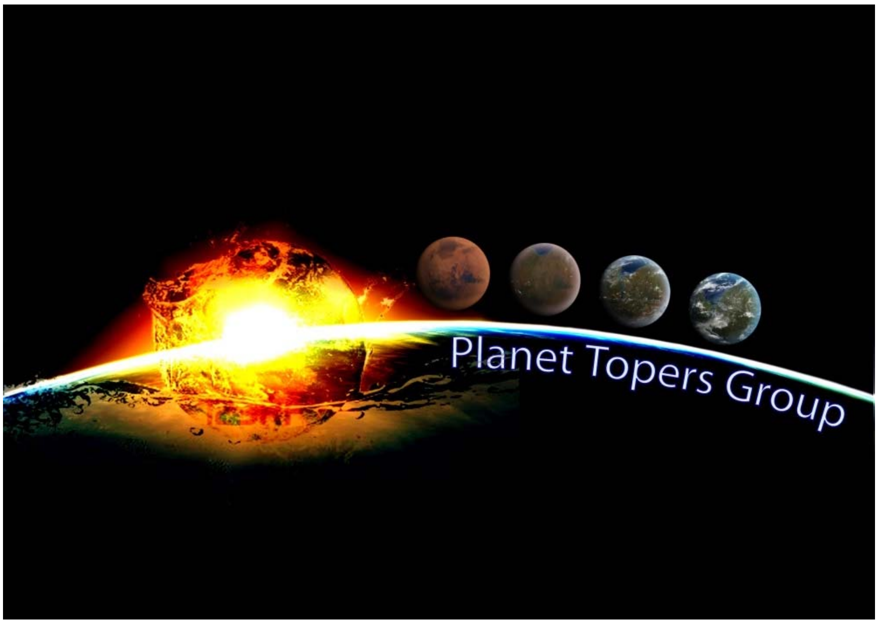
Interuniversity attraction poles - phase VII

Review Report
October 2012 – May 2016

P7-15 Planet TOPERS
Planets: Tracing the Transfer, Origin, Preservation, and Evolution of their ReservoirS



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List of abbreviations

3GM	Gravity and Geophysics of Jupiter and the Galilean Moons
AbGradCon	Astrobiology Graduate Conference
AbGradE	Astrobiology Graduates in Europe
ACE	Advanced Composition Explorer
AEIS	Académie Européenne Interdisciplinaire des Sciences
AGEX	Asteroid Geophysical Explorer
AGU	American Geophysical Union
AIDA	Asteroid Impact Deflection Assessment
AIM	Asteroid Impact Mission
ALVL	Azimuth Lidort VLidort
AMELIA	Atmospheric Mars Entry and Landing Investigation and Analysis
A&MS	Atomic and Mass Spectrometry
AOTF	Acousto-Optical Tunable Filter
ASIMUT-ALVL	Radiative transfer modelling and spectrum retrieval in a non-scattering atmosphere (ASIMUT) and scattering atmosphere ((V)LIDORT)
B2B	Back to Belgium
BELA	BEpicolombo Laser Altimetry experiment
BELSPO	BELgian Science POlitics
BC	BepiColombo
BIF	Banded Iron Formation
BISA	Belgian Institute for Space Aeronomy
BX	BoXcar
CHEOPS	CHaracterising ExOPlanet Satellite
CHUR	CHondritic Uniform Reservoir
Co-I	Co-Investigator
CLUPI	CLose-UP Imager
CHIC	Code for Habitability, Interior and Crust
CNES	Centre National d'Etudes Spatiales
CAI	Ca-Al-rich Inclusion
Co-I	Co-Investigator
Co-PI	Co- Principal Scientist
COPINS	Cubesat Opportunity Payloads
COST	European Cooperation in Science and Technology
CrossDrive	Collaborative Rover Operations and Satellites Science in Distributed Remote and Interactive Virtual Environments.
DART	Double Asteroid Redirection Test
DFG	Deutsche Forschungsgemeinschaft
DFMS	Double Focusing Mass Spectrometer
DLR	Deutsche Zentrum für Luft- und Raumfahrt
DOFS	Degree Of Freedom of the Signal
DREAMS	Dust characterization, Risk assessment and Environment Analyzer on the Martian Surface
EAI	European Astrobiology Institute
EANA	European Astrobiology Network Association
EARI	European Astrobiology Research Infrastructure
EC	European Commission
EDM	ExoMars Entry Descend Module
EEL	Early Earth and Life
EGU	European Geoscience Union
EHB	Early Heavy Bombardment

ELSI	Earth-Life Science Institute
EMTGO	ExoMars Trace Gas Orbiter
EON	Earth-Life Origins Network
EPSC	European Planetary Science Congress
ERC	European Research Council
ESA	European Space Agency
ET	ExtraTerrestrial
EU	European Union
EUV	Extreme Ultraviolet
FIB	Focused Ion Beam
FNRS	Fonds National de la Recherche Scientifique
FoV	Field of View
FRIA	Fonds pour la formation à la Recherche dans l'Industrie et dans l'Agriculture
FRS	Fonds de la Recherche Scientifique
FTIR	Fourier Transform InfraRed spectroscopy
FTS	Fourier Transform Spectrometer
FUNDP	Facultés Universitaires Notre-Dame de la Paix
Ga	Giga-annum (billion years)
GAIA	Name for mantle convection code developed at DLR
GaLA	Galilean moons Laser Altimeter
GCM	General/Global Circulation Model
GEM	Global Environmental Multiscale
GOE	Great Oxygenation Event
GSA	Geological Society of America
GSA	Geological Society of America Annual Meeting
HED	Howardite - Eucrite - Diogenite
HIRESMIR	High Resolution Microwave, Infrared and Raman molecular spectroscopy
HITRAN	HIgh-resolution TRANsmission molecular absorption)
HR	High Resolution
HRTEM	High Resolution Transmission Electron Microscopy
H-type	High iron abundance ordinary chondrite
HZ	Habitable Zone
IAG	International Association of Geodesy
IAGA	International Association of Geomagnetism and Aeronomy
IAP	Interuniversity Attraction Pole
IASI	Infrared Atmospheric Sounding Interferometer
IAU	International Astronomical Union
ICDP	International Continental Drilling Project/program
ICP	Inductively Coupled Plasma
ICP-MS	Inductively Coupled Plasma Mass Spectrometry/Spectrometer
ISEM	Infrared Spectrometer for ExoMars
JUICE	JUpiter ICy moons Explorer;
IPF	International Polar Foundation
ISSOL	International Society for the Study of the Origin of Life
IM	Instrument Manager
IMCCE	Institut de Mécanique Céleste et de Calculs des Ephémérides
InSIGHT	Mars Interior exploration using Seismic Investigations, Geodesy, and Heat Transport
IODP	International Ocean Discovery Program
IR	InfraRed
ISRO	Indian Space Research Organization
ISSI	International Space Science Institute

ISSOL	International Society for the Study of the Origin of Life and astrobiology
JAAS	Journal of Analytical Atomic Spectrometry
J-MAG	JUICE Magnetometer
KOM	Kick-Off Meeting
KT	Cretaceous-Tertiary
LA	Laser Ablation
LaRa	Lander Radioscience
LHB	Late Heavy Bombardment
LIDORT	Linearized Discrete Ordinate Radiative Transfer
LNO	Limb, Nadir and solar Occultation
LoD	Limit of Detection
LPSC	Lunar and Planetary Science Conference
LV	Late Veneer
Ma	Mega-annum (million years)
MAGIE	Mars Atmospheric Global Imaging Experiment
MAJIS	Moons And Jupiter Imaging Spectrometer
MAVEN	Mars Atmosphere and Volatile EvolutioN
MC	Multi-Collector
MC-ICP-MS	Multi-Collector -Inductively Coupled Plasma - Mass Spectrometry/Spectrometer
MER	Mars Exploration Rover
MEX	Mars Express
MGS	Mars Global Surveyor
MIR	Modular IR spectrometer
MORE	Mercury Orbiter Radioscience Experiment
MRO	Mars Reconnaissance Orbiter
MS	Mass Spectrometry
MSL	Mars Science Laboratory
µXRF	Micro-X-Ray Fluorescence
MY	Martian Year
NASA	National Aeronautics and Space Administration
NEXAFS	Near Edge X-Ray Absorption Fluorescence Synchrotron
NIPR	National Institute of Polar Research
NIRS	Near Infrared Spectrometer
NMI	Non-Magmatic Iron
NOMAD	Nadir and Occultation for MArs Discovery
OC	Ordinary Chondrite
ODY	Mars Odyssey
OLEB	Life and Evolution of Biospheres
OSPP	Outstanding Student Poster and PICO Awards
PDR	Projet de Recherche
PE	Princess Elizabeth
PGE	Platinum Group Element
PI	Principle Investigator
PLATO	PLAnetary Transits and Oscillations of stars
PRIDE	Planetary Radio Interferometry and Doppler Experiment
PS	Participating Scientist
PSA	ESA Planetary Science Archive
REE	Rare Earth Elements
RISE	Rotation and Interior Structure Experiment
ROB	Royal Observatory of Belgium
ROSINA	ROsetta Spectrometer for Ion and Neutral Analysis

RSC	Royal Society of Chemistry
SAG	Science Advisory Group
SAMBA	Search and Study of Antarctica Meteorites
SEDI	Study of the Earth's Deep Interior
SEIS	InSIGHT SEISmometer
SEM	Scanning Electron Microscopy
SIMBIO-SYS	Spectrometers and Imagers for MPO BepiColombo Integrated Observatory SYStem
SIMS	Secondary Ion Mass Spectrometry
SIROCCO	Synergetic SWIR and IR retrievals of near-surface concentrations of CH_4 and CO for Earth and Planetary Atmospheres
SNC	Shergottite, Nakhlite, and Chassignite
SOIR	Solar Occultation in the Infra-Red
SPICAM	Spectroscopy for Investigation of Characteristics of the Atmosphere of Mars
SPICAV	Spectroscopy for Investigation of Characteristics of the Atmosphere of Venus
SSA	Space Situational Awareness
SSAC	Solar System Advisory Committee
SWIR	Short-Wavelength InfraRed
SZA	Solar Zenith Angle
TEM	Transmission Electron Microscopy
TGO	Trace Gas Orbiter
TIR	Thermal Infrared
TIRVIM	Thermal Infrared V-shape Interferometer Mounting
TOPERS	Tracing the Transfer, Origin, Preservation, and Evolution of their ReservoirS
TTG	Tonalite-Trondhjemite-Granodiorite)
UCL	Université Catholique de Louvain
UGent	Universiteit Gent
UGent	University of Ghent
ULB	Université Libre de Bruxelles
ULg	Université de Liège
UPB	Ureilite Parent Body
UV	Ultraviolet
VEX	Venus Express
VMR	Volume Mixing Ratio
VUB	Vrije Universiteit Brussel
WG	Working Group
WP	Work Package
XANES	X-ray Absorption Near Edge Structure

1. INTRODUCTION

1.1. General information about the network:

Title of the project: Planet TOPERS – Planets: Tracing the Transfer, Origin, Preservation, and Evolution of their ReservoirS

Name of the partners and their institution:

<u>Coordinator</u>: <u>Partner 1</u> (**P1**) Name: Dehant Véronique Institution: Royal Observatory of Belgium Institution’s abbreviation: ROB
<u>Partner 2</u> (**P2**) Name: Vandaele Ann Carine Institution: Belgian Institute for Space Aeronomy Institution’s abbreviation: BISA
<u>Partner 3</u> (**P3**) Name: Claeys Philippe Institution: Vrije Universiteit Brussel Institution’s abbreviation: VUB
<u>Partner 4</u> (**P4**) Name: Vanhaecke Frank Institution: Universiteit Gent Institution’s abbreviation: UGent
<u>Partner 5</u> (**P5**) Name: Javaux Emmanuelle Institution: Université de Liège Institution’s abbreviation: ULg
<u>Partner 6</u> (**P6**) Name: Debaille Vinciane Institution: Université Libre de Bruxelles Institution’s abbreviation: ULB
<u>International Partner</u> (**INT**) Name: Spohn Tilman Institution: Deutsche Zentrum für Luft- und Raumfahrt Berlin Institution’s abbreviation: DLR Country: Germany

Budget:

	Name Partner	Institution's abbreviation	Budget
P1	Veronique Dehant	ROB	900100
P2	Ann Carine Vandaele	BISA	500100
P3	Philippe Claeys	VUB	500000
P4	Frank Vanhaecke	UGent	500000
P5	Emmanuelle Javaux	ULg	500000
P6	Vinciane Debaille	ULB	500000
INT1*	Tilman Spohn	DLR	100000

* The budget for the international-partner is the budget attributed by the IAP-programme only (<u>without</u> the 50% contribution of the international partner)

1.2. History of the IAP network throughout the different IAP programme phases

The idea of the Interuniversity Attraction Pole (IAP) has been generated from contacts initiated in the frame of a Contact Group created in 2006 (Astrobiology FNRS-FRS http://astrobio.oma.be/), which had already (1) produced several publications (e.g., Javaux and Dehant, 2010), (2) induced several master theses (e.g., a thesis on mantle convection in early Mars (ROB and ULB), a thesis on the methane clathrate hydrate (ULg and ROB), (3) participated in field projects (e.g., Antarctic SAMBA mission of VUB and ULB), (4) shared common instrumentation for meteorite analysis (VUB and UGent), (5) participated in the same ExoMars space missions (ROB and BISA)…

In Germany, the DLR Institute of Planetary Research, the international partner of this IAP, coordinated a Helmholtz Alliance "*Planetary Evolution and Life*" with the similar objective of addressing the much debated question of habitability of planets or moons in an interdisciplinary context. Furthermore, the question was also dealt with at the international level, as shown by three international workshops on "*Geology and Habitability of Terrestrial Planets*", "*Strategies of Life Detection*", and "*Quantifying the Martian Geochemical Reservoirs*" organized at ISSI (International Space Science Institute) in which several of the partners of this Pole had participated and contributed in published books. Members of the group also organized national and international astrobiology meetings and were actively involved in international astrobiology societies or sections (EANA, ISSOL, EGU, ...) as well as in public education and vulgarization.

This experience led to the present IAP group working together in a synergistic approach on common questions related to planetary evolution, life, and habitability at the intersection of several different disciplines: biology, geophysics, geochemistry, geology, paleontology, space-based exploration of planets (using orbital and/or in-situ instruments), study of meteoritic sample from Earth or Mars.

The group includes planetary and/or Earth scientists who are observing, modelling, simulating, either numerically or in the laboratory (experimentally), the physical, chemical (and for Earth, biological) processes occurring on or within the Earth, Mars, and the other terrestrial bodies of our Solar System.

The problem of planetary evolution, life, and habitability was partially addressed in Belgium by the different partners. Organic chemistry and liquid water are the bases of life-as-we-know-it and probably most important in extraterrestrial life (if it exists). However, our project goes beyond the strategy of "follow the water and the carbon" found at the time of the creation of the IAP in NASA and ESA roadmaps of on-going and future missions or other astrobiology programs. Strengthened from the individual expertise, we address habitability in a more synergistic approach, not only by examining life's envelope on Earth (the range of extreme conditions), but by considering all geophysical aspects important for habitability such as the exchange and interactions (including feedback mechanisms) between the geochemical reservoirs (core, mantle, crust, atmosphere, hydrosphere, cryosphere, and biosphere) of the terrestrial planets or moons of our Solar System, the effects of meteorites and comets impacts, the effects of mantle overturn and of the onset or not of plate tectonics, etc. The synergy also relies on observation coming from meteorites analysis, permitting to constrain the possible scenarios of planetary evolution.

This new approach to the question of habitability and planetary evolution fitted in the context of the exploration and astrobiological initiatives of space agencies, such as the joint ESA/ Roscosmos ExoMars (in which Planet TOPERS participants are deeply involved with three instruments at Principal Investigator level and with at several Co-Investigator level) and Mars Sample Return missions.

Besides providing a better understanding of the origin and sustainability of life on terrestrial planets, we wanted to improve our insight into key environmental contexts where potential habitats – and possibly life – can/could exist (or existed) in the Solar System and beyond, as well as a set of recommendations concerning the most appropriate methodologies to look for it.

1.3. Summary of the general objectives of the research project

Earth clearly stands out among the rocky planets of the inner Solar System. It harbors life, has water oceans, volcanic activity contributing to the atmosphere and plate tectonics continuously regenerating its surface and bioessential nutrients concentrated in minerals. Its biosphere is shielded from radiation by a self-sustained magnetic field, which further protects the atmosphere from erosion. The atmosphere erosion process is, for instance, complicated by the existence of hydrodynamic escape, not affected by the magnetic field. Connections thus exist between the presence and persistence of life and the geophysical characteristics of the host planet. Other bodies such as Mars, Venus, and some large satellites like the Jupiter moon Europa do share some but not all of Earth geophysical properties, and life seems absent there or at least not as abundant as on the Earth. The origin, evolution and distribution of life in the universe constitute crucial questions at the heart of the discipline of Astrobiology. The IAP Planet TOPERS makes major contributions to this field and thereby propels Belgium's planetary research at the forefront.

Habitability is commonly understood as "the potential of an environment (past or present) to support life of any kind" (Steele et al., 2005). Based on the only known example of Earth, the concept refers to whether environmental conditions are available that could eventually support life, even if life does not currently exist (Javaux and Dehant, 2010). To be meaningful, this concept requires an unambiguous definition of life, which is currently lacking (Tsokolov, 2010). Life includes properties such as consuming nutrients and producing waste, the ability to reproduce and grow, pass on genetic information, evolve by natural selection, and adapt to the varying conditions on a planet (Sagan, 1970). Terrestrial life requires liquid water. 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, but excludes these two planets. If the greenhouse effect is taken into account, the habitable zone may have included early Mars while the case of Venus is still debated. This simple definition neglects other important requirements for life such as a supply of biogenic elements (C, H, O, N, P, S, and trace elements-metals) and an energy source to drive biochemical reactions. Also, liquid water may exist in oceans covered by ice shells for example in the icy satellites of Jupiter (Schubert et al., 2004), which are located well outside the conventional habitable zone of the Solar System. On Earth, life mostly depends directly or indirectly on solar energy. However, habitats exist deep in the oceans in eternal darkness thriving on geothermal energy or deep in the crust (Chyba and Hand, 2001). In glacial areas, interfacial water between ice crystals may remain liquid at temperatures far below 0°C and concentrate nutrients (Petzold and Aguilera, 2009). The common view is that extraterrestrial life would probably be based on organic chemistry in a water solvent (Pace, 2001) although alternative biochemistries have been hypothesized (Bains, 2004; Benner et al., 2004; Houtkooper and Schulze-Makuch, 2007). Indeed, organic molecules (molecules composed of at least carbon and hydrogen) are common in the universe, in interstellar medium or in meteorites. Moreover, Carbon (C) builds complex molecules with high information content. Carbon (C), Hydrogen (H), Oxygen (O), Nitrogen (N), the building blocks of life, are among the first elements to form in stellar environments, and are ubiquitous in the universe. The origin of life on Earth is not constrained, and several hypotheses involving Panspermia (hypothesis that life exists throughout the Universe), hydrothermal or lukewarm origins exist. Considering the evolution of terrestrial life, the most probable form of life that could exist beyond Earth would be microbial (unicellular microorganisms) (see Javaux and Dehant, 2010).

As envisaged in Javaux and Dehant (2010), this IAP develops and closely integrates the **geophysical, geological, and biological aspects** of habitability with a particular focus on **Earth neighboring planets**, Mars and Venus. Important **geodynamic processes** affect the habitability conditions of a planet. The dynamic processes, e.g. **internal dynamo**, **magnetic field**, **atmosphere**, **plate tectonics**, **mantle convection**, **volcanism**, **thermo-tectonic evolution**, **meteorite impacts**, and **atmosphere erosion**, modify the planetary surface, the possibility to have liquid water, the thermal state, the energy budget and the availability of nutrients. Shortly after formation (Hadean 4.4-4.0 billion years ago), evidence supports the presence of a liquid ocean and continental crust on Earth (Wilde et al., 2001), Earth may thus have been habitable very early on (Strasdeit, 2010). The origin of life is not understood yet but the oldest putative traces of life occur in the early Archaean

(~3.5 Ga, see Figure 1). Studies of **early Earth habitats** documented in rock containing traces of fossil life provide information about the **environmental conditions suitable for life** beyond Earth, as well as the required methodologies for their identification and analyses. The extreme values of environmental conditions in which life thrives today can also be used to characterize the "envelope" of the existence of life and the range of potential extraterrestrial habitats. The requirement of nutrients for biosynthesis, growth, and reproduction suggest that a tectonically active planet, with liquid water in contact with minerals is required to replenish nutrients and sustain life (as currently known). These dynamic processes play a key role in the apparition and persistence of life.

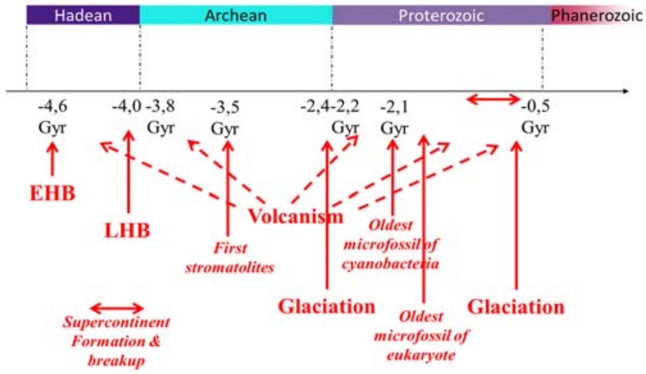

Figure 1: Earth's history (where EHB and LHB means Early / Late Heavy Bombardment respectively).

The IAP Planet TOPERS field of research supports a broad community whose research themes are shown in the previous paragraphs with key words underlined. The Pole focuses its contribution on the full integration of these themes in the following Work Packages (WP) to better demonstrate how life can be sustained and to characterize the existence and persistence of life through the development of potential habitats. Recent efforts in space exploration with spacecraft, landers, and rovers – Mars Express (Chicarro, 2002), Mars Exploration Rovers (Squyres et al., 2003; 2004a; 2004b), Venus Express (Svedhem et al., 2007) … –, have provided new opportunities to investigate the possibility of life beyond Earth and especially the habitability of the two closest terrestrial planets, Mars and Venus. Neither Venus nor Mars presently have liquid water reservoirs on their surfaces – Venus has very high surface temperatures due to excessive greenhouse effect (Bullock and Grinspoon, 2001) and Mars surface is very cold with nonexistent greenhouse effect (Forget and Pollack, 1996; Haberle et al., 2004; Forget et al., 2007). Nevertheless, early in their history, they could have had the atmospheric conditions necessary to sustain the presence of liquid water on their surfaces. Water is among the habitability conditions that have been developed and considered from different scientific perspectives on different spatial and time scales (see Lammer et al., 2009; Javaux and Dehant, 2010, for reviews). The surface temperature and the presence of an atmosphere form the essential ingredients for liquid water to appear and persist. The planet Mars could have been habitable at the beginning of its evolution, as the examination of its surface suggests the existence of surface water very early on (about 4 Ga ago, see Figure 2) (Bibring et al., 2005, 2006). Since then, Mars lost most of its atmosphere, preventing the presence of liquid water at the surface. In comparison, Earth is habitable at present and has been so for at least 4.3 Ga, and inhabited since at least 3.5 Ga, or more.

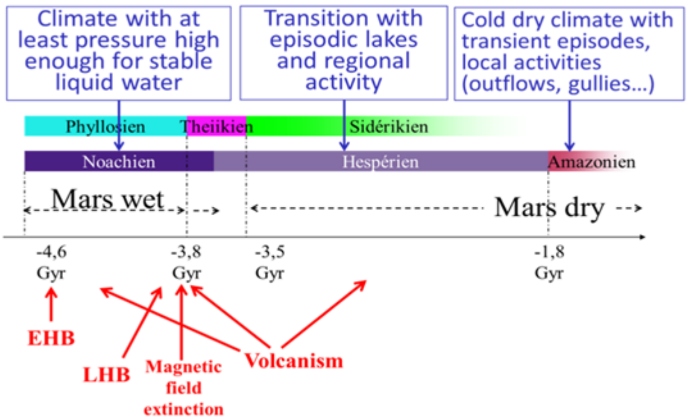

Figure 2: Mars' history, considering the major periods as described by Bibring et al., 2005; 2006.

Venus may have been habitable in its infancy with water and Earth-like oceans (Lammer et al., 2009). Venus, like Mars, has probably lost its water due to a runaway greenhouse effect. The "runaway greenhouse" occurs when water vapor increases the greenhouse effect, which, in turn, increases the surface temperature, leading to more water vapor that heats the atmosphere (Ingersoll, 1969). Another scenario leading to the same loss is the "moist greenhouse", where water is lost once the stratosphere becomes wet but in which most of the water of the planet remains liquid (Kasting, 1988). A better insight for the atmospheric evolution in general, can be obtained by comparative analysis of Earth with its neighboring terrestrial planets Venus and Mars.

All the three terrestrial planets had a significant flux of meteorites and comets in early history of the Solar System, which likely had consequences on the atmospheric evolution, on the habitability, and even possibly on the origin of life. Models capable of representing the basic aspects of impact erosion and delivery must be coupled with models of escape processes. All these processes, including the impact erosion depend on the atmosphere state. The altitudes of the magnetopause determined from the magnetic field evolution are determining the possibilities and amplitudes of the escape mechanism. Further influence from mantle degassing due to volcanism, and initial state of the thermal conditions must be considered for the overall model. The evolution of the surface pressure obtained can further be used to determine whether liquid water was sustainable at particular periods of the planet history. The IAP therefore considers, either for the whole system, or for subsystems, a number of "scenarios" that are believed to be relevant. For each scenario, one can compute the system forward or backward in time, as well as some feedback mechanisms.

The research program builds on, refines, and couples models of the individual reservoirs largely developed by the different partners. It also integrates new results of planetary geodesy – probing the deep interior, and 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 and constant shaper of planetary evolution, and on meteorites that document the early Solar System evolution and witness the geological processes taking place on and within 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 as follows:

A) GOAL: to better understand the concept of habitability, i.e. the environmental conditions capable of sustaining life.

B) OBJECTIVES:

- To improve our understanding of the thermal and compositional evolution of the different reservoirs (core, mantle, crust, atmosphere, hydrosphere, cryosphere, and space) considering interactions and feedback mechanisms;
- To investigate the chronology of differentiation processes, the onset conditions of plate tectonics and recycling of the crust and their implications for the early thermal and compositional evolution of a planet;
- To examine the role of impacts of asteroids and comets in the atmospheric evolution of the planets, providing loss 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 process and impact fluxes as a function of time;
- To identify preserved biosignature 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 the interacting reservoirs.

C) METHODOLOGIES:

- Remote sensing: analyzing and interpreting data recorded by existing instruments (space-based and ground-based), using improved models, such as radiative models of planetary atmospheres or thermal and compositional convection models of planetary interiors;
- In situ measurements: examining tracers of life in early Earth material (biosignatures) and extraterrestrial samples (meteorites), measurement of fields and particles in space from existing and future missions;
- Performing laboratory measurements and developing analytical and theoretical methods in support of such data;
- Developing and improving models and incorporating new results from laboratory data or spacecraft observations.

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1.4. Summary of the objectives of the partnership

The IAP Planet TOPERS field of research supports a broad community whose research themes are shown in the previous paragraphs with key words underlined and in italic. The Pole has focused its contribution on the full integration of these themes in the following Work Packages (WP) to better demonstrate how life can be sustained and to characterize the existence and persistence of life through the development of potential habitats (see Figure 3, where the partners are shown with the themes of research and WPs).

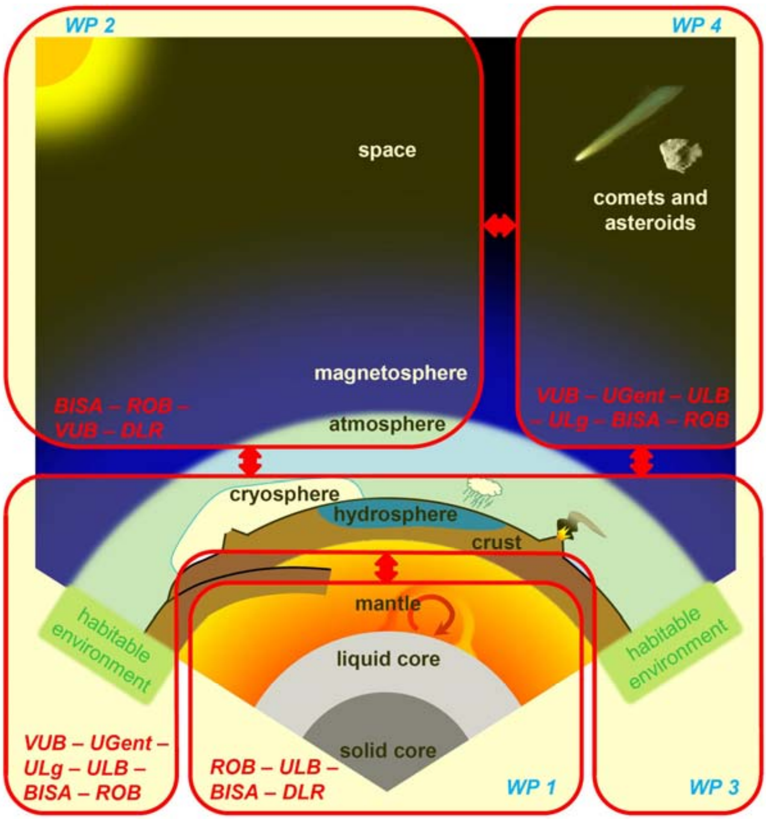

Figure 3: Sketch with all the actors and WP of the project.

1.4.1. WP 1: Internal Geophysics and Interaction with Atmosphere

The first work package studies key questions of the physics of the atmosphere and the interior interactions. It comprises the study of the thermal-chemical evolution of planetary interior relevant to atmospheric evolution and habitability. This includes the self-regulating (bio)geochemical cycles and models of mantle convection and tectonics in relation to magnetic field generation. The interactions between a solid and possibly partially liquid planet (existence of a liquid core) and its atmosphere encompass, in particular, the (partial) protection of the atmosphere from escape processes related to the existence of a magnetic field. The volatile exchange rates with the interior of the planet, and the dynamics of the interior are also of importance.

The objectives of WP 1 may be summarized with the following key words (to be recovered in the achievements below): atmosphere and interior interactions, thermal-chemical evolution of planetary interior, mantle convection models, tectonic plate models, understanding the difference between plate tectonic and stagnant lid convection, understanding early thermal evolution and plate tectonics, convection and evolution of a water-rich planet, core state and thermodynamics effects on magnetic field generation, interior models of planets, solid-atmosphere interaction, volatile exchange (regassing and outgassing), interior effects on atmospheric evolution, and (bio)geochemical cycles.

1.4.2. WP 2: Atmosphere and interaction with surface, hydrosphere, cryosphere, and space

The second work package deals with the thermal-chemical evolution of planetary atmospheres (net loss, sources and chemical reactions) and its interaction with surface, hydrosphere, cryosphere, and space to determine the evolution of pressure, temperature and composition in time, and the existence or not of liquid water. This includes the greenhouse effect as well as the regulating role of a magnetosphere on atmospheric losses. The comets and asteroids volatile mass influx from space into the atmosphere has been dealt with, as well.

The objectives of WP 2 may be summarized with the following key words (to be recovered in the achievements below): thermal-chemical evolution of planetary atmospheres, temperature and composition of atmosphere, greenhouse effect, radiative transfer, role of magnetosphere and the magnetic field on the atmosphere evolution, interaction between solar radiation and the atmosphere, atmospheric escape, impact effects on the mantle dynamics, atmosphere interaction with surface, and comets and asteroids effects on the atmosphere.

1.4.3. WP 3: Identification of life tracers, and interactions with planetary evolution

The third work package is related to the identification and preservation of life tracers. Life leaves traces by modifying microscopically or macroscopically the physical and chemical characteristics of its environment. The extent to which these modifications occur and to which they are preserved will determine the ability to detect them. By characterizing chemical and morphological biosignatures on macro- to micro-scale, preservation and evolution of life in early Earth or analogue habitats will be studied, with the objective to constrain the probability of detecting life beyond Earth and the technology needed to detect such traces. The Earth biosphere has been interacting with the atmosphere and crust at a planetary scale probably soon after its origin, in the Archaean, and most significantly since the 2.3 Ga oxygenation, with profound implications for planetary and biosphere evolution.

The objectives of WP 3 may be summarized with the following key words (to be recovered in the achievements below): identification and preservation of life tracers, microscopically or macroscopically modification of the environment physical and chemical characteristics, characterization of chemical and morphological biosignatures, preservation and evolution of life in early Earth, detection of early Earth life or habitats, interaction between life, crust, and atmosphere, and biosphere and atmosphere evolution.

1.4.4. WP 4: Accretion and evolution of planetary systems

The fourth work package investigates the chronology of differentiation processes, the onset of plate tectonics and the recycling of the crust and implications for life sustainability. Samples from the worldwide meteorite collections have been analyzed with the objective of relating their age (to be determined) and their composition to planetary evolution. The role of asteroid and comet impacts in planetary evolution of the planets are examined. In addition, the meteorites themselves document the early evolution of the Solar System and its solid bodies including their deep interiors.

The objectives of WP 4 may be summarized with the following key words (to be recovered in the achievements below): chronology of differentiation processes, onset of plate tectonics, recycling of the crust, meteorite analysis, origin of meteorites, role of asteroid and comet impacts in planetary evolution, early evolution of the Solar System from meteorites, early evolution of the Solar System from comets, small solid bodies and Solar System evolution.

1.4.5. WP 5: 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 fifth work package consists in developing, in a holistic approach, an integrated model of planetary thermodynamic engine that includes mass, energy, and entropy balances into a "*Global System dynamics*". The role of feedback cycles to stabilize habitable conditions are being examined. For instance, the net loss or gain of volatiles in the atmosphere depends on the atmospheric pressure itself. Case studies and comparisons of evolution pathways, such as between Mars, Venus, and Earth have been considered.

The objectives of WP 5 may be summarized with the following key words (to be recovered in the achievements below): integrated model of planetary thermodynamics, feedback cycles to stabilize habitable conditions, understanding the evolution of planets' atmosphere and habitability conditions, evolution of Mars, evolution of Venus, comparisons of evolutions of Mars, Venus, and Earth, understanding the habitability of ocean planets.

It must be noted that the progress in the different WPs were done in parallel but interrelated in such a way that it is at present difficult to put one research theme in one WP; it usually belongs to several WPs and almost all results are now incorporated in WP 5.

Ultimately, a roadmap for assessment of habitability on terrestrial bodies (terrestrial planets, asteroids, rocky and icy satellites, extrasolar terrestrial planets) will be provided in 2017. It will be the starting point of the next IAP phase (phase VII starting in 2018). An international interdisciplinary workshop entitled "*Geoscience for understanding habitability in the solar system and beyond*" with the participation of all the Planet TOPERS partners and of the international community, addressing key or hotly debated questions is being organized by us for September 2017. We envisage a set of keynote-reviews, followed by a set of keynote-controversial question summaries, and keynote-young scientist additional views, followed by discussions. We expect to contribute in a special issue (or at least a joint paper) of Icarus or other journal (to be decided later) where we will publish our results and the outcome of our discussions.

2. SCIENTIFIC ACHIEVEMENTS (01/10/2012 - 01/06/2016)

2.1. Early thermal evolution: magma ocean crystallization

WP involved	WP 1 – WP 5
Contributing partners	DLR – ROB – ULB – VUB
Summary description of the objectives	Understanding early thermal evolution
Summary description of the scientific activities and results	The various and intense energy sources involved in the early stages of planetary formation, such as kinetic energy of accretion, decay of short-lived radiogenic isotopes, 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. Global or local liquid magma oceans could thus have formed, whose solidification upon planetary cooling have exerted a significant impact on the differentiation and subsequent evolution of the interior of terrestrial bodies. The solidification of such magma oceans likely proceeds from the bottom upwards because of the steeper slope of the mantle adiabat with respect to the slope of the solidus, and 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. We investigated the thermal evolution of a whole-mantle magma ocean using a finite-volume code. We have studied the early planetary evolution, i.e. the magma ocean solidification phase by means of simulations involving primordial heat including radioactive elements, surface temperature evolution, cooling, crystallization and the existence of water, towards the onset of a solid-state convection prior to complete mantle crystallization.
Main achievements in relation to the initial objectives	Better understanding of the early thermal-chemical evolution of planetary interior
Comments in case of deviations from the initial project work-programme	
Illustration:	

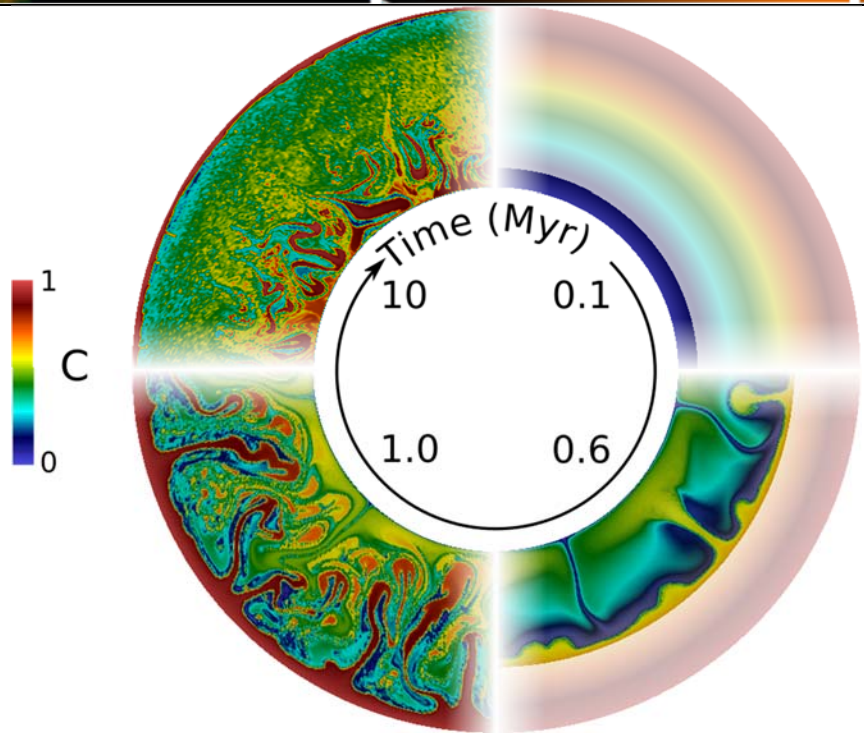

Figure 4: Time evolution of the composition field for a fractional crystallization model considering a magma ocean cooling time of 1 Myr, Ra = 10^9 and assuming a density contrast across the mantle of 239 kg/m^3.

2.2. Role of water and heat piping on volcanism/thermal evolution or vice versa

WP involved	WP 1 – WP 5
Contributing partners	DLR
Summary description of the objectives	Understanding early thermal evolution
Summary description of the scientific activities and results	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 affect 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. 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 Ga, 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. 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.
Main achievements in relation to the initial objectives	Better understanding of the early thermal-chemical evolution of planetary interior
Comments in case of deviations from the initial project work-programme	

Illustration:

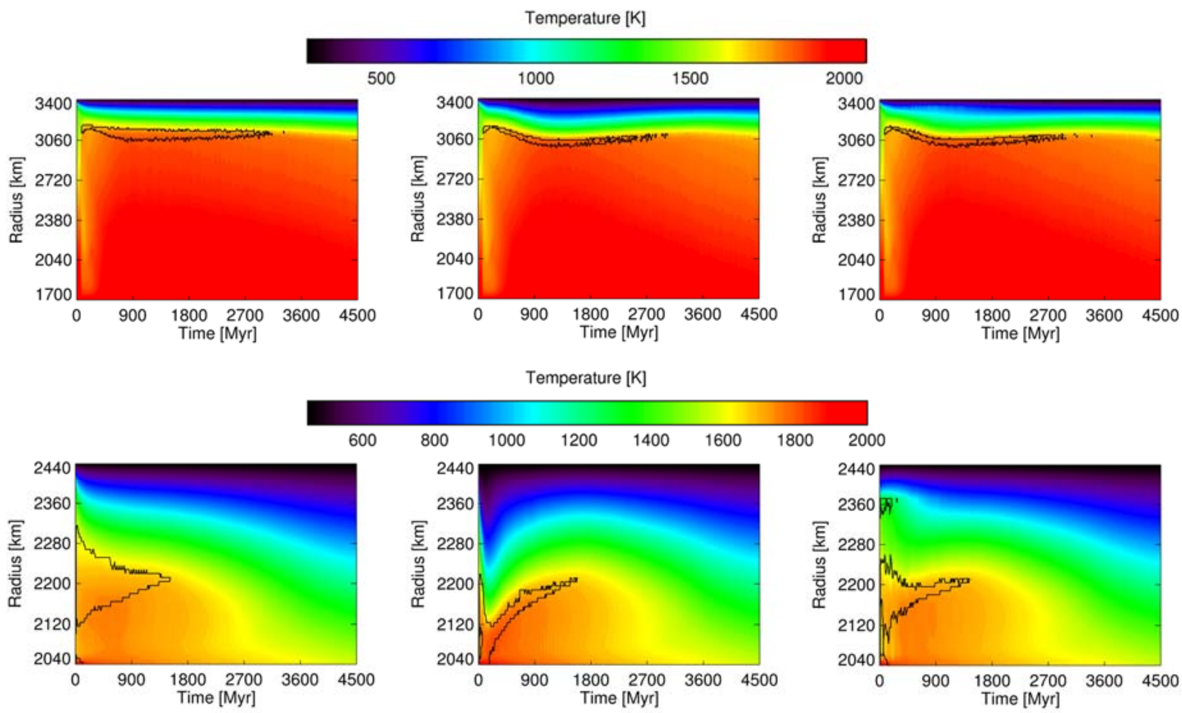

Figure 5: Heat-pipe effects in a simple thermal evolution model based on Mars-like (top row) and Mercury-like (bottom row) parameters. Time evolution of the radially averaged mantle temperature for models neglecting heat-pipe effects (left column), models including heat pipe effects with 100% melt extraction (middle column), and models assuming an extrusive-to-intrusive ratio of 0.2 (right column) – intrusive/extrusive rocks form by the crystallization of magma at depth/surface. The black contour line shows the evolution of the partial melt zone.

2.3. Mars: present thermal state and abundance of radiogenic heat sources

WP involved	WP 1 – WP 5
Contributing partners	DLR – ROB
Summary description of the objectives	Understanding early thermal evolution
Summary description of the scientific activities and results	We found that the Urey ratio of Mars – the ratio between surface heat flow and heat produced by radioactive elements – is mainly sensitive to the efficiency of mantle cooling, which is associated with the temperature dependence of the viscosity (thermostat effect), and to the abundance of long-lived radiogenic isotopes. The upcoming InSight (Interior exploration using Seismic Investigations, Geodesy and Heat Transport) mission, to be launched in 2018, will carry out the first in-situ Martian heat flow measurement and provide an important baseline to constrain the present-day heat budget of the planet and, in turn, the thermal and chemical evolution of its interior. Using an estimate of the average surface heat flow as determined by InSight, models of the amount of heat producing elements present in the deep interior can be constrained.
Main achievements in relation to the initial objectives	Better understanding of the thermal-chemical evolution of Mars
Comments in case of deviations from the initial project work-programme	
Illustration:	

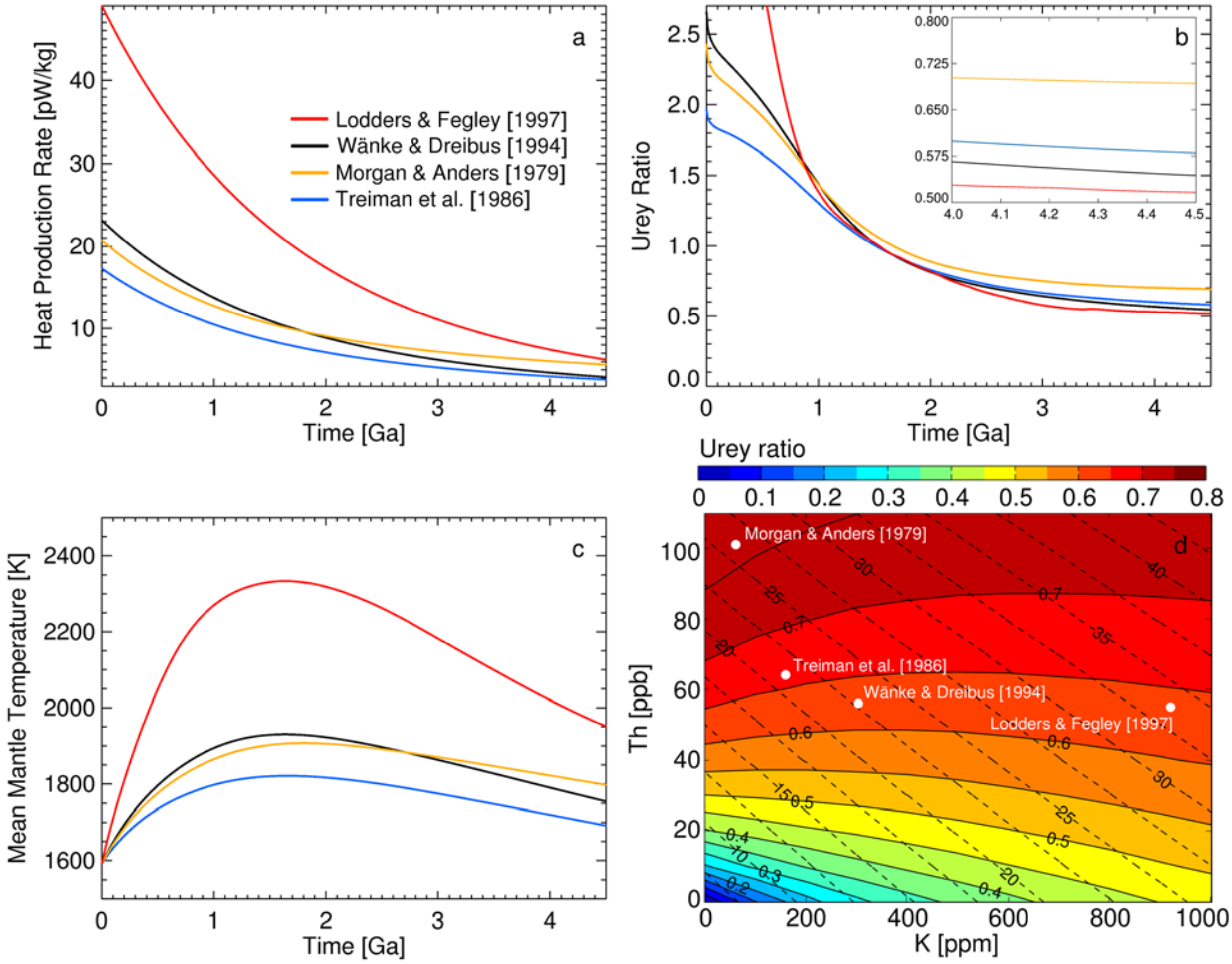

Figure 6: Effect of different heat producing elements models: (a) heat production as a function of time for the four compositional models considered; (b) corresponding Urey ratio obtained using a reference viscosity of 10^{21} Pa s; (c) time evolution of the mean mantle temperature; (d) map of the Urey ratio (solid lines) and surface heat flux in mW/m^2 (dashed lines) as function of Th and K content obtained from 1D parametrized models (white circles correspond to the heat producing elements concentrations of the four models of panel (a).

