planetary cooling could have exerted a significant impact on the differentiation and subsequent evolution of the interior of terrestrial bodies (see Debaille et al. 2008, 2009; Mezger et al. 2013). The solidification of such magma oceans controls the initial compositional stratification of the solid mantle, which, in turn, can play an important role in shaping the earliest forms of mantle convection and surface tectonics (see Plesa et al. 2014a, b). Upon cooling, the liquid magma ocean starts to freeze from the core-mantle boundary to the surface due to the steeper slope of the mantle adiabat compared to the slope of the solidus. The crystallization of such magma ocean is a complex process, most likely affected by the dynamics in both the liquid magma ocean and the solid cumulates. Often simplified solidification scenarios are considered, in which dynamic effects are neglected and a gravitationally unstable mantle is assumed to result, with dense cumulates being produced close to the surface due to iron enrichment in the residual liquid. Applying this simplified scenario to e.g. Mars poses problems in explaining the subsequent thermochemical evolution of the planet. The chemical stratification of the mantle as a result of the magma ocean crystallization and accompanying overturn (i.e. the process during which an unstable mantle stratification dynamically rearrange – one also finds in the literature an overturn arising when the mantle lower layer becomes less dense than the upper layer and when the two layers reverse positions rapidly) results in a stable configuration, which suppresses thermal convection and is at odds with long-lasting volcanism and sampling of geochemical reservoirs within the Martian mantle (Plesa et al. 2014b, Tosi et al. 2013). Hence, our results imply that a more complex crystallization sequence must have taken place in order to satisfy constraints derived from laboratory studies of meteorites, planetary mission data and observations. Recent results by Maurice et al. (2015) suggest that, even for a rapidly cooling liquid magma ocean, solid-state convection may occur prior to complete crystallization of the mantle. This finding can have important consequences for the initial distribution of compositional heterogeneities generated through the magma ocean crystallization and thus for the subsequent planetary evolution. Among all meteorites, achondrites provide clues about the various styles of differentiation that led to stratified, telluric-style terrestrial planets with cores, mantles and crusts. These include the sources of iron meteorites (McKibbin and Claeys 2014), basaltic crusts, the latter of which probably includes one of the largest asteroids, or dwarf planets, Vesta (Hublet et al., manuscript in preparation) and potential links between chondritic starting materials and achondritic products (Goderis et al. 2015; Van Roosbroek et al. 2015).

Plate Tectonics Onset, Stagnant Lid, Crust Formation, and their Role on Convection/Thermal History/Evolution or Vice Versa

In order to understand how Earth's surface might have evolved with time, we have examined the initiation of plate tectonics and the possible formation of continents on an Earth-like planet. Plate tectonics and continents seem to influence the likelihood of a planet to harbor life, and both are strongly influenced by the planetary interior (e.g. mantle temperature and rheology) and surface conditions (e.g. stabilizing effect of continents, atmospheric temperature, see Noack and Breuer 2013, 2014; Noack et al. 2014; Gillmann and Tackley 2014). We have investigated the parameters influencing the likelihood of plate tectonics and continent formation using a numerical code. We have shown that the formation of continents may start very early in Earth's evolution. Our simulations suggest that the first continental crust may have formed at diverging basaltic plate boundaries (similar to the present-day felsic crust formation at Iceland), and not by re-melting of subducted oceanic crust (Noack et al. 2014). In this scenario, subduction of the plates (a necessary process for our understanding of plate tectonics) does not occur this early, but initiates at a later time at the boundaries of the early-formed felsic crust. This result corroborates geochemical evidences that indicate that modern plate tectonics characterized by continuous subduction likely initiated around 2.7–3 Ga ago (Debaille et al. 2013). On the other hand, evidence for oceanic plateaus that could have been the nuclei of continental crust, has been found around 2.8 Ga ago in the West African Craton (El Atrassi et al. 2015). Those studies show that subduction may not be needed for generating continental crust.

Plate tectonics as on Earth may be limited by several factors and may be considered as being not a common mechanism on Earth-like planets. Numerical simulations suggest that high surface temperatures as on Venus inhibit plate tectonics (Noack et al. 2012; Gillmann and Tackley 2014), small planet masses lead to fast initial cooling and thick lithospheres that are unlikely to fracture (Noack and Breuer 2014), as can be seen for example for Mars and the Moon, and the interior structure of a planet furthermore influences the likelihood to initiate plate tectonics (Noack et al. 2014), where the optimal core size for plate tectonics initiation seems to be slightly larger than on Earth. The question, if plate tectonics can occur on large-massive super Earths, has been addressed manifold in the literature, with different results obtained. It has been suggested that plate tectonics on super-Earths is either less likely than on Earth (O'Neill and Lenardic 2007), more likely (Valencia et al. 2007) or equally likely compared to Earth and depending rather on surface water (Korenaga 2010). Our simulations provide the same range of possible trends, depending mostly on the assumptions on the initial mantle temperature and the mantle rheology including the water content (Noack and Breuer 2014; Stamenkovic and Breuer 2014), where large-massive planets with high interior temperatures seem less likely to initiate plate tectonics compared to Earth. It must be mentioned, however, that additional external and internal processes, like large impacts, as well as melt percolation through the lithosphere, not included in our model, may change the scenarios by locally lowering the plastic strength which could in turn introduce lid failure and surface mobilization.