2.4. Convection code CHIC

WP involved	WP 1 – WP 5
Contributing partners	ROB
Summary description of the objectives	Mantle convection model
Summary description of the scientific activities and results	For the simulation of the interior of terrestrial planets we developed the observatory code CHIC (Code for Habitability, Interior and Crust) using the programming language Fortran90, which is regularly updated with new features and involved in several papers and benchmark studies. Different studies that currently use the CHIC code focus on the convection in high-pressure ice (see Point 2.11), mantle convection and related volcanic outgassing in terrestrial planets, and 1D thermal evolution of water-rich planets (described in Point 2.11).

	We have extended the code CHIC to include compressibility and full 2D spherical convection and participated in several community benchmarks. Tidal heating was implemented in the CHIC code. The model is based on a simplified treatment of tidal dissipation under the assumption of a two-layered model (silicate mantle and iron core) with uniform density in each layer.
Main achievements in relation to the initial objectives	Better model mantle convection and mantle evolution
Comments in case of deviations from the initial project work-programme	

2.5. Formation of continents and very early dynamics of terrestrial planets

WP involved	WP 1 – WP 5
Contributing partners	ROB – DLR
Summary description of the objectives	Understand tectonic plate onset and surface evolution
Summary description of the scientific activities and results	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). 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 in Iceland), and not by re-melting of subducted oceanic crust. 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. 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. 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, small planet masses lead to fast initial cooling and thick lithospheres that are unlikely to fracture, 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, 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, more likely or equally likely compared to Earth and depending rather on surface water. 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, 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.
Main achievements in relation to the initial objectives	Better understanding of tectonic plate onset and surface evolution
Comments in case of deviations from the initial project work-programme	

Illustration:

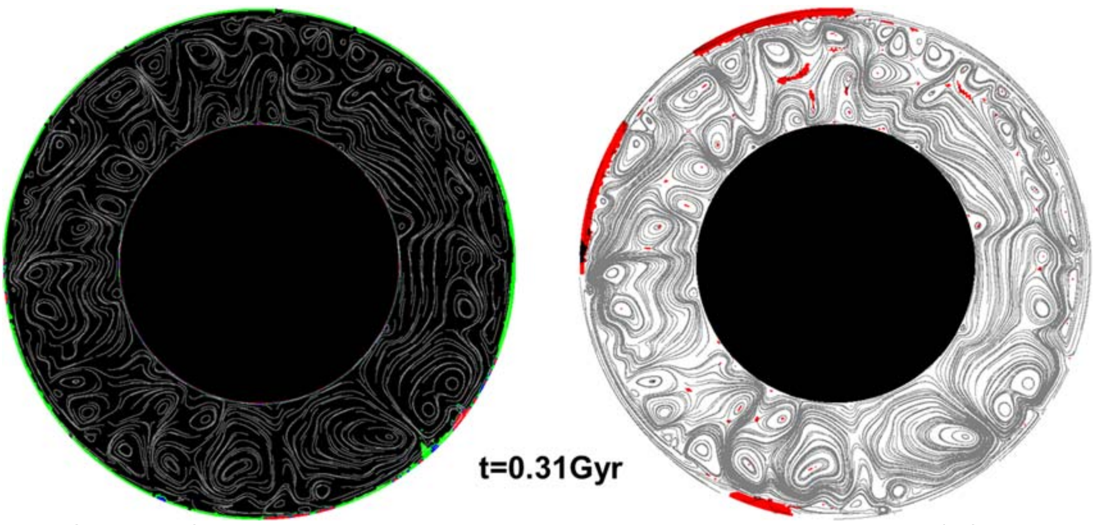

Figure 7: Continent formation and mantle convection. The primordial, basaltic crust (left panel, green crust) is mobilized after accretion of Earth, leading to crustal recycling and formation of continental crust (left panel, red crust). The right panel shows the convection strength where the larger part in white with black lines corresponds to the stronger convection and the red part corresponds to moderate convection.

2.6. Stagnant-lid regime, onset of plate tectonics and recycling of the crust

WP involved	WP 1 – WP 5
Contributing partners	ULB – ROB
Summary description of the objectives	Understanding early thermal evolution and plate tectonics
Summary description of the scientific activities and results	While everybody could agree that at the present time, the Earth is in a mobile plate tectonic regime, an important question remains to know if it has always been the case. Parent elements with short half-lives of radioactive decay that were present when the solar system began to condense into planets, can date very ancient events near or at the time when Earth began to form and undergo differentiation from 4.55 to 4.2 billion years ago. After the parent element goes extinct geological materials can retain the fingerprint of the decay of these short lived radioactive elements. Isotope analysis of old rocks indicates the efficient remixing of the first primitive crust into the Archaean convecting mantle that ultimately produces a well-mixed present-day convecting mantle. The implied long mixing time of ~1 Ga from the Hadean to Archaean for the whole mantle is paradoxical on several levels. This is much longer than the rapid mixing time (<100 Myr) inferred for the Archean due to vigorous mantle convection related to Earth's hotter thermal regime and similar to the mixing time inferred for the present-day Earth's mantle. Our results show efficient remixing of the first primitive crust into the Archaean convecting mantle. The requirement of a delayed mixing in a strongly convective mantle is best explained by long periods of stasis in the global plate system, with scarce episodes of subduction throughout the Hadean and Archean. Following this study where we are postulating that the Earth may have been in a stagnant-lid regime during the Archean, a new challenge is to explain the origin of the TTG (Tonalite-Trondhjemite-Granodiorite) suite. This suite is making the first continental crust, but its origin is poorly constrained. As the Earth is the only planet to show continental crust, it is of importance to understand why. Two views about the origin of the TTG are existing: they are related either to the melting of a recycled ocean crust in a subduction, or to the melting of the base of a thickened basaltic crust in a mantle plume context. The first view seems a priori inconsistent with a stagnant-lid regime, even though geochemical evidences favor this model. Despite this study is still ongoing, we have observed a temporal sequence with the basaltic rocks being older (3353 ± 75 Ma) and the acidic rocks (range of 2.7-2.9 Ga) being younger.
Main achievements in relation to the initial objectives	Better understanding of early thermal evolution and plate tectonics

Comments in case of deviations from the initial project work-programme	

2.7. Onset of plate tectonics and recycling of the crust and possible implication of life for sustainability

WP involved	WP 1 – WP 5
Contributing partners	DLR – ULB – ROB
Summary description of the objectives	Understanding volatile exchange (regassing and outgassing), tectonics, and the role of life
Summary description of the scientific activities and results	From the modelling point of view, we have constructed a model including (i) parameterized thermal evolution, (ii) continental growth and destruction, and (iii) mantle water regassing and outgassing. The biosphere enhances the production rate of sediments which eventually are subducted. These sediments are assumed to carry water to depth bound in stable mineral phases and they have the potential to suppress shallow dewatering of the underlying sediments and crust due to their low permeability. Our results suggest that the origin and evolution of life could have stabilized the large continental surface area of the Earth and its wet mantle, leading to the relatively low mantle viscosity we observe at present. Following the proposition that plate tectonics may not have active during the Archean period we investigated the West African Craton to understand if we can observe indicators of plate tectonics, such as subduction zones chemical signatures. Up to now, the basaltic rocks show no indication of subduction zone component, and the more acidic rocks proposed to resulting from subduction, are younger.
Main achievements in relation to the initial objectives	Better understanding of volatile exchange (regassing and outgassing)
Comments in case of deviations from the initial project work-programme	
Illustration:	

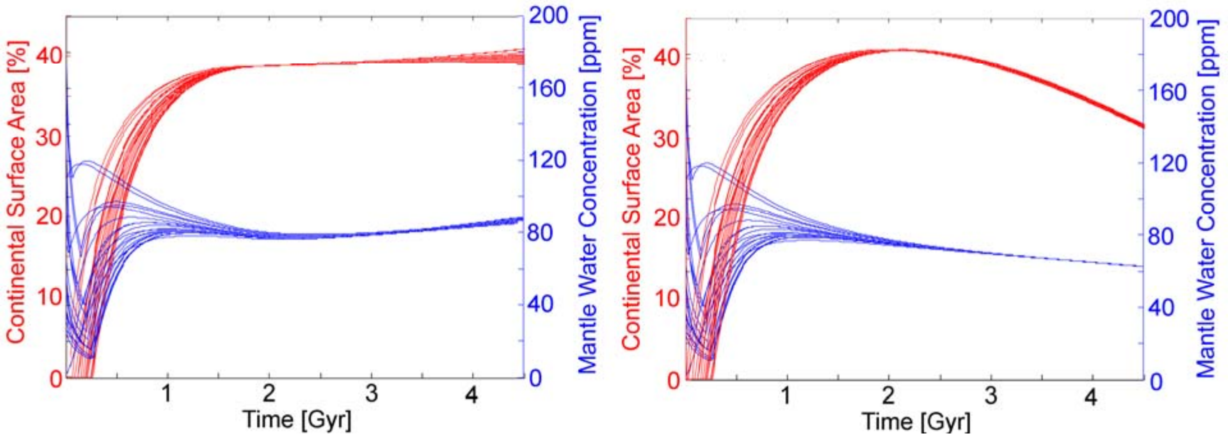

Figure 8: Continental growth (red) and mantle hydration (blue) for a model using reference parameters of the Earth (left) and for a model using the same parameters but a reduced rate of continental weathering and erosion by 20%, simulating the evolution of an abiotic Earth (right). Initial conditions for the biotic model are derived from a Monte-Carlo Scheme and treated as successful for 40 (±1) % continental coverage at t=4.5 Gyr. The abiotic model uses the same initial conditions. Smaller rates of continental weathering and erosion in the abiotic model reduce the rate at which sediments are subducted. Less water reaches mantle depths and the rates of continental production and mantle water regassing decrease. The biotic model features large net growth rates in early evolution and a steady state thereafter accompanied by an increasing mantle water concentration. In the abiotic model, continental coverage and mantle water concentration decrease during the last 2 Gyr.

2.8. Mars and Mercury: core material and evolution, magnetic field generation

WP involved	WP 1 – WP 5
Contributing partners	ROB – DLR
Summary description of the objectives	Understanding core state, composition, and thermodynamics effects on magnetic field generation
Summary description of the scientific activities and results	A precise thermodynamic description of planet's core materials is of fundamental importance for understanding of the core evolution. We have used high-pressure and high-temperature data about the thermoelastic properties and Fe-S core material melting properties in order to build a thermodynamic model of core materials. We have used gravity field and rotation observation of Mercury to constrain its internal structure. For interior models that give rise to solid iron crystallization (and thus magnetic field), we have computed the radius of the inner core. We have studied the thermal evolution of the whole planet to determine whether the buoyant upwellings generated by solid iron crystallization are larger enough to contribute substantially to the generation of the internally generated magnetic field. We have studied the various aspects of core crystallization and magnetic field generation of terrestrial planets and discussed in particular the iron snow regime of Ganymede as a mechanism for its present day

	dynamo.
Main achievements in relation to the initial objectives	Better understanding of core state, composition, and thermodynamics effects on magnetic field generation of Mars and Mercury
Comments in case of deviations from the initial project work-programme	

Illustration:

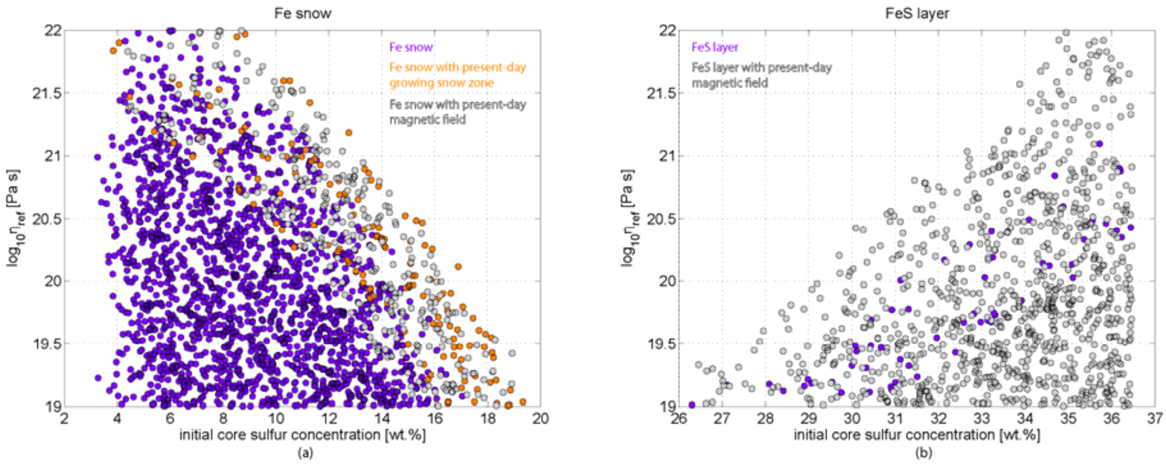

Figure 9: The reference mantle viscosity as a function of initial core sulfur concentration for Fe snow (a) and FeS layer (b) models. In (a), purple, orange and gray circles refer to all Fe snow models, Fe snow models with a present-day growing snow zone, and Fe snow models with a present-day magnetic field, respectively. In (b), purple and gray models refer to all FeS layer models and FeS layer models with a present-day magnetic field, respectively.

2.9. Knowledge on interior from present-day observation for understanding the evolution of the interior

WP involved	WP 1 – WP 5
Contributing partners	ROB – DLR
Summary description of the objectives	Interior models of planets
Summary description of the scientific activities and results	By using future observations, in particular within the InSight (Interior exploration using Seismic Investigations, Geodesy, and Heat Transport) and ExoMars future missions, we will be able to better constrain the interior of Mars. Measuring Doppler shifts on radio links between radio telescopes on Earth and landers on Mars, we have already been able to observe the precession and nutation of Mars. These observations were using the MER (Mars Exploration Rover) data when they were fixed at the surface of Mars. The existence of a liquid core inside Mars play indeed an important role in nutation amplitudes (periodic variation of Mars' orientation in space). An everyday example of the influence of the physical state of the interior on the rotation is that raw (liquid) and cooked (solid) eggs rotate differently. The nutation observations indicate that the core of Mars is liquid, confirming results obtained by the

	observation of the effect of Mars tides on the orbit of a spacecraft.
Main achievements in relation to the initial objectives	Better understanding of the deep interior of Mars
Comments in case of deviations from the initial project work-programme	

2.10. Habitability of terrestrial planets: outgassing and plate tectonics

WP involved	WP 1 – WP 5
Contributing partners	ROB
Summary description of the objectives	understanding the volatile exchange (regassing and outgassing) and the evolution of planets' atmosphere and habitability conditions
Summary description of the scientific activities and results	By using our convection and tectonic plate formation model, we have studied the geophysical limitations for terrestrial planets in terms of outgassing of greenhouse gases, which influences the possible habitability of these planets. We investigated the possible outgassing efficiency of terrestrial planets with masses ranging from Mars-size to super-Earth size and varying interior structure. We find that one-plate planets may suffer strong volcanic limitations if their mass and/or iron content exceeds a critical value, leading to an insufficient greenhouse effect. In that case, the outer boundary of the habitable zone moves inward, setting an important constraint for the possible surface habitability of these planets. For plate tectonics planets, no such limitations was found.
Main achievements in relation to the initial objectives	Better understanding of the volatile release and the evolution of planets' atmosphere and habitability conditions depending on planet mass and composition
Comments in case of deviations from the initial project work-programme	
Illustration:	

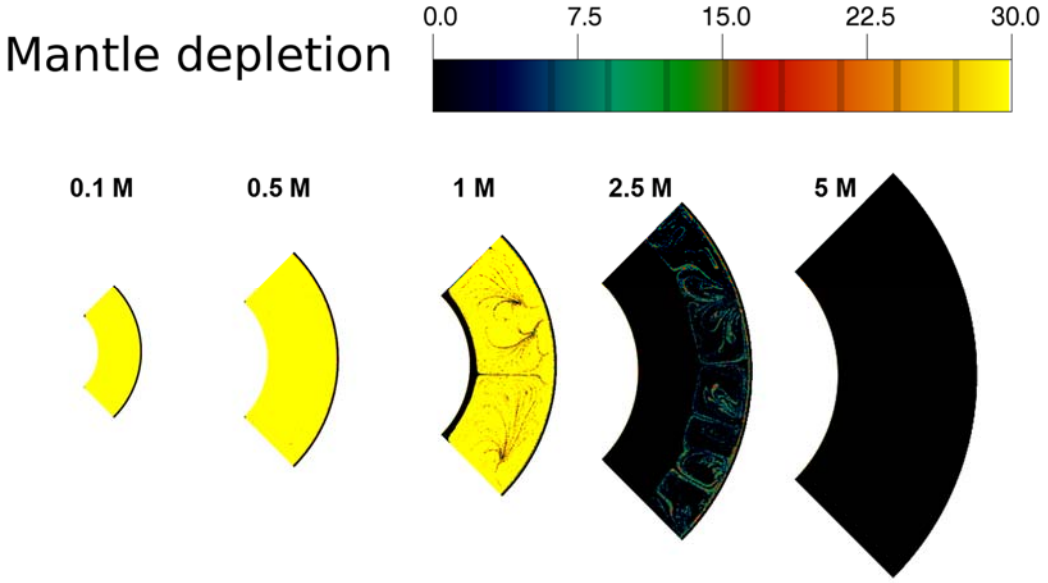

Figure 10: Mantle depletion by partial melting for planets of Earth-like composition but variable planet mass from Mars-size (0.1 Earth masses) to super-Earth size (here 5 Earth masses). Large-massive stagnant lid planets are not expected to show volcanic activity during their evolution.

2.11. Convection in high-pressure ice

WP involved	WP 1 – WP 5
Contributing partners	ROB
Summary description of the objectives	Understanding water-rich planet convection
Summary description of the scientific activities and results	We have worked on the simulation of the thermal evolution of high-pressure ice layers that occur in water-rich planets or moons and on the possibility to obtain convection and material exchange within the ice layer. The simulations include phase transitions between different high-pressure ice phases. We find that layered convection can occur, since phase transitions between high-pressure ice regimes can hinder material transport from bottom to surface of the ice layer.
Main achievements in relation to the initial objectives	Better understanding of convection and material exchange in high-pressure ice layers
Comments in case of deviations from the initial project work-programme	
Illustration:	

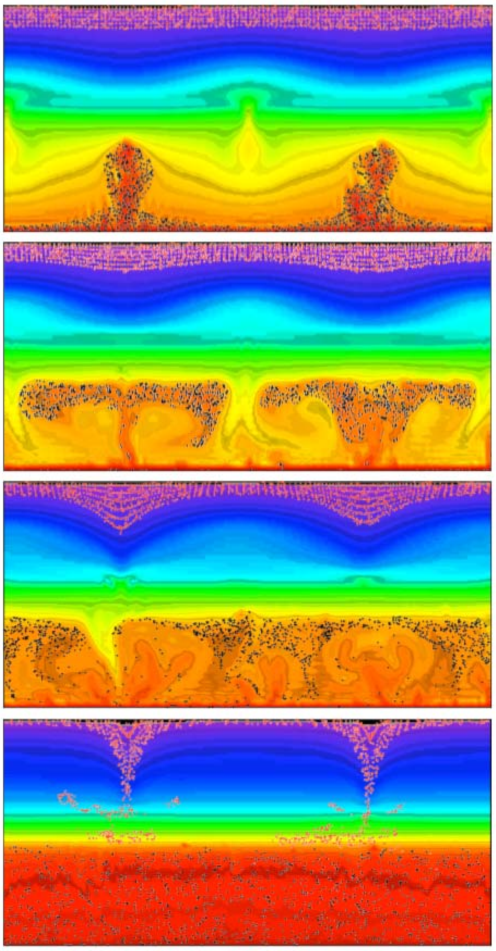

Figure 11: Ice convection using a diffusion rheology. Temperature field including material tracers for a 200km thick high-pressure ice sphere with phase transition between ice VI and ice VII at 0.05, 0.4, 1.3 and 11 Myr.

2.12. Quantitative study of water-rich exoplanets

WP involved	WP 1 – WP 5
Contributing partners	ROB – DLR
Summary description of the objectives	Understanding water-rich planet convection and evolution
Summary description of the scientific activities and results	Simulations have been performed to address the thermal evolution and possible habitability of water-rich exoplanets. We investigated possible interior structures for exoplanets of varying composition. The interior structure of water-rich planets cannot be determined uniquely, even if mass and radius of the planet are known exactly. For a core assumed to consist of liquid iron, for a mantle composed of Mg-silicates, and for a water layer consisting of liquid water or ice, we have investigated the existence and evolution of a water layer inside planets from about Mars-size to almost Neptune-size planets. The water layer on such planets could be hundreds of

	kilometers deep depending on the initial water content and the evolution of the proto-atmosphere. A new water planet model has been developed coupled with the interior structure model to infer the depth-dependent thermodynamic properties of high-pressure water and the possible formation of high-pressure ice. This high-pressure ice layer may melt from beneath leading to a thin ocean layer between ice and silicate mantle, which is a possible habitable niche for life to form on water-rich planets. The study has been complemented by a quantitative study using Monte-Carlo simulations. We have shown that the existence of liquid water beneath the high-pressure ice is mainly limited by the heat flowing out of the mantle and the planet mass, and that the surface temperature has the largest influence on the thickness of the lower ocean layer.
Main achievements in relation to the initial objectives	Better understanding of water-rich planet convection and evolution
Comments in case of deviations from the initial project work-programme	

Illustration:

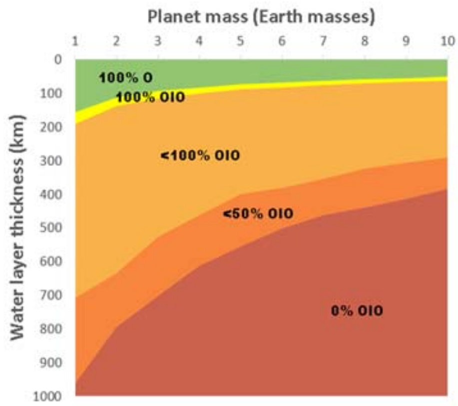

Figure 12: Lower ocean appearance regimes for different planet masses and water layer depths. OIO stands for ocean-ice-ocean structure. Values below 100% OIO indicate an episodic regime, 0% OIO means that ice is not molten from beneath.

2.13. Present-day constraints for understanding the evolution of the atmospheres

WP involved	WP 2 – WP 5
Contributing partners	BISA
Summary description of the objectives	Obtain composition of atmospheres, with focus on species related to their evolution, for ex. D/H ratio or CH_4 on Mars
Summary description of the scientific activities and results	Compositions of planetary atmospheres are derived from observations performed by instruments in orbit around planets such as Mars or Venus, using absorption lines or bands of the targeted species.

Of particular interest is the knowledge of abundances of water (H_2O) and its isotopologue HDO, or methane especially for Mars.

Water vapor in the Venus mesosphere is involved in the cloud formation process and contributes to the runaway greenhouse effect. Understanding water vapor abundance, distribution and variability is therefore important to Venus climate and dynamical modelling.

Measuring the abundances of H_2O and HDO allows the determination of the D/H ratio, which is crucial for the understanding of the evolution of atmospheres and climate through time. The observed enrichment of deuterium in water vapor on Venus by two orders of magnitude clearly indicates that the young Venus was wet and then lost most of its water with a significant isotope fractionation. However, there is still controversy on the exact value of the D/H ratio on Venus and on whether it varies with altitude. A variation with altitude is not supported by current photo-chemical models for H_2O and HDO that predicts a constant D/H ratio in H_2O up to 100 km.

Both H_2O and HDO are targeted with SOIR. H_2O is detected between 70 – 110 km and HDO is detected between 70 – 95 km altitude. Numerous H_2O and HDO SOIR observations have been obtained between 2006 – 2014 and with recent improvements in instrument calibration, data reduction and a long base line of data; the analysis of the whole data set has been initiated, starting with the 200 observations for which both species are targeted simultaneously, which are spread in latitude, local solar time and over the duration of the VEX mission. The figure below gives water vapor density, volume mixing ratio and D/H ratio profiles obtained for this subset of orbits. While a high variability is observed in both density and VMR (Volume Mixing Ratio) profiles, a long-term trend is observed only for the density profiles. No local solar time or latitudinal dependence was found. The D/H ratio was found to be constant up to 100 km of altitude and to increase with altitude above. Preferential photolysis of H_2O over HDO could be a driving force for isotopic enrichment at high altitudes.

Methane concentrations are important to know to understand its role on atmosphere evolution. The issue is very timely for Mars exploration. Indeed, methane has been observed from space and from Earth, although its presence was not foreseen in the atmosphere of Mars. Has it been produced a long time ago, then stored into the (sub-)surface and released nowadays? Is it still produced today? Obtaining maps of methane and vertical profiles will constrain the origin of the methane on Mars. The ExoMars TGO 2016 will try to answer these questions. One of the on board instrument, NOMAD, has been designed by BISA and will regularly measure CH_4.

	In preparation of the mission, sensitivity studies have been carried out to determine the detection limits on this species. Using the optical and radiometric models of the different channels and devising typical levels of radiation to be observed, we could derive the expected SNR (Signal to Noise Ratio) values in different observation conditions. Knowing the expected SNR, it is possible to derive the expected detection limits for various species present in the Martian atmosphere. This has been done for the different channels (IR and UV) and for the different observation modes (solar occultation and nadir). The Optimal Estimation Method was used to characterize the detection limits achievable with the LNO (Limb, Nadir and solar Occultation) channel in nadir observation mode for 17 molecules. Several orders of diffraction were considered in order to find out the best spectral ranges to study. For each molecule and each order, the values of the Degree Of Freedom of the Signal (DOFS) for all the retrievals. The detection limits were determined using the DOFS values.
Main achievements in relation to the initial objectives	Obtain abundances of H_2O and its isotopologue HDO, leading to D/H profiles in the atmosphere of Venus; Preparation for the measurement of CH_4 on Mars
Comments in case of deviations from the initial project work-programme	

Illustrations:

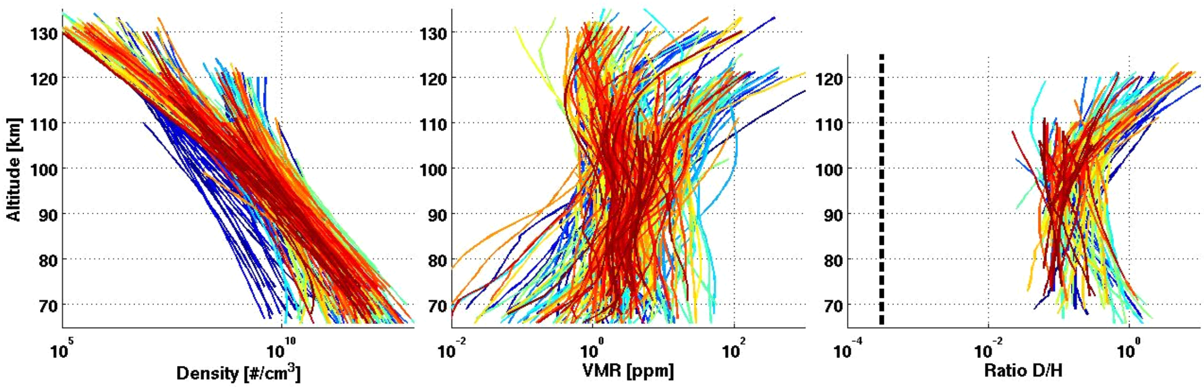

Figure 13: Water vapor and D/H ratio in the Venus mesosphere from the analysis of SOIR observations. H_2O and HDO density (left panel) and VMR (central panel) profiles, and D/H ratio (right panel). The dashed line is the D/H ratio value on Earth. The color code corresponds to the orbit number, from dark blue (August 2006) to brown (August 2014).

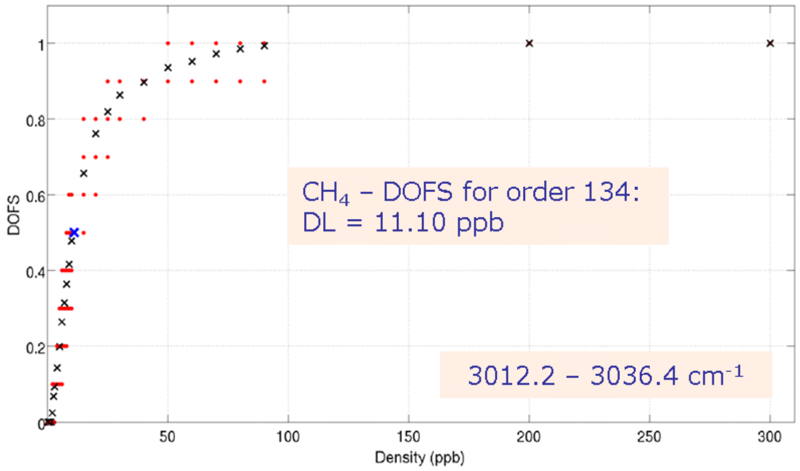

Figure 14: Degree of freedom for Signal (DOFS) of the retrievals in the LNO diffraction order 134 (3011.893 - 3036.072 cm^{-1}) for CH_4. The red dots correspond to each individual retrieval. The black crosses represent the averages of the DOFS for each considered factor. The blue cross indicates the value of DOFS=0.5, hence the value of the detection limit in abscissa, in ppb.

2.14. Planetary atmospheres – trace gases

WP involved	WP 2 – WP 5
Contributing partners	BISA - ULg
Summary description of the objectives	Obtain temperature and composition of atmospheres
Summary description of the scientific activities and results	Present-day search for biosignatures in spectra of other planets' atmospheres can be performed by using space data. In addition, planetary atmospheres derive from one or more reservoirs of primordial volatiles. The chemical and isotopic compositions of present-day atmospheres provide clues both to the characteristics of the source reservoirs and to the nature of the subsequent processing of the volatiles. The key diagnostic volatiles for tracing atmospheric origin and non-biogenic evolution are the noble gases, nitrogen as N_2, carbon as CO_2. BISA was responsible (PI) for the SOIR instrument on board the ESA mission Venus Express. The Venus Express mission sadly ended in Dec. 2014 after all its fuel had been used. The SOIR instrument is an IR spectrometer which allowed the detection of a broad series of species. Although the mission has ended, we still have continued the analysis of the wealth of data recorded by the instrument. The vertical profiles of the minor constituents and the CO_2 vertical profiles are obtained simultaneously. Up to now, CO, HCl, HF, H_2O and HDO are systematically retrieved with a very good precision. One of the major activities was the optimization of the procedure to obtain accurate transmittances from the spectra recorded by the instrument. We have implemented a complex algorithm to select the best spectra to derive the transmittances. This led to the

	creation of a new dataset, with a higher number of data (problematic observations which were not analyzed before, are now included) of higher quality. This dataset was ingested into the PSA database of ESA. In parallel, the analysis of the existing transmittances continued and the results of the analysis were published in a series of 9 papers which appeared in a special issue of PSS devoted to the “Exploration of Venus”. Study of Mars has continued through the analysis of the SPICAM ultraviolet spectra. The analysis of the UV domain allows to study different species and constituents of the Martian atmosphere such as ozone, dust and ice clouds. In the frame of this work, we developed a method capable of inverting the SPICAM spectra obtained in nadir viewing in order to simultaneously retrieve the integrated quantities of these different quantities i.e. the ozone total column, and the integrated optical depths of dust and ice clouds. The retrieval on several Martian years allowed to obtain climatologies of these different species such as the ozone seasonal distribution given in Figure 15.
Main achievements in relation to the initial objectives	Obtain temperature and composition of atmospheres, as well as volatile concentrations
Comments in case of deviations from the initial project work-programme	

Illustration:

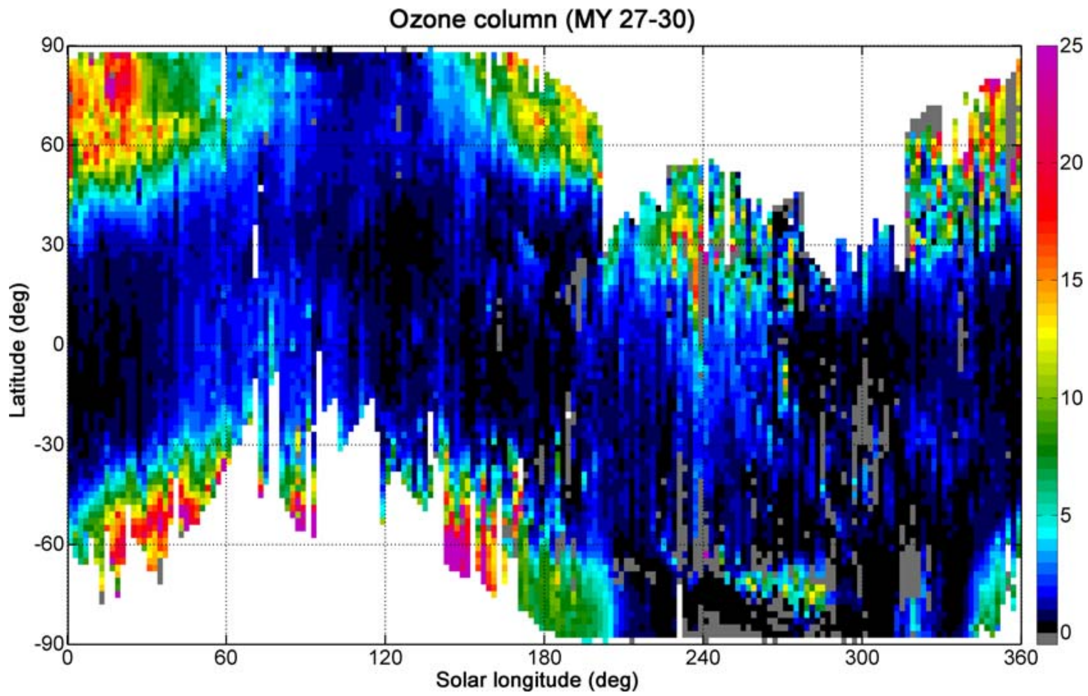

Figure 15: Seasonal evolution of the zonally averaged ozone total column (in μm-atm) retrieved from SPICAM data. The values are averaged on more than four Martian years of the dataset (from MY: 26.9 to 31.0). The white areas correspond to regions where no measurements were performed, the grey background represents the measurement coverage and the color scale ranging from black to purple indicates the retrieved ozone column.

2.15. Planetary atmospheres – clouds, dust and aerosols

WP involved	WP 2 – WP 5
Contributing partners	BISA – ROB
Summary description of the objectives	Obtain information on clouds, dust, and aerosols in general
Summary description of the scientific activities and results	Dust, aerosols and clouds are found in every planetary atmosphere. Their impact on the radiative balance is crucial, since they absorb and scatter radiation very effectively. The analysis of the aerosols on Venus using SOIR/VEX observations has been pursued with the focus on improving the retrieval of microphysical properties of the particles from the spectral dependence of the baseline of the spectra. BISA developed a method capable of inverting the SPICAM spectra obtained in nadir viewing in order to simultaneously retrieve the integrated quantities of these different quantities i.e. the ozone total column, and the integrated optical depths of dust and ice clouds. The method is based on the coupling of three different parts. First, a Martian GCM which provides the initial characteristics of the local atmosphere (temperature, pressure, gas concentrations, etc.). The second part is LIDORT, a full radiative transfer model, for the simulation of spectra and the calculation of the Jacobians (derivatives). And the last part is the optimal estimation method which is used to retrieve the integrated atmospheric quantities. The surface reflectivity was also considered and was retrieved in the cases where no ice clouds are present in the observed scenes, ice clouds reducing the sensitivity in the surface albedo. Therefore, a cloud detection algorithm has also been developed and its results were compared with results obtained with other instruments: the comparison with cloud detection results from OMEGA/MEX was shown to be very promising. In fine, the results of the retrieval method, obtained over more than four Martian years, were used to produce new climatologies of the different quantities under study: the spatial and seasonal distributions of the ozone column, the optical depths of dust and ice clouds (see Figure 16) and also the surface albedo.
Main achievements in relation to the initial objectives	Obtain maps of clouds occurrence, cloud opacities, dust opacities, and surface albedo
Comments in case of deviations from the initial project work-programme	
Illustration:	

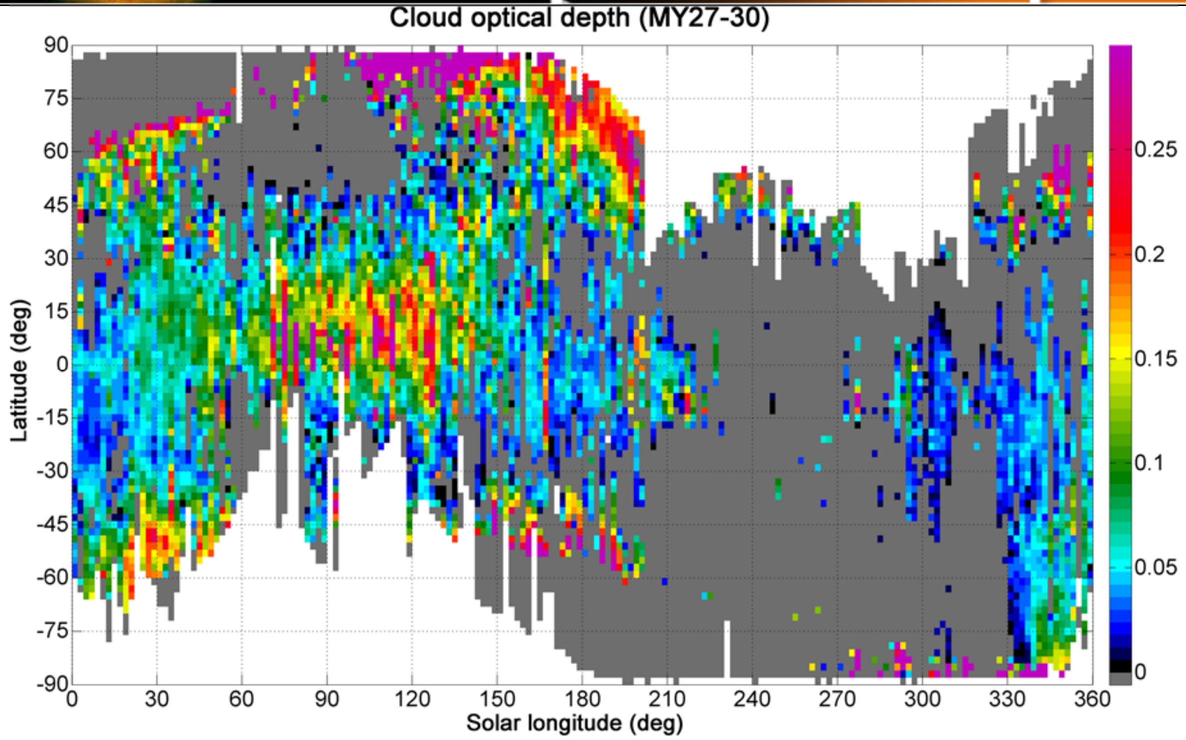

Figure 16: Seasonal evolution of the zonally averaged cloud opacity retrieved from SPICAM data. The values are averaged on more than four Martian years of the dataset (from MY: 26.9 to 31.0). The white areas correspond to regions where no measurements were performed, the grey background represents the measurement coverage and the color scale ranging from black to purple indicates the retrieved cloud opacity.

2.16. Planetary atmospheres – Radiative transfer

WP involved	WP 2 – WP 5
Contributing partners	BISA – ROB
Summary description of the objectives	Obtain thermal-chemical evolution of planetary atmospheres
Summary description of the scientific activities and results	The ASIMUT line-by-line radiative transfer code has been improved. Most of the improvements have been performed in the frame of the Radiative Transfer codes comparison exercise which was started between the members of the NOMAD consortium. The tests cover different simulation conditions, i.e. UV and IR, nadir and solar occultation. Other improvements have been carried out within the IAP and the H2020 UPWARDS project. They concern two aspects: (1) With the objective to improve our knowledge of the atmospheric behavior in the day-night transition region, we have: ● better understood and modeled the photochemistry of the Martian atmosphere at the terminator to derive gradients of density and temperature across the

	terminator, ● improved the retrieval scheme used to analyze solar occultation observations in order to handle concentration gradients along the line of sight, ● and applied the improved retrieval scheme to SPICAM solar occultation data, focusing on ozone (O_3). (2) With the objective of better exploiting the synergy between instruments/missions, we have investigated the retrievals not only carried out on single instrument but as well by combining different instruments. In the frame of the scientific preparation of ExoMars Trace Gas Orbiter, synergistic retrievals were performed on synthetic spectra of two different remote sensing instruments of the Martian atmosphere. To benefit from their diversity, we have simulated spectra of a Fourier transform spectrometer, working in the near to far infrared and of a grating spectrometer, working in the near infrared. As control runs, non-synergistic retrievals were performed as well. Two molecules were chosen to test this method: carbon monoxide and methane. Idealistic scenarios were selected and two different vibrational bands for each molecule were used to retrieve molecular volume mixing ratios. Synergistic retrievals for CO are useful both in solar occultation and in nadir, while for CH_4, the results are not as conclusive due to the weak signal in the ν_4 vibrational band compared to the stronger ν_3 band. In parallel a synergistic study has been started using experimental data from Mars Express. CO will be retrieved using two IR instruments: PFS and OMEGA. Again non-synergistic retrievals will be performed as test-cases. Diagnostic tools such as DOFS and Averaging Kernels will be used in order to assess the success of the synergies.
Main achievements in relation to the initial objectives	Obtain present-day constraints on thermal-chemical evolution of planetary atmospheres
Comments in case of deviations from the initial project work programme	
Illustration:	

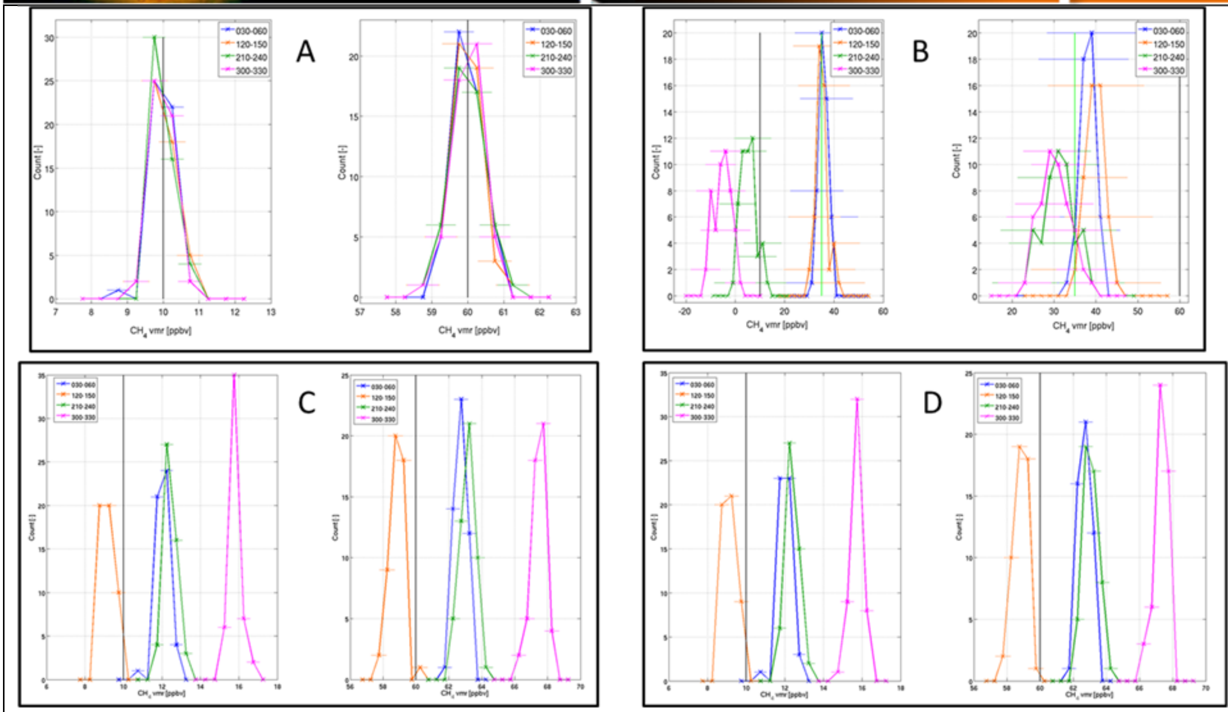

Figure 17: Statistical distribution of the 50 retrievals in the column mode of CH_4. (A) with the Grating-Acousto-Optic Tunable Filter (AOTF) instrument only, (B) with the Fourier Transform Spectrometer only, (C) in synergy Level 1/ Level 1, and (D) in synergy Level 2/ Level 1 in the case of low VMR (10 ppbv) on the left and high VMR (60 ppbv) on the right. The four different L_s periods are indicated in different colors. The a priori value was 35 ppbv in all cases. All results within 0.5 ppbv (A, C, D) or 2 ppbv (B) are binned together. The black vertical line on each plot represents the GEM value expected to be retrieved.

2.17. Planetary atmospheres – General Circulation Model – GCM

WP involved	WP 2 – WP 5
Contributing partners	BISA – ROB
Summary description of the objectives	Obtain thermal-chemical evolution of planetary atmospheres
Summary description of the scientific activities and results	With the objective to elaborate atmospheric models for the different planets (starting with Venus for which already a lot of data are available through the SOIR instrument), along with photochemical models of particular cycle or phenomenon (sulfur cycle on Venus, methane on Mars), Planet TOPERS members have developed and benchmarked a Global Circulation Models (GCM). With atmospheric models, we understand a repository of geophysical data accessible in terms of species, time, solar local time, longitude and latitude, etc. We have further developed GCM and radiative transfer codes all along these years. Simulations based on these codes and allowing sensitivity studies have been performed. The Mars GCM model was applied for continued support

	of observations by e.g. the Phoenix lander, and was successful in explaining observed dust layers by a phenomenon first discovered on Earth: the solar escalator (self-lifting of dust by radiative heating). One of the recent developments to the BISA GCM is the inclusion of radiatively active water ice clouds which allows a better representation of water vapor, trace gases and general circulation in the model simulations. In preparation of TGO, the precise evolution of methane throughout the atmosphere after a surface release has been simulated in our GCM. It was found that on the timescale of a few weeks, the released methane can establish a highly non-uniform vertical distribution including distinct vertical layers. Such layers will be detectable by NOMAD and are a signature of recent outgassing activity on Mars.
Main achievements in relation to the initial objectives	Obtain thermal-chemical evolution of planetary atmospheres and prepare for future observations
Comments in case of deviations from the initial project work-programme	
Illustrations:	

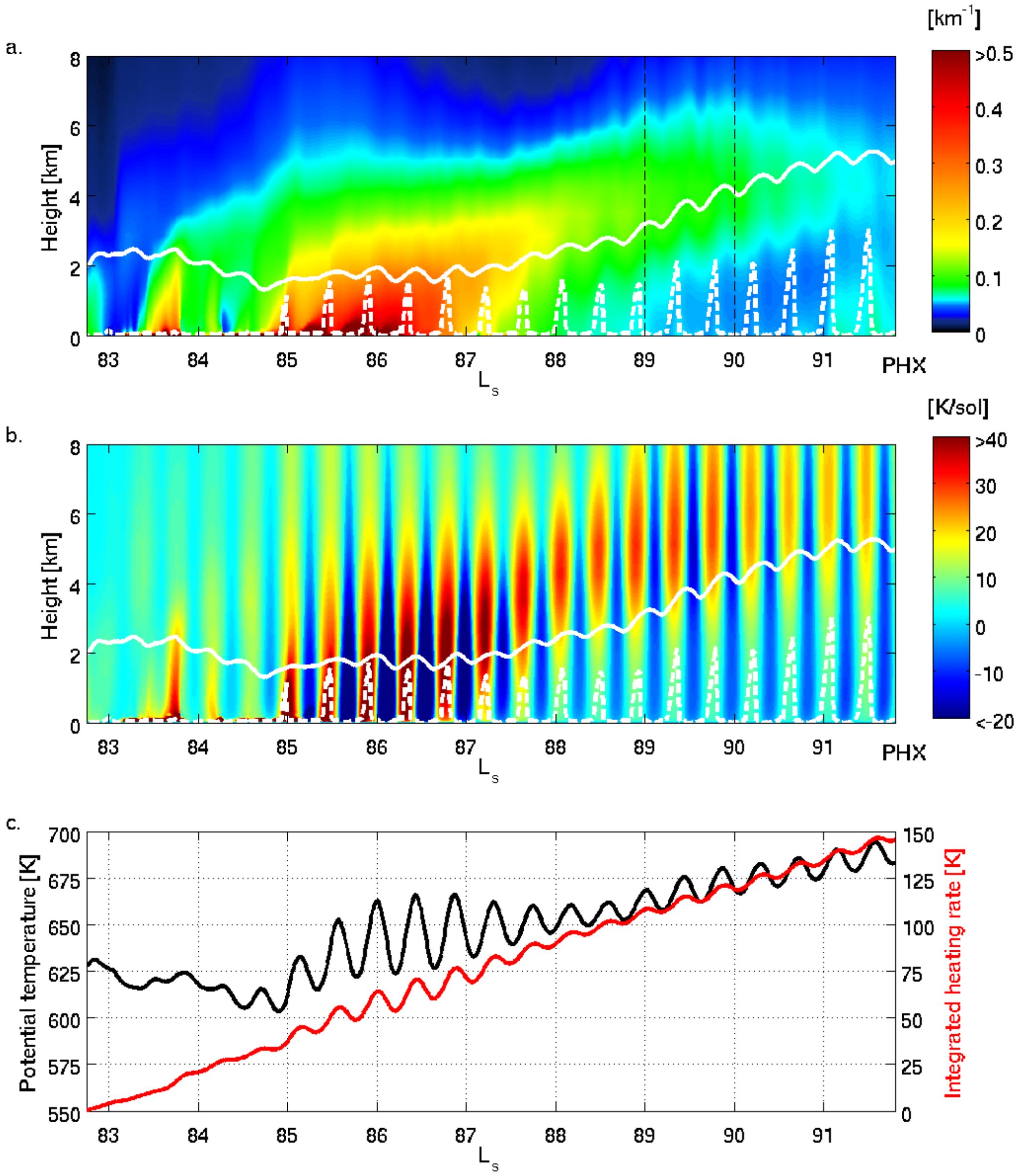

Figure 18: A solar escalator on Mars. The plots show GEM-Mars simulations of (a) dust extinction coefficient and (b) dust IR heating rate along a back trajectory starting from the Phoenix lander location at the time when detached dust layers were observed by the LIDAR (right hand side of the figures corresponds to Phoenix). The back trajectory was calculated using the simulated wind fields. The observed dust layers could be traced back to local dust storm activity at the edge of the north polar cap. The trajectory was found to rise due to the solar heating of the dust in the air parcel itself (self-lifting). Plot (c) shows that the integrated heating rate along the trajectory matches the change in potential temperature of the air, which proofs that it is the heating of the dust alone that is responsible for the rising of the air parcel. The diurnal cycle in solar heating leads to a step-like shape of the trajectory (escalator).

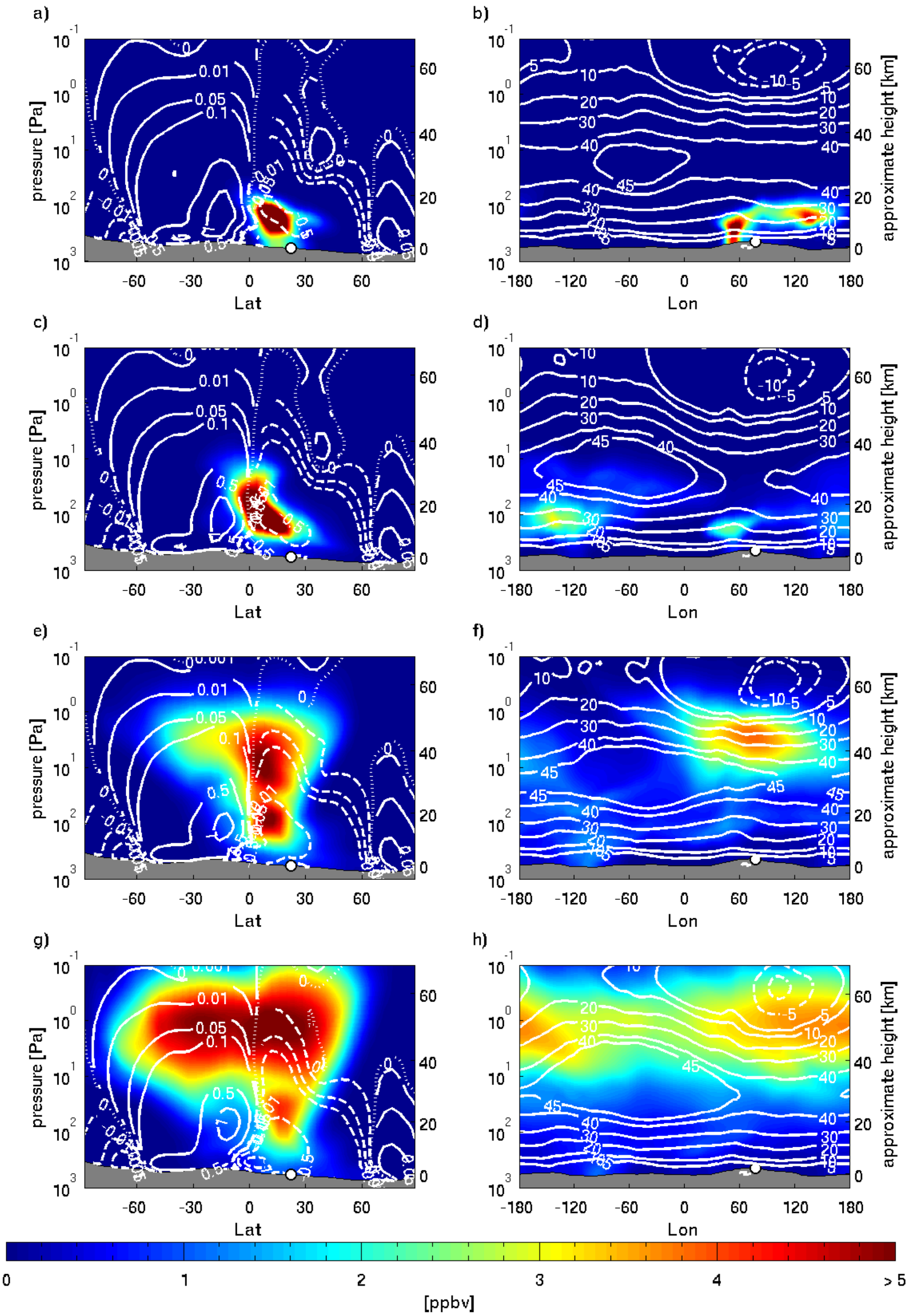

Figure 19: GEM-Mars simulation of methane outgassing on Mars. The figures show the vertical distribution of methane Volume Mixing Ratio (VMR) in ppbv for (a, b) 5, (c, d) 10, (e, f) 15, and (g, h) 20 sols after a surface emission at Nili Fossae (indicated with a white dot). Figures a, c, e, and g show zonal mean methane VMR with contour lines of the mass stream function (×10^9 kg/s) zonally averaged over the planet and over the five preceding sols. Full lines represent counterclockwise movement, and dashed lines represent clockwise movement of air. Figures b, d, f, and h show meridional mean methane VMR

with contour lines added of the zonal component of the wind fields averaged over all latitudes and over the five preceding sols. Westerlies and easterlies are, respectively, represented by the full and dashed lines. The simulations illustrate that it takes several weeks for methane to become more well-mixed throughout the atmosphere, and during this time its vertical distribution can be highly non-uniform. Such a vertical distribution could be detected by NOMAD.

2.18. NOMAD

WP involved	WP 2 – WP 5
Contributing partners	BISA – ROB
Summary description of the objectives	Obtain surface characteristics, temperature and composition in the Martian atmosphere, including clouds and dust
Summary description of the scientific activities and results	NOMAD (Nadir and occultation for Mars Discovery) – a UV-VIS and IR spectrometer suite on the ExoMars TGO 2016 has been delivered to ESA and integrated on the spacecraft. The launch was in March 2016 from Baikonur in Kazakhstan. The observation of methane is essential in the frame of Planet TOPERS. In recent years, several detections of methane in the atmosphere of Mars were reported from Earth-based observations and from Mars orbiter observations. The methane on Mars could be either abiotic or biotic. On Mars, methane has a non-uniform distribution involving an observed lifetime of 200 days, smaller than the 300 years predicted by photochemical models. Pinpointing the exact origin requires measurements of methane isotopes 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. Scenarios of observations were characterized varying geometries, instruments, aerosol loadings, solar zenith angles, concentrations of molecular species, tangent heights and solar longitudes. All spectra were simulated using atmospheric conditions obtained by GEM-Mars, the BISA GCM.
Main achievements in relation to the initial objectives	Instrument has been built and launched; Calibration observations were carried out on ground and in-flight; analysis is ongoing; scientific preparation of the instrument was started
Comments in case of deviations from the initial project work-programme	
Illustration:	

Figure 20: NOMAD instrument for TGO ExoMars mission launched in March 2016.

2.19. Clathrate, climate and habitability of Mars

WP involved	WP 2 – WP 5
Contributing partners	ROB – BISA
Summary description of the objectives	Understand atmosphere interaction with surface
Summary description of the scientific activities and results	Clathrates or gas hydrates are crystalline compounds formed by the inclusion of gas molecules in the cavities of water molecule networks and are typically stable at high pressure and low temperature. We have characterized the distribution and the temporal evolution of different components of the Martian atmosphere such as methane, focusing on the study of clathrates, their formation and degassing in the context of the evolution of Mars. The gas transport (water vapor and methane) through the Martian subsurface under evolving thermal model conditions (diffusion through porous regolith) and the outgassing processes have been modeled to study the atmospheric evolution of Mars and its present state. We have developed a thermal model of the interior of Mars based on existing mantle convection and lithosphere models in order to be able to compute the stability zones of clathrate as a function of the depth and depending on the temperature at the Martian surface. We have as well studied the diffusion of gas vapor in the Martian crust, in order to be able to compute the degassing effects on the atmosphere. We have introduced this as boundary layer in the GCM GEM-Mars (Global Environmental Multiscale) model for Mars' atmosphere of BISA, a 3D global circulation atmospheric model considering photochemistry. We have shown that impacts alone can hardly remove significant amounts of Mars atmospheric mass between the end of the Noachian (3.9 Ga ago) and the present. We have shown that during the first few hundreds of millions years, hydrodynamic escape of the atmosphere is dominant and very efficient. For later evolution, non-

	thermal escape becomes the main process but remains comparatively low. Except at the very beginning of the existence of Mars, the atmospheric loss by all mechanisms is thus small, except maybe by sequestration of carbon dioxide in carbonate reservoirs (to be studied). Based on the estimated atmospheric pressures and assumed greenhouse warming, we have shown that saline solutions, possible for temperatures higher than 245 K, can only flow sporadically on Early Mars, at high latitudes and during high obliquity periods. Other sources of transient warming (impacts or volcanism) are then needed to allow the presence of liquid water.
Main achievements in relation to the initial objectives	Better understanding of atmosphere interaction with surface
Comments in case of deviations from the initial project work-programme	

Illustrations:

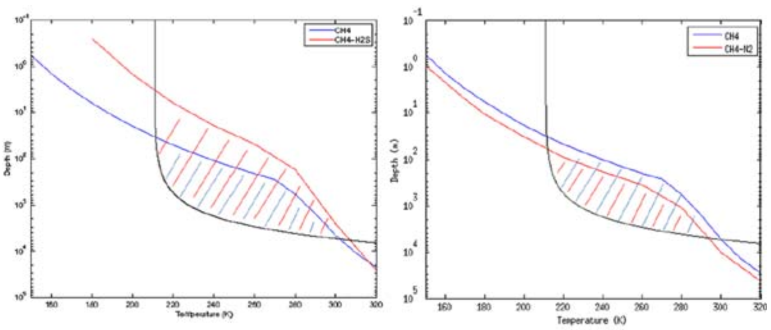

Figure 21: Mixture of CH_4 and H_2S Clathrate stability zone computed for particular present-day atmospheric conditions as a function of depth and temperature.

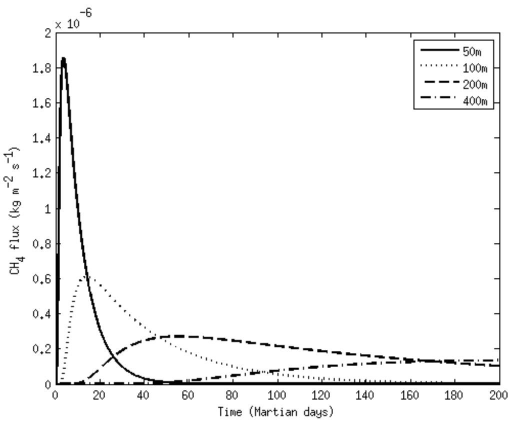

Figure 22: Methane flux over time between the subsurface and the atmosphere due to the dissociation of 1m^3 of CH_4 clathrates at 50, 100, 200 and 400 m deep.

2.20. Modelling of the interaction between the magnetic field and the atmosphere

WP involved	WP 2 – WP 5
Contributing partners	BISA – ROB

Summary description of the objectives	Understand the role of magnetosphere and the magnetic field on the atmosphere evolution
Summary description of the scientific activities and results	Planetary magnetic fields have long been considered as a shield protecting planetary atmospheres from erosion. They would prevent 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. This assumption has recently been challenged by suspiciously similar measurements of the escape taking place around Earth, Mars and Venus, making this topic an even more essential research area. Indeed, the Earth has still a magnetic field, while Mars and Venus have none. Mars, however, possesses a remnant crustal magnetic field from a dynamo that was operational in Mars' early history, sometime between core formation (~4.5 Ga) and the Late Heavy Bombardment (~4 Ga). The existence of crustal remnant magnetization on Mars indicates that a dynamo operated for a substantial time early in Martian history, but the timing, duration, and driving mechanism are unknown. Measurements of the present-day escape rate are of prime importance to better understand this (see Point 2.18). Furthermore, the amount of escaped planetary material that returns to the atmosphere under the effect of a planetary magnetic field is currently being revised downwards, increasing the escape rate. This situation is even more pronounced earlier in the history of the solar system. Atmospheric escape modelling 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 (see Point 2.21). Atmospheric escape can also happen through non-thermal processes involving in particular outflow of charged ionospheric material. The variability of the extreme UV (EUV) flux during the early stages of evolution can even be much larger and can differ significantly from star to star (providing the levels of high-energy radiation of a young Sun-type star). The intensity of stellar EUV flux is thought to have a strong effect on the non-thermal escape (that is non-hydrodynamic and still occurs at present-day, like sputtering, ion outflow …), 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. 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 and to govern the changes in surface conditions during the last 4 Ga of planetary history. Both observation (by the ASPERA instrument) and modelling are used to assess the strength of non-escape and its consequences on surface conditions, in particular the water surface inventory.

It is very likely that Earth, like Venus and Mars, has been subjected to a large amount of escape from different mechanisms, such as hydrodynamic escape. In this way (see Point 2.22), the top of the atmosphere could be subjected to strong escape unhindered by a magnetic field, even in the cases of planetary bodies capable of generating one early on.

Additionally, strong solar flux events may change the picture completely.

We also studied the response of the magnetopause to interplanetary perturbations and the magnetospheric mass circulation through an analysis of magnetospheric composition. The underlying idea is that this composition is essentially characterized by the O^+/H^+ ratio, where the O^+ is known to be of ionospheric origin only. One of the goals is to be able to estimate the ionospheric loss rates and mechanisms, important to understand atmospheric evolution.

We have also looked into polar cap arcs, and how these can tell us something about the mechanisms of atmospheric escape. Building on earlier results on the role of solar illumination to provide the initial acceleration of the ionospheric species and thereby modulating upflow, we have built a model for estimating the total escape rate from both polar caps. We have shown that the inclination of the magnetic axis with respect to the rotation axis can be an important parameter for atmospheric erosion as it impacts cold ionospheric ion outflow.

A significant amount of energy is transferred from the solar wind to the ionosphere and eventually drives ion outflow. This interaction takes place largely at the magnetopause. Large-scale statistical results on the magnetopause have become available recently, and demonstrate a dawn-dusk thickness asymmetry, which may be indicative of whether the magnetopause is permeable or not. We have shown, based on theoretical grounds, how the observed asymmetry can be explained in terms of the physical principles underpinning the

	formation of the magnetopause current layer. We have also worked on some fundamental aspects of plasma entry mechanisms, in particular the so-called "impulsive penetration" across the magnetopause, on magnetospheric mass circulation, polar cap arcs and ionospheric ion outflow.
Main achievements in relation to the initial objectives	Better understanding of the role of magnetosphere, solar flux, and ionosphere in atmosphere evolution
Comments in case of deviations from the initial project work-programme	

2.21. Modelling of the interaction between solar radiation and the atmosphere: the hydrodynamic escape

WP involved	WP 2 – WP 5
Contributing partners	BISA – ROB
Summary description of the objectives	Understand interaction between solar radiation and the atmosphere
Summary description of the scientific activities and results	Planets with atmosphere have been subjected to a large amount of escape from different mechanisms. Hydrodynamic escape, one of these mechanisms, occurs when the energy input from the Sun is large enough to allow the lighter species in the atmosphere to flow into space and be removed from the atmosphere. It depends on the temperature of the upper 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. Temperature estimates can be used to infer the theoretical absorption spectra of a planet and vice versa, and optical temperatures can be compared with these. This has allowed us to assess the rate of hydrodynamic escape, not affected by the magnetic field, in the history of planets. In this way, the top of the atmosphere could be subjected to strong escape unhindered by a magnetic field, even in the cases of planetary bodies capable of generating one early on.
Main achievements in relation to the initial objectives	Better understanding of the hydrodynamic escape in atmosphere and the interaction between solar radiation and the atmosphere
Comments in case of deviations from the initial project work-programme	
Illustration:	

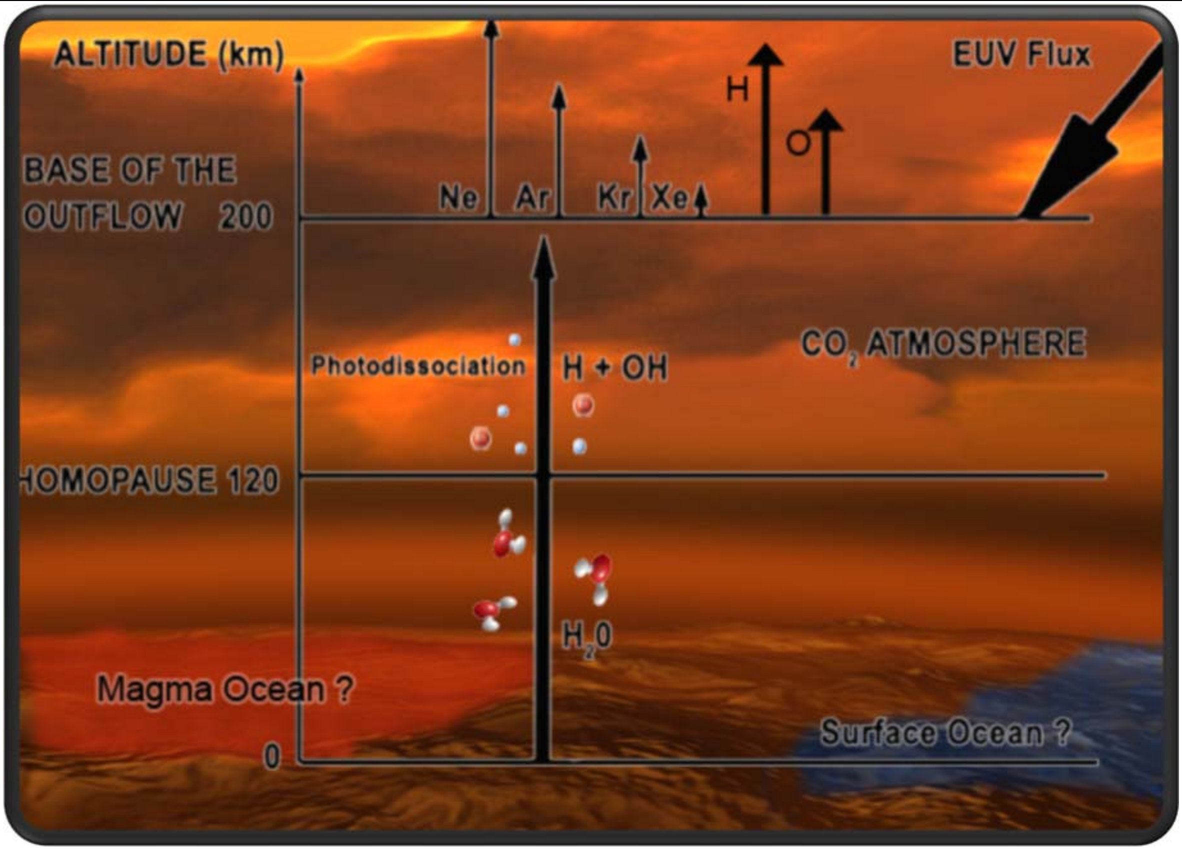

Figure 23: Schematic view of atmospheric processes leading to hydrodynamic escape during the early evolution of the Solar System.

2.22. Hydrodynamic escape during the accretion phase

WP involved	WP 2 – WP 5 – WP 1
Contributing partners	ROB – BISA
Summary description of the objectives	Understanding atmospheric escape during accretion phase
Summary description of the scientific activities and results	We have modeled the effects of hydrodynamic escape during the accretion phase and have focused on planetary embryos that are deemed to bring most of the volatiles and water to inner solar system terrestrial planets. The aim is to quantify how much water and volatiles can be expected to be available to terrestrial planets during the critical early evolution. Most embryos bring the bulk of the initial water endowment to terrestrial planets during the first 200 Myrs of the evolution of the Solar System. According to models, it seems the 30-70 Myr window accounts for most of the water delivery with only a late veneer at a later date. This period is also when hydrodynamic escape is most intense, leading to extreme loss of volatiles during the accretion phase. Small bodies can lose most of their volatile content before they reach the inner Solar System and will not contribute to the water

	budget. Only larger embryos will keep enough water to contribute, leading to most volatiles being accreted during a small number of events.
Main achievements in relation to the initial objectives	Better understanding of the atmospheric escape during accretion phase
Comments in case of deviations from the initial project work-programme	

Illustration:

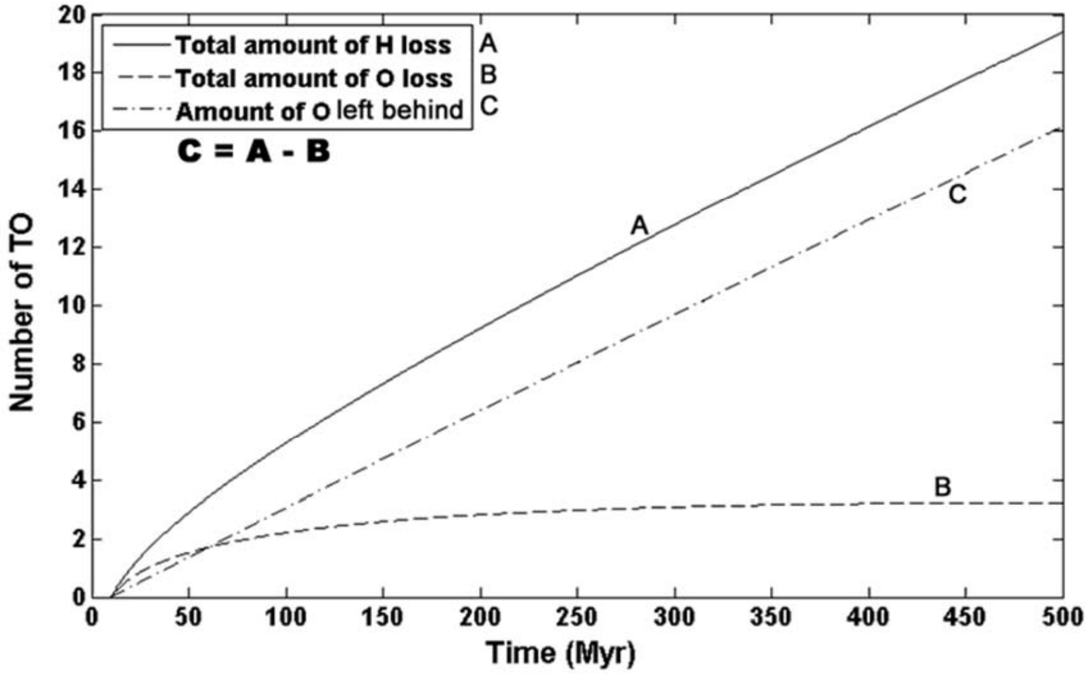

Figure 24: Loss of water by hydrodynamic escape during the early evolution of the Solar System. Hydrogen (curve A) escapes more easily than Oxygen (curve B) leading to the progressive accumulation of Oxygen in the atmosphere of the planetary body (curve C).

2.23. Mantle evolution, volcanism, convection as a consequence of an impact

WP involved	WP 2 – WP 1 – WP 5
Contributing partners	ROB –BISA
Summary description of the objectives	Understanding the impact effects on the mantle in terms of volcanism and convection
Summary description of the scientific activities and results	Large Impacts (>100km radius) have occurred on every terrestrial planet in the Solar System. They are a widespread mechanism associated with the accretion phase and early history of planetary bodies. They are very efficient at introducing large scale changes in early planetary systems. We developed a numerical model of the effects of large impacts on terrestrial planets using Venus as an example. Immediate consequences of the collision are

	studied as well as long term effects (from 10 kyr to several billion years) and the interactions with surface conditions. We report large scale volcanic activity on the impact location for long timescales (hundreds of million years) as a result of the emplacement of newly melted material. Subsequent volcanic activity is focused on precise points of the surface instead of being randomly located. Antipodal melting and volcanic activity has also been observed as a consequence of very large impacts. Mechanisms involved in antipodal melting have nothing to do with seismic wave concentration as previously proposed in the literature. Instead, it is due to a thick crust left from before the impact, where it was not destabilized by the impact. Mantle strain rates and velocity field indicates that antipodal downwelling are linked to global mantle dynamics generated by the impact and explained by the law of the conservation of mass. Additionally, large impacts can very efficiently deplete the upper mantle from its volatiles and especially water, leading to dry mantle conditions.
Main achievements in relation to the initial objectives	Better understanding of the impact effects on the mantle in terms of volcanism and convection
Comments in case of deviations from the initial project work-programme	

Illustrations:

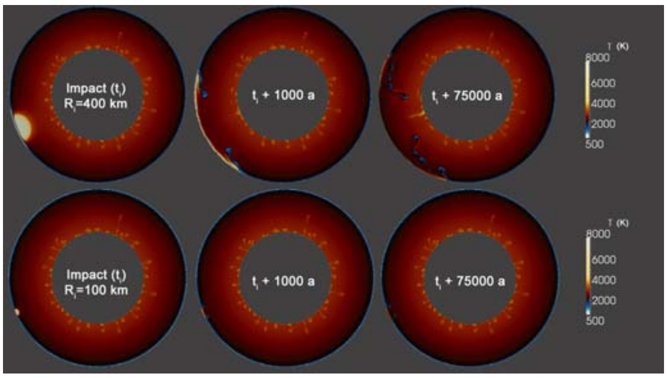

Figure 25: Illustration of the temperature anomaly occurring during and immediately after an impact, for two different impactors.

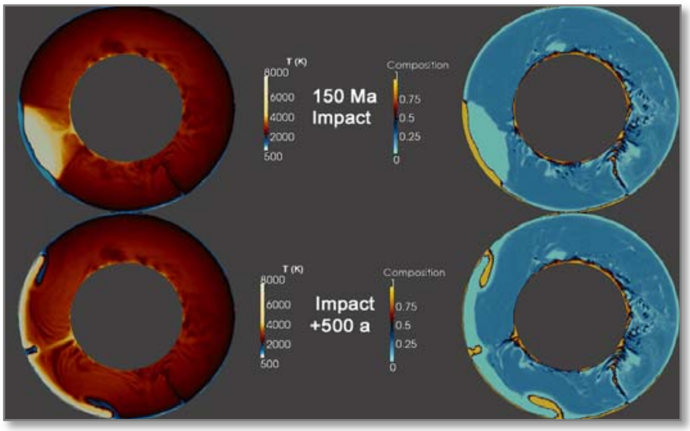

Figure 26: detail of the depletion taking place in the upper mantle, during the aftermath of a large impact. Left is temperature field of the mantle of Venus. Right is the corresponding composition field (light blue is depleted mantle and yellow is basaltic material).

2.24. Comets and asteroids effects on the atmosphere

WP involved	WP 2 – WP 5 – WP 1
Contributing partners	ROB – BISA – VUB
Summary description of the objectives	Understanding the comets and asteroids effects on the atmosphere
Summary description of the scientific activities and results	Large impacts have different consequences on the surface of a terrestrial planets aside from the energy they can deposit in the solid part of the terrestrial body. They can erode the atmosphere but they also bring and release volatiles. We demonstrated that single large impacts led only to a small erosion of the atmosphere which didn't alter significantly surface conditions. A large number of impacts is needed to make erosion significant (as our present research is suggesting). Additionally, massive degassing due to the impactor can efficiently replenish the atmosphere in water and other volatiles leading to high surface temperatures. This directly affects the mantle convection because of the interior/exterior feedback mechanisms this project previously underlined: high surface temperatures favor stagnant lid convection regime and hinders plates tectonics. Depending on the impact flux history, early impacts can degas the early mantle efficiently and desiccate it, leaving it dry for most of its history, which could have strong implications against plate tectonics regimes and habitability. Due to high escape during the early evolution of the solar system, most of the water present on and in the planet would thus be lost early. This loss could not be compensated for after the first 200 Myr of the evolution,

	preventing it from becoming habitable. One of the prevailing theories has been the possible delivery to Earth of volatiles (especially water) through comet bombardment (with Kuiper-belt comets) in the young solar system. However, in work that we have been involved in on Rosetta, it has been shown that the D/H ratio in comets generally is quite different from that in Earth's oceans, rendering this scenario improbable. The conclusion is at present that asteroids were responsible for most of the water brought to Earth. For more details, see Section 2.35. The timing of impacts has been shown to be an important factor for later evolution. Therefore, we are currently investigating the global effects of successive impacts following a realistic sequence for early Solar System evolution.
Main achievements in relation to the initial objectives	Better understanding of the comets and asteroids effects on the atmosphere
Comments in case of deviations from the initial project work-programme	

Illustrations:

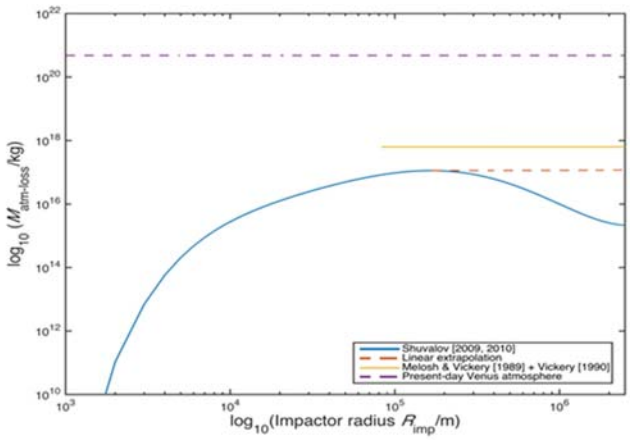

Figure 27: Comparison between the volatile content of the atmosphere of Venus (purple horizontal dashed line) and estimates for the amount of eroded volatiles by an impact for different impactor sizes. Large impacts can be found between the solid yellow line and the dashed red line.

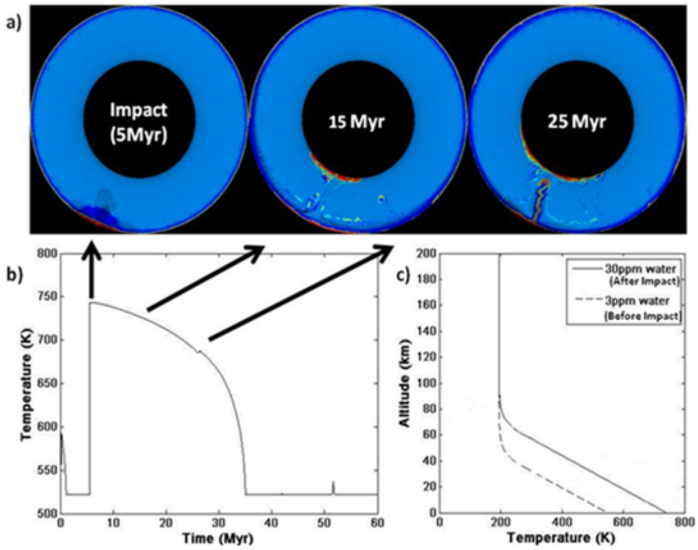

Figure 28: Illustration of the degassing caused by a large impact (300 km radius) on Venus. a) Composition field of the mantle (red is basalt, dark blue is a depleted mantle). b) Surface temperature evolution. c) Corresponding vertical profiles of temperature in the atmosphere.

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2.25. Effect of planetesimal volatile contents

WP involved	WP 2 – WP 5 – WP 1 – WP 3
Contributing partners	ROB – BISA – VUB
Summary description of the objectives	Understanding the comets and asteroids effects on the atmosphere
Summary description of the scientific activities and results	Collaboration with Russian teams (Prof. Svetsov and Shuvalov), working with dedicated hydrocodes for computing the impact effects on the atmosphere, has been coordinated to model the physical effects of large impacts and obtain a working parameterization. Degassing and volatile emplacement in the atmosphere are found to have a dominant effect during the process of large impacts. Three timescales are affected. - On the short term, the immediate release of volatiles increases surface temperature until atmospheric escape can remove it (several millions years to several tens of million years). - On the medium term, the energy released into the mantle and changes in surface conditions trigger some large scale volcanic effects after the impact but linked to it (of million years). - On the long term, the whole evolution of the surface conditions can be changed by impacts with the correct set of parameters (billions of years). The timing of the impact appears to be a very important parameter, with occurrence of impacts by the same object at different times leading to widely diverging evolutions.

Main achievements in relation to the initial objectives	Better understanding of the comets and asteroids effects on the atmosphere
Comments in case of deviations from the initial project work-programme	

2.26. Identification and Preservation of life tracers in early Earth and analog extreme environments

WP involved	WP 3
Contributing partners	ULg – ULB
Summary description of the objectives	Identification and preservation of life tracers, microscopically or macroscopically modification of the environment physical-chemical characteristics, characterization of chemical and morphological biosignatures, preservation and evolution of life in early Earth, detection of early Earth life or habitats, interaction between life, crust, and atmosphere.
Summary description of the scientific activities and results	We have characterized, at the macro- to the micro-scale, chemical and morphological biosignatures and their mode of preservation in (1) Archaean rocks from South Africa and Australia, (2) in Proterozoic siliciclastic sedimentary rocks, and in (3) recent sediments from extreme environments analogues for the early Earth or extra-terrestrial environments (Antarctic microbial mats from recent and 3 Ka (thousand years) old collected sedimentary core from Larseman Hills lakes, and laboratory cultures of cyanobacteria and other microorganisms). Through these studies, examination of possible abiotic processes mimicking biological processes and products is carried out to identify real biosignatures that could be used for the detection of life in early Earth and extraterrestrial record. This work includes the characterization of the geochemistry, geochronology, redox conditions, and mineralogy of Precambrian and recent extreme environments (modern analogs, high UV Antarctic habitat) as they determine the preservation conditions of biosignatures and the geological and geochronological context. Because of the destructive effects of the strong radiation environments at the surface of Mars, organic biosignatures need to be looked for under sediment or rock surfaces. Our study of the high UV Antarctic habitat showed the production of pigments and organic walls by cyanobacteria and, even more interestingly, their preservation in ancient lake sediments by the precipitation of nano-clays and nano-carbonates. Similar biosignatures could be searched for in ancient Earth rocks or analogs in extraterrestrial rocks when Mars surface was still protected by an atmosphere and

	magnetic field. The results will permit the identification of strategies for detection of biosignatures on Mars, as our studies are analog to those of the active and future Martian rovers and landing sites on clay-rich lake deposits. 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, and the atmosphere through time, linking to other WPs of this IAP. This work not only documents the first traces of life, the early evolution of cellular life, including complex life (eukaryotes), and possible biosignatures useful for paleobiology and astrobiology, but also 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. Our work has evidenced: - the preservation of microbial mats from a modern analog (Antarctica lacustrine cyanobacterial mats) through the precipitation of nanominerals, - for the first time the preservation of cyanobacterial pigments in ancient sediments and their potential as taxonomic signatures in the geological record, - the paleoecology and early evolution of biological innovations in the domain Eucarya in the early Mesoproterozoic of Australia (Roper Gp), and in late Mesoproterozoic-early Neoproterozoic of West Africa (El Mreiti Gp, Mauritania) and Central Africa (RDC Bushimay Spg), - for the first time, the worldwide diversification of eukaryotes to West Africa and Central Africa by the mid-Proterozoic, - the geochronology, chemostratigraphy, redox conditions, and nutrients availability of Proterozoic marine basins in West and central Africa where prokaryotes and complex life diversified, - the endogenicity, syngenicity, and biogenicity of large spindle-shaped microfossils forming chains, and preserved in shallow-water and occasionally evaporitic environment of 3.45 Ga SPF chert, Australia. These are probably the oldest unambiguous microfossils reported so far,

	- the diversification of cyanobacteria using molecular phylogeny and reassessment of the fossil record, which will lead to the production a new molecular clock and provide insight into the origin of the chloroplast, - the development of homemade sample support, sample preparation protocols, and electronic file format, and building of a searchable Infra-Red and Raman spectroscopic database of minerals and organic signatures, - the development of paleothermometers using Raman spectroscopy analyzes of organics.
Main achievements in relation to the initial objectives	We have identified life tracers and their preservation pathway, characterized the microscopically or macroscopically modifications of the environment physical-chemical characteristics, characterized the chemical and morphological biosignatures, characterized the preservation and evolution of life in early Earth, detected early Earth life and habitats, considering interaction between life, crust, and atmosphere.
Comments in case of deviations from the initial project work-programme	

Illustrations:

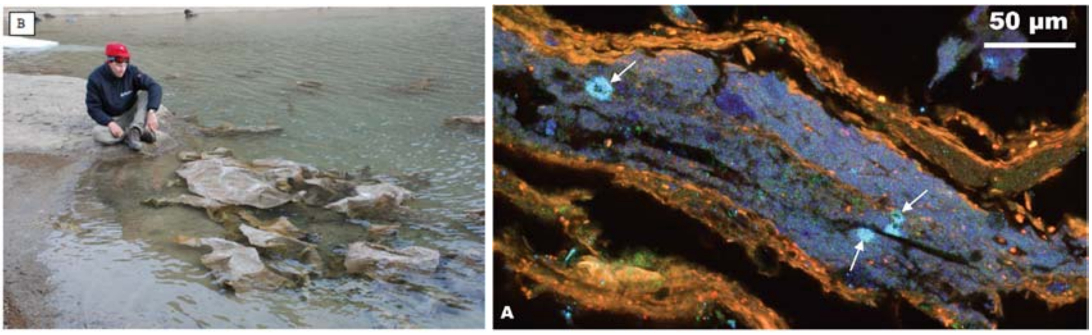


Figure 29: Microbial mats on the shore of a lake in Antarctica (left) and a confocal fluorescence microscopic image of the cyanobaterial mat with carbonates and clay minerals (right).