Asteroid and Comet Impacts (and their Timing), Atmosphere Erosion and Loss/Gain of Volatiles, Energy Transmission to Mantle, Mantle Convection/Thermal History/Evolution, Degassing, Volcanism, Atmosphere Evolution, Surface Temperature

We investigated the history of the atmosphere and surface conditions on Venus and other terrestrial planets. Our main focuses are mechanisms that deplete or replenish the atmosphere: volcanic degassing, atmospheric (mainly hydrodynamic) escape (see Lammer et al. 2012) and impacts (volatile delivery as well as atmospheric loss). We have considered long term evolution through a coupled mantle/atmosphere model (see Gillmann and Tackley 2014; Gillmann et al. 2016). Atmosphere erosion by single giant impacts has been shown to have a marginal effect on long term evolution of a terrestrial planet due to the minor loss of volatiles it generates. Indeed, that loss is usually compensated by (i) volatiles brought by the impactor and (ii) volatiles released into the atmosphere by melting of the target body. In comparison, those sources of volatiles do have lasting consequences on the history of a Venus-like planet. On the other hand, it must be noted that multiple smaller impacts could favor erosion (Schlichting et al. 2015). The competition between the two effects needs further investigations. Giant impacts are also able to modify the convection patterns of a terrestrial planet on the millions to billions of years timescale: impactors larger than 100 km radius generate a thermal anomaly that can produce sustained volcanism at the surface of the planet, large scale melting of the mantle leading to metal/silicate separation in previously undifferentiated bodies (McKibbin and Claeys 2014; Goderis et al. 2015; Van Roosbroek et al. 2015), as well as volatile depletion and early crust formation, as in the dwarf planet Vesta (Hublet et al., manuscript in preparation).

Role of Water and Heat Piping on Volcanism/Thermal Evolution or Vice Versa

The amount of water present in the mantle of terrestrial bodies influences the interior dynamics and melting as both the rheology and the melting temperature of mantle rocks strongly depend on water content. In turn partial melting of the mantle and melt extraction considerably affects the water budget of the interior through redistribution and outgassing of volatiles during the melting process. Heat transport associated with the rapid extrusion of large amounts of melt, the so-called heat-piping mechanism, is an effective way to transport thermal energy and volatiles from the melt-region to the planetary surface. It may have played an important role in the Earth's earliest evolution prior to the onset of plate tectonics and is likely the primary mechanism through which Jupiter's moon Io loses its tidally generated heat, leading to a present-day heat flux about 40 times higher than the Earth's average heat flux. Our results show that heat-pipe effects are most pronounced in the early stages of the thermal evolution when large amounts of melt are produced, resulting in an increased stagnant-lid thickness while the global average mantle temperature decreases. Intrusive volcanism reduces the cooling effect obtained with the heat-pipe mechanism, where the entire melt is placed at the surface (Prinz et al. 2014). If part of the generated melt remains trapped in the lithosphere, we observe a temperature increase in this region and hence a thinner stagnant lid. Comparing thermal evolution models with and without considering heat-pipe mechanisms for Mars- and Mercury-like parameters, our results show that efficient cooling due to heat-pipe melt transport levels of after about 3 Gyr, when the amount of melting is negligible. Nevertheless, heat-piping significantly reduces the amount of produced crust by efficiently cooling the mantle through heat transport by melt extraction (Plesa et al. 2015). Additionally, if significant amounts of melt are placed intrusively in the lithosphere this would necessarily result in regional enrichment of incompatible elements like radiogenics and water in the lithosphere and lower crust.

Petrography/Geochemistry of Ejecta Material, Meteorites, and Understanding Evolution

Analytical tools developed at Ghent University, at VUB, and at ULB (Izmer et al. 2013; Chernonozhkin et al. 2014; Costas-Rodriguez et al. 2014; Van Hoecke et al. 2014; Van Malderen et al. 2015a, b) have been used in the analysis of meteorites and micrometeorites that sample early Solar System planetesimals. In particular, we have used high-precision isotopic analyses by multi-collector ICP-MS (Inductively Coupled Plasma Mass Spectrometry/Spectrometer). A novel method was developed for the isolation of Ni for its subsequent isotopic analysis via multi-collector ICP-MS (Chernonozhkin et al. 2015). Laterally resolved isotopic analysis (microdrill sampling) of Fe and Ni was shown to provide complementary information.

Commercially available LA-ICP-MS (LA stands for Laser Ablation) instrumentation was used for mapping of the two-dimensional distribution of target elements over the surface of, among other, iron meteorites or a late Archean impact spherule layer (Izmer et al. 2013; Chernonozhkin et al. 2014). Computer fluid dynamics was relied on for designing an ultra-fast ablation cell (Van Malderen et al. 2015a) and of novel data acquisition/handling protocols (Van Malderen et al. 2015b) to extend the capabilities of laser ablation ICP-MS in this context ensuring a higher sample throughput and improved spatial resolution.

These analytical tools together with classical more mass and X-ray spectrometers, micro-drill microscope have been used on chondritic, achondritic, and iron meteorites (McKibbin et al. 2013; McKibbin and Claeys 2014; Goderis et al. 2015) and in the analysis of impact rocks, both terrestrial (Goderis et al. 2013a, b; Belza et al. 2015; Simonson et al. 2015) and extraterrestrial (Van Roosbroek et al. 2015). These studies of meteoritic and ejecta materials have provided access to elementary and isotopic composition, and have shed light on the impact crater and the overlying turbulent vapour plume environment responsible for the formation and distribution of ejecta material on Earth. They also shed light on the impact products of extraterrestrial bodies (which may also serve as drivers of, or analogues for, core-mantle separation in small bodies) and contribute towards testing the hypothesis of a CHondritic Uniform Reservoir (CHUR), or nebular starting material, for the planet Earth.

Trace Gases Evolution, Interior and Atmosphere

The methane on Mars could be either abiotic or biotic. On Mars methane has a non-uniform distribution involving an observed lifetime of about 200 days, shorter than the 300 years predicted by photochemical models. Pinpointing the exact origin requires measurements of methane isotopologues and of other trace gases related to possible methane production processes as planned in the future with ExoMars TGO, especially with NOMAD instrument of BISA (Vandaele et al. 2015a; Neefs et al. 2015). Scenarios of observations were characterized by varying geometries, instruments, aerosol loadings, solar zenith angles, concentration of molecular species, tangent heights and solar longitudes (Drummond et al. 2011; Vandaele et al. 2015b; Thomas et al. 2016; Robert et al. 2015). All spectra were simulated using atmospheric conditions obtained by global circulation model (GCM, Daerden et al. 2015). On the other hand, we studied the effects of soil composition on the stability zone of methane clathrates in the Martian crust. Clathrates, also called methane hydrates, are solid compounds similar to ice in which a large amount of methane is trapped within a crystal water structure. These clathrates are used to understand the present-day atmosphere (as measured by the instruments) as well as the evolution of the past atmosphere of Mars. For the present-day atmosphere understanding, an interface has been developed for the GCMs of the Martian atmosphere, which incorporates the clathrate degassing. We have studied trace gases also in conditions of Venus. The instruments on board Venus Express, which was declared lost end of Dec. 2014, provided a considerable amount of data during this 8 year mission. Several publications have recently appeared in a Special Issue of the PSS journal dedicated to the "Exploration of Venus" using data from the SOIR instrument developed at BISA. Trace gases and composition were addressed for example in Vandaele et al. (2015c) investigating the short term variations of CO, Mahieux et al. (2015a) on HCl and HF, Mahieux et al. (2015b) on SO_2, or Mahieux et al. (2015c) for the update of the VAST model. Recently, improvements to the Venus International Reference Atmosphere were proposed (Vandaele et al. 2016).