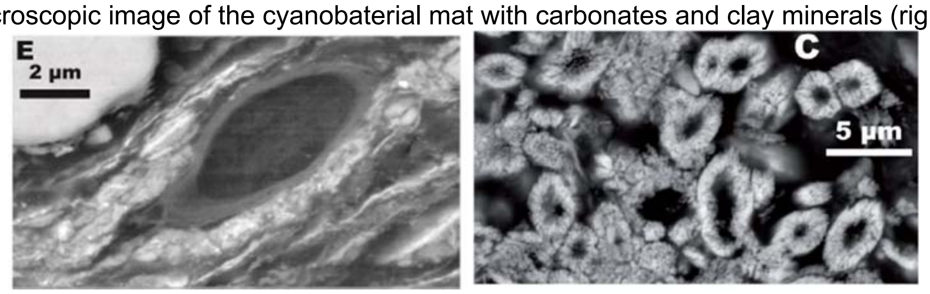


Figure 30: SEM images of cells incrusted by clay minerals (left) and nano-aragonites (right), in fossil samples of the microbial mats, from a drill core through sediments of the Antarctic lake.

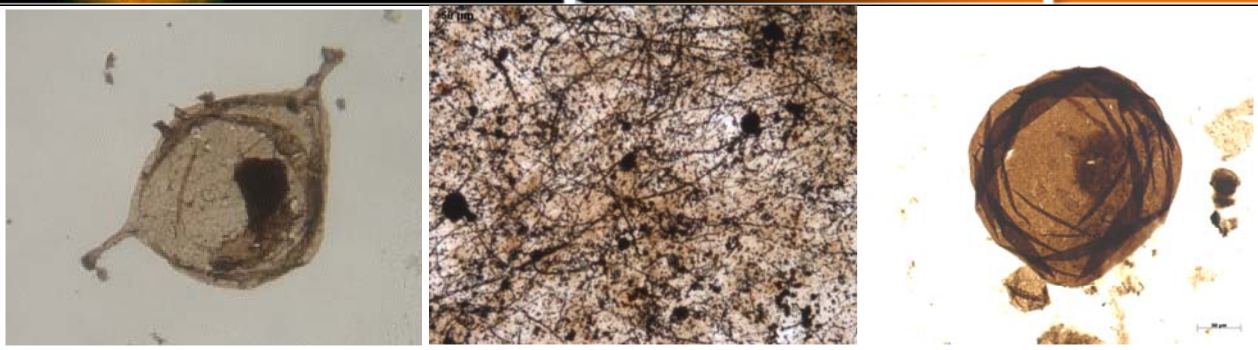


Figure 31: Picture of a 1.5 Ga protist (Roper Group, Australia), ~100 µm in diameter (left). Picture of a 1.1 Ga microbial mat (Taoudeni Basin, Mauritania), ~5 mm across (center). Picture of a ~1.1-0.8 Ga organic-walled microfossil (Mbuyi-Mayi Supergroup, RDC), about 80 µm in diameter (right).

2.27. Implication of life tracers' preservation for in situ detection on Earth and other planets

WP involved	WP 3 – WP 2
Contributing partners	ULg – ULB
Summary description of the objectives	Understand the preservation and evolution of life in early Earth, characterization of biosignatures and pseudosignatures for life detection
Summary description of the scientific activities and results	Our study of the high UV Antarctic habitat showed the production of pigments by cyanobacteria and, even more interestingly, their preservation in ancient sediments by precipitation of particular nanocarbonates and clays. Our studies also show exceptional preservation of biological organic walls in ancient clay-rich aqueous deposits, up to 3.2 Ga, and in silica-rich deposits up to 3.45 Ga. Complex organic molecules and simple and complex organic morphologies, and thus abiotic organics from meteorites or geological processes, can thus be preserved in clays and can be searched for in ancient Earth rocks or in extraterrestrial rocks with similar lithologies.
Main achievements in relation to the initial objectives	Better understanding of the preservation and evolution of life in early Earth. Our work provides reference measurements, material and database for the interpretation of space data in in situ missions and for defining strategies to optimize chance of life detection (sampling geological targets and their analyzes).
Comments in case of deviations from the initial project work-programme	

2.28. Influence of life on atmospheric evolution and vice versa

WP involved	WP 3 – WP 2
Contributing partners	ULg – ULB – ROB – BISA – DLR

Summary description of the objectives	Understand the interaction between life, crust, and atmosphere, as well as biosphere and atmosphere evolution.
Summary description of the scientific activities and results	The remote study of early Earth atmosphere before the evolution of oxygenic photosynthesis (liberating large amount of O_2 and consequently producing the ozone layer), might not have revealed the abundant presence of life before 2.45-2.3 Ga. The age of the onset of this biological evolution that impacted so strongly the evolution of our planet and of complex life is strongly debated. We have thus characterized new cyanobacteria biosignatures as well as made geochemical and geological analyses in order to constrain the chemical evolution of Earth early ocean and atmosphere. Large amounts of solar energy are harvested by photosynthetic life and converted to chemical energy, leading to alterations of chemical reservoirs eventually affecting the Earth's interior. We investigate the effect of the Earth's biosphere on the evolution of continental crust and the mantle water budget.
Main achievements in relation to the initial objectives	Better understanding of the interaction between life, crust, and atmosphere, and biosphere and atmosphere co-evolution.
Comments in case of deviations from the initial project work-programme	

Illustration:

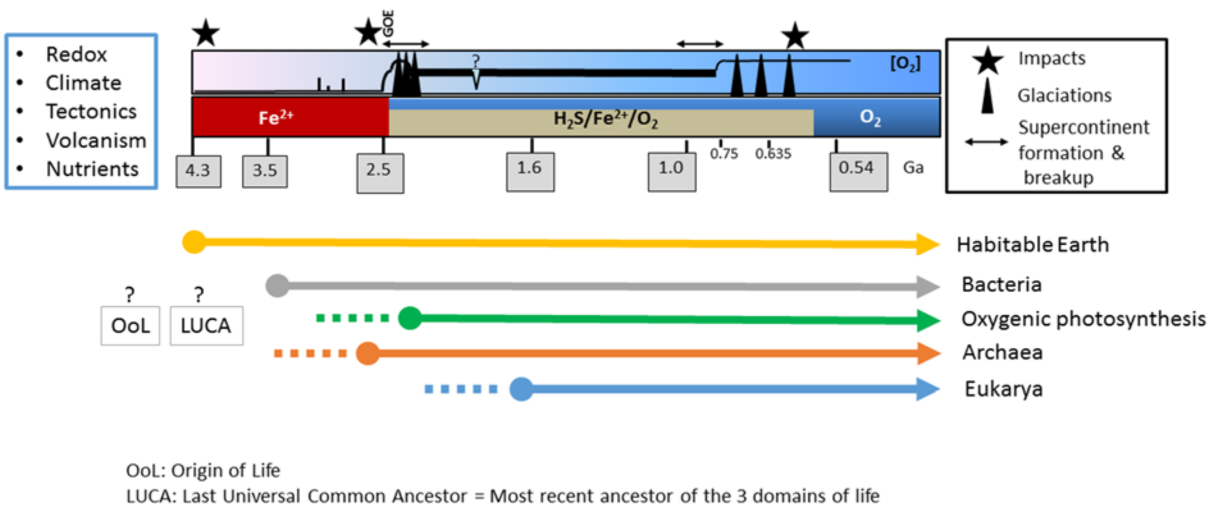


Figure 32: Evolution of Earth's atmospheric and ocean oxygen content and life through time.

2.29. Isotope cosmochemistry – method development of isotopic systems to be used

WP involved	WP 4 – WP 3 – WP 5

Contributing partners	UGent – VUB – ULB
Summary description of the objectives	development of analytical tools also using laser ablation; meteorite analysis
Summary description of the scientific activities and results	Since the start of the IAP, we are making progress in the development of analytical protocols for isolation of different elements (Ni, Li, B, Os). In parallel, we were exploring recently acquired new instruments offering the capability of simultaneous monitoring of the entire elemental mass spectrum and of spatially resolved information with a high accuracy. Laser ablation was also used, as it is an alternative introduction technique, permitting direct bulk and spatially resolved analysis of solid materials. Several approaches, all relying on ICP-MS (Inductively Coupled Plasma - Mass Spectrometry/Spectrometer), used for (ultra-)trace element determination, were assessed for their capabilities and limitations in terms of bulk elemental characterization using a set of iron meteorite samples. The samples were taken into solution via acid digestion and the digest thus obtained was subsequently sufficiently diluted for avoiding contamination and memory effects. Laser Ablation (LA) is an alternative introduction technique permitting direct analysis of solid materials. LA-ICP-MS and solution ICP-MS (after digestion of the solid sample) are complementary approaches. While LA-ICP-MS offers a higher sample throughput and the possibility of acquiring information on the distribution of the elements, solution ICP-MS allows adequate dilution and straightforward quantification. With LA-ICP-MS, we have also performed two-dimensional mapping of element distributions and demonstrated accurate quantification based on the sum normalization method. These analysis tools developed at Ghent University and at ULB have been used for the analysis of meteorites of different types: planetesimals, achondrites, non-magmatic iron meteorites, and CHUR (CHondritic Uniform Reservoir). Analytical tools developed at Ghent University, at VUB, and at ULB 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. A novel method was developed for the isolation of Ni for its subsequent isotopic analysis via multi-collector ICP-MS. Laterally resolved isotopic analysis (microdrill sampling) of Fe and Ni was shown to provide complementary information. Via a cooperation with the University of Hannover (Germany), spatially resolved Fe and NI isotopic analysis was accomplished using a femtosecond LA-unit (to the best of the authors' knowledge, such instrumentation is not available in

	Belgium) coupled to a multi-collector ICP-MS unit. Commercially available LA-ICP-MS 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. Computer fluid dynamics was relied on for designing an ultra-fast ablation cell that provides higher spatial resolution and/or faster sample throughput. Efforts are currently being done to make this ultrafast cell also amenable to samples with larger dimensions. Novel data acquisition / handling protocols were developed to extend the capabilities of LA- ICP-MS in this context, leading to spatial resolution below the beam diameter. These analytical tools were combined with more classical approaches relying on mass and X-ray spectrometry and the use of a micro-drill microscope to investigate chondritic, achondritic, and iron meteorites and for the analysis of both terrestrial and extraterrestrial impact rocks. These studies of meteoritic and ejecta materials have provided access to the elementary composition and selected isotope ratios, and have shed light on the impact crater and the overlying turbulent vapor 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 CHUR, or nebular starting material, for the planet Earth.
Main achievements in relation to the initial objectives	The instruments and machines have been acquired and the analytical tools (including using laser ablation) have been developed. Meteorites have been analyzed. Better understanding of crater, vapor plumes, distribution of ejecta material after impact, and products of extraterrestrial bodies Better understanding of planet starting material
Comments in case of deviations from the initial project work-programme	A novel type of ICP-MS instrument equipped with a double-focusing sector field mass spectrometer of Nier-Johnson geometry and thus providing simultaneous access to the entire elemental mass spectrum was evaluated in detail at UGent (during 2 years). This in-depth assessment showed that the technique is still not mature, does not meet the expectations raised and is too slow for combination with the ultra-fast ablation cell. As a result, ***this instrument was not acquired***. At the VUB, a ***new Micro-X-Ray Fluorescence instrument*** was installed in the Fall of 2014 (first in Belgium) making possible non-destructive major and trace elemental mapping at ~ 25 µm. This µXRF is now used routinely for mapping large (up to 50 cm if needed) polished section of meteorites or impactites, in order to determine the bulk chemical composition, detect minute

	mineral phases, study clast/matrix relationships, etc. Most of all, this approach selects the optimal sites for further isotopic analyses (either for laser ablation or micro-sampling).

2.30. Isotope cosmochemistry – meteorite analysis and lunar samples

WP involved	WP 4 – WP 3 – WP 5
Contributing partners	UGent – VUB – ULB
Summary description of the objectives	obtain element concentration trends in various meteorite groups and prepare for the lunar sample
Summary description of the scientific activities and results	Element concentration trends in various meteorite groups represent a valuable record of the processes that the parent bodies of these meteorites underwent in the Early Solar System. Spatially resolved element concentration data also provide time - and temperature scales of these processes. Additionally, our studies also need laterally resolved isotopic analysis. We have used several very performant tools/instruments to reach that goal: (1) ArF*-excimer laser ablation (LA), (2) single-collector inductively coupled plasma - mass spectrometry (ICP-MS), (3) multi-collector ICP-MS (MC-ICP-MS), (4) combination of femtosecond LA and MC-ICP-MS, (5) thermal ionization mass spectrometer. The methods used have been improved (patent pending, UGent patent application PCT/EP2015/07 1525, based on EP14185463.8). Several samples from the US Antarctic meteorite sample collection and from the collection of Antarctic meteorites curated by the Royal Belgian Institute of Natural Sciences have been investigated. A case study has been performed for demonstrating the validity of Ca isotope ratio measurements in preparation for the analysis of lunar samples. Those samples have been granted by NASA and arrived in January 2016. There are under analysis. Analytical developments have also been made in parallel in order to efficiently removing isobaric interferences for particular isotopes.
Main achievements in relation to the initial objectives	Element concentration trends in various meteorite groups have been obtained. Better understanding of the processes of the parent bodies of meteorites Cases studies have been performed for future lunar sample preparation.
Comments in case of deviations from the initial project work-programme	

2.31. Identification of elements of composition in planetesimals – meteorites achondrites and small solid bodies and Solar System evolution

WP involved	WP 4 – WP 5
Contributing partners	DLR – ULB – UGent – VUB
Summary description of the objectives	Understand the chronology of differentiation processes, small solid bodies in Solar System evolution, and early Solar System evolution
Summary description of the scientific activities and results	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. 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 of undifferentiated and unsintered regolith only. 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 Vesta, Lutetia instead, has potentially experienced little differentiation with an interior compacted by sintering below a porous layer, and for smaller km-size asteroids even wide-spread sintering is less likely. In addition, planetesimals consisting of ice and rock could have undergone water-rock differentiation as it is suggested by the observations of Ceres as well as by numerical studies. Vesta is differentiated with an iron-rich core, a silicate mantle and a basaltic crust. We have expanded the thermo-chemical evolution model to include accretion, compaction, melting and the associated changes of the material properties and the partitioning of incompatible elements such as the radioactive heat sources, advective heat transport, and differentiation by porous flow, to further consider convection and the associated effective cooling in a potential magma ocean. Partitioning of ^{26}Al and its transport with the silicate melt

is crucial for the formation of a global and deep magma ocean. The lifetime of the shallow magma ocean and convection in this thin shallow magma ocean layer is accompanied by the extrusion of ^{26}Al at the surface. The interior differentiates from the outside inward with a mantle that is depleted in ^{26}Al and core formation is completed within ~ 0.3 Ma.

A clear age difference is observed between the three main lithologies –basaltic eucrites, cumulate eucrites, diogenites–, for which a chronology could be put in place.

We show that the source of diogenites is clearly distinct from that of eucrites and we privilege the hypothesis of the diogenites being formed as plutons intruding the crust of Vesta.

On the other hand, we also studied primitive achondrites for investigating the very first step of asteroid differentiation, i.e. the melting of the metal part of chondrites but not the silicate part. We showed the existence of a 20% of partial melting of the metallic phase, as well as the existence of a loss of volatile, indicating an impact inducing differentiation or a primitive metamorphism.

Other meteorites, the ureilites, share primitive characteristics (i.e. heterogeneous oxygen isotope signatures) with igneous ones (as being mantle residue after partial melting). We have shown that the process of smelting is a viable process for explaining their evolution process.

The mysterious IIE non-magmatic iron meteorites contain silicate inclusions and their chemical composition does not correspond to a normal fractional crystallization path. Several processes, either endogenic or exogenic, have been involved for explaining the existence of those iron meteorites. We have shown that shock features must have been present, in favor of exogenic models.

Among all meteorites, achondrites provide clues about the different differentiation processes that led to differentiated terrestrial planets such as Vesta. Their study leads to the conclusion that there was a remelting of the magma ocean. A mantle overturn can be a process to explain this remelting event.

Our results show that partitioning of ^{26}Al and its transport with the silicate melt is crucial for the formation of a global and deep magma ocean. Due to the enrichment of ^{26}Al in the liquid phase and its accumulation in the sub-surface, a thin shallow magma ocean with a thickness of few tens of km forms, above which a basaltic crust forms. The lower mantle experiences a maximal melt fraction of 45%. Our results support silicate melt in the mantle for up to 150 Ma, and convection in a crystallizing core proceeds for

	approximately 100 Ma, supporting the idea of an early magnetic field to explain the remnant magnetization observed in some meteorites. In addition, our results suggest a younger age for Diogenite thought to be formed in intrusion within the eucrite crust during a second period of magmatic activity on Vesta, probably generated by the remelting of the magma ocean cumulates. This remelting can be explained by a mantle overturn.
Main achievements in relation to the initial objectives	Better understanding of the chronology of differentiation processes, small solid bodies in Solar System evolution, and early Solar System evolution
Comments in case of deviations from the initial project work-programme	

Illustrations:

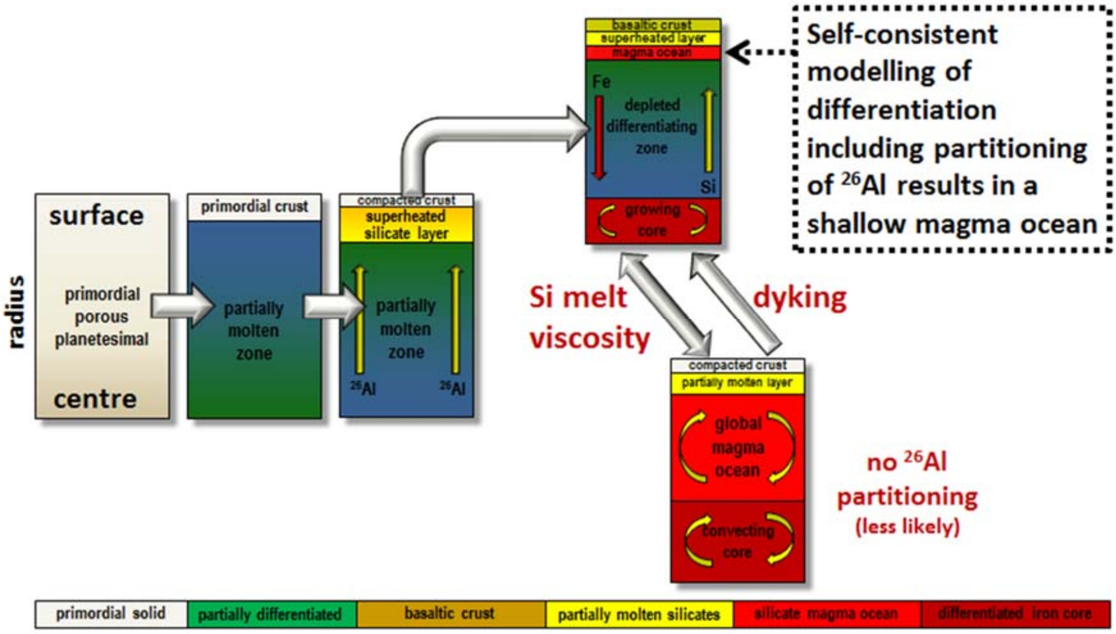


Figure 33: Sketch showing the evolution path starting from an accreting porous body to a differentiated body with different layers depending on partitioning of ^{26}Al.

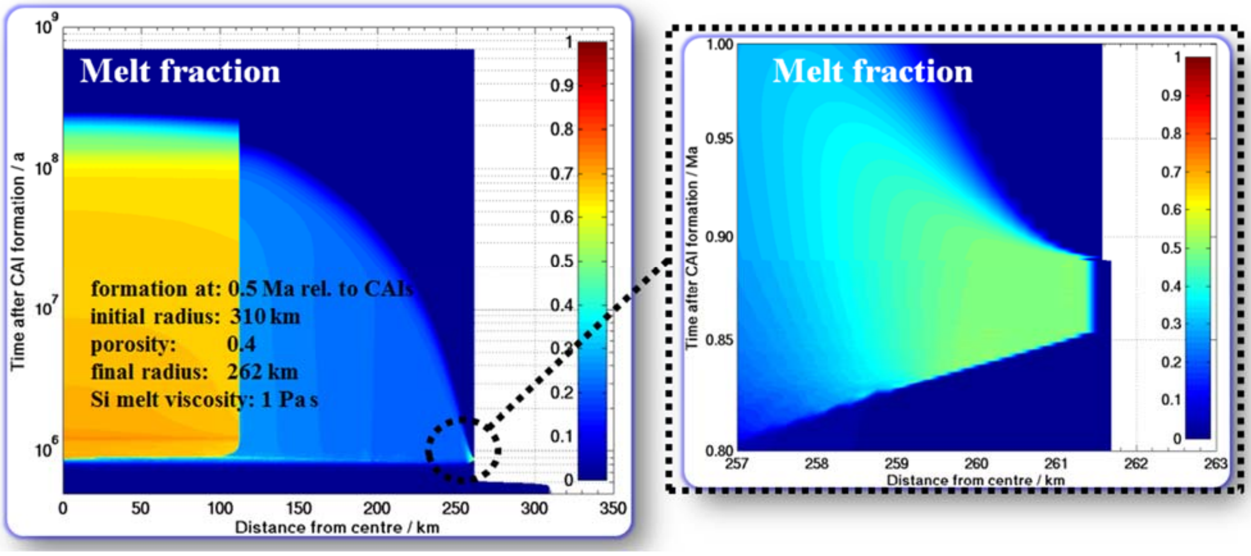


Figure 34: Melt fraction and one close-up in the sub-surface magma ocean of a Vest-size body which formed at t_0=0.5 Ma after the calcium-aluminum-rich inclusion (CAI).

2.32. Model of mantle overturn & meteorites

WP involved	WP 4 – WP 5
Contributing partners	DLR – ULB – ROB
Summary description of the objectives	Understand the chronology of differentiation processes and the onset of plate tectonics
Summary description of the scientific activities and results	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 fractional magma ocean crystallization and accompanying overturn (i.e. the process during which an unstable mantle stratification dynamically rearrange) 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. Hence, our results presented in Point 2.1 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. We have shown that, 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. Recent results 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, basaltic crusts, the latter of which probably includes one of the largest asteroids, or dwarf planets, Vesta and potential links between chondritic starting materials and achondritic products.
Main achievements in relation to the initial objectives	Better understanding of the chronology of differentiation processes and the onset of plate tectonics
Comments in case of deviations from the initial project work-programme	

Illustrations:

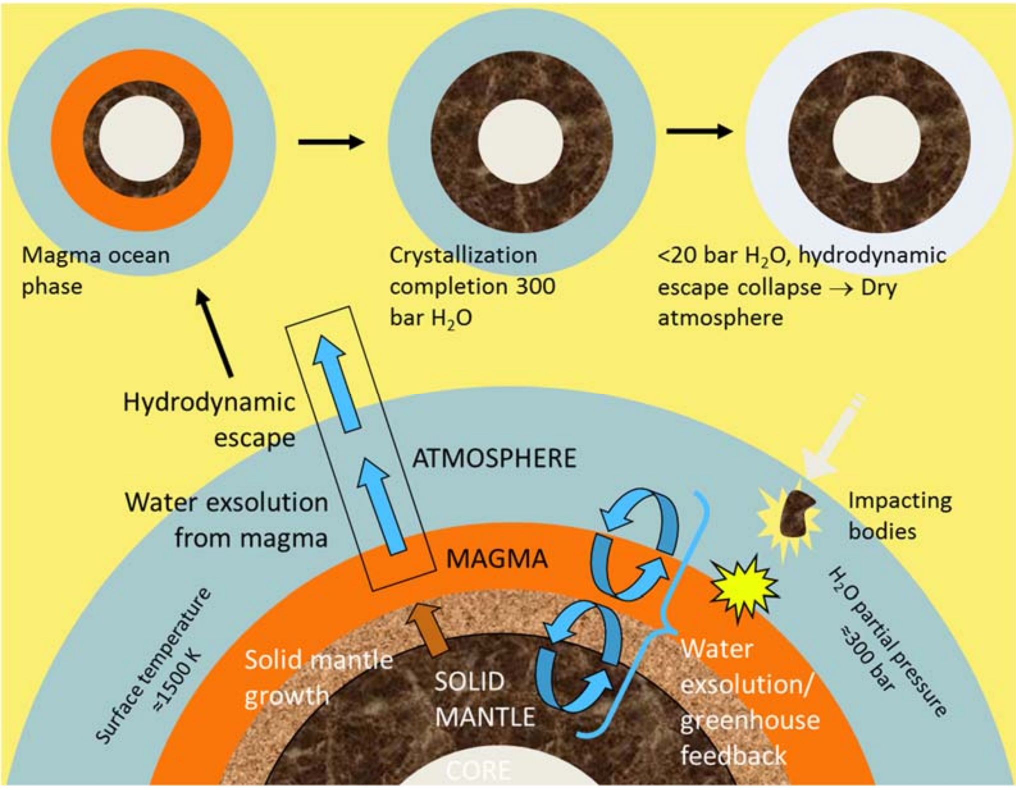


Figure 35: Sketch showing the evolution after the creation of the magma ocean of Venus and in terms of mantle convection patterns.

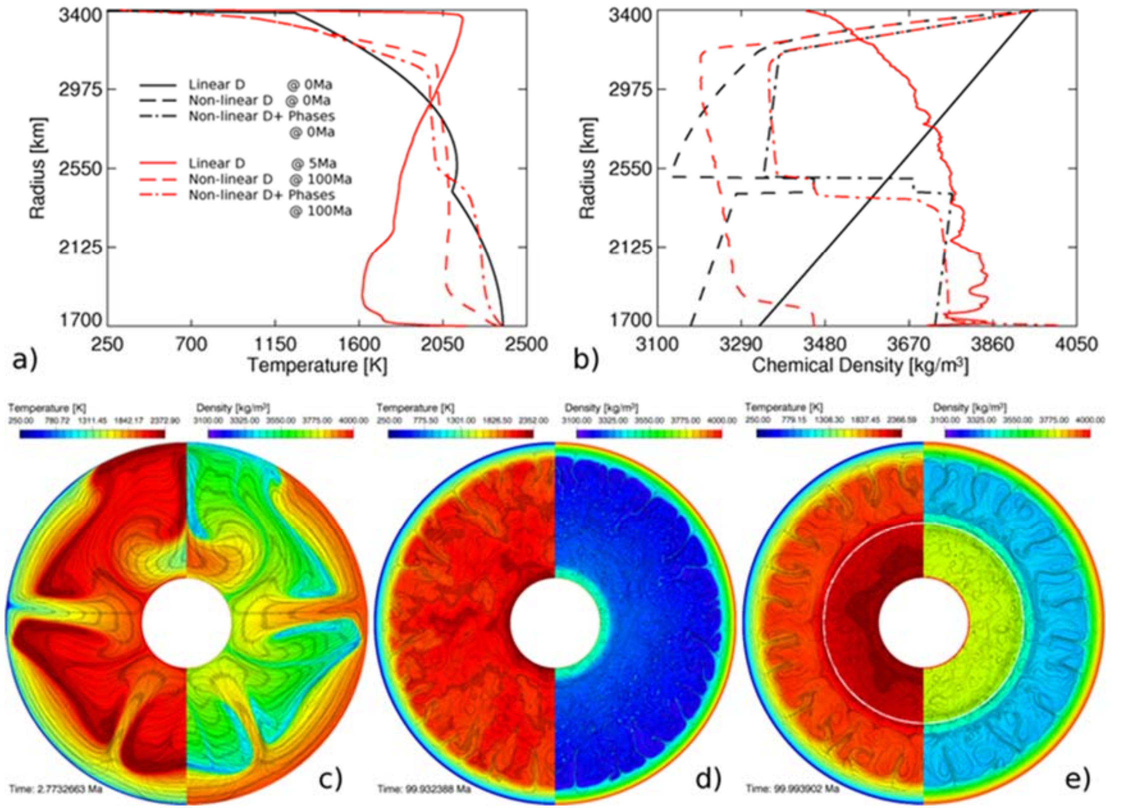


Figure 36: The magma ocean crystallization can lead to a mantle overturn. Depending on the assumed density profile in the mantle, the dense initial crustal layer may take part in the overturn process (c, linear profile) or stays stable at the surface (d and e, non-linear profile).

2.33. Geochronometers – Identification of elements of composition in meteorites and mantle overturn

WP involved	WP 4 – WP 5
Contributing partners	ULB – DLR – UGent – VUB
Summary description of the objectives	Understand the chronology of differentiation processes and the onset of plate tectonics
Summary description of the scientific activities and results	In cosmochemistry, the ^{147}Sm-^{143}Nd and ^{176}Lu-^{176}Hf isotopic systems are traditionally used together as tracers of early planetary processes. We have shown that in some contexts, they may not be robust and should be used with caution. We have developed a thermo-chemical evolution model, including accretion, compaction, melting, and the associated changes of the material properties and the partitioning of incompatible elements such as the radioactive heat sources, advective heat transport, and differentiation by porous flow, to further consider convection and the associated effective cooling in a potential magma ocean. Depending on the melt fraction, the heat transport by melt segregation is modelled either by assuming melt flow in a porous medium or by simulating vigorous convection and heat flux of a magma

	ocean with a high effective thermal conductivity (see Points 2.1 and 2.32 on mantle overturn simulations).
Main achievements in relation to the initial objectives	Better understanding of the chronology of differentiation processes and the onset of plate tectonics
Comments in case of deviations from the initial project work-programme	

2.34. Petrography/geochemistry of ejecta material in order to understand planetary impact process and ejecta distribution/interaction with the atmosphere

WP involved	WP 4 – WP 5
Contributing partners	VUB – UGent – ULB
Summary description of the objectives	Understand planetary impact process and ejecta distribution/interaction with the atmosphere
Summary description of the scientific activities and results	During fieldwork in Southern Mexico, we have collected highly unusual accreted lapilli related to the Cretaceous-Tertiary (KT) boundary impact in Yucatan. These so far poorly studied ejecta materials are suspected to have formed in the most turbulent part of the vapor plume that rose above the crater, shortly after impact. Macroscopic and petrographic descriptions are going (SEM/EDX imaging, electron microprobe analyses, and Raman spectroscopy) to shed light on the formation and distribution of ejecta material. This material is also being compared to similar ejecta produced by the 1.8 Ga Sudbury impact in Ontario (Canada). Analysis of accretionary lapilli reveals that they are composed of a variety of constituents, including quartz, calcite, dolomite, and glass (now chlorite) that were turbulently mixed during the formation process of the lapilli. Particles of various compositions are found throughout the lapilli, with the core and rim having similar composition. Carbonate alteration has resulted in slight degradation of the rims, but many original grains are still visible. To forward our understanding of impact processes, we have also studied Cretaceous-Tertiary impact spherules in detail. It was indeed important to study in situ and at high spatial resolution both the mixing of different target lithologies and the variation of the major and trace element budget during the alteration process, which can be very complex, including numerous competing reaction processes. With the same purpose of documenting impact crater ejecta product to learn about cratering on solid bodies, we have performed a comprehensive study of KT proximal spherules and a review of the platinum group element (PGE) distribution at the KT boundary and its use to identify the impacting projectile has been published recently, supporting again a carbonaceous chondrite. At the same time, we published the results of

	a new KT boundary section in the Western Interior of the US, which sheds light on the behavior of the meteoritic PGE, in particular Os after the impact. The platinum group element behavior originating from the meteorite and injected into the atmosphere during the impact has been documented, providing interesting information on the behavior of the Platinum group elements after the impact and the effects of post-depositional diagenesis. We have shown that the samples contain ~1-3% by mass of extraterrestrial material even though the spherules are highly diluted by intraclasts of ambient sediment. Samples of spherules on two different locations have been shown to correspond to distal ejecta from a single large impact around 2.49 Ga. If indeed, these thick spherules layer represent the last tail of the Late Heavy Bombardment, it is important to understand their distribution, size and magnitude of the collisions and type of impacting projectiles. In parallel, much older thick ejecta layers occurring at the Archean – Proterozoic boundary in Australia and South Africa are being studied using a variety of techniques. During cratering processes on terrestrial planets, the target rock is vaporized, melted, and fractured by the passage of the shock wave. In most terrestrial targets, the newly formed impact melt clasts can easily be distinguished from the surrounding lithologies. This is not case when the cratering event affects volcanic rocks. We have proposed to use cathodoluminescence (imaging and spectrometry), whose intensity is inversely correlated with the degree of shock metamorphism experienced by the investigated lithology, to aid in such a distinction. The shock metamorphism of the mineral olivine in meteorites was also studied at very fine scale with the objective to constrain impact events in the history of meteorites. It is based on the fact that shock release is believed to have caused opening of cracks and fractures in olivine and formation of olivine melt, which has lately crystallized under postshock equilibrium pressure conditions as olivine.
Main achievements in relation to the initial objectives	Better understanding of planetary impact process and ejecta distribution/interaction with the atmosphere
Comments in case of deviations from the initial project work-programme	
Illustrations:	

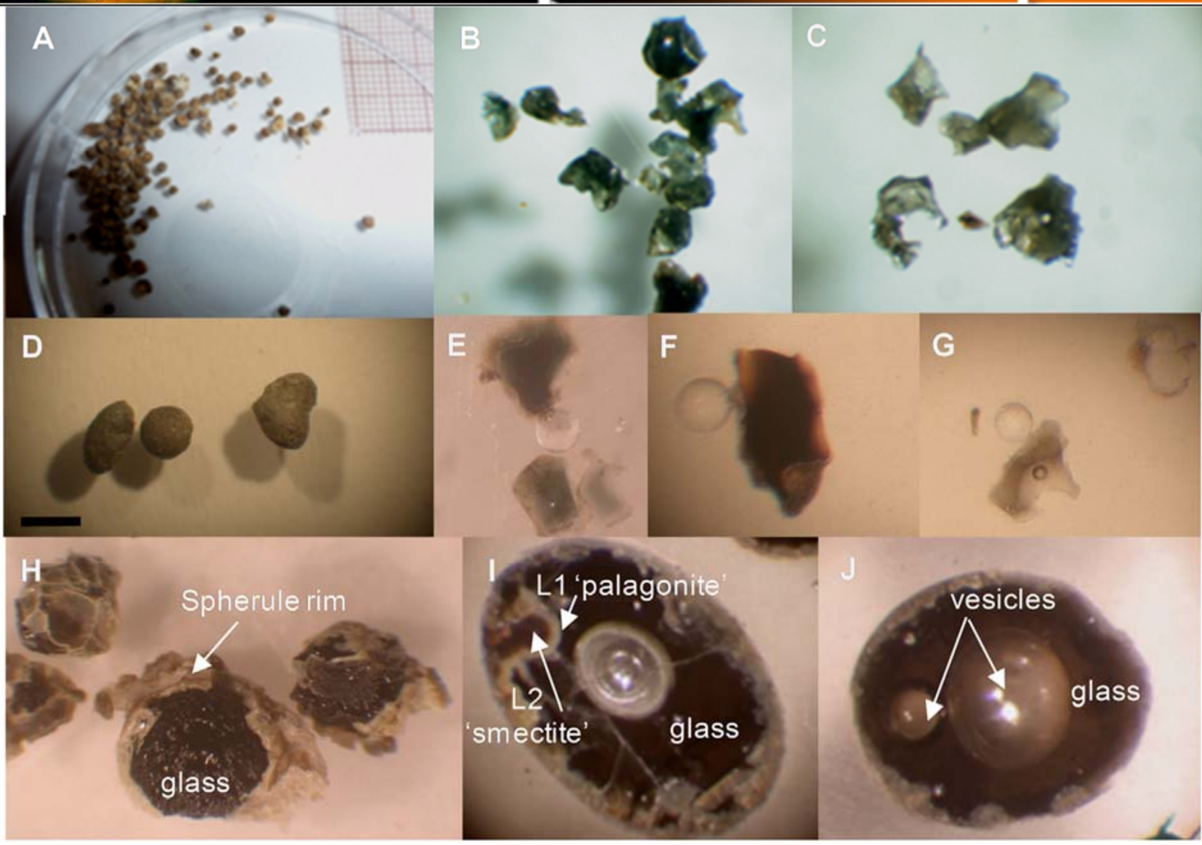


Figure 37: (A and D) Spherules separated from the Arroyo El Mimbral locality. Green glass fragments represent the most abundant variety, followed by black glass. (B and C) Note scalloped nature of the glass fragments. (E–G) Polished green (E), red (F) and black glass (G) from Mimbral. (H) Spherules from Beloc showing black glass core in the center of an alteration shell. (I and J) Polished cuts from Beloc spherules with glass core. In some spherules a double-layered alteration rim, consisting of gel-like 'palagonite'(L1) and 'smectite' (L2) can be observed. Note the presence of large vesicles in the center of the spherules.

Figure 38: KT boundary ejecta lapilli in El Guayal, Mexico.

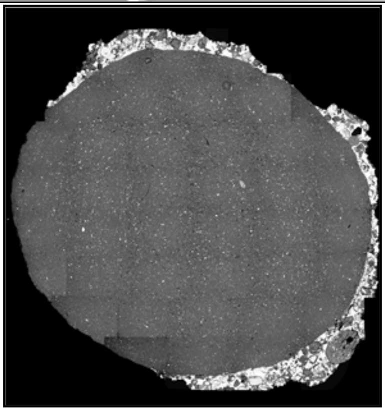


Figure 39: Scanning electron microscope image of accretionary lapillus with some of the surrounding matrix (FoV= ~ 1mm).

2.35. Comet composition and early Solar System evolution

WP involved	WP 4 – WP 5
Contributing partners	BISA – ULg
Summary description of the objectives	Understand early evolution of the Solar System from comets
Summary description of the scientific activities and results	As part of the team of the Rosetta mission to the comet 67P/Churyumov-Gerasimenko, we are deeply involved in studies related to establishing the composition. One of the first results that we obtained was the determination of the D/H ratio, which is of fundamental importance for understanding the origin of the solar system; a Science paper is being published on the subject. 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. A 3 times higher D/H value for the comet than for the Earth precludes the idea that the majority of the Earth's oceans would somehow have been delivered to Earth by comet impacts. We are deeply involved in the data processing and scientific interpretation of comet composition measurements made with the ROSINA-DFMS mass spectrometer on ESA's Rosetta mission currently exploring comet 67P/Churyumov-Gerasimenko. Part of the efforts went to a better understanding of the instrument to obtain more accurately calibrated results. More relevant for Planet TOPERS are the comet composition studies that we have participated in and that have been made possible by the instrument work. DFMS measures the composition of the escaping comet atmosphere, which is created by sublimation of volatile material on the comet surface. DFMS made several discoveries, such as establishing the heterogeneity of

	the volatile composition over the surface, finding not only that the D/H ratio is strongly different from Earth's, but making the first-ever detection of N_2 and Ar in a comet, and perhaps most puzzling of all the discovery of abundant O_2 in the comet at the level of 5 to 10%. In addition, the fortuitous combination early on in the mission of the Rosetta spacecraft being very close to the comet while the activity was still low, has allowed the observation of sputtered refractory elements from the surface of the comet (mostly Ca, K, Si, Na). All of these findings have consequences on the role of comet impacts on early Earth. They also provide strong constraints on the prevailing conditions during the formation of the Solar System. For instance, the D/H ratio seems to indicate that asteroid impacts rather than comets provided the lighter elements to Earth. Trapping of N_2 in the comet material is indicative of a low formation temperature of ~40 K. The presence of O_2 in comets, while O_2 is essentially not observed in protostellar clouds, seems to imply that it is formed during the solar system formation process. Further work about the origin of O_2 in comets suggest that it could be the result of irradiation of icy grains in molecular clouds which can induce radiolysis of water molecules which results in the production of O_2 trapped in the icy grains. Following the discovery of O_2 we modeled the impact of cosmic rays on cometary nucleus and showed that they significantly alter the cometary nucleus, changing its chemical composition and the structure of its ice in the first tens of meters inside it. This has to be taken into account when comets observations are used to constrain the early evolution of the solar system.
Main achievements in relation to the initial objectives	Better understanding of early evolution of the Solar System from comets
Comments in case of deviations from the initial project work-programme	
Illustrations:	

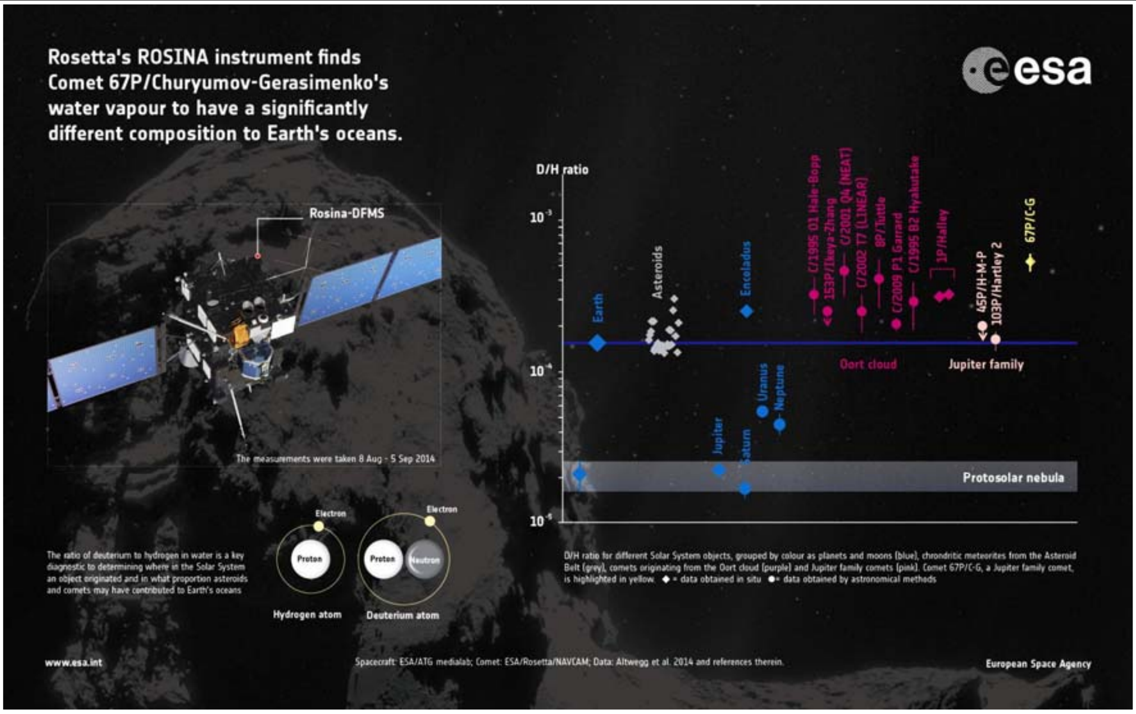


Figure 40: ESA infographic about the Rosetta/ROSINA/DFMS determination of the D/H ratio in 67P/Churyumov-Gerasimenko.

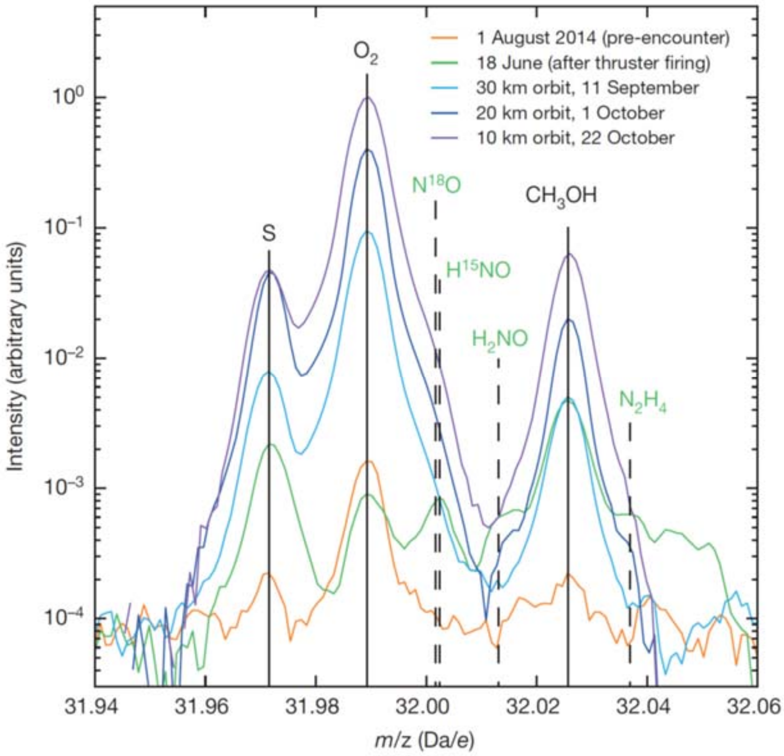


Figure 41: Typical spectra obtained with Rosetta/DFMS around mass-over-charge 32, showing the molecular oxygen peak (from Bieler et al., Nature, 2015).

2.36. Atmosphere evolution due to multiple impacts and impact warming

WP involved	WP 4 – WP 5 – WP 1 – WP 2 – WP 3
Contributing partners	ROB – BISA
Summary description of the objectives	Understanding the evolution of planets' atmosphere
Summary description of the scientific activities and results	We have modeled asteroid and comet impacts on terrestrial planets (Venus-Mars). The first process changing the atmosphere is the erosion and loss of volatiles during the impacts. The second process is the quantity of water vapor and carbon dioxide delivered to the atmosphere from both impactor material and the planet surface and subsurface. Since the soil heat flux also influences climate, impact warming of the subsurface is also modeled. According to these calculations for Mars, impacts can cause all possible Martian underground ice and water to evaporate into the atmosphere. We have implemented impact warming modelling in a three dimensional context. Comparisons will be performed with numerical simulations of impacts performed by Vladimir Svetsov from the Institute for Dynamics of Geospheres RAS in Moscow (Russia) – the visit is foreseen end of May 2016. With all the input parameters defined, impact flux, dimension, energy, wind and greenhouse gases delivery have been considered with the Martian three-dimensional climate model (GCM).
Main achievements in relation to the initial objectives	Better understanding of the evolution of planets' atmosphere and habitability conditions
Comments in case of deviations from the initial project work-programme	

Illustration:

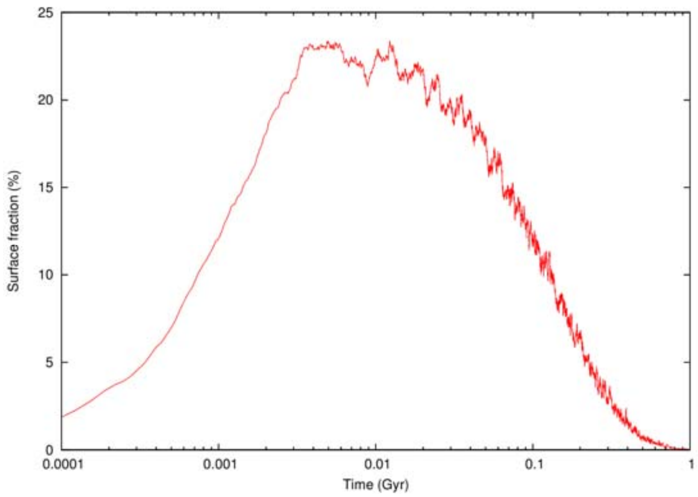


Figure 42: fraction of the surface of Mars showing conditions that favor liquid water as a result of impact warming during early evolution of the Solar System.

2.37. Atmosphere evolution due to single large impacts

WP involved	WP 4 – WP 5 – WP 2 –WP 1 –WP 3
Contributing partners	ROB – BISA
Summary description of the objectives	Understanding the comets and asteroids effects on the atmosphere of planets, Mars in particular
Summary description of the scientific activities and results	We have taken into account the effects of meteorites in coupled atmosphere-mantle evolution simulations by adapting each relevant part of the model. The impactors can bring volatiles as well as erode the atmosphere. 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. However, multiple smaller impacts could favor erosion. Giant impacts are also able to modify the convection patterns of a terrestrial planet on the millions to billions of years' timescale. Mantle dynamics is modified since the impact itself can also bring a large amount of energy to the mantle. We have worked with mechanisms that deplete or replenish the atmosphere: atmospheric hydrodynamic or non-thermal escape to space and volcanic degassing of the mantle. We have also incorporated a model for erosion from meteorite impacts into the existing framework of the long term evolution models previously developed. The current global coupled model of evolution of terrestrial planets has been upgraded with a newer version of the mantle convection code including a more precise calculation of melting during the impact. We have included modelling of meteoritic erosion for different assumptions on the strength of the process and concluded that, with the exception of very large impacts (r>500km), single impact erosion was likely a secondary mechanism for the long term evolution of surface conditions.
Main achievements in relation to the initial objectives	Better understanding of the comets and asteroids effects on the atmosphere of planets, Mars in particular
Comments in case of deviations from the initial project work-programme	
Illustrations:	

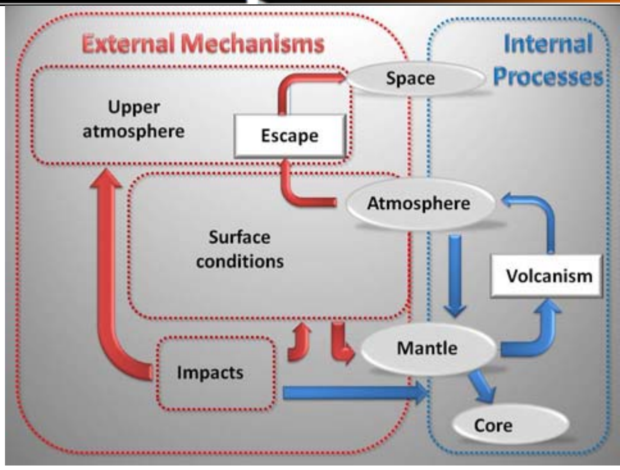


Figure 43: Mechanisms and feedbacks between layers in a terrestrial planet: current state of the model.

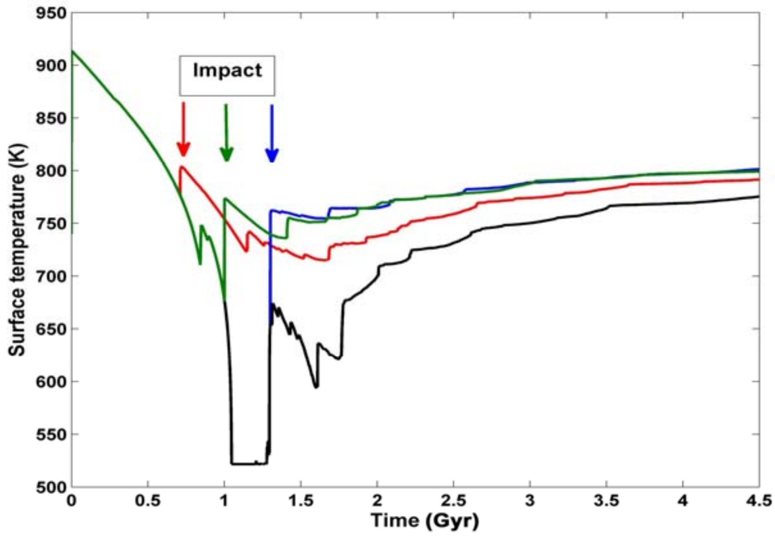


Figure 44: Examples of the effects of single large impacts (500 km radius) on the surface temperature of Venus compared to a reference “no-impact” case (black).

2.38. Atmosphere evolution for planets without plate tectonics

WP involved	WP 5 – WP 1 – WP 2 – WP 3 – WP 4
Contributing partners	ROB – DLR – BISA – ULB – VUB
Summary description of the objectives	Understanding the evolution of planets’ atmosphere, evolutions of Mars and Venus, feedback cycles to stabilize habitable conditions, using integrated model of planetary thermodynamics
Summary description of the scientific activities and results	We investigated the history of the atmosphere and surface conditions on Venus and terrestrial planets. Our main focuses are mechanisms that deplete or replenish the atmosphere: volcanic degassing (see Points 2.4 and 2.19), atmospheric (mainly hydrodynamic) escape (see Points 2.20 and 2.21) and impacts (volatile delivery as well as atmospheric loss, see Points 2.24, 2.36, and

	above). We have considered long term-evolution through a coupled mantle/atmosphere model. Atmospheric escape modelling involves different aspects. We have shown that during the first few hundreds of millions years, hydrodynamic escape is dominant and very efficient. It has strong effects on early conditions and may be responsible for Venus' dry state. For later evolution, non-thermal escape becomes the main process but remains low. Impacts similarly play an important part in the evolution of terrestrial planets. We investigate two aspects: (i) early volatile input by planetesimals during the late stage of accretion as opposed to hydrodynamic escape during this period to assess if Venus could have received large amounts of water, just like Earth and (ii) short, medium and long term effects of large impacts occurring during the Late Veneer period and Late Heavy Bombardment. Similarly, for Mars we have examined the evolution of the atmosphere. Calculations have been done to compute the quantity of water vapor and carbon dioxide delivered to the atmosphere from both impactor material and the Martian surface and subsurface. The study includes the heat effect from the impactor.
Main achievements in relation to the initial objectives	Better understanding of the evolution of planets' atmosphere, evolutions of Mars, Venus, and Earth, feedback cycles to stabilize habitable conditions, using integrated model of planetary thermodynamics
Comments in case of deviations from the initial project work-programme	

Illustrations:

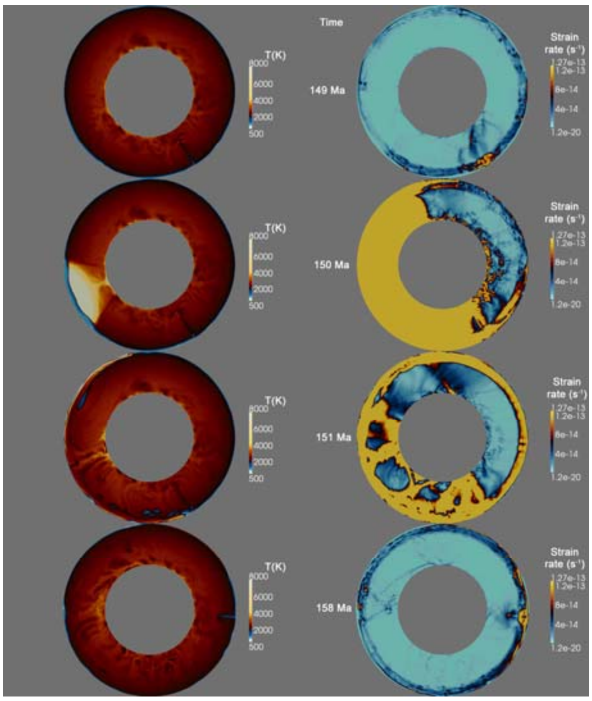


Figure 45: Temperature and strain rate fields in the mantle of Venus after an 800km radius impact in the

lower left quadrant of the annulus. At the impact location, the thermal anomaly and subsequent rising plume are visible. At the antipodal position, later downwelling can also be seen. Strain rates show the large effect of a very large impact on the mantle dynamics, in particular showing how the upper mantle is affected and material is "pushed" away from the impact location by the flattening of the anomaly, thus leading to later antipodal downwelling.

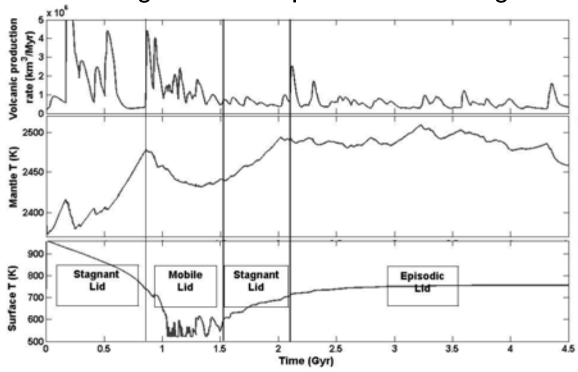


Figure 46: Comparative evolution of volcanic production rate, surface temperature and volume averaged mantle temperature with time for the reference case. Also indicated are the different convective regimes. The transition from mobile lid to stagnant lid is progressive. Early evolution (before 700Myr) follows an episodic, but mostly stagnant, lid pattern.

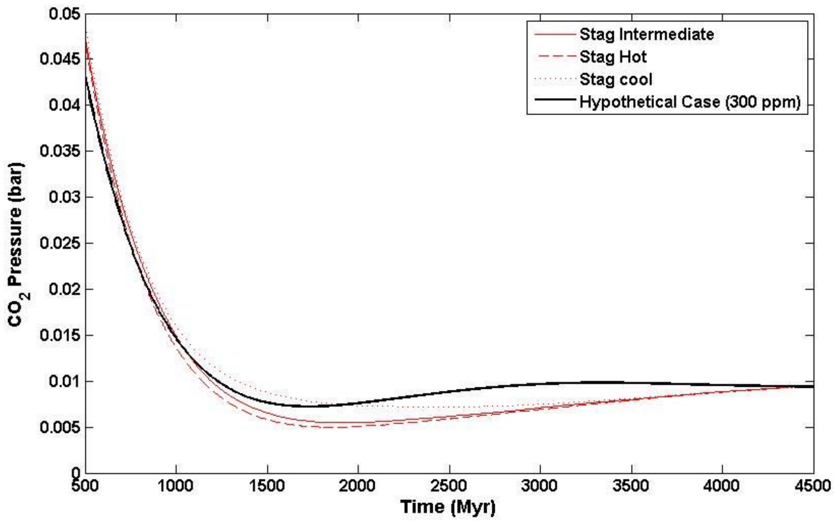


Figure 47: simulation of martian evolution for CO_2 partial pressure in the atmosphere (constituting the bulk of the atmosphere) over the last 4 Ga using different initial states.

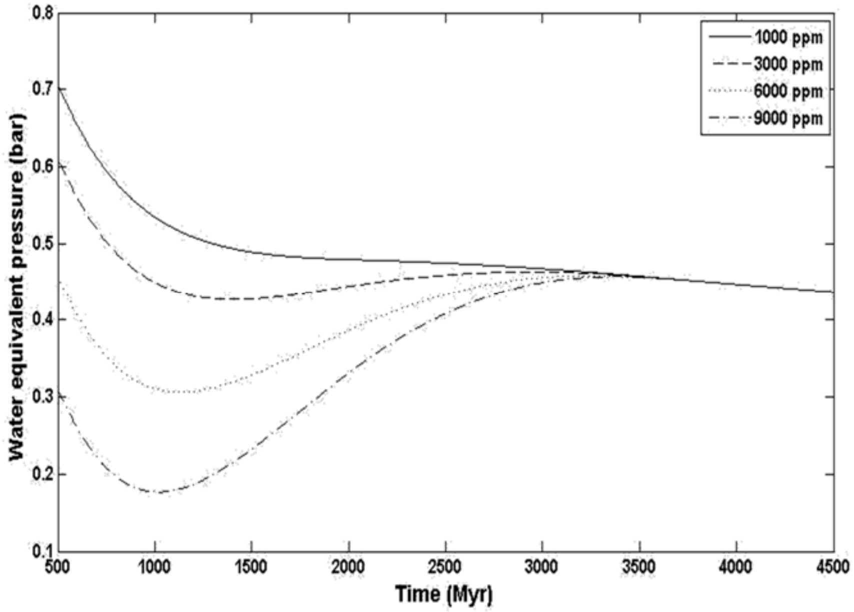


Figure 48: Water content at the surface of Mars (atmosphere and ice shelves) during the last 4 billion years reconstructed from present observation and modelling of volcanism and volatile escape.

2.39. Atmosphere evolution for planets with plate tectonics and biosphere

WP involved	WP 5 – WP 1 – WP 2 – WP 3 – WP 4
Contributing partners	DLR – ROB – BISA – ULB – VUB – ULg
Summary description of the objectives	Understanding the evolution of planets' atmosphere, evolutions of Earth, feedback cycles to stabilize habitable conditions, using integrated model of planetary thermodynamics
Summary description of the scientific activities and results	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 Planet TOPERS 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 (see Points 2.7, 2.23, 2.24). 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.

Main achievements in relation to the initial objectives	Better understanding of the evolution of planets' atmosphere, evolutions of Mars, Venus, and Earth, feedback cycles to stabilize habitable conditions, using integrated model of planetary thermodynamics
Comments in case of deviations from the initial project work-programme	

3. NETWORKING

3.1. Major joint activities performed as part of the network

3.1.1. Creation of a Scientific Council

A Scientific Council was created in order to help Planet TOPERS to maximize its productivity. The list of Scientific accompanying committee members:

- Anne Lemaître (FUNDP)
- Michel Crucifix (UCL)
- Alessandro Morbidelli (Nice Observatory, France)
- Gerda Horneck (DLR, Germany)

The Scientific Council was invited at the Planet TOPERS meetings and the annual reports were sent to them for advices. Its Members could and did provide the Planet TOPERS group with feedback, which was very useful for us.

3.1.2. Joint field experiments

Some of the Planet TOPERS partners have been involved in the same field trips, for sample collections.

For characterizing early Earth sedimentary and magmatic aqueous environments and early life traces, ULg and ULB went to the Barberton Greenstone Belt, in South Africa, and visited drill sites localities, local geology, and sampled Archean field outcrops and drill cores collected in the frame of the international ICDP "cradle of life" project. This is also part of the ERC Stg ELiTE project headed by Emmanuelle Javaux (ULg).

For the Antarctica mission in the frame of the SAMBA (Search for Antarctica Meteorites: Belgian Activities) project and the Planet TOPERS activities, a blog called "*The Planet TOPERS in Antarctica*!" was created (see http://antarctica.oma.be/).

From December 3 to February 12, scientists from VUB and ULB collected meteorites in the Nansen Ice Field, South of the Princess Elizabeth Station, Antarctica. The study of these new and unique meteorites provides valuable information about 4.5 Ga of evolution of the solar system, including planets and the Earth. Studying meteorites contributes to understand the formation and the age of the solar system, planets, asteroids and comets. The SAMBA program is a VUB-ULB research project, headed by Philippe Claeys (VUB) and Vinciane Debaille (ULB) and is made possible through the funding by the Belgian Science Policy (BELSPO) and the logistic support of the International Polar Foundation (IPF).

The VUB-ULB team composed of Planet TOPERS Vinciane Debaille, Wendy Debouge, Geneviève Hublet, Nadia Van Roosbroek and Harry Zekollari together with a Japanese team from the National Institute of Polar Research (Tokyo) searched the blue ice fields around PE (Princess Elizabeth) station in Antarctica for meteorites from December 2012 to February 2013. Systematic searches by skidoo were carried out in December and January, whenever the weather permitted, and covered the southern and eastern parts of the Nansen ice field. The conditions are harsh, even for Antarctic summer. Typically, temperatures easily reach -20˚C with an average wind speed of 50 km/h, resulting in a windshield factor of -37˚C; the actual temperature felt by the people working in the field. It was a pleasure for the entire Planet TOPERS group and the public to follow this adventure. The number of recovered meteorites reaches 424!!!! These new and unique samples were collected including an 18kg specimen, the largest found on the Southern Continent since 1988 (see Figure 49)! This attracted quite a bit of media coverage worldwide (http://iuap-planet-topers.oma.be/outreach.php) and for a short time was exposed at the Belgian Embassy in Tokyo to illustrate Belgian-Japanese scientific and technical exchanges. The blog (http://antarctica.oma.be/) of this expedition also received a lot of attention (statistics of the attendees are shown in Figure 56). The 18kg-meteorite found in Antarctica was shown at the Antarctic Treaty Consultative Meeting, on May 25-26, 2013, in Brussels. It is now on display at the Natural Science Museum of Brussels.

Figure 49: Planet TOPERS and the 18kg meteorite found in Antarctica.

In 2013, and 2015, VUB scientists carried out field work in Southern Mexico in search of impact ejecta from the Chicxulub crater. The ejecta material was collected in different locations ranging from 200 km (Quintana Roo, Yucatan, Campeche) to more than 800 km (Chiapas, Tabasco) away from the crater rim. This material is currently being studied at the VUB, see for example Belza et al. (2015). In May 2016, VUB scientists resampled the Ries crater (Bavaria, Germany) to obtain highly shocked basement material and glassy suevitic ejecta.

3.1.3. Transfer of tools – Common use of equipment and databases

The CHIC software from ROB and the GAIA software from DLR to model mantle dynamics have been benchmarked.

The UGent and ULB MC-ICP-MS facilities are shared with the partners of the Planet TOPERS for isotopic analyses. The ULB and UGent partners also regularly use the newly µXRF installed at the VUB (Hercules Foundation Flanders grant 2013) for major and trace element mapping at high resolution (25 µm) on meteorites, impactites and other rocks. Minor, traces and ultra-trace elements are being analyzed by the VUB-ULB-UGent partners using the HR-ICP-MS facilities at the UGent (coupled with Laser ablation) and VUB. Stable isotope analyses ($\partial^{18}O$, $\partial^{13}C$) are carried out in the AMGC laboratory at the VUB. TIMS measurements for all team members are available at ULB (ERC grant V. Debaille). In 2016, a new infra-red microscope coupled to a spectrometer will be operational at the VUB (Hercules Foundation Flanders grant 2015) together with the microdrill facility.

ULg works with ULB for major elements analyzes and Sm-Nd, and possibly Rb-Sr datings at ULB facilities. FTIR (Fourier Transform InfraRed)-microspectroscopy (ULg Impulsion grant E. Javaux) and Raman microspectroscopy (ERC grant E. Javaux) are available at ULg.

3.1.4. Knowledge between partners – Exchanges of researchers

The different partners have complementary knowledge, which has been shared with others.

Working Groups among the partners have been set up at the beginning of the IAP and have met all along the IAP.

Backbone activities of the IAP include PhD student and post-doc training, working groups, and informal meetings between the Members. All these activities have further strengthened the Members of the IAP by soft skill exchange and communication that focus on optimizing the interactions between the participating scientists.

Some of the PhDs and postdocs have been working at different places within the IAP, e.g. Elodie Gloesener has been working at ROB and BISA, Lena Noack has been working at DLR and ROB, Joint PhD have been awarded between the ULB and VUB (Nadia Van Roosbroek, 2015) and between the VUB and UGent (Joke Belza, 2015). ULg postdoc Camille François, Dan Asael and ULg PhD student Blaise K. Baludikay have been doing measurements in ULB.

3.1.5. Annual and WP meetings

There were several WP specific or subgroup meetings. Additional informal meetings were also organized to discuss specific questions. Some of these work meetings were organized during congresses that we attended.

Informal meetings were also organized to celebrate some of the medals and prizes awarded to Planet TOPERS members. In addition, we held team-building aperitif-party's (summer party's) in the garden of ROB for a get-together, breakfasts with members of the Steering Committee, get-togethers between postdocs and PhD students, Christmas party's etc. At each EGU, the Planet TOPERS members attending the meeting have organized a dinner together. These informal events were highly appreciated by the Planet TOPERS members and were very efficient in terms of exchange of ideas and information.

The Planet TOPERS Members benefit as well from the Astrobiology FNRS Contact Group (http://astrobio.oma.be/) with Emmanuelle Javaux as President and Véronique Dehant as Secretary. This Contact Group meets each year. The Planet TOPERS Members are a sub-group of the Contact Group members and therefore benefit from these meetings. FNRS financial support allows for invited speakers from abroad.

More formally, Planet TOPERS members have organized a kick-off meeting and annual meetings. The Steering Committee met at these occasions and met as well several times during the IAP existence. Minutes and Action item lists of these meetings are sent by email and/or available on the Planet TOPERS ftp site for all the partners and for the Scientific committee as well as the BELSPO representatives.

- The research and interactions between the teams were initiated during a fruitful kick-off meeting on 1st Oct. 2012 (see Figure 50).

Figure 50: Kick-off meeting at ROB.

- The first Annual Joint Meeting was organized on May 21-23, 2013, at the DLR Berlin-Adlershof in the frame of the Helmholtz Alliance "Planetary Evolution and Life" as this year is their last year functioning as a Helmholtz Alliance.
- The 2013 annual meeting of the Astrobiology contact group was held at ROB on March 8th (the Women day!). We invited Mareike Godolt (Technische Universität Berlin and DLR Berlin) to talk about "PLAnetary Transits and Oscillations of stars (PLATO)" and Kevin Lepot (University of Lille) to present his work on "Isotopic and nanoscale textural evidences for the biogenicity of the oldest

cellular structures (3.4 billion years old)". We also took this opportunity to have a Steering Meeting.

- Planet TOPERS members have organized their second year meeting together with the Helmholtz Alliance meeting in Berlin (in which the DLR international partner is participating).
- An additional Steering Meeting with presentations of the WPs has been held in BISA on 29 November 2013.
- On November 3d 2014 there was a meeting of the Consortium as part of the Astrobiology FNRS Contact Group, and another meeting of the Steering Meeting has been organized as well on November 4th.

Figure 51: Contact Group meeting at Liege University on November 3d 2014. more than 50 people attended the workshop!

- Our 3d year meeting was foreseen on November 27, 2015 and organized at ROB. However, this meeting has been postponed due to the Level 4 security level against terrorism. It was thus held in ROB in January 2016 together with a Steering Meeting, and followed by a meeting of the Astrobiology contact group. The new date is 22d January 2016, during which the WP leaders present their work. There were as well several WP specific or subgroup discussions. Minutes of these meetings are available on the Planet TOPERS ftp site.
- The Planet TOPERS Members benefited again from the Astrobiology FNRS Contact Group. We invited Nicolas Mangold (Univ. Nantes) to talk about "Water on Mars". His talk was followed by a "Table ronde" involving all participants and including points of view of Emmanuelle Javaux, Veronique Dehant and Planet TOPERS members. There was interesting discussion on latest results on habitability. We also invited Doris Breuer (DLR Berlin) to talk about "Geodynamics of planets and habitability" and Johan De Keyser (Belgian Space Aeronomy) to present the "Latest results from Rosetta".
- In addition to the forthcoming meetings of the Planet TOPERS group, we will organize an international workshop in the Azores in September 2017. The Azores belong to one of 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. This meeting does not only include field trips but as well a dense interdisciplinary workshop entitled "*Geoscience for understanding habitability in the solar system and beyond*". Within the Planet TOPERS 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 order to better assess the future roadmap of their work. In the coming years a lot of efforts in this direction will be made and the workshop will help in assessing the answers to these questions in a constructive critical way. The workshop would also play the role of a broader platform to bring the discussions of participants to all these groups at the international level and to reveal the controversies on hot-topic subjects. These groups have attracted young scientists who will be able to participate in the workshop. We plan to organize the workshop as a set of keynote-reviews, followed by a set of keynote-controversial question summaries and keynote-young scientist additional views, followed by discussions. Money outside the Planet TOPERS group have been ensured for the young scientists, the invited talks, and the Planet TOPERS participants/organizers.

3.1.6. Organization of national and international workshops

Planet TOPERS members attended several international meetings to present the work of the Consortium, and establish its scientific presence within the community.

They also organized sessions at congresses or conferences themselves (given as a function of time):

- Planet TOPERS Members were responsible for the organization of 3 sessions at **EGU** (European Geosciences Union) **2013**. The first entitled "PS8.1: Planetary Evolution and Life", was convened by Tilman Spohn, Doris Breuer, Lena Noack, Véronique Dehant (and others outside our IUAP). Planet TOPERS Tilman Spohn was awarded the Runcorn-Florensky Medal; the honorary lecture was given during the session. The other two Planet TOPERS sessions at EGU, called "GD1.1/PS2.7: Planetary Geodynamics", conveners: Doris Breuer (and others outside our IUAP) (V. Dehant had an invited talk in that session), and called "BG1.1: Biogeosciences", conveners: Emmanuelle Javaux (and others outside our IUAP).
- Planet TOPERS Members participated in the organization of the Astrobiology Graduate Conference (**AbGradCon**) 2013 meeting, in Montreal, Canada, on June 10-14, **2013**, along with a workshop taking place the following weekend. ESA fully supported the participation of European students (travel, lodging, meals and registration fees were funded by ESA, NASA and the Canadian Space Agency CSA).
- The Planet TOPERS Consortium has organized a complete session at **2013 EPSC**, entitled "AB4: Planetary Habitability in the Solar System and Beyond", conveners: V. Dehant, L. Noack, T. Spohn, D. Breuer, J.-P. Lebreton, O. Prieto-Ballesteros.
- Planet TOPERS Member E. Javaux was chair of a session at the **International Biogeoscience Conference 2013**, Nov. 1-4th, Nagoya, Japan.

- Planet TOPERS members (A.C. Vandaele, A. Mahieux, and V. Wilquet) are leading an **ISSI** International Team to study the role of SO_2 in the Venusian atmosphere. The project was granted and entitled “Venus SO_2: investigation of the role of SO_2 in the Venusian atmosphere” - PI: A.C. Vandaele and O. Korablev, 12 international experts - expert from Planet TOPERS: A. Mahieux - http://www.issibern.ch/teams/venusso2/. The first meeting was in November **2013**, next meetings in June 2014 and November **2014**.
- VUB and ULB Planet Topers members organized a 1-day national meeting at the Royal Belgian Institute of Natural Sciences titled “*Meteorites and Dinosaurs*” for the official inauguration of the exhibit showing on permanent display of the new 18 kg meteorite recovered in Antarctica.
- Planet TOPERS members are moreover participating to 2 other **ISSI** International Teams on Venus as experts (Venus Cloud and Venus Temperature). “Venus Atmos: towards a self-consistent model of the thermal structure of the Venus atmosphere” - PI: S Limaye - experts from Planet TOPERS: A.C. Vandaele and A. Mahieux - http://www.issibern.ch/teams/venusatmos/. The first meeting was in November **2013** (next meetings in June 2014 and Nov **2014**),
- “Venus Clouds: investigating the role of clouds in the Venusian atmosphere” - PI: C. Wilson and E. Marcq, expert from Planet TOPERS: V. Wilquet - http://www.issibern.ch/teams/venusclouds/. The first meeting was in November 2013 (next meetings in June 2014 and Nov 2014),
- One Planet TOPERS member (R. Maggiolo) is members of the **ISSI** international team “Heavy Ions: Their Dynamical Impact on the Magnetosphere” - PI: E. Kronberg - expert from Planet TOPERS: R. Maggiolo - http://www.issibern.ch/teams/ionmagneto/ - meetings 11-15 Feb **2013** and 21-25 Oct 2013.
- One Planet TOPERS member (R. Maggiolo) is coordinator of the **ISSI** international team “Polar Cap Arcs: Understanding Magnetosphere-Ionosphere Coupling and Magnetospheric Topology during Periods of Northward IMF” - PI: R. Maggiolo (from Planet TOPERS) - http://www.issibern.ch/teams/polarcap/ - Meetings on 4-8 Feb. 2013, 21-25 Oct. **2013**.
- One Planet TOPERS member (L. Maes) is members of an **ISSI** international team: “Magnetosphere-ionosphere-thermosphere coupling: differences and similarities between the two hemispheres” - PI: I. Cnossen and M. Förster, http://www.issibern.ch/teams/twohemispheres/, meetings 1-5 Dec **2014**, 2-3 Jun **2015** and 25-29 Apr **2016**.
- Planet TOPERS members were responsible for the organization of two sessions at **EGU** (European Geosciences Union) **2014**, PICO Session PS8.1/BG8.2 “Evolution of planetary habitability: conditions for the origin of life on Earth and beyond Earth”, Convener: Emmanuelle Javaux, Co-Conveners: Doris Breuer, Véronique Dehant, Özgur Karatekin, Lena Noack, Tilman Spohn, Ann Carine Vandaele (all from Planet TOPERS) and the PICO session BG 8.1 “Evidence and Habitats for Life on the Archean-Proterozoic Earth”, Conveners: Nicola McLoughlin, co-conveners: Emmanuelle J. Javaux, Dan Asael, Noah Planavsky.
- We have also organized a complete session at **EPSC** (European Planetary Science Congress) **2014**, Session AB2 “Planetary Habitability in the Solar System and Beyond”, Convener: V. Dehant, Co-Conveners: L. Noack, T. Spohn, and D. Breuer (all from Planet TOPERS).
- Planet TOPERS Members participated in the organization of the Astrobiology Graduate Conference (**AbGradCon**) **2014** meeting, L. Noack is a founding member of the European Astrobiology network for young scientists Astrobiology Graduates in Europe (**AbGradE**) and was an organizer for its first symposium in October 2014.
- Planet TOPERS Members E. Javaux and V. Dehant (ROB), member of SOC and co-Convener of **COST ORIGINS March 2015** conference “Habitability in the universe: from the early Earth to Exoplanets” and workshop “Biosignatures and abiotic processes”, 22-27 March 2015, Porto, Portugal
- Planet TOPERS Member E. Javaux, member of SOC and co-Convener of **COST ORIGINS October 2015** conference “missions to habitable worlds”, Budapest 20-26 October 2015.
- Planet TOPERS members were responsible for the organization of 8 sessions at **EGU** (European Geosciences Union) **2015**:
    - PICO Session PS8.1/BG8.2 “Evolution of planetary habitability: conditions for the origin of life on Earth and beyond Earth”, Convener: Emmanuelle Javaux, Co-Conveners: Doris Breuer, Véronique Dehant, Özgur Karatekin, Lena Noack, Tilman Spohn, Ann Carine

Vandaele, completely organized by Planet TOPERS members,
  - Union Oral Session US4 "What is inside? Planetary interiors as viewed from space", Conveners: Mioara Mandea, Özgur Karatekin, Tilman Spohn,
  - PICO Session PS9.1/GD3.6/GM10.2/GMPV7.11/TS9.6 "Processes in the Solar and Other Planetary Systems - Comparative Planetology", Conveners: Lena Noack, Co-Conveners: Ana-Catalina Plesa, Cedric Gillmann,
  - PICO Session PS6.1 "Habitability, observations, formation and dynamics: From the Solar System to Exoplanets", Co-Conveners: Doris Breuer, Lena Noack,
  - Oral and Poster Session PS8.1/BG8.1 "Origin of life and habitability: From Early Earth to the Solar System and Beyond", Convener: Tilman Spohn, Co-Conveners: Doris Breuer, Véronique Dehant, Lena Noack, Emmanuelle J. Javaux, Cedric Gillmann, Jean-Yves Storme, Camille François,
  - Oral Session SC22 "Open Science, Public Engagement and Outreach: why bother?", Convener: Lena Noack,
  - Oral Session SC33 "Oral presentation feedback round.", Co-Convener: Lena Noack,
  - Poster Session BG1.1 "Open session on Biogeosciences", Co-Convener: Emmanuelle J. Javaux.
- We have also organized sessions at **EPSC** (European Planetary Science Congress) **2015**:
  - Session AB2 "Planetary Habitability in the Solar System and Beyond", Convener: V. Dehant, Co-Conveners: L. Noack, T. Spohn, and D. Breuer,
  - Session TP8 "Numerical modelling of planetary dynamics", Co-Convener: L. Noack.
- Planet TOPERS Member L. Noack participated in the organization of the Astrobiology Graduates in Europe (**AbGradE**) meeting **2015**.
- Planet TOPERS members L. Maes and V. Dehant organized a session at the **2015 AGU** Fall Meeting in San Francisco, U.S:
  - Ionospheric Outflow from Earth and Other Terrestrial Planets and Its Importance as a Source of Plasma for Magnetospheres, Conveners: L. Maes, V. Eccles, C. Chappell, W. K. Peterson;
  - Earth and Planetary Rotation: Improving Theories, Models, and Observations, Conveners: R. Gross, A. Brzezinski, V. Dehant, and J. Ferrandiz.
- Planet TOPERS members organized three sessions at **EGU 2016**:
  - PS7.1/BG8.2: "Origin of life and habitability: from early Earth to the Solar System and beyond", T. Spohn (Convener), D. Breuer, V. Dehant, E. Javaux, L. Noack, C. Gillmann, J.-Y. Storme, C. François, Ö. Karatekin (Co-Conveners)
  - ST3.3: "Ionospheric outflow from Earth and other terrestrial planets – The Dynamic Ionosphere", L. Maes (Co-Convener)
  - PS6.1: "Exoplanets: Observations and modeling", PICO Session, L. Noack (Co-Convener)
- Planet TOPERS member C. Gillmann will co-organize the Planetary Atmosphere session at **AGU 2016** (session submitted) in San Francisco, USA.
- Planet TOPERS Member E. Javaux, member of SOC and co-Convener of **COST ORIGINS April 2016** conference "From Star and planet formation to early life", Vilnius, Lituania, April 24-29th, 2016. And Invited talk "Excitements and challenges in tracking the early traces of life".
- Planet TOPERS Member E. Javaux is Member of SOC of **ISSOL 2017** conference (International Society for the Study of the Origin of Life and astrobiology), San Diego, California, July 2017
- A future international workshop entitled "*Geoscience for understanding habitability in the solar system and beyond*" will be organized in September 2017 by Planet TOPERS as described in the previous point.

3.1.7. Organization of network-driven training activities

The network-driven training activities were mainly WP meetings, exchange of idea per email, skype, face-to-face, or meetings. The meetings are detailed in Section 3.1.5.

Also training was foreseen by choosing the appropriate invited lectures during the sessions and workshop we have organized, including for the Astrobiology contact group.

Network-driven activities for young scientists were particularly useful and have been detailed in Section 3.3.4.

An Astrobiology class (http://progcours.ulg.ac.be/cocoon/cours/GEOL0263-1.html) for master student, PhDs and Postdocs in Geology, Spatial Sciences, Biology, Chemistry, Engineering, is organized every other year at ULg and includes Planet TOPERS members and other scientists as teachers.

Specific series of classes related to planet TOPERS topics are organized every year at the Royal Academy of Sciences of Belgium in Brussels and involve Planet TOPERS members among which 2 are academicians. Previous classes dealt with: Astrobiology, early eukaryote evolution, icy moons, habitability.

Planet TOPERS Member T. Van Hoolst is co-director of the International School of Space Science on “Planetary Interiors” to be held in L’Aquila, Italy, in September 2016, open to PhD students and young postdoctoral researchers and engineers.

Planet TOPERS Member E. Javaux will also co-organize a training school “EEL: Early Earth & Life” in Russia, Karelia, in August 2017, in the frame of COST ORIGINS, open to international and Planet TOPERS students.

3.1.8. Newsletters, Website, and Ftp

The planet TOPERS have a website at http://planet-topers.oma.be/ and a private ftp site at https://planet-topers.oma.be/index_library.php where all information necessary for the group is provided.

The planet TOPERS website contains:

- Home (where the latest news are displayed)
- Objectives
- Partners
- Definition of Habitability
- Scientific Concept and Overall Planning
- Useful Links (including e.g. the Astrobiology Contact Group and the Helmholtz Alliance)
- Outreach (with all press released, interviews etc.)
- News (the archive of all news)
- Planet TOPERS Meetings (with the details and the agendas)
- Other Conferences-Events (of interest for the group)
- Publications (will be updated after this report)
- Annual reports (will be updated after this report)
- Jobs
- Ftp (this is a private ftp as explained below; it requires a password).

The content of our ftp is the following: https://planet-topers.oma.be/index_library.php

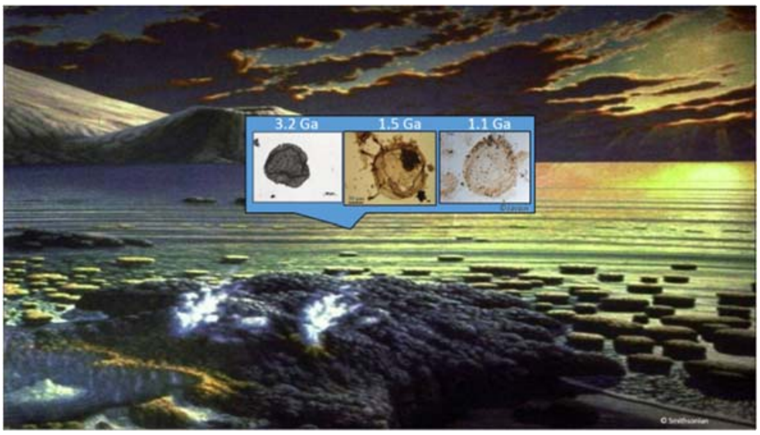
- Acknowledgements - logos
- Action item list
- Administration documents (each institute = one directory)
- CVs
- Steering Meetings
- Consortium Meetings
- Helmholtz Alliance
- Internal (WG) meetings
- Kickoff meeting
- Reports - Lists publications & presentations
- Outreach
- Project
- WP1 2 3 4 5

3.1.9. Involvement in Outreach

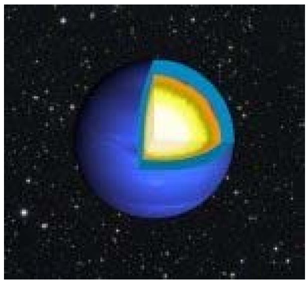
The planet TOPERS have several blogs, press releases, TV interviews, radio interviews, paper press, and have given several public conferences. See Section 5.

Something not addressed in that Section is the fact that our PICO session at EGU has been one of the first PICO session and as we had made an effort for this session to be very efficient, it was taken as an example on the web for presenting the definition of PICO session.

On the EGU website one can now find an advertisement video for PICO presentations. The video used last year's PICO session PS8.1/BG8.2 “Evolution of planetary habitability: conditions for the origin of life on Earth and beyond Earth” and PICO session BG8.1 “Evidence and Habitats for Life on the Archean-Proterozoic Earth” organized by several Planet Topers as mentioned above. This is a great advertisement for our work: see http://www.egu2015.eu/pico.html. If you look at the video, you see for instance Lena for PICO PS8.1/BG8.2 then you can listen to Kurt Konhauser, invited speaker in the other PICO BG8.1.



Billions of years ago, cyanobacteria transformed the chemistry of our planet, a period known as the Great Oxidation Event. This episode was a pivotal point in Earth’s history, opening the evolutionary door to oxygen-breathing animals. Until recently, the event was thought to have taken place 2.3-2.4 billion years ago. But recent results have pushed this milestone back, resetting the date for the origin of oxygen-releasing photosynthesis and highlighting the long-lasting and dynamic nature of the transition from an oxygen-poor to an oxygen-rich world. This press conference explores new research on when and how Earth came to have an oxygen-rich atmosphere, and discusses what the conditions for life in our planet can tell us about the possible habitability of other worlds, particularly of ocean-bearing planets (see Point 2.12). The press conference was streamed online. The video of the press conference is available at this link (http://media.egu.eu/press-conferences-2014/#habitability).



3.1.10. Participation in calls together and “Snow-ball effect”

Planet TOPERS Members participate in several calls and obtained several new contracts.

3.1.10.1. ERC Grants

Three Planet Topers received ERC grants in the course of the project. Two Members obtained an **ERC Starting Grants** from the European Research Council. Close to a total of 3 million Euros are being invested in the two researchers' very high level research projects, exploring unexpected and audacious pathways in the study fields of the early evolution of life on Earth (E. Javaux, ULg) and initial composition of the solar system and terrestrial planets (V. Debaille, ULB). The extremely selective process (a 12% success rate) only retains the best researchers and very high level research projects, known as high gain, high risk, in other words projects in which the researchers demonstrate both their skills and their audacity in tackling very new research pathways which are likely to, should they prove successful, greatly enrich knowledge of the area concerned.

Véronique Dehant started her **ERC Advanced Grant** RotaNut in October 2015. The ERC Advanced Grant RotaNut (Rotation and Nutation of a wobbly Earth) addressing the causes of the irregular rotation and orientation of the Earth, namely those related to the core and the coupling mechanisms at the core-mantle boundary. This is also of interest for the IUAP Planet TOPERS as the physical phenomena that will be studied in the Earth's core like inertial waves and instabilities inside the liquid core, might also be relevant in other terrestrial planets having a liquid core like Mars, Venus, and Mercury.

In summary:

- Emmanuelle Javaux got an ERC StG called ELITE, for Early Life Traces, Evolution & Implications for Astrobiology), on early evolution of life on Earth, 2013-2018, total amount 1,500,000 €.
- Vinciane Debaille got an ERC StG called ISoSyc: Initial solar system composition, 2014-2019, total amount 1,500,000 €.
- Véronique Dehant got an ERC AdG called RotaNut, for Rotation and Nutation of a wobbly Earth, 2015-2020, total amount 2,500,000 €.

3.1.10.2. EU projects

Several **EU FP7 projects** submitted by Planet TOPERS (BISA) members have been granted

- FP7 'CrossDrive': to create a virtual environment to better merge data from different missions to Mars (http://planetary.aeronomie.be/en/fp7crossdrive.htm)
- FP7 'EuroVenus': to better exploit the Venus Express results and ground-based observations of Venus (http://planetary.aeronomie.be/en/fp7eurovenus.htm)

Three Planet TOPERS Members participate in a new **COMPET 8 of H2020**.

- Vinciane Debaille is co-PI of the EURO-CARES COMPET 8 H2020 project dedicated to create a roadmap for the implementation of a European Extra-terrestrial Sample Curation Facility (ESCF).
  See http://www.euro-cares.eu/.
- Ann Carine Vandaele (BISA) and Özgur Karatekin (ROB) are Co-I of UPWARDS (Understanding Planet Mars With Advanced Remote-sensing Datasets and Synergistic studies) COMPET 8 H2020 project dedicated to the understanding planet Mars with advanced remote-sensing datasets and synergistic studies of which the PI is Agencia Estatal Consejo Superior de Investigaciones Científicas (CSIC). The goals of the UPWARDS project match the topics, challenges and scope of the Compet-8-2014 call (Horizon 2020). The UPWARDS Consortium undertake five grand science themes which challenge our current understanding of the complex couplings of the Mars' climate:
  - exchange of trace species between subsurface & atmosphere;
  - global cycle of Martian water;
  - surface properties and behavior of suspended aerosols and dust storms;
  - drastic changes at the day/night terminator;
  - coupling of the lower and upper atmosphere and escape to space.

  All topics are addressed by experts in the field, exchanging results and knowledge in a truly synergistic and interdisciplinary collaboration.
  See http://planetary.aeronomie.be/en/upwards.htm.

Three Planet TOPERS Members participate in an **H2020 Research Infrastructure** (RI)

- **H2020 EuroPlaNet Research Infrastructure** (RI) is a €9.95 million project to integrate and support planetary science activities across Europe. The project is funded under the European Commission's Horizon 2020 programme; it was launched on 1st September 2015 and will run until 31 August 2019. The project is led by the Open University, UK, and has more than 50 beneficiary institutions from ~20 European countries. EuroPlaNet 2020 RI will address key scientific and technological challenges facing modern planetary science by providing open access to state-of-the-art research data, models and facilities across the European Research Area. DLR and BISA take part of this RI (see http://planetary.aeronomie.be/en/news.htm, 15 Sept. 2015; http://www.europlanet-2020-ri.eu/) and ROB has just signed the MoU. EuroPlaNet 2020 RI provides:

- Transnational access to world-leading laboratory facilities that simulate conditions found on planetary bodies as well as specific analogue field sites for Mars, Europa and Titan.
- Virtual access to diverse datasets and visualization tools needed for comparing and understanding planetary environments in the Solar System and beyond.