Solar Radiation, Atmospheric Erosion by the Solar Wind, Trapping of Planetary Ions, Magnetic Field Role, Outflow Rate

Planetary magnetic fields have long been considered as a shield protecting planetary atmospheres from erosion. They would prevent part of direct atmospheric erosion by the solar wind and trap planetary ions allowing a substantial return flow into the atmosphere and reducing the net loss of atmospheric material. The Earth has still a magnetic field. Mars and Venus have none, but Mars possesses a remnant crustal magnetic field from a dynamo that was operational in Mars' early history (Acuña et al. 1998, 1999, 2001), sometime between core formation (~4.5 Ga) and the Late Heavy Bombardment. The existence of crustal remnant magnetization on Mars (Connerney et al. 1999) indicates that a dynamo operated for a substantial time early in Martian history, but the timing, duration, and driving mechanism are unknown. The differences between Earth, Mars, and Venus atmosphere could thus partly be due to the presence of a strong magnetic field on Earth contrary to Mars and Venus, even if recent observations challenge the idea that planetary magnetic fields offers a perfect shield to atmospheres. Latest measurements show that the outflow rate on Earth is actually equal or greater than the outflow rate on Mars, and Venus (see Maes et al. 2015). Furthermore, the amount of escaped planetary material that returns back to the atmosphere under the effect of planetary magnetic field is also being revised downwards. This situation would probably be even more pronounced earlier in the history of the Solar System. It is very likely that Earth, like Venus and Mars, has been subjected to a large amount of escape from different mechanisms. Atmospheric escape modeling involves mainly two different aspects. First, this can happen through hydrodynamic escape, which occurs when the energy input from the Sun is large enough to allow lighter species in the atmosphere (hydrogen mainly, but also oxygen or even CO_2) to flow into space and be removed from the atmosphere. Such a mechanism can only occur during the first few hundred million years of the evolution when the solar wind was probably stronger than at present-day and the Extreme UV (EUV) flux could reach up to 100 times its present value. The variability of the extreme UV flux during the early stages of evolution can even be much large and can differ significantly from star to star (see Tu et al. 2015, providing the levels high-energy radiation of a young Sun-type star). Second, the high EUV flux is also thought to have a strong effect on the non-thermal escape (that is non-hydrodynamic and still occurs at present-day, like sputtering, photo dissociation…), probably enhancing its efficiency by orders of magnitude. During early evolution, moreover, it is now thought that magnetic field protection could only have prevented a small fraction of the escape. Indeed, hydrodynamic escape is not affected by it, as its effect covers neutral species. Additionally, at that time, the energy input from the Sun would have been high enough to lead to the expansion of the atmosphere well above its present-day levels and, possibly, well above the altitudes that are offered protection by the magnetic field. We have shown that during the first few hundreds of millions years, hydrodynamic escape is dominant and very efficient (see Gillmann et al. 2009a, b; model also used in Gillmann et al. 2015, 2016; Gillmann and Tackley 2014). For later evolution, non-thermal escape becomes the main process but remains comparatively low. Non-thermal escape can however have important consequences on the late evolution of terrestrial planets. It is for example thought to be the cause of the fractionation of isotopes of H, N and C on Mars or Venus (Gillmann et al. 2009a, b) and to govern the changes in surface conditions during the last 4 Gyr of planetary history. Both observation (by the ASPERA instrument, Lundin and Barabash 2004) and modeling are used to assess the strength of non-escape and its consequences on surface conditions, in particular the water surface inventory.

Water Rich Planet Interior, Internal Ocean beneath High-Pressure Ice and Constraints on Ocean Floor, Thermal Evolution and Habitability

We studied deep water layers inside water-rich planets (from about Mars-size to almost Neptune-size planets) and inferred the depth-dependent thermodynamic properties of high-pressure water and the possible formation of high-pressure ice. The water layer on such planets could be hundreds of kilometers deep depending on the water content and the evolution of the proto-atmosphere. A deep water layer will likely form high-pressure ice from a specific depth on. A new water planet model has been developed coupled with an interior structure model to infer the depth-dependent thermodynamic properties of high-pressure water and the possible formation of high-pressure ice (Noack et al. 2015). The simulations show that depending on the ice layer thickness and model parameters, the high-pressure ice layer can be re-molten from below at the water-mantle boundary (in some cases episodically) due to heat loss from the interior (Noack et al. 2016).

Comets and Water on Planets

In August 2014, the Rosetta spacecraft arrived near its target, comet 67P/Churyumov-Gerasimenko. We are deeply involved in studies that are related to establishing the composition of comets using the ROSINA/DFMS mass spectrometer. While it is still rather early to draw many conclusions, we highlight here some of the first results that we obtained with the DFMS science team. An important measurement was the determination of the D/H ratio, which is of fundamental importance for understanding the origin of the Solar System. The provenance of water and organic compounds on the Earth and other terrestrial planets has been discussed for a long time without reaching a consensus. One of the best means to distinguish between different scenarios is by determining the D/H ratios in the reservoirs for comets and the Earth's oceans. The direct in situ measurement of the D/H ratio in the Jupiter family comet is found to be ~3 times the terrestrial value (see Altwegg et al. 2014). Previous cometary measurements and our new finding suggest a wide range of D/H ratios in the water within Jupiter family objects. This high D/H value precludes the idea that the majority of the Earth's oceans would somehow have been delivered to Earth by comet impacts. Other major discoveries are the first observations of N_2 (Rubin et al. 2015) and O_2 (Bieler et al. 2015), as well as Ar (Balsiger et al. 2015). All these findings suggest that comets have formed at cold temperatures and are a heterogeneous aggregate of material from the pre-solar nebula (Hässig et al. 2015), that had little contribution to Earth through impacts in the early Solar System.