Ann Carine Vandaele (co-I) is involved in the Virtual Observatory VESPA work package. VESPA aiming at helping people to get easy access to data and to help people who have data to put them easily on that virtual observatory data center. BISA is putting their Venus data, spectra, atmospheric profiles & composition. This provides visibility and it is thus important to participate. Even models' results can be shared through the VESPA interface. The infrastructure provides help to those who want to use that site as depository. See http://europlanet-vespa.eu/call.shtml.

3.1.10.3. COST Action

Several planet TOPERS Members, Emmanuelle Javaux, Philippe Claeys, Véronique Dehant, Özgur Karatekin, Cédric Gillmann, and Lena Noack are part of a new FP7 TransDisciplinary Project TDP 1308 **COST Action: ORIGINS** "Origin and Evolution of Life on Earth and in the Universe" (PI: M Gargaud, Univ. Bordeaux; 54 proposers, now 29 countries). Emmanuelle Javaux and Philippe Claeys are the Belgian representatives in the managing committee and Véronique Dehant is suppliant. E. Javaux and V. Dehant (substituted in 2016 by L. Noack) are also working group leaders (Early and extreme life, and Planetary habitability, respectively). V. Dehant is Monitoring Process Coordinator for ORIGINS.

3.1.10.4. ESA projects and instrument selection

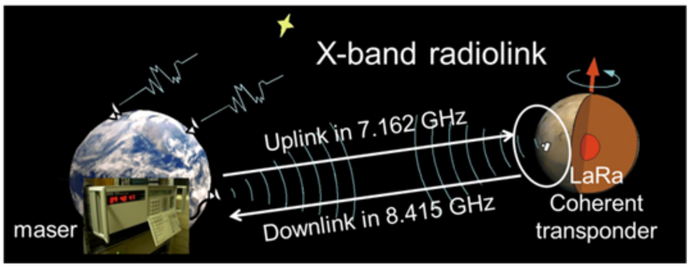


Figure 52: LaRa principle.

One Planet TOPERS Member (BISA) has obtained the SIROCCO project in **answer to the ESA AO**/1-7019/12/NL/AF: Synergetic SWIR and IR retrievals of near-surface concentrations of CH_4 and CO for Earth and Planetary atmospheres. The study objectives were:

- To specify the user requirements in terms of remote sensing Level 2 products (TIR and SWIR single measurements), derived from the user needs associated with clear applications for the two planets;
- To make a critical review of the already existing datasets and retrieval algorithms dedicated to CO and CH_4;
- To develop synergetic retrieval algorithms for deriving near-surface concentrations of CH_4 and CO from SWIR and TIR passive remote sensing channels obtained by current and planned Earth and Mars satellite missions;
- To foster as much as possible, the cross-fertilization between the Earth and planetary scientific expertise;
- To compare the usefulness and accuracy of the synergetic retrieval methods with the direct assimilation of SWIR and IR measurements in chemical transport models;
- To provide recommendations on the needs and specifications for co-located SWIR and IR measurements for the monitoring of near-surface CO and CH_4 concentrations.

Planet TOPERS members have developed an **instrument** that has been **selected** for the ExoMars 2018 platform. This instrument is called LaRa (Lander Radioscience). LaRa uses X-band[1] radio signals between the lander and the Earth. It sends the signal received from Earth back to large ESA and NASA antennas on Earth. Measurements of the Doppler shift on the radio link between LaRa on Mars and the antennas on Earth will be used to determine the rotation and orientation of Mars in space with a precision never reached before. This is possible since the rotation and orientation of

[1] The X-band is the part of the electro-magnetic spectrum between approximately 7 and 11.2 GHz, a gigahertz corresponding to one billion of cycles per second

the Earth are almost perfectly (precision below the centimeter level) known in space and the lander is fixed to the surface of Mars. The transponder has been designed by the Belgian company Orban Microwave Products (OMP) with funding from BELSPO (Belgian Federal Science Policy Office) via the PRODEX Programme of ESA (PROgramme for the Development of scientific EXperiments). The purpose of the instrument is to understanding the structure of and processes in the deep interior of planets is crucial for learning about the origin and evolution of planets. As deep planetary interiors are inaccessible to direct observation, the most effective way to explore them is through geophysics, which can be used as a tool for “remote sensing” of the interior. The four major classes of geophysical techniques that are used to probe planetary interiors are seismology, geodesy, heat flow measurements, and electro-magnetism. The LaRa (Lander Radioscience) team proposes a radioscience geodesy experiment to precisely measure the rotation and orientation of Mars. Most of us know that the rotation of a boiled egg noticeably differs from that of a raw egg. This simple observation shows that information on the inside of an egg can be obtained from its rotation. The same idea applies to the rotation and orientation of Mars.

A team led by a Planet TOPERS Member (Ö. Karatekin, ROB) has been selected by ESA to participate in an ESA/NASA **mission study of asteroid deflection**. The international consortium will study the technical challenge of operating Cubesat Opportunity Payloads (COPINS) in support of the objectives of a proposed ESA mission - the Asteroid Impact Mission (AIM). As part of the Asteroid Impact Deflection Assessment (AIDA) initiative, AIM will conduct in-situ measurements of the deflection of the binary asteroid 65803 Didymos caused by the impact of NASA's DART spacecraft. The mission would test for the first time full-scale technologies needed to protect the Earth from a potentially catastrophic impact! The study will last eight months, after which ESA will announce, among five studies, the concept that will be finally selected (June 2016). The mission AIM will be proposed to the Council of the European Space Agency in November 2016 for implementation.

One Planet TOPERS Member (E. Javaux) is part of the international CLUPI (CLose-UP Imager) team onboard the ESA rover ExoMars 2020, an exobiology mission. The ExoMars rover will travel across the Martian surface to search for signs of life. It will collect samples with a drill and analyze them with next-generation instruments. ExoMars will be the first mission to combine the capability to move across the surface and to study Mars at depth. CLUPI is a camera system designed to acquire high-resolution, color, close-up images of outcrops, rocks, soils, drill fines and drill core samples. The visual information obtained by CLUPI will be similar to what a geologist would get using a hand lens. This will provide the geological context and therefore improve the scientists' ability to interpret the results obtained by the other rover instruments.

3.1.10.5. ISSI workshops and International Teams

Planet TOPERS do also participate in **several ISSI workshops** as mentioned in the paragraph on Meeting Organization.

- “Venus SO_2: investigation of the role of SO_2 in the Venusian atmosphere”, PI: A.C. Vandaele (BISA) and O. Korablev (IKI), 12 international experts - expert from Planet TOPERS: A. Mahieux (BISA).
  See http://www.issibern.ch/teams/venusso2/.
- Planet TOPERS member have co-organized the ISSI/HISPAC Workshop on “High Performance Clocks, with Special Emphasis on Geodesy and Geophysics and Applications to Other Bodies of the Solar System”, Organizing Committee: V. Dehant (ROB), ~40 international experts, - expert from Planet TOPERS: T. Van Hoolst (ROB), T. Spohn (DLR).
  See http://www.issibern.ch/workshops/hispac/.
- As expert, Planet TOPERS member (Lena Noack, ROB) was participating in the ISSI workshop "The Delivery of Water to Proto-planets, Planets and Satellites" in January 2016.

A Planet TOPERS Member (E. Javaux) participates in an **International ISSI Bern & Beijing Team** on “Astrobiology in the New Age”, with the objective to develop astrobiology roadmap and education in China. The Project Coordinator is Feng Tian. The team is made of 6 Chinese scientists (Feng Tian, Yongyun Hu, Wei Leng, Yi-liang Li, Yunfeng Yang, Ting Zhu) and 6 European and North

American scientists (Muriel Gargaud, Lee Grenfell, Emmanuelle Javaux, Helmut Lammer, Alain Leger, Daniele L. Pinti) as well as 7 international and Chinese supporters, working on related but different aspects of astrobiology.

3.1.10.6. International Programs

Planet TOPERS Members (Ph. Claeys and E. Javaux) have succeeded to be elected and funded with their projects within the **ICDP** (International Continental Scientific Drilling Program) and **IODP** (International Ocean Discovery Program):

- The Chicxulub crater drilling: the offshore drilling of the 200 km in size Chicxulub crater in Yucatan started in April 2016 with ICDP and IODP funding, with the objective to obtain about 1.5 km of core within the peak-ring area of this 200 km size impact structure. Co-investigator: Ph. Claeys (VUB), also Member of the ICDP Science Advisory Group (SAG).
  See web http://www.eso.ecord.org/expeditions/364/364.php
- The Barberton Greenstone Belt in South Africa drilling: the ICDP "Peering into the Cradle of Life", official participating scientist: E. Javaux (ULg). Javaux (ULg) and V. Debaille (ULB) are participating to sample analyzes.
- The FAR-DEEP (Fennoscandia Arctic Russia - Drilling Early Earth Project) in Archean/Paleoproterozoic transition of Russia, participating scientist: E. Javaux (ULg).

ULg and DLR became collaborators of selected teams of the **NAI** (NASA Astrobiology Institute) of which the PI is Tim Lyons of the University of California, "mission to early Earth" http://astrobiology.nasa.gov/articles/2014/10/7/nais-new-teams-a-preview-of-the-research/.

Planet TOPERS Members are participating in **Tournesol (France-Belgium) collaboration**. ULB in particular is working with a well-known group of Aix-en-Provence. VUB is working with Paris-Tech. Univ. on a similar FWO-CNRS Tournesol grant (2016-2018) that funds visits between the two institutions.

Frank Vanhaecke has obtained an "Institutional Researcher Excellence grant" from EuRAmet – EMRP (European Association of National Metrology Institutes – European Metrology Research Programme). This Researcher Excellence Grant (REG) was connected to the multi-center research programme SIB-09 Elements and was entitled "Mass discrimination affecting Hg isotope ratio measurements via multi-collector ICP-MS". The budget was 180 k€. The results were summarized in: An in-depth evaluation of accuracy and precision in Hg isotopic analysis via pneumatic nebulization and cold vapor generation multi-collector ICP-mass spectrometry, A. Rua-Ibarz, E. Bolea-Fernandez and F. Vanhaecke, Analytical and Bioanalytical Chemistry, 408, 417-429, 2016.

Ann Carine Vandaele (BISA) was selected to be part of the iMARS II international team to investigate the requirements and needs for a Sample Return Mission from Mars.

3.1.10.7. FNRS-FRS and FWO and BAEF grants

Two Planet TOPERS Members (V. Dehant and E. Javaux) have obtained an **FNRS-FRFC** on Extensive study of the orbital dynamics of extrasolar systems to improve the habitability definition (name: ExtraOrDynHa) together with Univ. Namur (A. Lemaître, A.S. Libert) (1 July 2013-December 2016).

One Planet TOPERS Member (J. De Keyser) has obtained an **FNRS-FRFC** on laboratory and model comparison for spectroscopy calibration and comparative study of atmospheric erosion, with Univ. Namur and ULB (Nathalie Vaeck, PI). ULB does also participate in an **FNRS-New equipment** on analytical/isotopic analysis (PI: N. Mattielli and Co-PI: V. Debaille, both from ULB Planet TOPERS team). Name: AIMS: Advanced Isotopic Multitracing Spectrometry.

Johan De Keyser is involved in an **FNRS-FRFC project** that supports the work on ionospheric and cometary chemistry. The PI is N. Vaeck of the ULB: N. Vaeck, De Keyser J., X. Urbain, P. Quinet. Modelling of atmospheric and cometary erosion processes - Production of missing atomic and molecular data. FNRS project (Research Project T.107314, 205 k€, 2 FTE-year, involving ULB, BISA, UCL, UMons), 1 July 2014 - 30 June 2016.

One Planet TOPERS Member (Vandaele A.C.) has obtained an **FNRS-PDR project** called CRAMIC (CaRbon species in the Atmosphere of Mars from Infrared Composition sounders) on IR sounding of carbonate species in atmospheres, with ULB (Pierre-François Coheur, PI).

Vinciane Debaille has obtained an **incentive grant** from the **FNRS** (2012-2015).

Two Planet TOPERS Members (Ph. Claeys and F. Vanhaecke) have obtained **FWO funding** (2013-2016) for the development of Lithium isotope as tracer of planetary processes. Philippe Claeys is also co-PI of another FWO project (2013-2016) to study the Cretaceous-Tertiary mass extinction with Prof. R. Speijer (KUL). FWO aspirants David De Vleeschouwer and Joke Belza completed their PhD in 2014 and 2015, respectively on the effect of astronomical parameters on paleoclimates and on the ejecta material from the KT boundary Chicxulub crater. Currently, FWO aspirant Matthias Sinnesael (2015-2019) works on paleoenvironmental reconstruction across the KT boundary and the Ordovician-Silurian mass extinction events. FWO Post-doctoral researchers Dr. Koen Stein, Dr. Seann McKibbin, Dr. Steven Goderis are also contributing their expertise to the Planet Topers projects.

Dr. Justin Erwin (Univ. Tucson, USA) has received a **BAEF grant** to spend 1 year as a post-doc researcher at the Planetary Aeronomy group at BISA (A.C. Vandaele).

Arnaud Mahieux (BISA) received a **BAEF grant** for spending 6 months as a post-doc researcher at the University of Arizona in the Lunar and Planetary Laboratory of Pr. Roger Yelle.

Arnaud Mahieux (BISA) has received a **post-doctoral grant from the FNRS** (Chargé de Recherches - 2013-2016).

Luc Doucet (ULB) has received a **post-doctoral grant from the FNRS** (Chargé de Recherche - 2013-2016).

Elodie Gloesener (ROB) has obtained a **FRIA PhD grant** from FNRS, 2013-2016.

Maria Valdes (ULB) has obtained a **FRIA PhD grant** from FNRS (2015-2018).

3.1.10.8. University specific Research Grants

One Planet TOPERS Member (Ph. Claeys, VUB) has obtained a prestigious **VUB Strategic Research Grant** on Tracers of Past and Present Global Changes. Philippe Claeys and VUB colleagues obtained funding from the **Hercules Foundation** in 2012, 2014, and 2016 for new instrumentation respectively a HR-ICP-MS (450 000€), a XRF platform (573 000€) and a new state of the art Infra-red instruments (836 706€).

Emmanuelle Javaux is PI of a 2014 **ULg equipment grant** (40.000 euros + TVA, laser for micro-Raman spectrometer) and partner of a 2014 ULg large equipment grant (contribution to 1 of the 4 robotic telescopes for the project SPECULOOS: searching for the first habitable terrestrial exoplanets for biosignatures detection, PI: Gillon M., co-I: Van Grootel V., partners: Jehin E., Lendl M., Dupret M.A., Absil O., Grodent D., Javaux E.J.).

3.1.10.9. BELSPO international collaboration

Planet TOPERS Members (O. Karatekin, V. Dehant, A.C. Vandaele, and Ph. Claeys) have obtained a budget for networking with **Russian science institutions** (Space Research Institute (IKI) and Russian Academy of Sciences (RAS)) for working on planetary and solar system sciences. In particular, the objectives are to better understand the meteorite and comet impacts on the atmosphere evolution of a planet and the influence on habitability, and to prepare the next missions for Mars exploration as well as for the exploration of the icy moons of the solar system. 15 October 2013-14 October 2016.

Planet TOPERS members are part a bi-lateral project **BeMind** between Belgium (BISA) and **India** (ISRO and other research centers). In the frame of this project, Belgian and Indian researchers collaborate for the different space missions to Mars.

3.1.10.10. BELSPO grants B2B

We have a new Planet TOPERS member: Dr. Bernard Charlier. Bernard is a geologist and who obtained his PhD at the Université de Liège. He went in postdoc at MIT in the US with a Marie Curie Fellowship before going to the Leibniz Universität Hannover in Germany. His research interests focus on magmatic processes that have led to the chemical differentiation of the Earth and other terrestrial planets, and to the formation of ore deposits. He has been awarded a '**Back to Belgium Grant (B2B)**' of the Federal Science Policy to join our research network. He recently applied for a ERC consolidator grant and is selected for an interview this fall.

3.1.10.11. BELSPO Brain projects

Planet TOPERS Members have obtained an **SSD (Science for a Sustainable Development) BELSPO project** BELAM (Belgian Antarctic meteorite): Co-PI: Ph. Claeys (VUB) and Vinciane Debaille (ULB), (01/03/2012 - 30/11/2016)

Planet TOPERS Members have obtained **brain-be Network Projects** funded by BELSPO Belgian Science Policy:

- Brain Network project COME-IN (COnstraining MErcury's INterior structure and evolution), PI: Tim Van Hoolst (ROB), partners: ULg, UGent, VU University Amsterdam, Leibniz University Hannover, 15/12/2014 - 15/03/2019.
- Brain Network project SCOOP (Towards a SynergistiC study Of the atmOsphere of terrestrial Planets), PI: Valérie Wilquet (BISA), partners: ULg and ROB, 15/12/2014 - 15/03/2019.
- Brain Network project METRO (Meteor Trajectories and their origin), PI: Johan De Keyser (BISA), partners: VKI, 15/12/2014 - 15/03/2019.
- Brain Network project AMUNDSEN (Antarctic Meteorites Curation, Digitalization And Conservation), Co-PI: Ph. Claeys-VUB and Vinciane Debaille-ULB, 15/12/2015 - 15/03/2018
- Brain Network project COLDCASE (Cold Case: Re-Opening Of The Bernissart Iguanodon Crime Scene), Co-Pi: Ph. Claeys, 1/12/2015 - 31/12/2018.

Planet TOPERS Members have obtained **brain-be Pioneer Projects** funded by BELSPO Belgian Science Policy:

- Brain pioneer project LOTIDE (Localized Tidal Heating on Enceladus), PI: Mikael Beuthe (ROB), 15/12/2014 - 15/03/2017.
- Brain pioneer project MAGICS (Mars Atmosphere Global Interactive Chemistry Simulator), PI: Frank Daerden (BISA), 1/10/2013 - 31/12/2015.

3.1.10.12. BELSPO Supplementary Researchers

Planet TOPERS Members have obtained **Supplementary Researchers**;

- "Rotation and tides of icy moons", PI: Tim Van Hoolst, for Antony Trinh (ROB)
- "Mars Atmospheric Entry Descent Landing Radio Link Analysis for ExoMars' AMELIA investigation", PI: V. Dehant/Ö. Karatekin, for Nicolas Gerbal (ROB)
- "Analysis of Mars lander tracking data, from Viking to InSight, and scientific preparation of the Belgian LaRa experiment on ExoMars", PI: V. Dehant, for S. Le Maistre (ROB)
- "Rosetta/DFMS data analysis" for A. Gibbons, PI: J. De Keyser (BISA)

3.1.10.13. Patent

Frank Vanhaecke and his team at UGent have developed a novel type of ultrafast ablation cell for LA-ICP-MS purposes in which any turbulence is avoided, substantially improving the washout behavior to 6 ms instead of 700 ms, thus enabling a laser repetition frequency that is enhanced by > 2 orders of magnitude. A patent is pending (UGent patent application PCT/EP2015/07 1525, based on EP14185463.8).

3.1.11. Other/New International Responsibilities since IAP

Özgur Karatekin (ROB) is President of Planetary Science Section of EGU (until 2016).

Lena Noack (ROB) was the Early-Career Scientists Representative of the Planetary and Solar System Sciences Section of EGU 2014-2016 and is the EGU Early-Career Scientists Representative 2016-2017. Cédric Gillmann and Elodie Gloesener are responsible for part of the Planetary Science outreach activities. Emmanuelle J. Javaux was Secretary of EGU Biogeosciences section "Early life and astrobiology" until 2016.

Vinciane Debaille has been elected councilor of the European Association of Geochemistry (2015-2017).

Vinciane Debaille has been invited to participate to the nomination committee for meteorite classification (2015-2018).

Véronique Dehant (ROB) is Member of the SSAC (Solar System Advisory Committee), an advisory committee of ESA (2012-2014).

Tim Van Hoolst (ROB) is Member of the SSEWG (Space Science and Exploration WG), an advisory committee of ESA (2017-2019).

Lena Noack (ROB) is the AbGradE (Astrobiology Graduates in Europe) representative within the EANA (European Astrobiology Network Association) network.

Ann C. Vandaele (BISA) is member of the JWST (James Webb Space Telescope) Mars Focus Group whose objectives are to define observations of Mars using instruments of JWST.

Tim Van Hoolst (ROB) is chairing the JUICE (JUpiter ICy moons Explorer) WG on "Internal structure, subsurface and geophysics of giant icy moons" to define mission strategies related to the geophysics objectives.

Veronique Dehant (ROB) is chairing the NASA InSIGHT (Interior exploration using Seismic Investigations, Geodesy, and Heat Transport) WG B5 on "Ephemerides and tide processing" of the InSIGHT mission.

Lena Noack (ROB) became a member of the advisory committee of the UK Centre for Astrobiology.

New international responsibilities (PI, co-PI, Co-I, PS, IM levels) in present and future missions (see Section 4.2.2.3).

Planet TOPERS in almost all presently active ESA missions and many NASA missions in Solar System (ESA: MEX, VEX, Cassini-Huygens in the Saturnian system, Rosetta (to comet 67P/Churyumov–Gerasimenko), DAWN (to asteroids, Vesta, Ceres), Cluster (quartet of satellites as a space plasma microscope); NASA: MGS, Pathfinder Rover on Mars, ODY, MRO, MER, MSL, ACE, MAVEN);

Planet TOPERS in almost all future ESA missions and many NASA missions in Solar System (ESA: ExoMars (TGO (instrument NOMAD), EDM (experiments AMELIA and DREAMS), Rover (instruments ISEM and CLUPI), BepiColombo to Mercury, JUICE (experiments MORE, BELA, and SIMBIO-SYS), JUICE (experiments 3GM, MAJIS, GaLA, J-MAG, and PRIDE); NASA: MAVEN, InSIGHT, MSL2020).

Planet TOPERS Members are involved in **editorial responsibilities**:

- Chair of the editorial board of the Journal of Analytical Atomic Spectrometry: F. Vanhaecke
- Scientific responsible Editor of the publications « l'Académie en poche »: V. Dehant
- Associate Editor for Journal of Geophysical Research Planets: Ö. Karatekin
- Associate Editor for Geochemical Journal: Ph. Claeys
- Managing-Guest-Editor for Planetary and Space Science: Ö. Karatekin
- Associate Editor of Journal of Space Weather and Space Climate (SWSC): V. Dehant
- Associate Editor for Journal Biogeosciences: E. Javaux.

3.1.12. Medals, Prizes, Awards

Several Members of Planet TOPERS have received Prizes or Awards (they are given below as a function of time):

- Philippe Claeys was elected as "fellow" by the Geological Society of America (2012) for major contribution to the field.
- Elodie Gloesener, PhD student on TOPERS Planet, receive the ODISSEA prize for her work in the framework of a Master in Space Sciences at the University of Liège on methane and clathrates of Mars (Promoter Véronique Dehant and Özgur Karatekin). She studied the temperature and pressure conditions allowing clathrates to be stable in the interior of Mars and those that allow the degassing of methane observed in the Martian atmosphere.
- Vinciane Debaille (ULB) received the Prize Baron van Ertborn of the Royal Academy of Belgium for her work in geology, isotope geochemistry and planetary science.
- Attilio Rivoldini (ROB) won a competition for the Class of Sciences of the Belgian Royal Academy (Académie Royale des Sciences, des Lettres et des Beaux-Arts de Belgique) entitled: "One demands an original contribution, experimental or theoretical, on the physics of planets and moons of solar system" in 2012.
- Tilman Spohn was awarded with the 2013 Runcorn-Florensky Medal for his fundamental contributions to the study of the interior structures of terrestrial planets and outer satellites and for pioneering work in modelling their thermal evolution.
- Philippe Claeys, received the "Prix Adolphe Wetrems" 2013, given by the Class of Sciences of the Belgian Royal Academy (Académie Royale des Sciences, des Lettres et des Beaux-Arts de Belgique), for major contribution in the natural sciences.
- Emmanuelle Javaux was promoted Full Professor (Professeur ordinaire) at the Geology Department, ULg in 2013.
- Pascal Rosenblatt, received the "Prix Vanderlinden" 2013, given by the Class of Sciences of the Belgian Royal Academy (Académie Royale des Sciences, des Lettres et des Beaux-Arts de Belgique), for major contribution in the field of electromagnetic wave propagation.
- Emmanuelle Javaux from University of Liege got one of the Francqui Research Professorship 2013-2016. The theme of her research is "Evolution of Life in the Precambrian and implications for astrobiology".
- Ann Carine Vandaele has been nominated « Maître de Conférences – Chargée d'enseignement visiteuse » at Department of Physics, Namur University – 2013-2014 – Course « Sondage et physique de l'atmosphère » (SPHY M127 - 15h, master in Physics)
- Ann Carine Vandaele has been nominated « Maître de Conférences – Chargée d'enseignement visiteuse » at Department of Physics, Namur University – 2015-2016 – Course « Sondage et physique de l'atmosphère » (SPHY M127 - 15h, master in physics)
- Frank Vanhaecke was designated 'Fellow of the Society for Applied Spectroscopy – SAS'.
- IUAP Planet TOPERS members Emmanuelle Javaux (University of Liège) became Member of the Royal Academy of Belgium in 2014. Also Alessandro Morbidelli, Member of the Scientific Advisory Committee of Planet TOPERS, has been nominated as Associate Member. The ceremony was held on May 17th 2014. For more information, see
  http://www.academieroyale.be/cgi?lg=fr&pag=774&tab=87&rec=1757&frm=0
  and for the photo gallery, see
  http://www.academieroyale.be/cgi?lg=fr&pag=774&tab=87&rec=1788&frm=0.
  Interview of Emmanuelle Javaux on the Royal Academy website
  http://www.academieroyale.be/cgi?lg=fr&pag=774&tab=87&rec=1830&frm=0
- Véronique Dehant received the "Doctorat Honoris Causa" of Paris Observatory. The ceremony is 13 November 2014.
- Vinciane Debaille received the price Atomia 2014 for the Brussels Capital region rewarding a young female scientist for her innovative ideas.
- Vinciane Debaille was selected as "Rising talent" in the frame of the Women's forum for the economy and society in 2014.
- PhD student J. Beghin (ULg) received the EGU young scientist award support for his abstract to the EGU session BG8.1 in 2014.
- Emmanuelle Javaux became Director of UR GEOLOGY, ULg, in 2016.
- Emmanuelle Javaux was chosen as Exceptional Reviewer for 2015 for the journal Geology.
- Lena Noack was selected for the Best-Paper-Award of the 2015 INFOCOMP conference (The

Fifth International Conference on Advanced Communications and Computation).

- Lena Noack obtained a Poster Award at the EANA 2015 Network Association conference in Noordwijk.
- Véronique Dehant became “Membre Etranger” of the Académie des Sciences de Paris, 2015.
- Cédric Gillmann has won the contest of the Science Class of the Academy 2015. The contest requested an original contribution, experimental or theoretical, on the habitability and / or the geophysics of planets and moons of the solar system. Cédric Gillmann answered the contest with a manuscript entitled “HOME: HOw to Make an Earth?” or “Modelling the emergence of habitability through the long term evolution of a terrestrial planet: focus on Venus”.
- Emmanuelle became elected member of the AEIS (Académie Européenne Interdisciplinaire des Sciences) of Paris, in 2016.
- David De Vleeschouwer (PhD 2014, VUB) is the 2016 laureate of the Stratigraphy, Sedimentology and Paleontology Division Outstanding Young Scientist Awards given by the European Geosciences Union.

3.2. Added value gained through the network activities

3.2.1. Complementary expertise, skill exchange, and collaborations

The IAP network involves teams combining different but highly **complementary expertise**. The partners belong to two Belgian federal institutions, four Belgian universities and one German Research Center. The IAP Planet TOPERS has gathered 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. Through this **synergy**, it has enabled the most advanced research in planetary evolution and habitability to be carried out. As the research strategy mainly focused on unraveling and understanding the mechanisms and exchanges between the various planetary reservoirs, we have strengthened **collaborations**, e.g. by putting the emphasis on the interaction between the different reservoirs, in a **trans-disciplinary approach** between teams.

Backbone activities of the IAP include PhD student and post-doc training, working groups, and informal meetings between the Members. All these activities have further strengthened the Members of the IAP by **soft skill exchange**.

The numerous **meetings** have allowed the Planet TOPERS members to exchange knowledge and to build on their own knowledge. The meetings, workshops, network-driven activities are listed in Sections 3.1.5, 3.1.6, and 3.1.7. Exchange of researchers in that frame has been mentioned in Section 3.1.4.

3.2.2. Interdisciplinarity/Multidisciplinary

Fundamental questions in science like “How and when did life emerge on Earth?”, “How did our solar system evolve?” and “Is there life on other celestial bodies?” are not be answered by one discipline alone but require a **concerted and coordinated approach involving many researchers with seemingly unrelated scientific backgrounds**. Planet TOPERS provided us with the ideal platform to address these.

The research landscape is rapidly changing on a global scale. Boundaries between disciplines disappear and **new cross-disciplinary fields emerge**. Astrobiology is one of them. Research in such fields requires interaction and exchange of ideas and new finding between scientists from many countries and fields. Planet TOPERS provided us with the ideal forum for that.

Multidisciplinary research requires a new generation of scientists capable of **working across boundaries between disciplines**, possess an **understanding about methods and fundamental issues in other branches of science** and successfully can **interact** with colleagues with scientific backgrounds different from their own. Planet TOPERS has provided researchers, postdocs, students and early career researchers that possess these capabilities.

Our approach has provided us with **publications** in high-level peer-reviewed journals.

3.2.3. International competitiveness
As seen from the above mentioned **new projects/contracts** (e.g. **3 ERC Grants** gathered by Planet TOPERS partners during the period of this IAP, see Section 3.1.10), as seen from the **international responsibilities** (such as President of Planetary Science Section of EGU, Member of SSAC, etc.) also mentioned above and entrusted during this IAP period (see Section 3.1.11), and as seen from the **awards, prizes, medals, and nomination** (such as Doctorat Honoris Causa of Observatoire de Paris, Member of the Académie royale de Belgique, “Membre Etranger” of the Académie des Sciences de Paris, Prix Wetrems, etc., see Section 3.1.12), the IAP has reinforced the **international competitiveness** of the Belgian teams involved.

3.2.4. Attractive transdisciplinary theme
Determining the possibility and limitations of extraterrestrial life is of fundamental importance to mankind with profound philosophical implications. 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. This is a very attractive transdisciplinary theme that has led to a lot of **public attention** (see Section 5 for public conferences, press release, press conferences, press articles, or TV/radio interviews, internet etc.). This is also important in addition to providing excellent science. It has attracted students for **early stages**, **master theses** and **PhD theses** as well. Within Planet TOPERS, we offered to them to open new frontiers and get out of the existing avenues and address innovative questions and approaches related to habitability.

3.2.5. Collaboration with our international partner
Our international partner, DLR, was the main Coordinator of the Helmholtz Alliance “Planetary Evolution and Life”, working in the same theme as Planet TOPERS.

The Helmholtz Alliances in general aim to identify important new research topics and use them to achieve greater international visible progress in the field. The Helmholtz Alliances make it possible to quickly identify new topics of interest for the scientific community and provide them with the necessary financial resources. The Helmholtz Alliance “Planetary Evolution and Life” has been selected in that frame in 2008 for a 6-year program funded at the level of 4 million Euros per year (50% from Helmholtz, 50% own funding). It is functioning as a network of different partners in Germany. It is the **big brother** of our IAP Planet TOPERS. The Helmholtz Alliance “Planetary Evolution and Life” has received comfortable supplements of medium for a long-term programme-oriented funding and has performed activities of a very high scientific standard in a trans-disciplinary approach, based on the well-established expertise of the participants in addressing astrobiology through planetary formation and evolution. It was the perfect example for Planet TOPERS. Their expertise in planetary science is internationally recognized and has helped us a lot. They have remarkably and successfully managed to attract many young and high-level scientists and students in Germany and Europe, some of which actively participate in Planet TOPERS (Lena Noack, Ana-Catalina Plesa, Dennis Höning…). This is thus perfectly in agreement with our own strategy for the foreseen multi-disciplinary scientific activity of Planet TOPERS. The benefit from having the Helmholtz Alliance “Planetary Evolution and Life” and in particular his PI and his team as international partners are inestimably high. See as well Section 4.2.1.

3.2.6. Evolution into a new IAP and an excellence center
Stronger from our new expertise and our international recognition, our intention is to evolve into an **excellence center** in planetology, astrobiology and habitability at the national level.

First steps into this direction have already been recognized as this Excellence Center is already part of the strategic plan of the Minister Elke Sleurs, as explicitly written in the Management Plan of the Federal institutions involved. It was also retained in the previous strategic plan of BELSPO.

We definitely enjoyed working together, recognize the high added value, and intend to submit a **new proposal** for the next IAP phase, the objectives of which will be better assessed in an important international workshop that we organize in the Azores (see last bullet of Section 3.1.5). See as well the Section on the evolution for the 5-10 years of our IAP (Section 4.1.4).

Another step into this direction is our very active participation in transdisciplinary projects or bodies like the **COST** Action: ORIGINS "Origin and Evolution of Life on Earth and in the Universe", the European Astrobiology Institute (**EAI**), and the European Astrobiology Research Infrastructure (**EARI**), see Sections 3.2.7 and 3.2.8.

3.2.7. Participation into European/international astrobiology activities

Planet TOPERS members do very actively participate in the TransDisciplinary Project TDP 1308 **COST Action: ORIGINS** "Origin and Evolution of Life on Earth and in the Universe" (PI: M Gargaud, Univ. Bordeaux; 54 proposers, now 29 countries, see http://life-origins.com/). Four planet TOPERS Members, Emmanuelle Javaux, Philippe Claeys, Véronique Dehant, and Lena Noack are even part of the organization of the COST action. Emmanuelle Javaux and Philippe Claeys are the Belgian representatives in the managing committee. Véronique Dehant is Monitoring Process Coordinator. E. Javaux, L. Noack (since 2016), and V. Dehant (until 2016) are also working group leaders (Early and extreme life, and Planetary habitability, respectively). L. Noack is co-leader of the outreach team.

The main objective of the COST action ORIGINS (TD 1308) is to address, using an interdisciplinary approach, three great questions about the origin, evolution and distribution of life: (1) Where, when and how did life emerge and evolve on Earth? (2) What are the conditions under which life can exist? (3) Does life exist elsewhere in the Universe and, if it does, how can it be detected and identified? These questions are very much related to our themes of research. The ultimate objective of the COST ORIGINS is the creation of a **European Astrobiology Institute (EAI)** in which our Planet TOPERS IAP or Excellence Center would be the natural Belgian component. All what we are doing now at the Planet TOPERS level such as enabling and facilitating access to research infrastructures, meetings etc. will be performed at the European level and with a broader scope. Our IAP/Center of Excellence will enable Belgium to be one of the privileged participant. A well-organized and efficient group such as Planet TOPERS can act as a strong voice for the astrobiology community.

3.2.8. Participation into European/international astrobiology research infrastructures

The development of an interdisciplinary research approach such as the one envisaged within the above-mentioned COST ORIGINS or EAI is crucial or our Planet TOPERS group. Only multidisciplinary teams can mediate effective exchange of information, and design and develop the new approaches and projects necessary for astrobiology research. An essential prerequisite for such research is access to the research infrastructures that each of the involved communities has developed (geologists, physicists, biologists, astronomers, chemists, astronomers, engineers).

For example, terrestrial field sites opened by the geosciences community provide examples of extreme habitats that allow the 'envelope of life' to be explored whilst geological records provide a reference for establishing how and when life was established and evolved on Earth. (Micro)biology, physics and chemistry laboratories in combination with specific planetary and space simulation facilities are necessary to explore the physico-chemical and biological processes that are essential to answering astrobiology questions. Exploitation of new analytical tools is core to such studies, for example the use of nanotechnology is revolutionizing our study of fossilized (micro)biological structures in geological materials. In biology the impressive development of high-throughput technologies and systems approaches in the last years, e.g. in the area of genomics, transcriptomics, proteomics, metabolomics, has increased our capability to investigate the interaction of organisms and whole communities with the environment substantially. However, to date, the exploitation of such facilities by transdisciplinary communities such as that required for astrobiology research is at best modest and often impossible due to financial, administrative, and cultural handicaps.

The European astrobiology community has therefore submitted a proposal in response to the EU Research and Innovation Action (RIA) H2020 Call (INFRAIA-02-2017) of which the topic is "Integrating Activities for Starting Communities". Their proposal entitled "**European Astrobiology Research Infrastructure (EARI)**" aims to provide a new approach to astrobiology research, to link key European and international field sites and laboratory facilities in the area of astrobiology, in a trans-disciplinary approach, and to foster cross-discipline research. The overarching research goal for a European-centered Astrobiology community is, henceforth, to obtain a better understanding of

Life, its origin and evolution within the context of cosmic evolution, i.e. regarding Life as a cosmic phenomenon. In order to achieve this goal, the EARI proposal advocates the implementation of the following objectives:

1) Provide a comprehensive array of state-of the-art research facilities and field sites to researchers that enables the execution of ground-breaking multidisciplinary research projects.
2) Develop and carry out novel research projects in the field using these infrastructures.
3) Create a community of researchers through organization of generic high-level meetings in the field to develop new research ideas as well as specialized workshops to plan new research project and foster new collaborations.
4) Enhance interaction between scientists from different disciplines and optimize synergy between lab-based and field work through organization of concerted field campaigns.
5) Offer a coherent, well-structured and comprehensive training programme for students and early career investigators in astrobiology using the present research infrastructures and field sites.
6) Encourage European universities and research institutions to develop astrobiology research and training programmes.
7) Approach and inform decision makers in governmental and non-governmental organizations on a national, regional and European level in order to promote astrobiology research in Europe as transdisciplinary research activity.
8) Initiate, coordinate and carry out European initiatives in outreach to the general public and promote astrobiology-related outreach material and initiatives across Europe.
9) Use the wide interest of the general public to coordinate and promote involvement of citizen scientists in astrobiology research projects.

Planet TOPERS members have actively taking part in writing this proposal.

3.2.9. Participation in international thematic schools

Planet TOPERS Members were participating in the organization or in the lecturing in summer and winter thematic schools.

- Thematic school “(Exo)planet Global Climate Models”, 15-16 April 2013, Leuven, Belgium
- Thematic schools "Astrobiology”, Höör, Sweden; 6-9 June 2013: Emmanuelle Javaux gave a course entitled “Fossil records of early life”
- Training school “AbGradCon 2013“, Montreal, Canada, 10-14 June 2013: Lena Noack gave a course entitled “Self-consistent Formation of Continents on Early Earth” and Dennis Höning gave a course entitled “On the Impact of Life on the Evolution of Plate Tectonic Planets”
- Thematic schools HIRESMIR – High Resolution Microwave, Infrared and Raman molecular spectroscopy for atmospheric, planetological and astrophysical applications, Fréjus (France), 2-7 July 2013: Ann C. Vandaele (BISA) gave a course entitled “Comparative planetology: Venus and Mars”
- Training school “Origin, Evolution and Future of the Biosphere”, Banyuls, France, 19-30 August 2013: Emmanuelle Javaux was Coordinator and Lecturer.
- Training school “AbGradCon 2014“, Troy, New York, 27-31 July 2014: Lena Noack was in the advisory committee.
- Training school “Origin, Evolution and Future of the Biosphere”, Banyuls, France, 18-29 August 2014: Emmanuelle Javaux was Coordinator and Lecturer.
- Thematic schools "Spectroscopy and physico-chemistry of planetary atmospheres", Fréjus (France), 7-12 June 2015: Ann C. Vandaele (BISA) gave a course entitled “Exploration of Venus and Mars”
- Thematic school "The geophysics of the terrestrial planets”, Alpbach Summer school 2014, Alpbach/Tyrol, Austria, 15-24 July 2014: Doris Breuer gave a course entitled “Interior structure and magnetic fields” and Tilman Spohn gave a course entitled “The terrestrial planets”
- Training school “AbGradE Symposium 2014”, Edinburgh, UK, 10-11 October 2014: Lena

Noack was in the organization team and gave a keynote talk together with Doris Breuer on "How does the interior of a planet influence its habitability?"

- Training school "AbGradE Symposium 2016", Athens, Greece, 25-27 September: Lena Noack is a co-organizer.
- Training school "Planetary Interiors", L'Aquila, Italy, 12-16 September 2016: Tim Van Hoolst (ROB) is co-organizing and lecturer.
- Training school "EEL: Early Earth & Life", Russia, Karelia, in August 2017: Emmanuelle Javaux (ULg) is co-organizing, in the frame of COST ORIGINS, open to international and Planet TOPERS students (http://life-origins.com/event-category/training-schools).

These participations have allowed as well participation of our students.

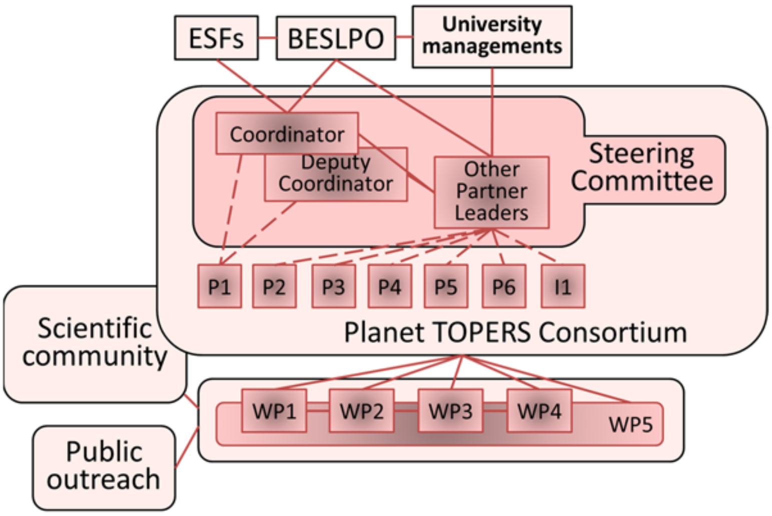
3.3. Organization and management of the network

3.3.1. Management structure

The Consortium was organized as presented in the chart that followed, incorporating the notions of

- Coordinator: Veronique Dehant
- Deputy Coordinator (DC): Tim Van Hoolst
- Steering Committee (SC)
- Belgian Partners (P1, P2, …P6)
- International Partner (I1)
- Work Packages (WP 1, WP 2, …WP 5)
- WP Leaders
- Planet TOPERS Consortium

These notions are explained in the chart and for some of them in the subsections below.



3.3.1.1. Planet TOPERS consortium

The Planet TOPERS Consortium consists of the members of the whole IAP or the WP contributors.

The Planet TOPERS Consortium members have met regularly (see Consortium meetings/workshop, Section 3.1.5).

The Planet TOPERS Consortium was the platform to inform the partners in detail about the Planet TOPERS work program and progress, to exchange data, information, WP output, and motivate them to contribute where suitable.

The members of the Planet TOPERS Consortium were working on the WPs, participating in the general Consortium meetings and workshops, and were responsible for reaching cooperation at trans-institutional level.

3.3.1.2. Steering Committee (SC)

In order to ensure agility of decision-making in the project the Steering Committee (SC) has been installed. The SC consists of the Coordinator and Deputy Coordinator (DC) and all the Research Unit leader (or their representative), a young scientist representative, i.e. 9 persons all together: Véronique Dehant from ROB, Tim Van Hoolst from ROB, Philippe Claeys from VUB, Frank Vanhaecke from UGent, Emmanuelle Javaux from ULg, Vinciane Debaille from ULB, Ann Carine Vandaele from BISA, Tilman Spohn from DLR, Lena Noack from ROB, respectively.

Project management and coordination were the responsibility of the SC, which is chaired by the Coordinator. The SC prepared as well the Consortium meetings/workshops with the different Local Organizing Committees (LOCs) and prepare the agenda of these meetings.

The SC has met face to face at least once per year every year in the frame of the Consortium meetings/workshop and more (see Section 3.1.5). The SC was the first consultative body in litigious case. Only two of such cases aroused (1) when there was a problem with the meteorite collection curation. The problem has been solved (letter from Coordinator), (2) when there was a problem of a non-performing PhD student hired at VUB (a dedicated person hired on the coordinator budget to make the synergy in that same field).

3.3.1.3. Affiliated Experts

The Consortium had foreseen to consider some scientists, not paid by the project, but participating in the discussions for particular subjects, Consortium meetings/workshops, and possibly Consortium work. This was the case for Bernard Charlier and Anne-Sophie Libert.

Bernard Charlier obtained a return-grant from BELSPO affiliated to our IAP. This Back-to-Belgium Grant of the federal Science Policy is intended to foster the return to Belgium of talented researchers doing R&D in an international research center. The selection criteria are mainly based on the scientific level of the candidate, the quality and the feasibility of the research proposal, the post-doc expertise acquired abroad and its possible use and its contribution to the host unit as well as the career perspectives in Belgium. The project of Bernard Charlier on “Early differentiation of terrestrial planets” at ULg perfectly fitted our Planet TOPERS IAP.