Identification and Preservation of Life Tracers in Early Earth and Analog Extreme Environments, Implication for Detection of Life

We are pursuing the characterization of chemical and morphological biosignatures at the macro- to the micro-scale, and of their mode of preservation, in Precambrian rocks and in modern analogs from extreme environments. Examination of possible abiotic processes mimicking biological processes and products is carried out as well to identify real biosignatures that could be used for the detection of life in early Earth and extraterrestrial record. These studies also document the changing habitability conditions of Earth that sustained life from (at least) its earliest traces in the Archean through the Proterozoic, and the interactions between the biosphere, the geosphere, and the atmosphere. We thus investigated the early traces and diversification of life and the changing habitability conditions of Earth that sustained life, from its earliest traces in the Archean through the Proterozoic. These studies are improving the characterization of (1) biosignatures and analytical protocols useful for paleobiology and exobiology missions; and of (2) interactions between the biosphere, the geosphere, the hydrosphere, and the atmosphere through time, linking to WPs of the IUAP Planet TOPERS. Important findings include the characterization of some of the earliest microfossils preserved in 3.45 Ga shallow marine environments (Sugitani et al. 2015), of biosignatures identification and preservation in microbial mats and cyanobacteria from modern analog extreme environments (Lepot et al. 2014; Storme et al. 2015), and the diversification of complex life (eukaryotes) in Proterozoic redox-stratified oceans (Beghin et al., in review; Baludikay et al. 2016; Javaux and Knoll, 2016). Additionally, we have performed complementary geochronological studies, in particular on diagenetic minerals, to better constrain the age of the microfossils (François et al. 2015).

Influence of Life on Planet Evolution

By harvesting solar energy and converting it to chemical energy, photosynthetic life plays an important role in the energy budget of Earth. This leads to alterations of chemical reservoirs eventually affecting Earth's interior. Research on the interaction between life and planetary interiors is a major element of DLR's "Planetary Evolution and Life" programme. An evolution model (including parameterized thermal evolution of Earth with a mantle viscosity depending on temperature and the concentration of water, continental growth and destruction, and mantle water regassing and outgassing) has been developed which suggests that the Earth without its biosphere could have evolved into a state with smaller continent coverage and a dryer mantle than observed today. On the other hand, Earth's biosphere provides enhanced weathering, erosion and sediment sedimentation. An increased rate at which sediments are subducted in turn might induce more water to be retained, potentially impacting processes in subduction zones (see Höning et al. 2014; Höning and Spohn 2016).

Next Stage Program

The above-presented recent results show the ongoing research performed by the IAP planet TOPERS group. The next steps of the program will not only continue the various research topics mentioned in the previous sections of this manuscript, but as well integrate all results together into a comparative history of habitability conditions for Mars, Earth, and Venus. Future steps will further investigate and closely integrate the geophysical, geological, and biological aspects of habitability with the objective of developing, in a holistic approach, an integrated model of planetary thermodynamic engine that includes mass, energy, and entropy balances into a "Global System dynamics". Moreover, the role of feedback cycles in stabilizing habitable conditions as well as the net loss or gain of volatiles in the atmosphere depending on the atmospheric pressure itself will be examined. Ultimately, we aim to assess the habitability not only of terrestrial planets, asteroids, rocky and icy satellites, but also of extrasolar terrestrial planets.

See http://iuap-planet-topers.oma.be/ for future detail.

Acknowledgments We thank for the support from BELSPO IAP PLANET TOPERS, ERC StG ELiTE 308074, ERC StG ISoSyC 336718, TDP 1308 COST Action ORIGINS, FP7 EuroVenus (FP7-Space 606798), FP7 CrossDrive (FP7-Space 607177), BELSPO PRODEX PlanetInt, the German Helmholtz Association, and the Deutsche Forschungsgemeinschaft DFG.

References

Acuña MH, Connerney JEP, Wasilewski P, Lin RP, Anderson KA, Carlson CW, McFadden J, Curtis DW, Mitchell D, Rème H, Mazelle C, Sauvaud JA, D'Uston C, Cros A, Medale JL, Bauer SJ, Cloutier P, Mayhew M, Winterhalter D, Ness NF (1998) Magnetic field and plasma observations at mars: initial results of the mars global surveyor mission. Science 279(5357):1676. doi:10.1126/science.279.5357.1676

Acuña MH, Connerney JEP, Ness NF, Lin RP, Mitchell D, Carlson CW, McFadden J, Anderson KA, Rème H, Mazelle C, Vignes D, Wasilewski P, Cloutier P (1999) Global distribution of crustal magnetization discovered by the Mars Global Surveyor MAG/ER Experiment. Science 284(5415):790–793. doi:10.1126/science.284.5415.790

Acuña MH, Connerney JEP, Wasilewski P, Lin RP, Mitchell D, Anderson KA, Carlson CW, McFadden J, Rème H, Mazelle C, Vignes D, Bauer SJ, Cloutier P, Mayhew M, Ness NF (2001) Magnetic field of Mars: summary of results from the aerobraking and mapping orbits. J Geophys Res 106(E10):23403–23418. doi:10.1029/2000JE001404

Altwegg K, Balsiger H, Bochsler P, Calmonte U, Eberhardt P, Gasc S, Kopp E, Jäckel A, LeRoy L, Rubin M, Sémon T, Tzou C, Wurz P, Berthelier JJ, De Keyser J, Neefs E, Fiethe B, Fuselier S, Hässig M, Waite H, Mall U, Korth A, Rème H, Bieler A, Combi M, Hansen KC, Gombosi T, Bar-Nun A, Marty B, Mousis O, Owen T, Briois C (2014) Comet 67P/Churyumov-Gerasimenko, a true Kuiper belt comet as judged from its D/H in water. Science 347:6220. doi:10.1126/science.1261952

Balsiger H, Altwegg K, Bar-Nun A, Berthelier J-J, Bieler A, Bochsler P, Briois C, Calmonte U, Combi M, De Keyser J, Eberhardt P, Fiethe B, Fuselier SA, Gasc S, Gombosi TI, Hansen KC, Hässig M, Jäckel A, Kopp E, Korth A, Le Roy L, Mall U, Marty B, Mousis O, Owen T, Rème H, Rubin M, Sémon T, Tzou C-Y, Waite JH, Wurz P (2015) Detection of argon in the coma of comet 67P/Churyumov-Gerasimenko. Sci Adv 1(8): e1500377. doi:10.1126/sciadv.1500377

Baludikay BK, Storme J-Y, François C, Baudet D, Javaux EJ, (2016) A diverse and exquisitely preserved organic-walled microfossil assemblage from the Meso – Neoproterozoic Mbuji-Mayi Supergroup (Democratic Republic of Congo) and biostratigraphic constraints. Precambrian research (in press)

Belza J, Goderis S, Smit J, Vanhaecke F, Baert K, Terryn H, Claeys P (2015) High spatial resolution geochemistry and textural characteristics of 'microtektite' glass spherules in proximal cretaceous-Paleogene sections: insights into glass alteration patterns and precursor melt lithologies. Geochim Cosmochim Acta 152:1–38

Bieler A, Altwegg K, Balsiger H, Bar-Nun A, Berthelier J-J, Bochsler P, Briois C, Calmonte U, Combi M, De Keyser J, van Dishoeck EF, Fiethe B, Fuselier SA, Gasc S, Gombosi TI, Hansen KC, Hässig M, Jäckel A, Kopp E, Korth A, Le Roy L, Mall U, Maggiolo R, Marty B, Mousis O, Owen T, Rème H, Rubin M, Sémon T, Tzou C-Y, Waite JH, Walsh C, Wurz P (2015) Abundant molecular oxygen in the coma of comet 67P/Churyumov-Gerasimenko. Nature 526:678–681. doi:10.1038/nature15707

Chernonozhkin SM, Goderis S, Bauters S, Vekemans B, Vincze L, Claeys P, Vanhaecke F (2014) Evaluation of pneumatic nebulization and ns-laser ablation ICP-MS for bulk elemental analysis and 2-dimensional element mapping of iron meteorites. J Anal At Spectrom 29:1001–1016. doi:10.1039/c3ja50387a

Chernonozhkin SM, Goderis S, Lobo L, Claeys P, Vanhaecke F (2015) Development of an isolation procedure and MC-ICP-MS measurement protocol for the study of stable isotope ratio variations of nickel. J Anal At Spectrom 30:1518–1530. doi:10.1039/C5JA00080G

Connerney JEP, Acuña MH, Wasilewski PJ, Ness NF, Rème H, Mazelle C, Vignes D, Lin RP, Mitchell DL, Cloutier PA (1999) Magnetic lineations in the ancient crust of Mars. Science 284:794–798

Costas-Rodriguez M, Lobo L, Vanhaecke F (2014) A novel approach to measure isotope ratios via multi-collector - inductively coupled plasma - mass spectrometry based on sample mixing with a non-enriched standard. Anal Bioanal Chem 406:4393–4399

Daerden F, Whiteway JA, Neary L, Komguem L, Lemmon MT, Heavens NG, Cantor B, Hébrard E, Smith MD (2015) A solar escalator on Mars: self-lifting of dust layers by radiative heating. Geophys Res Lett. doi:10.1002/2015GL064892

Debaille V, Yin Q-Z, Brandon A, Jacobsen B (2008) Martian mantle mineralogy investigated by the 176 Lu–176 Hf and 147 Sm–143 Nd systematics of shergottites. Earth Planet Sci Lett 269:186–199

Debaille V, Brandon A, O'Neill C, Yin Q-Z, Jacobsen B (2009) Early martian mantle overturn inferred from isotopic composition of nakhlite meteorites. Nat Geosci 2:548–552

Debaille V, O'Neill C, Brandon A, Haenecour P, Yin Q-Z, Mattielli N, Treiman A (2013) A delayed onset for modern plate tectonics revealed by 142Nd isotopes. Earth Planet Sci Lett 373:83–92

Drummond R, Vandaele A-C, Daerden F, Fussen D, Mahieux A, Neary L, Neefs E, Robert S, Willame Y, Wilquet V (2011) Studying methane and other trace species in the Mars atmosphere using a SOIR instrument. Planet Space Sci 59(2–3):292–298. doi:10.1016/j.pss.2010.05.009

El Atrassi F, Debaille V, Mattielli N, Berger J (2015) Geochemistry and petrogenesis of Archean mafic rocks from the amsaga area, West African craton, Mauritania. Goldschmidt Conference, Prague

François C, Baludikay BK, Storme JY, Baudet D, Javaux EJ (2015) Geochronological constraints on the diagenesis of the Mbuji-Mayi supergroup, Democratic Republic of Congo (DRC). Goldschmidt Conference, Prague

Gillmann C, Lognonné P, Chassefière E, Moreira M (2009a) “A consistent picture of early hydrodynamic escape of Venus atmosphere explaining present Ne and Ar isotopic ratios and low oxygen atmospheric content”. Earth Planet Sci Lett 286(3–4):503–513. doi:10.1016/j.epsl.2009.07.016

Gillmann C, Lognonné P, Chassefière E (2009b) “The present-day atmosphere of Mars: Where does it come from?”. Earth Planet Sci Lett 277(3–4):384–393. doi:10.1016/j.epsl.2008.10.033

Gillmann C, Tackley P (2014) Atmosphere/mantle coupling and feedbacks on Venus. J Geophys Res Planets 119(6):1189–1217. doi:10.1002/2013JE004505

Gillmann C, Chassefière E, Lognonné P (2015) A consistent picture of early hydrodynamic escape of Venus atmosphere explaining present Ne and Ar isotopic ratios and low oxygen atmospheric content. Earth Planet Sci Lett 286(3–4):503–513. doi:10.1016/j.epsl.2009.07.016