Anne-Sophie Libert was our partner in an FNRS-FRFC contract with us on that subject called ExtraOrDynHa (“Extensive study of EXTRAsolar systems’ ORbital DYnamics to improve the HAbitability definition”). The objective of the project is to study the concept of habitability for Earth-like extrasolar planets, mixing the dynamical, geophysical and astrobiological points of view, to get a more realistic characterization of habitable worlds.

3.3.1.4. WP Leaders

For each Work Package (WP) or Sub-WP, there was a WP Leader who was responsible for the good working of the WP and its progress. Table 1 provides the list of names (when several names are mentioned, this means the responsibilities are rotating between institutions).

Table 1: List of Work Packages and responsible institutes/scientists

WP Name	Institutes involved (the first is the responsible one)	Responsible scientist
WP1. Internal Geophysics and Interaction with Atmosphere		
WP 1.1. Interior modelling and consequences on thermal state and convection	ROB, DLR, ULB	Tim Van Hoolst, Lena Noack, and Doris Breuer
WP 1.2. Interior modelling and consequences on magnetic field	ROB, VUB, DLR	Tim Van Hoolst
WP 1.3. Atmospheric Chemical Composition; Internal and external volatile content	BISA, ROB, VUB, ULB, DLR	Ann Carine Vandaele

WP 1.4. Atmosphere Evolution and Clathrates	ROB, BISA	Özgur Karatekin
WP2. Atmosphere and interaction with surface, hydrosphere, cryosphere, and space		
WP 2.1. Radiation & Atmosphere Spectroscopy; Solar illumination, solar wind, magnetosphere and atmosphere interactions in order to determine the net loss of atmospheric material	BISA, ROB	Johan De Keyser
WP 2.2. Atmosphere Evolution & Impacts; Sources of abiotic atmospheric gases: volcanism and impacts	ROB, BISA	Özgur Karatekin
WP 2.3. Atmosphere Evolution & CO_2-H_2O cycles	ROB, BISA	Özgur Karatekin
WP3. Identification of life tracers, and interactions with planetary evolution		
WP 3.1. Early Earth Biological Record; Identification and preservation of life tracers in early Earth and analog extreme environments	ULg, VUB, UGent	Emmanuelle Javaux
WP 3.2. Biological Signatures; Implication of life tracers preservation for in situ detection on Earth and other planets	ULg, VUB, UGent	Emmanuelle Javaux
WP 3.3. Radiation Environment; Interaction of life with the atmosphere; implications for planetary and biosphere evolution and for remote detection	BISA, ULg, VUB, ULB, UGent	Johan De Keyser, Emmanuelle Javaux
WP4. Accretion and evolution of planetary systems		
WP 4.1. Isotopic Analysis; cosmochemistry	UGent, VUB, ULB	Frank Vanhaecke, Vinciane Debaille, Philippe Claeys
WP 4.2. Field Work on Craters; Role/effects of meteorites and comets impacts	VUB, UGent, ULB, ROB	Philippe Claeys
WP 4.3. Tools & Dating; Chronology of differentiation processes (core segregation, magma ocean, mantle overturn and early to recent volcanism) in the Solar System	VUB, UGent, ULB	Vinciane Debaille
WP 4.4. Metamorphism & Thermal History; Onset of plate tectonics and recycling of the crust, and possible implication for life sustainability	ULB, ROB, DLR	Vinciane Debaille, Doris Breuer
WP5. Integration of information into "Global System dynamics": Case study and comparisons of evolution pathways; definition of habitability conditions and its sustainability on different bodies		
WP 5.1. Comparison between Mars, Earth, and Venus evolutions	All	Véronique Dehant

and understanding of the present state differences		
WP 5.2. Roadmap for assessment of habitability on terrestrial bodies (terrestrial planets, asteroids, rocky and icy satellites, extrasolar terrestrial planets)	All	Véronique Dehant

The interaction between the WP is obvious as seen from Table 1 and Figure 53. Names of the involved institutes (but not exhaustive list) and the responsible persons are mentioned in the Table.

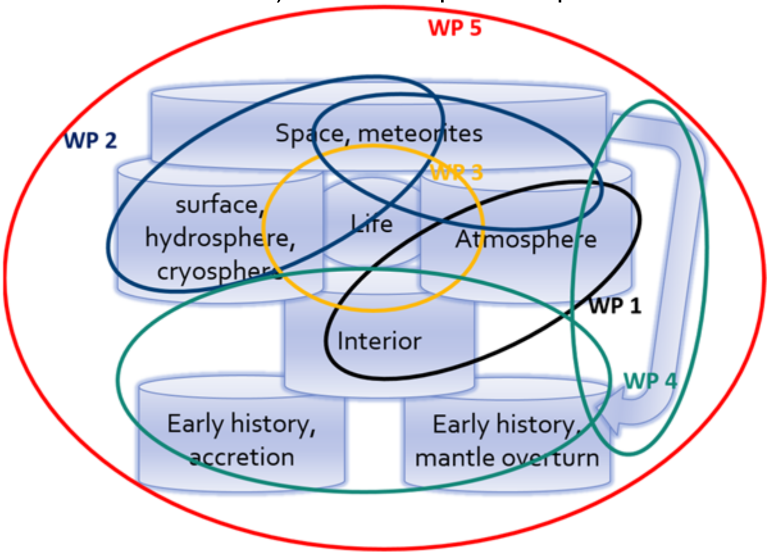


Figure 53: Reservoirs inside a planet and how the WPs account for their interactions.

The WP leaders have given short progress updates at the Consortium meetings or larger written reports once per year. If task results are relevant/necessary for other tasks within one WP or another WP, it has been provided to the corresponding WP leader(s) or responsible person(s).

3.3.2. Meetings, Workshops, and Teleconferences

There were Consortium Meetings/Workshops foreseen, from which 4 were performed:

(1) A Kick-Off Meeting (KOM) aiming at setting all the necessary explanations, schedules, and management procedures, held October 1st, 2012;

(2) One workshop together with the Helmholtz Alliance at DLR Berlin, held May 21-23, 2013;

(3) An Annual meeting (Yearly Meeting), chairing the experiences, data, methods, approaches, procedure, ideas, reporting, work output… and emphasizing exchanges on data used, methods and approaches envisaged, and knowledge of the problem, held November 3d, 2014;

(4) Another Annual meeting (Yearly Meeting), held November 3d 2014 and November 27, 2015 (replaced by January 22d, 2016).

We will have a last annual meeting in November 2016 and the Workshop in Azores in September 2017 (see last bullet of Section 3.1.5).

Each year, Planet TOPERS Members have participated in the FNRS Contact Group on Astrobiology workshop (see http://astrobio.oma.be/).

Several teleconferences, WG meetings, and face-to-face meetings were held as well.

3.3.3. Website, Action item list, Schedule, Website, and Newsletters

ROB has maintained a website with a secured part for the Consortium: see http://iuap-planet-topers.oma.be/. The website contains the objectives of the project, the description of the WPs, the results, the schedule/agenda of meetings, and the publication list of the Consortium. The overall communication between the members of the Consortium was not only be done via emails, teleconferences, workshops, and meetings, but also by using a secured website (with passwords) that was hosted at the ROB. The structure of this website reflects the WPs and has ftp possibility for file exchanges. See Section 3.1.8.

The actions that come out of these teleconferences and meetings have been consigned in a dedicated evolving file maintained by the Coordinator and available for the Consortium on the secured website. The file clearly mentions the actions, the due dates, the responsible person, the input needed by/from other partners, and the expected output. This file is in particular updated after each Steering Committee Meeting.

For particular events/results/meetings/actions/outreach events, emails have been sent out to all partners of the Consortium using a dedicated alias.

3.3.4. Network-driven activities for PhD students and postdocs

Backbone activities further include PhD student and post-doc training/information, in particular in the beginning of the project. This includes the organization of lectures/conferences in the frame of the Doctoral Schools such as those we have performed at

- Collège Belgique at the Royal Academy of Belgium (see Section 5.17; specific series of classes related to planet TOPERS topics have been organized every year at the Royal Academy of Sciences of Belgium in Brussels and involve Planet TOPERS members among which two are academicians; previous classes dealt with: habitability, astrobiology, early eukaryote evolution, icy moons, etc.),
- the Contact Group on Astrobiology where we have chosen the appropriate invited speakers in themes of interest for Planet TOPERS for instance, and
- through the ABC-Net lecture courses, a live teleteaching program is available on the web; it was performed by EANA in cooperation with ESA, interconnecting several European universities (see http://eana-net.eu/education.html).

Transfer of information about the summer or winter schools related to our theme (and in particular those where we also gave lectures, see Section 3.1.7).

An important part of the training occurs as well during the Consortium Meetings and Workshops. Students (and their supervisors) and Post-docs have been requested to participate actively in these meetings by presenting their work.

Additionally, the senior members of the IAP Planet TOPERS give lectures open to master and PhD students on habitability and astrobiology at ULg once every two years (Coordinator: E. Javaux). This is open to the students outside ULg and in particular to the students involved in Planet TOPERS. This Astrobiology class (http://progcours.ulg.ac.be/cocoon/cours/GEOL0263-1.html) for master student, PhDs and Postdocs in Geology, Spatial Sciences, Biology, Chemistry, Engineering, and is organized every other year at ULg. It includes Planet TOPERS members and other scientists as teachers.

The young postdocs and PhD students of Planet TOPERS were involved in AbGradE (Astrobiology Graduates in Europe). In 2013, the young scientists network "Astrobiology Graduates in Europe" - short AbGradE - formed during the annual EANA Astrobiology Workshop in Stettin, Poland. AbGradE (Astrobiology Graduates in Europe) is an independent association with the main goal of promoting scientific networking among early-career astrobiologists. It was initiated by EANA and it is managed by an enthusiastic group of PhD students and post-docs that are responsible for organizing activities that foster networking as well as give a broader background in the different disciplines that Astrobiology comprises. A bi-annual symposium based in Europe is the main gathering for this purpose. In the years between the two symposia, AbGradE organizes a one-day workshop in line with EANA's topic. Lena Noack (ROB Planet TOPERS) is responsible for the AbGradE, co-organizes AbGradE events and EANA conferences. She is the AbGradE representative in the EANA council. She also maintains the AbGradE website http://www.eana-net.eu/AbGradE/about.html.

For 15 years, EANA has organized an annual workshop on astrobiology, providing a tangible forum for interaction and collaboration, and is very active in the area of education through the ABC-Net lecture courses, a live teleteaching program performed in cooperation with ESA, interconnecting several European universities (see http://eana-net.eu/education.html). Planet TOPERS Members and young postdocs or PhDs have access to these lectures as well. Planet TOPERS Member Lena Noack (ROB) is involved in the organization at the level of AbGradE representative in the EANA and maintains the EANA website.

European early-career astrobiologists are also organizing their networking through the AbGradE association (see http://eana-net.eu/AbGradE/about.html). Since 2014, this association organizes symposia and workshops during which master classes, keynote lectures, and scientific sessions are provided and held. As already mentioned, Planet TOPERS participate in this organization.

The young postdocs and PhD students can participate in a competition organized by EGU, the Outstanding Student Poster and PICO (OSPP) Awards, which is coordinated by Lena Noack (ROB Planet TOPERS), who was the Early-Career Scientists Representative of the Planetary Science Division of EGU and is now the Early-Career Scientists Representative of the EGU.

All the information concerning training courses, AbGradE meetings, Outstanding Student Poster and PICO (OSPP) Awards are gathered by Lena Noack and send to the Planet TOPERS young scientists via emails and websites.

Several meetings between the Planet TOPERS young scientists were organized by Lena Noack and Elodie Gloesener around young outdoors/get-together events.

4. POSITION OF THE IAP NETWORK

4.1. Cutting-edge research

4.1.1. Science within present-day roadmaps

4.1.1.1. Cosmic vision of ESA

Main source of this text: AstRoMap (http://astromap.esf.org/fileadmin/ressources_conferences/astromap/user_ressources/AstRoMap_AST.pdf) – It was modified for accounting for the latest developments.

At the European Space Agency ESA, astrobiology research themes are covered by the Directorate of Science and Robotic Exploration and the Directorate of Human Spaceflight and Operations. ESA's mandatory space science program funds the development and construction of the spacecraft and the launch and operation of space missions but not the development and construction of scientific instrumentation nor the exploitation of scientific data or ground-based laboratory research. Support for the latter needs to be obtained from national organizations. ESA's optional space research program includes work on robotic and human exploration in the context of three potential destinations: Low-Earth orbit (LEO), the Moon, and Mars.

Astrobiology (originally termed ''exobiology'') was recognized by ESA as a future research area as early as 1996. This first European initiative to embrace astrobiology resulted in a comprehensive exobiological view of the Solar System by exploring the four following topics:

(1) Chemical evolution in the Solar System;
(2) Limits of life under extreme conditions;
(3) Morphological and biochemical signatures of extraterrestrial life: utility of terrestrial analogues;
(4) Potential sites for extraterrestrial life.

This far-seeing initiative strongly influenced the definition and setup of the Aurora program as an optional program, ESA's strategic framework for space exploration. Aurora commenced in January 2002 by setting out a strategy over the next 30 years for Europe's robotic and human exploration of Mars, the Moon, and even beyond to asteroids. ExoMars, the first European Mars mission dedicated to astrobiology, was one of the program's flagship missions. The very ambitious plans of the program also envisaged two Mars sample return missions, a robotic outpost on Mars, and a possible human mission to the Moon and a human mission to Mars in the horizon 2025–2030. However, the Aurora program was not sufficiently backed by high-level political commitment and was later terminated. Although the Aurora program was cancelled, its first flagship mission, ExoMars, is in the process of being implemented. The ExoMars mission is structured in two elements:

(1) The first element, launched on March 14, 2016, includes the ExoMars Trace Gas Orbiter (TGO, atmospheric gas analysis, in particular methane mapping) and the Schiaparelli lander (Entry, Descent, and Landing Demonstrator Module and meteorological payload).
(2) The 2020 element will carry the ExoMars rover with its suite of astrobiology experiments (the Pasteur payload) intended to assess the habitability of past and present Mars and detect signatures of extinct life. This rover will be placed on a Surface Platform (SP) where Russian and European instruments will be placed aiming at the same objectives complementary to the rover.

The Planet TOPERS Members are involved at all levels:

(1) Ann Carine Vandaele (BISA) is PI of the NOMAD (Nadir and Occultation for MArs Discovery) instrument on TGO; additional BISA AND ROB scientists are Co-Is of NOMAD.
(2) Özgur Karatekin (ROB) is Co-PI of AMELIA on the Schiaparelli lander.
(3) BISA AND ROB scientists are Co-Is of DREAMS (Dust characterization, Risk assessment and Environment Analyzer on the Martian Surface) surface investigation for the 2016 Schiaparelli lander.
(4) A ROB scientist (Ö. Karatekin) and a ULg Scientist (E. Javaux) are Co-Is of ISEM (Infrared Spectrometer for ExoMars) and CLUPI (Close-UP Imager – Wide Angle Camera) respectively, on the ExoMars 2020 rover.
(5) Véronique Dehant (ROB) is PI of LaRa (Lander radioscience) on the ExoMars 2020 Surface Platform.

In the early 2000s, in addition to its exploration strategy and to follow up on the previous plan (Horizon 2000 plus), ESA developed as well the framework and the backbone of its mandatory science program for the period 2015-2025. The Cosmic Vision program was issued in October 2005. Among the scientific questions subdivided into topics where important progress was expected, the first theme of the program is strongly related to astrobiology, although the term astrobiology is not mentioned: What are the conditions for planet formation and the emergence of life? This theme is divided into three topics:

- From gas and dust to stars and planets. Place the Solar System into the overall context of planet formation, aiming at comparative planetology. Map the birth of stars and planets by peering into the highly obscured cocoons where they form.
- From exoplanets to biomarkers. Search for planets around stars other than the Sun, looking for biomarkers in their atmospheres, and image them.
- Life and habitability in the Solar System. Explore in situ the surface and subsurface of the solid bodies in the Solar System most likely to host – or have hosted – life. Explore the environmental conditions that make life possible.

The Cosmic Vision program was used to delineate the boundary conditions of the subsequent call for scientific missions open to the community. As of mid-2015 six missions have been selected and are in various stages of development; half of those missions have relevance to astrobiology. Two missions, CHaracterising ExOPlanet Satellite (CHEOPS, launch planned in 2017) and PLAnetary Transits and Oscillations of stars (PLATO 2.0, launch planned in 2024), are dedicated to the detection of exoplanets; and one large mission, JUpiter ICy moons Explorer (JUICE, launch planned in 2028), will explore the Jovian system, flying by three of its icy moons (Callisto, Europa, and Ganymede) before orbiting Jupiter.

Planet TOPERS is heavily involved in the JUICE mission (BISA, ROB, ULg, DLR).

In 2013, ESA's High-level Science Policy Advisory Committee (HISPAC) published a report in which four major science themes were recommended as scientific challenges that should be tackled by the agency in the next decades, beyond the already defined scientific objectives being currently implemented in the various programs. In this report, the third theme specifically addresses ''Life in the Universe", and ''Astrobiology'' is outlined as a case study.

In addition to the ExoMars and Cosmic Vision program, astrobiology is mentioned and fully integrated in ESA's optional European Life and Physical Sciences in Space program (ELIPS). Started in 2001, ELIPS allows research teams to have access to the European Columbus laboratory on the International Space Station (ISS) as well as to other ISS platforms (including exposure facilities) and ground-based platforms and facilities (for example, drop towers, sounding rockets, radiation facilities).

ESA has as well a program called SSA (Space Situational Awareness). Within this program, one of the foreseen (but not yet definitely adopted) mission is the Asteroid Impact Mission (AIM). AIM is a candidate mission currently undergoing preliminary design work (phase B1). The mission concept is being consolidated in view of a potential discussion at ESA's Council of Ministers in December 2016 for approval. Assuming success, the mission concept will then become an actual ESA mission. ESA considers AIM to be a small mission of opportunity to demonstrate technologies. Launched in 2020, AIM would travel to a binary asteroid system – the paired Didymos asteroids, which will come a comparatively close 16 million km to Earth in 2022. The 800 m-diameter main body is orbited by a 170 m moon, informally called 'Didymoon'. As part of the Asteroid Impact Deflection Assessment (AIDA) initiative, AIM will conduct in-situ measurements of the deflection of the binary asteroid 65803 Didymos caused by the impact of NASA's DART (Double Asteroid Redirection Test) spacecraft. Belgian industry is involved in the AIM spacecraft and scientists from Planet TOPERS are involved in the AIM mission (P. Claeys from VUB, V. Debaille from ULB, E. Jehin from ULg, J. De Keyser from BISA, V. Dehant, T. Van Hoolst, and Ö. Karatekin from ROB). Additionally, an international consortium led by ROB is presently studying the technical challenge of operating Cubesat Opportunity Payloads (COPINS) in support of the objectives of a AIM. The objectives of the CubeSat named AGEX (Asteroid Geophysical Explorer) are to provide geophysical properties of Didymoon. AGEX includes the SeisCube, a 3-U CubeSat seismometer deployed to the surface of Didymos-β (also called Didymoon) to characterize the subsurface, together with a deployment of Pixie class femtospacecraft from Bradbury, another 3-U CubeSat. The Pixies, 10 grams in mass in the current strawman design, will also provide information about its global geodynamics, and also to obtain in-situ observations of surface properties. The study will last eight months, after which ESA will announce, among five studies, the concept that will be finally selected (June 2016).

The AIM mission and its CubeSats are a very good example of the Planet TOPERS involvement in future missions.

4.1.1.2. The European astrobiology community

Main source of this text: AstRoMap (http://astromap.esf.org/fileadmin/ressources_conferences/astromap/user_ressources/AstRoMap_AST.pdf) – It was modified for accounting for the latest developments.

In addition to the programmatic arena, the European astrobiology community benefits from networking and interaction platforms at national, European, and international levels. At the European level, the European **Astrobiology Network Association (EANA)** was established in 2001 and provides a platform and a forum for the astrobiology community in Europe (19 European countries are represented) and beyond (see eana-net.eu). For 15 years, EANA has organized an annual workshop on astrobiology, providing a tangible forum for interaction and collaboration, and is very active in the area of education through the ABC-Net lecture courses, a live teleteaching program performed in cooperation with ESA, interconnecting several European universities (see http://eana-net.eu/education.html). Planet TOPERS Members and young postdocs or PhDs have access to these lectures as well. Planet TOPERS Member Lena Noack (ROB) is involved in the organization at the level of AbGradE representative in the EANA.

As already mentioned in Section 3.3.4, European early-career astrobiologists are also organizing their networking through the **Astrobiology Graduates in Europe (AbGradE)** association (see http://eana-net.eu/AbGradE/about.html). Since 2014, this association organizes symposia and workshops during which master classes, keynote lectures, and scientific sessions are provided and held. As already mentioned, Planet TOPERS participate in this organization.

4.1.1.3. Cooperation in Science and Technology (COST) Action ORIGINS (TD1308)

Launched in 2014 for a period of 4 years, the Cooperation in Science and Technology (COST) Action ORIGINS (TD1308) is a European network involving researchers from 29 European countries and focuses on scientific questions related to the origins and evolution of life on Earth and habitability of other planets. It provides a common platform for interdisciplinary interactions and coordination of nationally funded investigations (see http://life-origins.com). Planet TOPERS are very much involved in this organization. They are participating in the forum discussions concerning the main questions related to the origin, evolution and distribution of life (see Section 3.2.7). They take active part in the conferences (http://life-origins.com/event-category/international-conferences, http://life-origins.com/event-category/workshops), training schools (http://life-origins.com/event-category/training-schools), and discussions (see http://forum.life-origins.com/). Important questions are discussed in this virtual forum such as the establishment of the European Astrobiology Institute (EAI), the definition of Astrobiology, the roadmap etc.

The development of an interdisciplinary research approach such as the one envisaged within the COST ORIGINS or EAI group is crucial for, and the basis of, the development of astrobiology. Our Planet TOPERS is perfectly aligned with this. Only multidisciplinary teams can mediate effective exchange of information, and design and develop the new approaches and projects necessary for astrobiology research. This does not only come out from the roadmaps provided by the international community but as well from the different initiatives of the international community. This community is mostly composed of planetologists interested in habitability and life detection, as well as biologists interested in extremophiles and fossils of early life on Earth, as in Planet TOPERS.

4.1.1.4. European Planetary Network (EuroPlaNet)

Building on the success of two previous European Union-funded projects and structured around a platform gathering together more than 60 research institutions (all signatories to the EuroPlaNet Memorandum of Understanding), the European Planetary Network (EuroPlaNet) has developed and is implementing the 2020 Research Infrastructure project (EPN2020-RI) supported by the Horizon 2020 Research Infrastructure program. EPN2020-RI is a 4-year, ~10M€ initiative that started in September 2015 (see http://www.europlanet-2020-ri.eu) and brings together more than 50 partners from ~20 European countries including Belgium. Its main objective is to provide a Pan-European Union infrastructure dedicated to planetary sciences. EPN2020-RI will (i) network state-of-the-art research facilities and provide access to them; (ii) organize access to planetary analog sites on Earth; and (iii) set up a ‘‘virtual observatory’’ for planetary science, making high-level data accessible to the community. EPN2020-RI will provide the community with a platform that will catalyze and facilitate multidisciplinary research for European planetary scientists. The EuroPlaNet collegial organization, linked by a Memorandum of Understanding (MoU), has a membership of over 70 research institutes and companies.

Some of the Planet TOPERS institutions have signed the MoU and pass the information and discussions/roadmaps of that organization to the group.

One of the EuroPlaNet objectives is to encourage and realize collaborations and coordinated actions between participants, with the specific objectives to build effective and efficient networking between participants, to contribute to the optimal use of complementary facilities, and to emphasize advances and key issues in planetary science. In EuroPlaNet there are also WGs of which the key tasks are among others, deciding on the key questions and goals to be addressed by coordinated efforts. One of the discipline WGs is on astrobiology.

Steven Goderis (VUB) obtained funding to carry out stable isotope analyses on micrometeorites recovered from Antarctica at the Open University (UK).

4.1.1.5. AstRoMap European Astrobiology Roadmap

The European AstRoMap project surveyed the state of the art of astrobiology in Europe and beyond and produced the first European roadmap for astrobiology research.

(http://astromap.esf.org/fileadmin/ressources_conferences/astromap/user_ressources/AstRoMap_AST.pdf) The full reference of this text is:

Horneck G., Walter N., Westall F., Grenfell J.L., Martin W.F., Gomez F., Leuko S., Lee N., Onofri S., Tsiganis K., Saladino R., Pilat-Lohinger E., Palomba E., Harrison J., Rull F., Muller C., Strazzulla G., Brucato J.R., Rettberg P., and Capria M.T. Astrobiology. March 2016, 16(3): 201-243. doi:10.1089/ast.2015.1441.

In the context of this roadmap, astrobiology is understood as the study of the origin, evolution, and distribution of life in the context of cosmic evolution; this includes habitability in the Solar System and beyond, as considered in Planet TOPERS.

In 2013, the AstRoMap project organized a survey of the European astrobiology science community; this survey was later published in Acta Astronautica (Horneck et al., 2015[2]). Compilation of the data provided by 105 European investigators allowed for the creation of a detailed profile of the community involved in astrobiology in Europe.

The AstRoMap Roadmap identifies five research topics, specifies several key scientific objectives for each topic, and suggests ways to achieve all the objectives. The five AstRoMap Research Topics and their objectives (where we have put in red those concerned in Planet TOPERS, please verify) are

Research Topic 1: Origin and Evolution of Planetary Systems

Objective 1. To assess the elemental and chemical picture of protoplanetary stellar discs.

Objective 2. To better understand our solar system: planet formation, dynamical evolution, and water/organics delivery to Earth and to the other planets/satellites.

Objective 3. To better understand the diversity of exoplanetary systems and the development of habitable environments.

Research Topic 2: Origins of Organic Compounds in Space

Objective 1. To promote our understanding of the diversity and the complexity of abiotic organics.

Objective 2. To better understand the molecular evolution of abiotic organics present in Solar System objects, including early Earth, under the combined role of physical agents such as thermal variations, high-energy particles, photons, and solar wind irradiation.

Objective 3. To understand the role of spontaneous inorganic (organic) self-organization processes in molecular evolution.

Research Topic 3: Rock-Water-Carbon Interactions, Organic Synthesis on Earth, and Steps to Life

Objective 1. To better characterize and understand the dynamic redox interactions of rock, water, and carbon in their geological context on planets and moons.

Objective 2. To better characterize and understand transition metals as electron sources and catalysts in geoorganic chemistry.

Objective 3. To better characterize and understand carbon reduction in modern serpentinizing hydrothermal

Objective 4. To better characterize and understand hydrothermal modification of carbon delivered to Earth from space.

Objective 5. To better understand the role of molecular self-organization, higher-order organization, and cellular organization in the origin of life.

Research Topic 4: Life and Habitability

Objective 1. To expand our knowledge of the diversity, adaptability, and boundary conditions of life on Earth.

Objective 2. To expand our understanding of the general principles of life and habitability.

2 Horneck, G., Rettberg, P., Walter, N., and Gomez, F. (2015) European landscape in astrobiology, results of the AstRoMap consultation. Acta Astronaut. 110:145–154.

Objective 3. To assess the habitability of extraterrestrial environments. Mars/Icy moons/Exoplanets.

Research Topic 5: Biosignatures as Facilitating Life Detection

Objective 1. To distinguish life from nonlife.

Objective 2. To follow the energy: Identify energy sources, redox couples, and photoreactions.

Objective 3. To follow the data: Evaluate the potential for life in different planetary environments (from microscale to planets).

4.1.1.6. NASA astrobiology roadmap

The NASA astrobiology roadmap addresses the following main goals and objectives where we have put in red those which are addressed by Planet TOPERS, please verify:

Goal 1 – Understand the nature and distribution of habitable environments in the universe. Determine the potential for habitable planets beyond the Solar System, and characterize those that are observable.

Objective 1.1 – Formation and evolution of habitable planets.

Objective 1.2 – Indirect and direct astronomical observations of extrasolar habitable planets.

GOAL 2 – Determine any past or present habitable environments, prebiotic chemistry, and signs of life elsewhere in our Solar System. Determine the history of any environments having liquid water, chemical ingredients, and energy sources that might have sustained living systems. Explore crustal materials and planetary atmospheres for any evidence of past and/or present life.

Objective 2.1 – Mars exploration.

Objective 2.2 – Outer Solar System exploration.

GOAL 3 – Understand how life emerges from cosmic and planetary precursors. Perform observational, experimental, and theoretical investigations to understand the general physical and chemical principles underlying the origins of life.

Objective 3.1 – Sources of prebiotic materials and catalysts.

Objective 3.2 – Origins and evolution of functional biomolecules.

Objective 3.3 – Origins of energy transduction.

Objective 3.4 – Origins of cellularity and protobiological systems.

GOAL 4 – Understand how life on Earth and its planetary environment have co-evolved through geological time. Investigate the evolving relationships between Earth and its biota by integrating evidence from the geosciences and biosciences that shows how life evolved, responded to environmental change, and modified environmental conditions on a planetary scale.

Objective 4.1 – Earth's early biosphere.

Objective 4.2 – Production of complex life.

Objective 4.3 – Effects of extraterrestrial events upon the biosphere

GOAL 5 – Understand the evolutionary mechanisms and environmental limits of life. Determine the molecular, genetic, and biochemical mechanisms that control and limit evolution, metabolic diversity, and acclimatization of life.

Objective 5.1 – Environment-dependent, molecular evolution in microorganisms.

Objective 5.2 – Co-evolution of microbial communities.

Objective 5.3 – Biochemical adaptation to extreme environments.

GOAL 6 – Understand the principles that will shape the future of life, both on Earth and beyond. Elucidate the drivers and effects of microbial ecosystem change as a basis for forecasting future changes on time scales ranging from decades to millions of years, and explore the potential for microbial life to survive and evolve in environments beyond Earth, especially regarding aspects relevant to US Space Policy.

Objective 6.1 – Effects of environmental changes on microbial ecosystems.

Objective 6.2 – Adaptation and evolution of life beyond Earth.

GOAL 7 – Determine how to recognize signatures of life on other worlds and on early Earth. Identify biosignatures that can reveal and characterize past or present life in ancient samples from Earth, extraterrestrial samples measured in situ or returned to Earth, and remotely measured planetary atmospheres and surfaces. Identify biosignatures of distant technologies.

Objective 7.1 – Biosignatures to be sought in Solar System materials.

Objective 7.2 – Biosignatures to be sought in nearby planetary systems.

4.1.1.7. Planet TOPERS with respect to these roadmaps

As seen from the above Sections, Planet TOPERS has addressed a lot of the objectives described in the roadmaps that are available. We have addressed themes related to planetary habitability and requiring an integrated approach which couples the evolution and internal dynamics of a planet, through various processes such as volcanism, outgassing, and dynamo action producing a magnetic field, with the evolution, dynamics and chemistry of a planet's atmosphere. We have characterized the early Earth life and its biosignatures, therefore providing some answers to the above objectives highlighted in red. This is very satisfying that our objectives were meeting these, while the roadmaps were quite recent.

Due to the background and competences of the Planet TOPERS group, we were concentrated on life in the Solar System, characterizing it, its signatures, understanding habitability of terrestrial planets in a wide sense. Exoplanets was addressed but not very deeply as it was not initially foreseen to intensively study planets outside of our Solar System. We have in particular looked at exoplanets in terms of their interior modelling derived from observation, at outgassing of terrestrial exoplanets, and at the thermal evolution of water-rich exoplanets, based on the codes develop for the Solar System planets. We have as well addressed that theme via contacts and discussions in the Astrobiology Contact Group and with an Affiliated Expert. We plan to work more into this direction in the future.

Furthermore, dedicated questions in our own objectives will be addressed in the future and first priorities will be discussed during the Azores international workshop entitled "*Geoscience for understanding habitability in the solar system and beyond*" in September 2017. This is perfectly aligned with the roadmaps mentioned above.

Besides putting forward scientific priority topics, the AstRoMap roadmap also strongly recommends that a European Astrobiology Platform (or Institute) should be set up to streamline scientific investigations, maximize interdisciplinary collaboration and optimize the use and development of infrastructures. This is exactly one of the first priority of the COST Action ORIGINS as mentioned previously (see Sections 3.2.7 and 4.1.1.3).

4.1.2. Scientific highlights of the network

The latest scientific highlights of our network have been condensed in a joint paper that is presently in press. It is put in Annex 2. We still have more than one year to accomplish our work and have many joint papers in mind with results that are presently presented at congresses.

4.1.3. Comparison with the mainstream in the scientific domain (Benchmark)

We have thought about four groups in Europe that can be compared to the Planet TOPERS Consortium.

1. The Belgian Planet TOPERS
   (Planets: Tracing the Transfer, Origin, Preservation, and Evolution of their ReservoirS) (see http://iuap-planet-topers.oma.be/), coordinated by V. Dehant, addresses the following objectives: (1) to improve our understanding of the thermal and compositional evolution of the different reservoirs (core, mantle, crust, atmosphere, hydrosphere, cryosphere, and space) considering interactions and feedback mechanisms; (2) to investigate the chronology of differentiation processes, the onset conditions of plate tectonics and recycling of the crust

and their implications for the early thermal and compositional evolution of a planet; (3) to examine the role of impacts of meteorites and comets in the atmospheric evolution of the planets, providing loss and replenishment of the atmosphere or possibly even changing the magnetic field; (4) to determine the observational constraints related to meteorites, in order to better understand the impact process and impact fluxes as a function of time; (5) to identify preserved biosignatures 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; (6) to perform a detailed comparison of the habitability of Mars, Earth, and Venus, based on the integrated analysis of the interacting reservoirs.

2. The German Helmholtz Alliance Planetary Evolution and Life
(see http://www.dlr.de/pf/en/desktopdefault.aspx/tabid-4843/), coordinated by T. Spohn, addresses the habitability of planets, biosignatures, and the interaction of life and planetary evolution. The chosen approach is, like Planet TOPERS, more radical and comprehensive than previous studies, because the whole planet from its envelope (atmosphere and magnetosphere) to the interior is taken into account. Furthermore, the habitability of Earth-like planets like Mars and Venus, and of some planetary moons, like Titan and Europa and planets outside our Solar System are considered. The following six main topics are the scientific basis: (1) biosphere-atmosphere-surface interactions and evolution, (2) interior-atmosphere interaction, magnetic field, and planetary evolution, (3) impacts and planetary evolution, (4) geological context of life, (5) physics and biology and interfacial water, and (6) tools and strategies for exploration missions for planetary habitability.

3. The Austrian Project Pathways to Habitability
(see http://homepage.univie.ac.at/manuel.guedel/path.html), focusing on the evolution of protoplanetary disk material and on radiation, wind, and high-energy particle conditions around young stars and their possible induced atmospheric erosion.

4. The Nordic Network of Astrobiology
(see http://www.nordicastrobiology.net) dedicated towards Nordic research and training in astrobiology and forming the backbone of Nordic scientific co-operation. In the field of the conference, Nordic research focuses on plate tectonics, hydrothermal systems and life, biosignatures to detect life on Early Earth and exoplanets, detection of exoplanets and life in extreme environments.

5. Center for Space and Habitability in Bern
(see http://csh.unibe.ch). The primary objective of this Center is to foster a scientific environment conducive to multi-disciplinary research in the field of planet formation, evolution and habitability, as well as the origin of life. The experimental, laboratory, and theoretical activities taking place at CSH provide a framework that allow researchers, at the University of Bern in particular and in Switzerland in general, to play a significantly enhanced role in the interpretation of measured data as well as in the development of future space missions or ground based instrumentation.

The Planet TOPERS Consortium is similar at the Belgian scale to the German Helmholtz Alliance "Planetary Evolution and Life". The other groups address complementary objectives.

These groups are collaborating closely since their formation and also within the trans-domain COST Action ORIGINS (see Sections 3.2.7 and 4.1.1.3). They will all be involved in the workshop we organize in the Azores in September 2017.

Other centers exist which can also be mentioned here such as the Center of Astrobiology (Centro de Astrobiologia – CAB) in Madrid addressing themes like (1) Molecular Evolution and Adaptation, (2) Formation and Evolution of Stars, Brown Dwarfs and Planets, (3) Formation and Evolution of Galaxies, (4) Planetary Geology, (5) Development of Advanced Instrumentation, (6) Molecular mechanisms of biological adaptation, (7) Interstellar and circumstellar medium, (8) Data Archive and Virtual Observatory, (8) Prebiotic Chemistry. This Center is organized in Departments and Support units. The answer to questions about life and its origin come from the combined efforts of many disciplines through interdepartmental research lines. The scientists in this Center are physically situated at the same place, which is far from our network.

Similarly, the UK Centre for Astrobiology is based at the University of Edinburgh. The Centre is affiliated to the NASA Astrobiology Institute. Planet TOPERS member Lena Noack is in the advisory committee of the UK Centre for Astrobiology. “The mission of the UK Centre for Astrobiology is to advance our understanding of molecules and life in extreme environments on the Earth and beyond. It does this with a combination of theoretical, laboratory, field and mission approaches. We apply this knowledge to improving the quality of life on Earth and developing space exploration as two mutually enhancing objectives.” This mission encounter the objectives of Planet TOPERS but again the scientists in this Center are physically situated at the same place, which is far from our network.

In France, one finds the Société Française d’Exobiologie founded in 2009 and with the main aims of (1) federating research in exobiology at the French level by facilitating interdisciplinary contacts between the French researchers, (2) to make known and explain exobiology to meet the socio-cultural demand from a diverse audience, through conferences, workshops, exhibitions. This group is more equivalent to our Astrobiology Contact Group.

4.1.4. Perspectives of the network’s research domain for the coming 5 to 10 years

Ultimately, Planet TOPERS intends to provide its own roadmap for assessment of habitability on terrestrial bodies (terrestrial planets, asteroids, rocky and icy satellites, extrasolar terrestrial planets) in 2017 as an output of this IAP phase and consolidated by discussions on critical questions in our workshop entitled “*Geoscience for understanding habitability in the solar system and beyond*” in the Azores in September 2017 (see last bullet of Section 3.1.5 and 4.1.1.7). It will be the starting point of the next IAP phase (phase VII starting in 2018, see Section 4.3). This international interdisciplinary workshop with the participation of all the Planet TOPERS partners and of the international community, is addressing key or hotly debated questions by a set of keynote-reviews, a set of keynote-controversial question summaries, and a set of keynote-young scientist additional views, followed by discussions. All of them are related to the objectives listed in the above roadmaps. A particular important issue is the difference between the evolutions of Earth and Mars, which we will address further in Section 4.3 on the continuation of the network.

Based on our integrated models of planetary evolution of solar system terrestrial planets, we will also be able to **address complementary questions on exoplanets** and **extend our methods to terrestrial and water-rich exoplanets**, whatever our future. Ideally, the IAP should be continued with an additional emphasize on terrestrial exoplanets.

4.1.5. Critical mass recognized as such at national and international levels

Belgium is a small country but our teams’ activities were reinforced by horizontal exchanges of competences thanks to the IAP and the interactions between the scientists involved favor complementarity and Interdisciplinarity. We were able to attract young researchers in our teams and expand the teams by generating extra-funding from FWO, FNRS, BELSPO, etc. In addition, the IAP allowed us to obtain other projects further expanding the teams (snowball effect), reaching the critical mass necessary for such interdisciplinary project. For instance, since the creation of our IAP Planet TOPERS network, three teams have obtained ERC (European Research Council) funding from the European Union. This is an undoubtable sign of excellence.

The total mass of researchers within the framework of an IAP is optimum for a wide-scale research project that places Belgium in an international network, in international projects or simply to strengthen the position and visibility of Belgian researchers in the field of scientific research.

The Planet TOPERS IAP has stimulated research in our domain in Belgium and on an international level. For instance, we organized entire sessions in international congresses. We have discussed/invited with high level scientists and we are also recognized as such.

Internal collaboration in the group is an enriching experience for everyone, both from a scientific and human point of view. We have created strong links that allow us to better position ourselves on an international level.

Pooling of expertise in the IAP network has undoubtfully built a critical mass recognized as such at national and international levels.

Other organizations mentioned below provide the ground for the contacts/networking at the international level in addition to what we have in place in Planet TOPERS. We are actively taking part in these organizations.

- There is a **trans-domain COST Action** entitled "Origins and evolution of life on Earth and in the Universe (ORIGINS)" (see http://life-origins.com/) addressing the same set of fundamental questions that fascinate and intrigue scientists, but covering broader aspects of the origin of life, detection and habitability (see Sections 3.2.7 and 4.1.1.3).
- There is as well the **EuroPlaNet 2020 Research Infrastructure (RI)** (see http://www.europlanet-2020-ri.eu/). The EuroPlaNet 2020 Research Infrastructure (RI) is a €9.95 million project to integrate and support planetary science activities across Europe. The project is funded under the European Commission's Horizon 2020 programme; it was launched on 1st September 2015 and will run until 31 August 2019. The EuroPlaNet project has been described in Section 4.1.1.4.

4.2. International role

4.2.1. Collaboration with international partner(s) within the network

Our international partner, DLR, was the main Coordinator of the Helmholtz Alliance "Planetary Evolution and Life", working in the same theme as Planet TOPERS. As mentioned in Section 3.2.5, was functioning as a network of different partners in Germany in 2008. It is the **big brother** of our IAP Planet TOPERS and was an example for us. The benefit from having the Helmholtz Alliance "Planetary Evolution and Life" and in particular his PI and his team as international partners are inestimably high. We did not have to make an effort to integrate our international partner in the network as we had already a lot of contacts and in particular the Coordinator of Planet TOPERS, V. Dehant, was in the Advisory Committee of the Helmholtz Alliance, coordinated by our international partner DLR (by T. Spohn). Additionally, DLR, ROB, and BISA are involved in the space same missions such as MarsExpress, InSight, which provides already initial contact. Additionally, **ROB has hired Lena Noack coming from DLR**.

The budget for the international partner was used to pay 50% of the salary of Ana Catalina Plesa with whom we have collaborated a lot and to travel money for them to meet with us in the frame of the annual meetings or the WP/WG meetings. Several of them where held at ROB, involving participants from ULB, DLR, and ROB.

One of the first annual meetings of Planet TOPERS was held at DLR in conjunction with one of the last Helmholtz Alliance meeting.

Figure 54: Group Photo of the Helmholtz Alliance meeting of 2013 where several Planet TOPERS members were participating.

Several working meetings were held at ROB or DLR for discussion related to the scientific work.

Figure 55: Lena Noack (right) and Ana-Catalina Plesa (left) at DLR discussing mantle convection in terrestrial planets and plate tectonics.

DLR international partner members (underlined here below) and the Belgian Planet TOPERS members (not underlined here below) were co-organizing several sessions at EGU and EPSC:

- EGU 2013. Session PS8.1: “Planetary Evolution and Life”, conveners: T. Spohn, D. Breuer, L. Noack, V. Dehant (and others outside our IUAP).
- EPSC 2013. Session AB4: “Planetary Habitability in the Solar System and Beyond”, conveners: V. Dehant, L. Noack, T. Spohn, D. Breuer (and others outside our IUAP).
- EGU 2014. PICO Session PS8.1/BG8.2: “Evolution of planetary habitability: conditions for the origin of life on Earth and beyond Earth”, Convener: E. Javaux, Co-Conveners: D. Breuer, V. Dehant, Ö. Karatekin, L. Noack, T. Spohn, A.C. Vandaele (all from Planet TOPERS)
- EPSC 2014. Session AB2 “Planetary Habitability in the Solar System and Beyond”, Convener: V. Dehant, Co-Conveners: L. Noack, T. Spohn, D. Breuer (all from Planet TOPERS).
- EGU 2015. PICO Session PS8.1/BG8.2: “Evolution of planetary habitability: conditions for the origin of life on Earth and beyond Earth”, Convener: E. Javaux, Co-Conveners: D. Breuer, V. Dehant, Ö. Karatekin, L. Noack, T. Spohn, A.C. Vandaele (all from Planet TOPERS).
- EGU 2015. Union Oral Session US4: “What is inside? Planetary interiors as viewed from space”, Conveners: Ö. Karatekin, T. Spohn (and one person outside Planet TOPERS).
- EGU 2015. PICO Session PS9.1/GD3.6/GM10.2/GMPV7.11/TS9.6: “Processes in the Solar and Other Planetary Systems - Comparative Planetology”, Conveners: L. Noack, Co-Conveners: A.-C. Plesa, Cedric Gillmann.
- EGU 2015. PICO Session PS6.1: “Habitability, observations, formation and dynamics: From the Solar System to Exoplanets”, Co-Conveners: D. Breuer, L. Noack (and others outside our IUAP).
- EGU 2015. Oral and Poster Session PS8.1/BG8.1: “Origin of life and habitability: From Early Earth to the Solar System and Beyond”, Convener: T. Spohn, Co-Conveners: D. Breuer, V. Dehant, L. Noack, E. Javaux, C. Gillmann, J.-Y. Storme, C. François (all from Planet TOPERS).
- EPSC 2015. Session AB2: “Planetary Habitability in the Solar System and Beyond”, Convener: V. Dehant, Co-Conveners: L. Noack, T. Spohn, and D. Breuer (all from Planet TOPERS).
- EGU 2016. PS7.1/BG8.2: “Origin of life and habitability: from early Earth to the Solar System and beyond”, Convener: T. Spohn, Co-Conveners: D. Breuer, V. Dehant, E. Javaux, L. Noack, C. Gillmann, J.-Y. Storme, C. François, Ö. Karatekin (and others outside our IUAP).