Gillmann C, Golabek G, Tackley P (2016) Effect of a single large impact on the coupled atmosphere-interior evolution of Venus. Icarus 268:295–312. doi:10.1016/j.icarus.2015.12.024

Goderis S, Simonson BM, McDonald I, Hassler SW, Izmer A, Belza J, Terryn H, Vanhaecke F, Claeys P (2013a) Ni-rich spinels and platinum group element nuggets condensed from a late Archaean impact vapour cloud. Earth Planet Sci Lett 376:87–98. doi:10.1016/j.epsl.2013.06.027

Goderis S, Tagle R, Belza J, Smit J, Montanari A, Vanhaecke F, Erzinger J, Claeys P (2013b) Reevaluation of siderophile element abundance and ratios across the cretaceous-Paleogene (K-Pg) boundary: implications for the nature of the projectile. Geochim Cosmochim Acta 120:417–446. doi:10.1016/j.gca.2013.06.010

Goderis S, Brandon AD, Mayer B, Humayun M (2015) s-Process Os isotope enrichment in ureilites by planetary processing. Earth Planet Sci Lett. doi:10.1016/j.epsl.2015.09.021

Hässig M, Altwegg K, Balsiger H, Bar-Nun A, Berthelier JJ, Bieler A, Bochsler P, Briois C, Calmonte U, Combi M, De Keyser J, Eberhardt P, Fiethe B, Fuselier SA, Galand M, Gasc S, Gombosi TI, Hansen KC, Jackel A, Keller HU, Kopp E, Korth A, Kuhrt E, Le Roy L, Mall U, Marty B, Mousis O, Neefs E, Owen T, Reme H, Rubin M, Semon T, Tornow C, Tzou C-Y, Waite JH, Wurz P (2015) Time variability and heterogeneity in the coma of 67P/Churyumov-Gerasimenko. Science 347:aaa0276. doi:10.1126/science.aaa0276

Höning D, Spohn T (2016) Continental growth and mantle hydration as intertwined feedback cycles in earth’s thermal evolution. Phys Earth Planet Int. doi:10.1016/j.pepi.2016.03.010

Höning D, Hansen-Goos H, Airo A, Spohn T (2014) Biotic vs. abiotic Earth: A model for mantle hydration and continental coverage. Planet Space Sci special issue ‘Planetary evolution and life’ 98:5–13. doi:10.1016/j.pss.2013.10.004

Izmer A, Goderis S, Simonson BM, McDonald I, Hassler SW, Claeys P, Vanhaecke F (2013) Application of laser ablation - ICP - mass spectrometry for 2-dimensional mapping of element distributions in a late Archean impact spherule layer. J Anal At Spectrom 28:1031–1038

Javaux EJ, Knoll AH (2016) Micropaleontology of the lower Mesoproterozoic Roper Group, Australia and implications for early eukaryote evolution. J. Palaeontology (in press)

Korenaga J (2010) On the likelihood of plate tectonics on super-earths: does size matter? Astrophys J Lett 725(1): L43–L46. doi:10.1088/2041-8205/725/1/L43

Lammer H, Chassefière E, Karatekin Ö, Morschhauser A, Niles PB, Mousis O, Odert P, Möstl UV, Breuer D, Dehant V, Grott M, Gröller H, Hauber E, Pham LBS (2012) Outgassing history and escape of the Martian atmosphere and water inventory. Space Sci Rev 174(1–4):113–154. doi:10.1007/s11214-012-9943-8

Lepot K, Deremiens L, Namsaraev Z, Compère P, Gérard E, Verleyen E, Tavernier I, Hodgson DA, Wilmotte A, Javaux EJ (2014) Organo-mineral imprints in fossil cyanobacterial mats of an Antarctic lake. Geobiology 12(5):424–450. doi:10.1111/gbi.12096

Lundin R, Barabash S (2004) Evolution of the Martian atmosphere and hydrosphere: solar wind erosion studied by ASPERA-3 on Mars express. Planet Space Sci 52:1059–1071

Maes L, Maggiolo R, De Keyser J, Dandouras I, Fear RC, Fontaine D, Haaland S (2015) Solar illumination control of ionospheric outflow above polar cap arcs. Geophys Res Lett 42(5):1304–1311. doi:10.1002/2014GL062972

Mahieux A, Wilquet V, Vandaele AC, Robert S, Drummond R, Bertaux JL (2015a) Hydrogen Halides measurements in the venus upper atmosphere retrieved from SOIR on board venus express, special issue venus conference. Planet Space Sci 113:264–274. doi:10.1016/j.pss.2014.12.014

Mahieux A, Vandaele AC, Robert S, Wilquet V, Drummond R, Belyaev D, Bertaux JL (2015b) Venus mesospheric sulfur dioxide measurement retrieved from SOIR on board venus express, special issue venus conference. Planet Space Sci 113:193–204. doi:10.1016/j.pss.2014.12.011

Mahieux A, Vandaele AC, Bougher SW, Drummond R, Robert S, Wilquet V, Piccialli A, Montmessin F, Tellmann S, Pätzold M, Häusler B, Bertaux JL (2015c) Update of the Venus high altitude temperature profiles measured by SOIR on board Venus Express, Special issue « Exploration of Venus ». Planet Space Sci 113:309–320. doi:10.1016/j.pss.2015.02.002

Maurice M, Tosi N, Plesa A-C, Breuer D (2015) Evolution and consequences of magma ocean solidification. Goldschmidt Abstracts, 2015, 2060

McKibbin S, Claeys P (2014) Heterogeneous, rapid crystallization of the Main-Group pallasite parent body: Planetesimal history from principle component analysis of metal geochemistry and accessory phase mineralogies. 5th Symposium on Polar Science. National Institute of Polar Research, 2nd–5th December, Tokyo, Japan

McKibbin S, Terryn H, Hecht L, Claeys Ph (2013) Olivine in EH Chondrites as an indicator of metamorphism in the enstatite chondrite parent body. 4th Symposium on Polar Science. National Institute of Polar Research, 12th–15th November, Tokyo, Japan

Mezger K, Debaille V, Kleine T (2013) Core formation and mantle differentiation on Mars. Space Sci Rev 174: 27–48

Neefs E, Vandaele AC, Drummond R, Thomas I, Berkenbosch S, Clairquin R, Delanoye S, Ristic B, Maes J, Bonnewijn S, Pieck G, Equeter E, Depiesse C, Daerden F, Van Ransbeeck E, Nevejans D, Rodriguez J, Lopez-Moreno J-J, Sanz R, Morales R, Candini GP, Pastor C, Aparicio del Moral B, Jeronimo JM, Gomez J, Perez I, Navarro F, Cubas J, Alonso G, Gomez A, Thibert T, Patel MR, Belucci G, De Vos L, Lesschaeve S, Van Vooren N, Moelans W, Aballea L, Glorieux S, Baeke A, Kendall D, De Neef J, Soenen A, Puech PY, Ward J, Jamoye JF, Diez D, Vicario A, Jankowski M (2015) NOMAD spectrometer on the ExoMars trace gas orbiter mission: part 1–design, manufacturing and testing of the infrared channels. Appl Opt 54(28): 8494–8520. doi:10.1364/AO.54.008494

Neumann W, Breuer D, Spohn T (2012) Differentiation and core formation in accreting planetesimals. Astron Astrophys, Planets and planetary systems, 543, A141, 21p. doi: 10.1051/0004-6361/201219157

Neumann W, Breuer D, Spohn T (2013) The thermo-chemical evolution of Asteroid 21 Lutetia. Icarus 224(1): 126–143. doi:10.1016/j.icarus.2013.02.025

Neumann W, Breuer D, Spohn T (2014a) Differentiation of Vesta: implications for a shallow magma ocean. Earth Planet Sci Lett 395:267–280. doi:10.1016/j.epsl.2014.03.033

Neumann W, Breuer D, Spohn T (2014b) Modelling of compaction in planetesimals. Astron Astrophys, Planets and Planetary Systems, 567, A120, 15p. doi:10.1051/0004-6361/201423648

Neumann W, Breuer D, Spohn T (2015) Modelling the internal structure of Ceres: coupling of accretion with compaction by creep and implications for the water-rock differentiation. Astron Astrophys, Planets and Planetary Systems, 584, A117, 16p. doi:10.1051/0004-6361/201527083

Noack L, Breuer D (2013) Interior and surface dynamics of terrestrial bodies and their implications for the habitability. In: de Vera J-P, Seckbach F (eds), Habitability on other planets and satellites: The quest for extraterrestrial life, Springer, Dordrecht, pp. 203–233, ISBN: 978-94-007-6545-0

Noack L, Breuer D (2014) Plate tectonics on rocky exoplanets: Influence of initial conditions and rheology. Planet Space Sci special issue 'Planetary evolution and life' 98:41–49. doi:10.1016/j.pss.2013.06.020

Noack L, Breuer D, Spohn T (2012) Coupling the atmosphere with interior dynamics: implications for the resurfacing of Venus. Icarus 217(2):484–498. doi:10.1016/j.icarus.2011.08.026

Noack L, Godolt M, von Paris P, Plesa A-C, Stracke B, Breuer D, Rauer H (2014) Can the interior structure influence the habitability of a rocky planet? Planet Space Sci special issue 'Planetary evolution and life' 98: 14–29. doi:10.1016/j.pss.2014.01.003

Noack L, Rivoldini A, Van Hoolst T (2015) CHIC - Coupling Habitability, Interior and Crust: A new Code for Modeling the Thermal Evolution of Planets and Moons. INFOCOMP 2015, 21–26 June 2015, Brussels, Belgium, ISSN 2308-3484, ISBN 978-1-61208-416-9, pp. 84–90

Noack L, Höning D, Rivoldini A, Heistracher C, Zimov N, Lammer H, Van Hoolst T, Bredehöft JH (2016) Water-rich planets: how habitable is a water layer deeper than on Earth? Icarus 277:215–236 doi:10.1016/j.icarus.2016.05.009

O'Neill C, Lenardic A (2007) Geological consequences of super-sized Earths. Geophys Res Lett 34(19):CiteID L19204. doi:10.1029/2007GL030598

Plesa A-C, Breuer D (2014) Partial melting in one-plate planets: implications for thermo-chemical and atmospheric evolution. Planet Space Sci special issue 'Planetary evolution and life' 98:50–65. doi:10.1016/j.pss.2013.10.007

Plesa A-C, Breuer D, Spohn T (2013) A particle-in-cell method to model the influence of partial melt on mantle convection. High Performance Computing in Science and Engineering '12, doi:10.1007/978-3-642-33374-3_34

Plesa A-C, Tosi N, Breuer D (2014a) Magma Ocean Cumulate Overturn and its Implications for the Thermo-chemical Evolution of Mars. High Performance Computing in Science and Engineering '13, doi:10.1007/978-3-319-02165-2

Plesa A-C, Tosi N, Breuer D (2014b) Can a fractionally crystallized magma ocean explain the thermo-chemical evolution of Mars? earth planet. Sci Lett 403:225–235. doi:10.1016/j.epsl.2014.06.034

Plesa A-C, Tosi N, Hüttig C, Breuer D (2015) Thermal evolution and heat-pipe melt transport: implications for one-plate planets. XIV International Workshop on Modelling of Mantle and Lithosphere Dynamics. 31. Aug. - 5. Sep. 2015, Oleron, France

Prinz S, Tosi N, Plesa A-C, Breuer D (2014) Numerical modeling of mantle convection with heat-pipe melt transport. AGU Fall meeting. 15–19 Dec. 2014, San Francisco CA, USA

Robert S, Vandaele AC, Thomas I, Willame Y, Daerden F, Delanoye S, Depiesse C, Drummond R, Neefs E, Neary L, Ristic B, Lopez-Moreno JJ, Patel MR, Bellucci G (2015) Expected performances of the NOMAD/ExoMars instrument. Icarus. Planet Space Sci 124:94–104. doi:10.1016/j.pss.2016.03.003

Rubin M, Altwegg K, Balsiger H, Bar-Nun A, Berthelier J-J, Bieler A, Bochsler P, Briois C, Calmonte U, Combi M, De Keyser J, Dhooghe F, Eberhardt P, Fiethe B, Fuselier SA, Gasc S, Gombosi TI, Hansen KC, Hässig M, Jäckel A, Kopp E, Korth A, LeRoy L, Mall U, Marty B, Mousis O, Owen T, Rème H, Sémon T, Tzou C-Y, Waite JH, Wurz P (2015) Molecular nitrogen in comet 67P/Churyumov-Gerasimenko indicates a low formation temperature. Science 348:232–235

Schlichting HE, Sari R, Yalinewich A (2015) Atmospheric mass loss during planet formation: the importance of planetesimal impacts. Icarus 247:81–94

Simonson BM, Goderis S, Beukes NJ (2015) First detection of extraterrestrial material in ca. 2.49 Ga impact spherule layer in Kuruman iron formation, South Africa. Geology 43:251–254

Stamenkovic V, Breuer D (2014) The tectonic mode of rocky planets: part 1 – driving factors, models, and parameters. Icarus 234:174–193

Storme J-Y, Golubic S, Wilmotte A, Kleinteich J, Velázquez D, Javaux EJ (2015) Raman characterization of the UV-protective pigment gloeocapsin and its role in the survival of cyanobacteria. Astrobiology 15:843–857

Sugitani K, Mimura K, Takeuchi M, Lepot K, Ito S, Javaux EJ (2015) Early evolution of large micro-organisms with cytological complexity revealed by microanalyses of 3.4 Ga organic-walled microfossils. Geobiology. doi:10.1111/gbi.12148

Thomas I, Vandaele AC, Robert S, Neefs E, Drummond R, Daerden F, Delanoye S, Depiesse C, Ristic B, Mahieux A, Neary L, Willame Y, Wilquet V, Aballea L, Moelans W, De Vos L, Lesschaeve S, Van Vooren N, Lopez-Moreno JJ, Patel MR, Bellucci G (2016) Optical and radiometric models of the NOMAD instrument. Part II: the infrared channels - SO and LNO. Opt Express 24(4):3790–3805. doi:10.1364/OE.24.003790

Tosi N, Plesa A, Breuer D (2013) Overturn and evolution of a crystallized magma ocean: a numerical parameter study for Mars. J Geophys Res Planets 118(7):1512–1528. doi:10.1002/jgre.20109

Tu L, Johnstone CP, Güdel M, Lammer H (2015) The extreme ultraviolet and X-ray sun in time: high-energy evolutionary tracks of a solar-like star. Astron Astrophys 577(L3):4. doi:10.1051/0004-6361/201526146

Valencia D, O'Connell RJ, Sasselov DD (2007) Inevitability of plate tectonics on super-earths. Astrophys J 670(1):L45–L48. doi:10.1086/524012

Van Hoecke K, Devulder V, Claeys P, Degryse P, Vanhaecke F (2014) Comparison of microsublimation and ion exchange chromatography for boron isolation preceding its isotopic analysis via multi-collector ICP-mass spectrometry. J Anal At Spectrom 29:1819–1826. doi:10.1039/C4JA00111G

Van Malderen SJM, van Elteren JT, Vanhaecke F (2015a) Development of a fast laser ablation − inductively coupled plasma − mass spectrometry cell for sub-μm scanning of layered materials. J Anal At Spectrom 30:119–125

Van Malderen SJM, van Elteren JT, Vanhaecke F (2015b) Submicrometer imaging by laser ablation-inductively coupled plasma mass spectrometry via signal and image deconvolution approaches. Anal Chem 2015(87):6125–6132. doi:10.1021/acs.analchem.5b00700

Van Roosbroek N, Debaille V, Pittarello L, Goderis S, Humayun M, Hecht L, Jourdan F, Spicuzza MJ, Vanhaecke F, Claeys P (2015) The formation of IIE iron meteorites investigated by the chondrule-bearing Mont Dieu meteorite. Meteorit Planet Sci 50:1173–1196

Vandaele AC, Mahieux A, Robert S, Drummond R, Wilquet V, Bertaux JL (2015a) Carbon monoxide short term variability observed on Venus with SOIR/VEX, special issue venus conference. Planet Space Sci 113:237–255. doi:10.1016/j.pss.2014.12.012

Vandaele AC, Neefs E, Drummond R, Thomas IR, Daerden F, Lopez-Moreno J-J, Rodriguez J, Patel MR, Bellucci G, Allen M, Altieri F, Bolsée D, Clancy T, Delanoye S, Depiesse C, Cloutis E, Fedorova A, Formisano V, Funke B, Fussen D, Geminale A, Gérard J-C, Giuranna M, Ignatiev N, Kaminski J, Karatekin O, Lefèvre F, López-Puertas M, López-Valverde M, Mahieux A, McConnell J, Mumma M, Neary L, Renotte E, Ristic B, Robert S, Smith M, Trokhimovsky S, Vander Auwera J, Villanueva G, Whiteway J, Wilquet V, Wolff M (2015b) Science objectives and performances of NOMAD, a spectrometer suite for the ExoMars TGO mission. Planet Space Sci 119:233–249. doi:10.1016/j.pss.2015.10.003

Vandaele AC, Willame Y, Depiesse C, Thomas I, Robert S, Patel MR, Mason P, Leese M, Lesschaeve S, Antoine P, Daerden F, Delanoye S, Drummond R, Neefs E, Ristic B, Lopez-Moreno JJ, Bellucci G (2015c) Optical and radiometric models and performances of the NOMAD instrument - part I: the UVIS channel. Opt Express 23(23):30028–30042. doi:10.1364/OE.23.030028

Vandaele AC, Chamberlain S, Mahieux A, Ristic B, Robert S, Thomas I, Trompet L, Wilquet V, Belyaev D, Fedorova A, Korablev O, Bertaux JL (2016) Contribution from SOIR/VEX to the updated Venus International Reference atmosphere (VIRA). Adv Space Res 57(1):443–458. doi:10.1016/j.asr.2015.08.012