4.2.2. International activities

4.2.2.1. Participation in European and international organizations

4.2.2.1.1. TransDisciplinary Project TDP 1308 COST Action: ORIGINS

Several planet TOPERS Members, Emmanuelle Javaux, Philippe Claeys, Véronique Dehant, Özgur Karatekin, Cédric Gillmann, and Lena Noack are part of a new FP7 TransDisciplinary Project TDP 1308 COST Action: ORIGINS “Origin and Evolution of Life on Earth and in the Universe” (PI: M Gargaud, Univ. Bordeaux; 54 proposers, now 29 countries). Emmanuelle Javaux and Philippe Claeys are the Belgian representatives in the managing committee and Véronique Dehant is suppliant. E. Javaux, V. Dehant, and L. Noack are also working group leaders (Early and extreme life, and Planetary habitability, respectively). V. Dehant is Monitoring Process Coordinator for ORIGINS.

More information on the COST Action ORIGINS are provided in Sections 3.2.7 and 4.1.1.3.

4.2.2.1.2. European Astrobiology Institute (EAI)

The ultimate objective of the COST ORIGINS is the creation of a European Astrobiology Institute (EAI) in which our Planet TOPERS IAP are the natural Belgian component. Our IAP will enable Belgium to be one of the privileged participant. A well-organized and efficient group such as Planet TOPERS can act as a strong voice in the European astrobiology community. Participants of the COST Action ORIGINS from our IAP are taking part of the elaboration of the EAI (founding members).

More information on the future EAI are provided in Sections 3.2.7 and 4.1.1.3.

4.2.2.1.3. NASA Astrobiology Institute (NAI)

The National Aeronautics and Space Administration (NASA) established the NASA Astrobiology Institute in 1998 as an innovative way to develop the field of astrobiology and provide a scientific framework for NASA flight missions. NAI is a virtual, distributed organization of competitively-selected teams that integrate astrobiology research and training programs in concert with the US and international science communities.

DLR and ULg take part of the selected teams of the NAI. Planet TOPERS member E. Javaux is part of the NAI team lead by PI T. Lyons (Univ. Riverside, CA, USA) “Alternative Earths: Explaining Persistent Inhabitation on a Dynamic Early Earth”, US $8 million, 2014-2019.

4.2.2.1.4. Astrobiology Network Association (EANA)

At the European level, the European **Astrobiology Network Association (EANA)** was established in 2001 and provides a platform and a forum for the astrobiology community in Europe (19 European countries are represented) and beyond (see http://eana-net.eu). For 15 years, EANA has organized an annual workshop on astrobiology, providing a tangible forum for interaction and collaboration, and is very active in the area of education.

Planet TOPERS Members take part in EANA. One Planet TOPERS member, Emmanuelle Javaux (ULg) was an elected Member of Executive Council of EANA (European Astrobiology Network Association) (2009-2013).

More information on EANA are provided in Sections 3.3.4 and 4.1.1.2.

4.2.2.1.5. Astrobiology Graduates in Europe (AbGradE)

European early-career astrobiologists are also organizing their networking through the Astrobiology Graduates in Europe (AbGradE) association (see http://eana-net.eu/AbGradE/about.html). Since 2014, this association organizes symposia and workshops during which master classes, keynote lectures, and scientific sessions are provided and held. As already mentioned, Planet TOPERS participate in this organization. One Planet TOPERS member, L. Noack, was even founding member.

More information on AbGradE are provided in Sections 3.3.4 and 4.1.1.2.

4.2.2.1.6. European Geoscience Union (EGU)

Since the beginning of Planet TOPERS, one member, Özgur Karatekin (ROB), became President of the Planetary and Solar System Sciences division. One Planet TOPERS member, Emmanuelle Javaux (ULg), became Secretary of Biogeosciences Section “Early life and astrobiology”. Lena Noack (ROB) became Young Scientist Representative of the Planetary and Solar System Sciences Section and Young Scientist Representative at the Council of EGU.

We also continuously participated in organization of sessions at EGU (see Section 3.1.6).

4.2.2.1.7. International Society for the Study of the Origin of Life and Astrobiology Society (ISSOL)

One Planet TOPERS member, Emmanuelle Javaux (ULg) was an elected Member of the Executive Council of ISSOL, the International Society for the Study of the Origin of Life and Astrobiology Society

(2011-2013), and is participating in the organization as member of the SOC of the next ISSOL meeting in 2017, San Diego.

4.2.2.1.8. Earth-Life Science Institute (ELSI) Origins Network (EON)

Japan is developing Astrobiology in the Earth-Life Science Institute (ELSI) at Tokyo Tech University. Planet TOPERS Member E. Javaux is a member of the advisory board of Earth-Life Science Institute (ELSI) Origins Network (EON), funded by the John Templeton Foundation, Institute for Advanced Study, Tokyo Institute of Technology, Japan since May 2015.

4.2.2.1.9. International team ISSI BEIJING

China also wants to develop astrobiology in research and education. A Planet TOPERS Member (E. Javaux) participates in an International ISSI Bern & Beijing Team on “Astrobiology in the New Age”, with the objective to develop astrobiology roadmap and education in China. The Project Coordinator is Feng Tian. The team is made of 6 Chinese scientists (Feng Tian, Yongyun Hu, Wei Leng, Yi-liang Li, Yunfeng Yang, Ting Zhu) and 6 European and North American scientists (Muriel Gargaud, Lee Grenfell, Emmanuelle Javaux, Helmut Lammer, Alain Leger, Daniele L. Pinti) as well as 7 international and Chinese supporters, working on related but different aspects of astrobiology.

4.2.2.2. Participation in European and international research projects

4.2.2.2.1. European Union FP7 and H2020 projects

Planet TOPERS Members participate in two FP7 projects

(1) FP7 ‘CrossDrive’: to create a virtual environment to better merge data from different missions to Mars, involving BISA and DLR. CrossDrive targets on creating the foundations for collaborative distributed virtual workspaces for European space science. Space exploration missions have produced huge data sets of potentially immense value for research as well as planning and operating future missions. However, currently expert teams, data and tools are fragmented, leaving little scope for unlocking this value through collaborative activities. The question of how to improve data analysis and exploitation of space-based observations can be answered by providing and standardizing new methods and systems for collaborative scientific visualization and data analysis, and space mission planning and operation. This does not only allow scientist to work together, with each other's data and tools, but importantly to do so between missions. The consortium brings together unprecedented expertise from space science, visualization of space science and collaborative visualization. The proposed collaborative workspace encompasses various advanced technological solutions to coordinate central storage, processing and 3D visualization strategies in collaborative immersive virtual environments for the data. A specific focus is given to the preparation of the ExoMars 2016 and 2020 missions. http://www.cross-drive.eu/public/index.php

(2) FP7 ‘EuroVenus’: to better exploit the Venus Express results and ground-based observations of Venus. The participants in this project are investigating in detail the dynamics and composition of the middle and lower atmosphere of Venus by combining data from Venus Express instruments (VIRTIS, VMC) with simultaneous data acquired from several ground-based telescope facilities. The project performs coordinated observations to provide a detailed analysis of dynamical and chemical couplings between different levels of the atmosphere that are probed simultaneously by different instruments. It is time critical in the context of (1) the extension of the Venus Express (VEx) mission only until the end of 2014; (2) the expertise and coordination in wind and trace species measurements developed in our institutions, currently unique in the world; (3) the availability of new techniques of ground-based investigation of Venus' atmosphere, which benefits from coordination and cross-calibration with in-orbit Venus Express payload instruments and beyond. http://www.eurovenus.eu/

Planet TOPERS Members participate in COMPET 8 of H2020.

(3) Vinciane Debaille is co-PI of the EURO-CARES COMPET 8 H2020 project dedicated to

create a roadmap for the implementation of a European Extra-terrestrial Sample Curation Facility (ESCF). EURO-CARES (European Curation of Astromaterials Returned from Exploration of Space) is a three year, multinational project, funded under the European Commission's Horizon2020 research programme. The multidisciplinary team of experts from academia and industry are developing a roadmap for a European Sample Curation Facility (ESCF), designed to curate precious samples returned from Solar System exploration missions to asteroids, Mars, the Moon, and comets. It is a 36-month project (started on 01.01.2015) concentrates on 6 key themes:

- Planetary Protection (WP2)
- Curation of extraterrestrial materials (WP3)
- Infrastructure requirements (WP3)
- Instruments and methods for sample handling, preparation, and analysis (WP4)
- Analogue samples as proxies for extraterrestrial materials (WP5)
- Technologies for sample reception and transport (WP6).

http://www.euro-cares.eu/

(4) Ann Carine Vandaele (BISA) and Özgur Karatekin (ROB) are Co-I of UPWARDS (Understanding Planet Mars With Advanced Remote-sensing Datasets and Synergistic studies) COMPET 8 H2020 project dedicated to the understanding planet Mars with advanced remote-sensing datasets and synergistic studies of which the PI is Agencia Estatal Consejo Superior de Investigaciones Científicas (CSIC).
The goals of the UPWARDS project match the topics, challenges and scope of the Compet-8-2014 call (Horizon 2020). The UPWARDS Consortium undertake five grand science themes which challenge our current understanding of the complex couplings of the Mars' climate:

- exchange of trace species between subsurface & atmosphere;
- global cycle of Martian water;
- surface properties and behavior of suspended aerosols and dust storms;
- drastic changes at the day/night terminator;
- coupling of the lower and upper atmosphere and escape to space.

All topics are addressed by experts in the field, exchanging results and knowledge in a truly synergistic and interdisciplinary collaboration. http://planetary.aeronomie.be/en/upwards.htm

4.2.2.2.2. Other international projects

Planet TOPERS member E. Javaux is co-PI of a research project supported by the Agouron Foundation (USA) "Eukaryote evolution in the Proterozoic of Arctic Canada", PI: G Halverson (McGill), co-PIs: E. Javaux, R. Rainbird, H. Turner, T. Schulski, J. Brocks, C. Hallmann, and N. Butterfield (2016-2018).

4.2.2.3. Participation in European and international space missions

BISA, ROB, and DLR participate in the following current missions (in bold: PI level, Co-PI, or PS):

- MarsExpress MaRS (Mars Express Radio Science experiment), Co-I: V. Dehant, P. Rosenblatt; team member: Ö. Karatekin – ROB
- MarsExpress HRC (High Resolution Camera), **Co-PI**: R. Jaumann – DLR
- MarsExpress SPICAM (Spectroscopy for Investigation of Characteristics of the Atmosphere of Mars), Co-I: A.C. Vandaele, Y. Willame – BISA
- Rosetta ROSINA (Rosetta Orbiter Spectrometer for Ion and Neutral Analysis), Co-I: J. De Keyser – BISA, R. Jaumann – DLR
- Rosetta MUPUS (Multi-Purpose Sensor for Surface and Subsurface Science), **PI**: T. Spohn – DLR
- NASA DAWN mission to asteroids, Vesta and Ceres, **PI**: R. Jaumann – DLR
- Cassini-Huygens mission, Participating Scientist (**PS**) working with the Radio Science and Radar Science teams in Cassini Data Analysis and Participating Scientists (CDAPS): Ö. Karatekin – ROB
- Cassini-Huygens RADAR instrument in the Cassini mission, Co-I: Ö. Karatekin – ROB

- Cassini-Huygens, Radio Science Subsystem (RSS) instrument in the Cassini mission, Co-I: Ö. Karatekin – ROB
- NASA MAVEN (Mars Atmosphere and Volatile EvolutioN), Participating Scientist (**PS**), project MAGE (Maven Atmospheric drag and Gravity Experiment) experiment of the NASA's Participating Scientist program: P. Rosenblatt – ROB
- ExoMars 2016 Trace Gas Orbiter (TGO), NOMAD (Nadir and Occultation for MArs Discovery) **PI**: A.C. Vandaele – BISA, Co-I: Ö. Karatekin – ROB
- ExoMars 2016 AMELIA (Atmospheric Mars Entry and Landing Investigation and Analysis) entry and descent science investigation, **Co-PI**: Ö. Karatekin – ROB
- ExoMars 2016 EDM DREAMS (Dust characterization, Risk assessment and Environment Analyzer on the Martian Surface) surface investigation, Co-I: Ö. Karatekin – ROB
- NASA 2018 InSIGHT (Interior exploration using Seismic Investigations, Geodesy, and Heat Transport), RISE (Rotation and Interior Structure Experiment), Co-I: V. Dehant, Team Members: S. Le Maistre, A. Rivoldini, T. Van Hoolst, M. Yseboodt – ROB
- NASA 2018 InSIGHT, SEIS, Co-I: V. Dehant, Team Members: A. Rivoldini, T. Van Hoolst, Ö. Karatekin – ROB
- NASA 2018 InSIGHT, HP3 (Heat Flow and Physical Properties Probe), **PI**: T. Spohn, Co-I: M. Grott – DLR, Team Members: D. Breuer, A.-C. Plesa – DLR
- BepiColombo MORE (Mercury Orbiter Radio science experiment of BepiColombo mission), Co-I: V. Dehant, Team Member: T. Van Hoolst – ROB
- BepiColombo BELA (BepiColombo Laser Altimeter), **Co-PI**: T. Spohn – DLR, Co-I: V. Dehant – ROB, Team Member: D. Breuer – DLR
- BepiColombo SYMBIO-SYS (High resolution camera experiment of BepiColombo mission), Co-I: T. Van Hoolst – ROB
- ExoMars 2020 Surface Platform, LaRa (Lander radioscience), **PI**: V. Dehant; Co-I: T. Van Hoolst, P. Rosenblatt, Ö. Karatekin, M. Yseboodt; Project/Instrument Manager: M. Mitrovic – ROB
- ExoMars 2020 Surface Platform, Co-I of HABIT (Habitability, Brine Irradiation and Temperature package): Ö. Karatekin – ROB
- ExoMars 2020 Surface Platform, Co-I of RDM (Radiation and Dust sensors, part of the METEO package): Ö. Karatekin – ROB
- ExoMars 2020 Rover, Co-I of CLUPI (Close-UP Imager – Wide Angle Camera): E. Javaux – ULg
- ExoMars 2020 Rover, ISEM (Infrared Spectrometer for ExoMars), Co-I: Ö. Karatekin – ROB
- MSL (Mars Science Laboratory) 2020 accelerometer for EDL (Entry-Descend-Landing) data analysis, Co-I: Ö. Karatekin – ROB
- JUICE (JUpiter ICy moons Explorer), Gravity and Geophysics of Jupiter and the Galilean Moons (3GM), Co-I: T. Van Hoolst, Team Member: V. Dehant – ROB
- JUICE (JUpiter ICy moons Explorer), Galilean moons Laser Altimeter (GALA), **PI**: H. Hussmann, Co-I: M. Yseboodt – ROB, D. Breuer – DLR
- JUICE (JUpiter ICy moons Explorer), Moons And Jupiter Imaging Spectrometer (MAJIS), Co-I: Ö. Karatekin – ROB, A.C. Vandaele – BISA
- JUICE (JUpiter ICy moons Explorer), Planetary Radio Interferometry and Doppler Experiment (PRIDE), Co-I: P. Rosenblatt – ROB
- JUICE (JUpiter ICy moons Explorer), JUICE Magnetometer (J-MAG), Co-I: T. Van Hoolst – ROB
- ESA-NASA Asteroid Impact Deflection Assessment (AIDA) initiative, ESA AIM (Asteroid Impact Mission)-COPINS (Cubesat Opportunity Payloads), **PI** of AGEX (Asteroid Geophysical Explorer): Ö. Karatekin, Co-I of AGEX (Asteroid Geophysical Explorer): V. Dehant – ROB
- JAXA MMX mission to Mars and Phobos, Near Infrared Spectrometer (NIRS4), Co-Is: A.C. Vandaele – BISA, Ö. Karatekin – ROB

4.2.2.4. Participation in European and international research infrastructures

4.2.2.4.1. H2020 EuroPlaNet Research Infrastructure

H2020 EuroPlaNet Research Infrastructure (RI) is a €9.95 million project to integrate and support planetary science activities across Europe. The project is funded under the European Commission's Horizon 2020 programme; it was launched on 1st September 2015 and will run until 31 August 2019.

The project is led by the Open University, UK, and has more than 50 beneficiary institutions from ~20 European countries. EuroPlaNet 2020 RI will address key scientific and technological challenges facing modern planetary science by providing open access to state-of-the-art research data, models and facilities across the European Research Area.

EuroPlaNet 2020 RI provides:

- Transnational access to world-leading laboratory facilities that simulate conditions found on planetary bodies as well as specific analogue field sites for Mars, Europa and Titan.
- Virtual access to diverse datasets and visualization tools needed for comparing and understanding planetary environments in the Solar System and beyond.

DLR, BISA, and ROB from Planet TOPERS take part in this RI.

More information are provided in Section 4.1.1.4.

4.2.2.4.2. European Astrobiology Research Infrastructure (EARI)

The European astrobiology community has submitted a proposal in response to the EU Research and Innovation Action (RIA) H2020 Call (INFRAIA-02-2017) of which the topic is "Integrating Activities for Starting Communities". Their proposal entitled "European Astrobiology Research Infrastructure (EARI)" aims to provide a new approach to astrobiology research, to link key European and international field sites and laboratory facilities in the area of astrobiology, in a trans-disciplinary approach, and to foster cross-discipline research. The overarching research goal for a European-centered Astrobiology community is, henceforth, to obtain a better understanding of Life, its origin and evolution within the context of cosmic evolution, i.e. regarding Life as a cosmic phenomenon.

DLR, ULg, and ROB from Planet TOPERS take part in this RI.

More information are provided in Section 3.2.8.

4.2.2.4.3. International Continental Scientific Drilling Program (ICDP)

Scientific drilling is an indispensable and unique tool for exploring and unraveling the myriad natural and anthropogenic processes that are part and parcel of our dynamic Earth. The International Continental Scientific Drilling Program (ICDP) is an infrastructure for scientific drilling that facilitates outstanding science. ICDP is the only international platform for scientific research drilling in terrestrial environments.

See http://www.icdp-online.org/home/.

ICDP provides the means for conducting cutting edge research:

- workshop support for establishing scientific drilling programmes,
- cost effective, co-mingled funding support for drilling programs,
- operational support for individual projects,
- drilling facilities, such as drill rigs, logging tools, and sample and data management,
- Earth science education and knowledge transfer.

ICDP brings together scientists and stakeholders from 23 nations to work together at the highest scientific and technical level. More than 30 drilling projects and 55 planning workshops have been supported to date. ICDP has an average annual budget of about $5 million, and further third-party drilling support more than doubles this yearly investment.

Planet TOPERS Members (Ph. Claeys and E. Javaux) have succeeded to be elected and founded with their projects within the ICDP (International Continental Scientific Drilling Program). See Section 3.1.10.6. The two projects are:

- The Chicxulub crater drilling, co-investigator: Ph. Claeys (VUB).
- The Barberton Greenstone Belt in South Africa drilling, "Peering into the Cradle of Life", participating scientist: E. Javaux (ULg).
- The FAR-DEEP (Fennoscandia Arctic Russia - Drilling Early Earth Project) in Archean/Paleoproterozoic transition of Russia, participating scientist: E. Javaux (ULg).

4.2.2.5. Organization of international symposia

Planet TOPERS did also organize several ISSI workshops as mentioned in the paragraph on Meeting Organization.

- Planet TOPERS members (A.C. Vandaele, A. Mahieux, and V. Wilquet, from BISA) have organized the ISSI International Team to study the role of SO_2 in the Venusian atmosphere. The project was granted and entitled "Venus SO_2: investigation of the role of SO_2 in the Venusian atmosphere", PI: A.C. Vandaele and O. Korablev, 12 international experts - expert from Planet TOPERS: A. Mahieux - http://www.issibern.ch/teams/venusso2/. The first meeting was in November 2013, next meetings in June 2014 and Nov 2014, held at ISSI, Bern, Switzerland.
- Planet TOPERS member (V. Dehant, from ROB) have co-organized the ISSI/HISPAC Workshop on "High Performance Clocks, with Special Emphasis on Geodesy and Geophysics and Applications to Other Bodies of the Solar System", ~40 international experts, November 30-December 4, 2015, held at ISSI, Bern, Switzerland.

It must be mentioned as helpful for the beginning of our IAP, that Emmanuelle Javaux co-organized before the IAP an ISSI workshop on "Strategies for life detection" (SOC: Botta O., Javaux EJ, Summons R, Rosing M, Bada J, Gomez Elvira J, and Selsis F.), of which the main conclusions were published in the ISSI Space Science series. Springer-Verlag. 380 p.

Ultimately, Planet TOPERS are presently organizing an international workshop entitled "*Geoscience for understanding habitability in the solar system and beyond*" in the Azores in September 2017 (see last bullet of Section 3.1.5). This international interdisciplinary workshop with the participation of all the Planet TOPERS partners and of the international community, is addressing key or hotly debated questions by a set of keynote-reviews, a set of keynote-controversial question summaries, and a set of keynote-young scientist additional views, followed by discussions.

Additionally, Planet TOPERS members have organized several sessions at EGU or EPSC or other international congresses, as already mentioned in Section 3.1.6.

4.2.2.6. Invitations to give lectures at prestigious international conferences

2012

- Javaux E.J., 2012, Les trois premiers milliards d'années d'évolution de la vie. Classe des Sciences, Académie Royale des Sciences de Belgique, 6 Oct. 2012.
- Javaux E.J., Martin H., 2012, Evolution de l'objet Terre. Workshop Evolution (Lecointre G and Gaurgaud M). MNHN, Paris, December 13th 2012
- Javaux E.J., 2012, Les trois premiers milliards d'années d'évolution de la vie. MNHN, Paris, December 7th 2012.
- Javaux E.J., 2012, Evolution of early eukaryotes. Keynote speaker, International Geological Congress, Brisbane, August 5-10th 2012, Australia.

2013

- Dehant V., 2013, "Planetary Interiors and Geodesy.", European Geosciences Union (EGU) General Assembly 2013, GD6.1/GMPV11, Vienna, Austria, April 8-12, 2013.
- Dehant V., Folgueira M., Puica M., Koot L., Van Hoolst T., and Trinh A., 2013, "Next step in Earth interior modeling for nutation.", Journées Systèmes de Référence Spatio-Temporels 2013, on 'Scientific developments from highly accurate space-time reference systems', Observatoire de Paris, Paris, France, 16-18 September, 2013.
- Marius E., De Keyser J., Lamy H., Maggiolo R., 2013, "On the modeling of the quasi-stationary coupling between magnetospheric generators and the auroral ionosphere.", International Workshop on Advances and Perspectives in Auroral Plasma Physics (APPW), Centre Paul Langevin, Aussois, France, April 1-5, 2013.
- Maggiolo R., M. Echim, R. Fear, D. Fontaine, C. Simon Wedlund, and Y. Zhang, 2013, "Coupling between the polar ionosphere and the magnetosphere during periods of Northward IMF: Cluster observations.", XII IAGA Scientific Assembly, Merida Mexico, 26-31 August 2013.
- Maggiolo R., Echim, M., Fear, R., Fontaine, D., Simon-Wedlund, C., and Zhang, Y., 2013, "Magnetosphere-ionosphere coupling above the polar caps during periods of northward IMF.", 23rd Cluster workshop, Tromso Norway, 16-20 December 2013.

- De Keyser J., and F. Dhooghe, 2013, “Rosetta/ROSINA coma chemistry models.”, ROSINA CoI Meeting, Vitznau, Switzerland, 17-20 June 2013.
- Claeys Ph., 2013, Belgian-Japanese meteorite searches in Antarctica. GEOTOP, network McGill-UQUAM, Montreal, Québec, Canada, September 23, 2013.
- Claeys Ph., 2013, Belgian-Japanese meteorite searches in Antarctica. Museum d’Histoire Naturelle de Paris, France, June 12, 2013.
- Claeys Ph., 2013, Belgian-Japanese meteorite searches in Antarctica. University of Oslo, Olso, Norway, May 28, 2013.
- Goderis S., 2013, “Tracing the impact history of the Earth through projectile identification in ejecta layers.”, in the seminar series Dept. of Earth and Atmospheric Science at the University of Houston, November 8, 2013.
- Javaux EJ, 2013. Les premiers microorganismes. Rencontres Géosciences « Les débuts de la vie ». Société Géologique de France, Muséum National d’Histoire Naturelle de Paris, Paris, Nov. 22nd 2013.
- Javaux E.J., 2013, Les organismes primitifs. Colloque « les débuts de la vie ». Société Géologique de France, Museum National d’Histoire Naturelle, Paris, Nov. 22nd 2013.
- Javaux E.J., 2013, The first three billion years of life Evolution. June 6-9th, Höör, 1st Astrobiology Education workshop. Sweden.
- Debaille V., 2013, Collecting meteorites in Antarctica: an exploration towards the end of the Earth, Ensisheim meteorite fare.
- Breuer, D., 2013, Core formation and magma oceans: from planetesimals to planets. In: Gordon conference ‘Interior of the Earth’, 2-7 June 2013, South Hadley, MA, USA.
- Breuer, D., 2013, Interior structure and magnetism on Mars. In: Mars Workshop, 20-25 October 2013, Les Houches, France.
- Grott, M., 2013, The thermal evolution of Mercury. In: MESSENGER-BepiColombo Joint Science Meeting, 22-24 Apr. 2013, Chicago, USA.
- Noack L., 2013, Formation of continents on early Earth. In: European Astrobiology Network Association (EANA), 22.-25. July 2013, Szczecin, Poland.
- Spohn T., 2013, Thermal History of Planetary Objects: From Asteroids to Super Earths, from Plate-Tectonics to Life, April 2013 Runcorn Florensky Medal Lecture, EGU.
- Spohn T., 2013, Planetary Evolution and Life: Astrobiology from a Planetary Science Perspective, June 2013 IAPS Shanghai.
- Spohn T., 2013, How could Plato serve planetary physics and what can we learn from Solar System planets for terrestrial exoplanets? July 2013 Plato Workshop ESTEC.
- Spohn T., 2013, Thermal History of Planetary Objects: From Asteroids to Super Earths, from Plate-Tectonics to Life, August 2013 SETI Institute, Palo Alto.
- Spohn T., 2013, Exploration of the Solar System, November 2013 Space World Frankfurt.
- Gail H.-P., D. Breuer, T. Spohn, T. Kleine, M. Trieloff, 2013, Early thermal evolution of planetesimals and its impact on processing and dating of meteoritic material. In: Protoplanets and Stars VI, 15.-20. July 2013, Heidelberg, Germany.
- Van Hoolst T., Rivoldini A., 2013. On the interpretation of the observed libration in terms of Mercury's interior. MESSENGER-BepiColombo Joint Science Meeting, Chicago, Il, USA, 22-24 April 2013
- Vanhaecke F., 2013, Unleashing the full power of ICP-MS by exploiting isotopic information, European Winter Conference on Plasma Spectrochemistry, February 2013, Krakow, Poland.
- Vanhaecke F, 2013, Sector-field mass spectrometers – high sensitivity and low interferences. What more could you want? Pittcon, March 2013, Philadelphia, PA, USA.
- Vanhaecke, F., 2013, Use of multi-collector ICP – mass spectrometry in applications based on isotope fractionation of metals and metalloids, Isotopes 2013, June 2013, Sopot, Poland.

2014

- Noack, L. and D. Breuer, 2014, How does the interior of a planet influence its habitability? (Keynote Talk). AbGradE Symposium 2014, 9.-10. Oct. 2014, Edinburgh, Scotland.
- Noack, L., D. Höning, H. Lammer and J.H. Bredehöft, 2014, Interior structure and possible habitability of ocean worlds (Keynote Talk). EANA 2014, 13.-16. Oct. 2014, Edinburgh, Scotland.

- Noack, L., 2014, Terrestrial vs. ocean planets: Characterization and habitability (Invited Talk). Seminar at ETHZ, 5. Nov. 2014, Zurich, Switzerland.
- Dehant V., 2014, “Planetary deep interiors, geodesy, and habitability.”, European Geosciences Union (EGU) General Assembly 2013, Invited Pico presentation, Vienna, Austria, 27 April-02 May, 2014.
- Van Hoolst, T., 2014, “The libration and interior structure of large icy satellites and Mercury”, IAU Symposium No. 310, Complex Planetary Systems, 7-11 July 2014, Namur.
- Robert S., S. Chamberlain, Mahieux A., I. Thomas, Wilquet V., Vandaele A.C., 2014, SOIR and NOMAD: Characterization of Planetary Atmospheres, The 13th HITRAN Conference, Boston, USA, June 23-25 (2014).
- Wilquet V., Robert S., Mahieux A. and Vandaele A.C., 2014, The atmosphere of Venus: eleven Venusian years of observations by Venus Express, PAMO Conference, Lille, France, July 7-10 (2014).
- Vandaele A.C., Mahieux A., R. Drummond, Robert S., I. Thomas, Wilquet V., S. W. Bougher, A. Brecht, R. Schulte, 2014, Venus Terminator Temperature Structure: Venus Express SOIR and VTGCM Comparisons, The 40th COSPAR Scientific Assembly, Moscow, Russia, Aug. 2-10 (2014).
- Vandaele A.C., Mahieux A., R. Drummond, Robert S., I. Thomas, Wilquet V., D. Belyaev, A. Fedorova, O. Korablev, A. Piccialli, F. Montmessin, J.L. Bertaux, 2014, Composition of the Venus mesosphere: a synthesis of SOIR/VEX observations, The 40th COSPAR Scientific Assembly, Moscow, Russia, Aug. 2-10 (2014).
- Altwegg K., B. Fiethe, U. Mall, De Keyser J., J.-J. Berthelier, H. Rème, S. Fuselier, T. Gombosi, P. Wurz, and M. Rubin, 2014, High precision mass spectrometry in a cometary coma: first results from the Churyumov-Gerasimenko comet nucleus exploration. International Mass Spectrometry Conference, Geneva, Switzerland, 24-29 August 2014.
- Javaux EJ, 2014, Early Life Traces and Evolution, and implications for the search of life beyond Earth. Session “Early Earth Evolution”, EU ESOF2014 conference, Copenhagen, DK, June 21-26 2014.
- Javaux EJ, 2014, Early diversification of life. Colloque Académie Interdisciplinaire Européenne des Sciences. Paris, Feb 5-6th 2014.
- Breuer, D., 2014, Interior structure and magnetic fields. In: Alpbach Summer school 2014, Space Missions for Geophysics of the Terrestrial Planets 15.-24. July, Alpbach/Tyrol, Austria.
- Breuer, D., 2014, Some new findings on the deep interiors of terrestrial planets and moons. In: 14th symposium of SEDI, 3.-8. August 2014, Kanagawa, Japan.
- Breuer, D., Plesa, A.-C., Grott, M., and Morschhauser A. (2014) Mantle dynamics, early reservoir formation and degassing of the Martian Interior, Workshop on ‘Volatiles in the Martian interior’, November 3-4, 2014, Houston, Texas.
- Breuer, D., Plesa, A.-C. and Tosi N. (2014) Enigmatic martian mantle reservoirs: Can dynamic models help? College de France, Symposium: ‘Structure and Dynamics of Earth-like Planets’, November 20-21, 2014, Paris.
- Grott, M., 2014, Mars as an igneous system: Our changing view from orbit, ground, meteorite. In: 8th International conference on Mars, 14.-18. July 2014, Pasadena, California, USA.
- Spohn, T., 2014, The terrestrial planets. In: Alpbach Summer school 2014, Space Missions for Geophysics of the Terrestrial Planets 15.-24. July, Alpbach/Tyrol, Austria.
- Spohn, T., 2014, Planetary Evolution and Life. Earth and Life Science Institute, Chiba Institute of Technology, Japan, August 2014, A DLR-lead Research Alliance in Germany.
- Spohn, T., 2014, Thermal Histories of Planetary Objects: From Asteroids to super-Earths, from plate-tectonics to Life. Center of Planetary Studies, University of Toronto, Canada, September 2014.
- Spohn, T., 2014, Future Space Missions of Interest to the HP4 Community. High Pressure, Plasma and Planetary Physics Workshop, University Rostock, Germany, October 2014.
- Spohn, T., 2014, Geophysics of the Earth and Rocky Exoplanets. Center for Space and Habitability, University of Berne, Switzerland, October 2014.
- Spohn, T., 2014, Continents and Life and the Evolution of the Earth’s Interior. Weizmann Institute

of Technology, Rehovot, Israel, November 2014.

- Grott, M., 2014, Mars as an igneous system: Our changing view from orbit, ground, meteorite. In: 8th International conference on Mars, 14.-18. July 2014, Pasadena, California, USA.
- Sohl, F., 2014, Structural models of terrestrial planet interiors. In: Planet Formation & Evolution 2014, 08.-10. September 2014, Christian-Albrechts-Universität zu Kiel, Germany.
- Claeys Ph., 2014, The Global Human Resource Program Bridging Across Physics & Chemistry, Tokyo Metropolitan University, Tokyo, Japan, January 31, 2014 (http://www.comp.tmu.ac.jp/tmuorg/topGP.html)
- Claeys Ph., ActUA – Antwerp University, Antwerpen, Belgium, January 9, 2014.
- Vanhaecke F., 2015, Extending the application range of provenance determination based on isotopic analysis, December 2015, Honolulu, HI, USA.
- Goderis S., 2015, Isotopic Heterogeneity in the Early Solar System, Invited Speaker 2015 Goldschmidt conference in Prague to Session 24d.
- Goderis S., 2015, Geochemistry of impacts and nailing down the impactors, Keynote lecture at 2015 Goldschmidt conference in Prague to Session 23g.

2015

- Van Hoolst T., 2015, “The rotation and tides of large icy satellites.”, Invited lecture, 3GM Team meeting, JUICE Science Working Team, Roma, Italy, 15-16 January 2015.
- Van Hoolst T., and Dougherty M., 2015, “J-MAG Magnetometer.”, Invited lecture, 3GM Team meeting, JUICE Science Working Team, Roma, Italy, 15-16 January 2015.
- Van Hoolst, T., Rivoldini, A., and M. Yseboodt, 2015, Mercury’s interior from rotation and gravity with MORE, BepiColombo 12th Science Working Team, 8-9 September, Milton Keynes, UK.
- Van Hoolst, T., 2015, Precise timing and the interior structure of terrestrial planets and icy satellites, ISSI Workshop on High Performance Clocks, with Special Emphasis on Geodesy and Geophysics and Applications to Other Bodies of the Solar System, Bern, Switzerland, 30 November - 4 December.
- Noack, L., 2015, Geophysics and Plate Tectonics of Terrestrial Planets, Invited seminar at the FU Berlin, Germany, 5 Feb. 2015.
- Noack L., 2015, “The habitable zone and its limitations from a geophysical point of view.”, 1st Conference of the COST Life-Origins (TD1308) project, Porto, Portugal, 22-27 March 2015.
- Noack, L., A. Rivoldini and T. Van Hoolst, 2015, Plate tectonics on Earth and Earth-like planets: Influence on habitability, Invited talk at Japanese-German Colloquium Astrobiology, University of Kiel, 9-10 December, 2015
- Dehant V., 2015, “Interior of Mars from spacecraft and complementary data.”, EGU, Union Session US4, Vienna, Austria, 12-17 April 2015.
- Baland R.M., Van Hoolst T., Tobie G., and Dehant V., 2015, “Determination of the tides and the rotation state of Ganymede with JUICE radio science experiment.”, European Geosciences Union (EGU), Invited talk, Session PS3.1, Vienna, Austria, 12-17 April 2015.
- Gloesener E., Ö. Karatekin, and Dehant V., 2015, “Modeling gas transport in the Martian subsurface.”, European Geosciences Union (EGU), Invited talk, Session PS9.3/GD3.6, Vienna, Austria, 12-17 April 2015.
- Karatekin Ö., 2015, “Asteroid and comet impacts on Mars and their influence on atmospheric mass evolution and habitability.”, invited Talk, EGU General Assembly 2015, Vienna, Austria, April 13-17, 2015.
- Cessateur G., M. Barthelemy, J. De Keyser, F. Dhooghe, J. Loreau, R. Maggiolo, A. Gibbons, N. Vaeck, K. Altwegg, L. Le Roy, J.-J. Berthelier, U. Calmonte, S. Fuselier, M. Hässig, M. Rubin, T.I. Gombosi, and M. Combi, 2015, Space weather phenomena at Galilean moons and comets. European Planetary Science Congress 2015, La Cité des Congrès, Nantes, France, 27 September-02 October (2015).
- Haaland S., M. Andre, L. Baddeley, A. Barakat, R. Chappell, V. Eccles, A. Eriksson, C. Johnsen, K. Li, L. Maes, R. Schunk, D. Welling, Estimation of cold plasma outflow during geomagnetic storms, AGU Fall meeting, December 14-18 (2015).
- Javaux EJ, 2015. Paleobiology and evolution of early eukaryotes. Yale Spring colloquium, The Department of Geology and Geophysics, Yale University, April 22nd 2015.

- Javaux EJ, 2015. Interpreting the record of early eukaryotes. Workshop "Eukaryo-/archaeogenesis; where do we stand?", The Company of Biologists, Wiston House, Wilton Park, Sussex, UK, March 8-11th 2015.
- Javaux EJ, 2016. "Evolution of biological innovations in early complex cells: insights from the fossil record". Nangyang Technological Univ. Singapour, & Bintam islands, Feb 1-7th 2016.
- Debaille V., O'Neill C. & Brandon A.D. (2015), To Subduct or not to Subduct? that is the Archaean Question…, Goldschmidt abstract #679, Prague, Czech Republic.
- Debaille V., Pittarello L., Armytage R., Decrée S., Claeys Ph..An Antarctic chondrite story: from the field to the lab. Invited contribution. NIPR Symposium on Antarctic meteorites, Tokyo, Japan, 2015.
- Breuer, D; K. Wünnemann, and T. Spohn, 2015, Numerical Models in Planetary Geology – Specifics of One-Plate Planets. In: EGU General Assembly 2015, 12-17 Apr. 2015, Vienna, Austria.
- Breuer, D.; and V. Stamekovic, 2015, Scaling Laws and the Problem of the Prediction of Tection Modes. In: Comparative Tectonics and Geodynamics of Venus, Earth, and Rocky Exoplanets. 4-6 May, Pasadena CA, USA.
- Plesa, A.-C, 2015, Thermo-chemical evolution and present day interior of Mars. In: Geophysical Fluid Dynamics Seminar, 1 April, Prague, Czech Republic.
- Plesa, A.-C., 2015, Thermo-chemical evolution and the present-day state of the Martian mantle. In: Geophysical Fluid Dynamics Seminar, 23 April, Bayreuth, Germany.
- Rückriemen, Tina, 2015, Can the Fe-snow regime explain a present-day dynamo in Ganymede's core? In: Seminar "Experimentelle Geochemie und Geophysik" at Bayerisches Geoinstitut, 5 Feb., Bayreuth, Germany.
- Spohn, T., 2015, Planetary Evolution and Life: Astrobiology from a Planetary Tectonics Perspective. In: Comparative Tectonics and Geodynamics of Venus, Earth, and Rocky Exoplanets. 4- 6 May, 2015, Pasadena CA, USA.
- Philippe Claeys, GEOTOP undergraduate-graduate seminar, Université du Québec at Montréal, 29 November, 2015, Montréal, Canada.

2016

- Vanhaecke F., 2016, From outer space to within the human body: natural isotope ratios as proxies, 2016 Winter Conference on Plasma Spectrochemistry, January 2016, Tucson, AZ, USA.
- Vanhaecke F., 2016, seminars – (1) ICP-mass spectrometry: a versatile technique for the determination, speciation and isotopic analysis of trace elements and (2) The power of isotopes: high-precision isotopic analysis via multi-collector ICP-mass spectrometry in various application contexts at Hong Kong Baptist University, April 2016, Hong Kong.
- Breuer D., 2016, Any news about the thermo-chemical evolution and the magnetic field history of Mars? In: Seminar (3 March 2016) at IPGP, Paris.
- Plesa A.-C., Maurice M., Tosi N. and Breuer D. 2016, Chemical Heterogeneities in the Interior of terrestrial planets. In: EGU General Assembly 2016, 17-22 April 2016, Vienna, Austria.
- Noack, L., D. Höning, A. Rivoldini, C. Heistracher, N. Zimov, B. Journaux, H. Lammer, T. Van Hoolst, and J.H. Bredehöft, 2016, Geophysical constraints on the habitability of water-rich planets, Invited seminar at University of Nantes, 28 January 2016, Nantes, France.
- Noack, L.; D. Höning, A. Rivoldini, C. Heistracher, N. Zimov, B. Journaux, H. Lammer, T. Van Hoolst, and J.H. Bredehöft, 2016, Possible habitability of water worlds, Invited talk at ISSI workshop on "The Delivery of Water to Proto-planets, Planets and Satellites", 11-15 January 2016, Bern, Switzerland.
- Debaille V. « Météorites en Antarctique : archives de notre système solaire », Grands séminaires, Université Paul Sabatier-Observatoire Midi-Pyrénée, Toulouse, France, March 2016.
- Noack, L., Rivoldini, A., Van Hoolst, T., 2016, "Plate tectonics and volcanism on terrestrial planets: Influence on habitability", DGG 2016, Münster, Germany, 14-17 March 2016.
- Noack, L., 2016, Geophysical influences on the possible habitability of Earth-like planets, Invited keynote lecture at PEPSci meeting, Delft, the Netherlands, 5 April, 2016.
- Javaux E.J., 2016, "Evolution of biological innovations in early complex cells: insights from the fossil record". Nangyang Technological Univ. Singapour, & Bintam islands, Feb. 1-7th 2016.

- Javaux E.J., 2016, "From inhabitable Earth to the first traces of life and implications for habitability and life detection.", ISSI Beijing workshop, Bern, 11-13 April 2016.
- Javaux E.J., 2016, "Excitements and challenges in tracking the early traces of life", COST ORIGINS "From star and planet formation to early life". Vilnius Lituania, 24-29 April 2016.
- Vandaele A.C., A. Mahieux, V. Wilquet, S. Chamberlain, B. Ristic, S. Robert, I.R. Thomas, L. Trompet, 2016, "VEX Legacy: SOIR data", International Venus Conference 2016, Oxford, UK, 4-8 April 2016.
- Vandaele A.C., J.-J. Lopez-Moreno, M. R. Patel, G. Bellucci, E. Neefs, I. R. Thomas, R. Drummond, J. Rodriguez-Gomez, F. Daerden and the NOMAD team, 2016, "The NOMAD Spectrometer Suite on ExoMars Trace Gas Orbiter", European Geosciences Union General Assembly, EGU, Vienna, Austria, 17-22 April 2016.
- Van Hoolst, T., 2016, Europa Geophysics, In: Europa Initiative Workshop, 29 February 2016, Madrid, Spain.
- Dehant V., 2016, "Earth Rotation: Theoretical aspects, observation of temporal variations and physical interpretation", European Geosciences Union General Assembly, EGU, Vienna, Austria, 17-22 April 2016.
- Dehant V., 2016, "Study of the nutation of the Earth and application to Mars", Invited talk, GAGER2016, Wuhan, Hubei, China, 18-23 July 2016.
- Dehant V., 2016, "Rotation of the Earth and planets from observation to understanding of the deep interior", Invited Lecture, GAGER2016, Wuhan, Hubei, China, 18-23 July 2016.
- Dehant V., 2016, "Other Planets Observations", 15th SEDI (Study of the Earth's Deep Interior) Symposium, Nantes, France, 24-29 July 2016.
- Gillmann C. 2016. The evolution of Venus: how did it diverge from Earth? 15-17 June 2016, University of Nantes, France.
- Gillmann C. 2016. Modelling the evolution of Venus. 7-11 November 2016, University of Bayreuth, Germany.

Planet TOPERS members were invited as lecturers to **several international thematic schools**: on interior structure and magnetic field of terrestrial planets (July 15-24, 2014, Alpbach/Tyrol, Austria), on (Exo)planet Global Climate Models (April 15-16, 2013, Leuven), on Spectroscopy and Planetology (June 3-7, 2013, in Fréjus, France), on Astrobiology [The First Educational Workshop on Astrobiology] (June 6-9, 2013, Höör, Sweden), on Astrobiology [AbGradCon 2013] (June 10-14, 2013, Montreal, Canada), Planetary Interiors [AbGradE 2014] (10-11 October, 2014, Edinburgh, UK), on Origin, Evolution and Future of the Biosphere (August 19-30, 2013, and August 18-29, 2014, Banyuls, France). See Section 3.2.9.

Not mentioned here are the invited seminary abroad.

4.2.2.7. Bilateral cooperation projects related to the IAP

Planet TOPERS Members (O. Karatekin, V. Dehant, A.C. Vandaele, and Ph. Claeys) have obtained a BELSPO project for networking with **Russian science institutions** (Space Research Institute (IKI) and Russian Academy of Sciences (RAS)) for working on planetary and solar system sciences. In particular, the objectives are to better understand the meteorite and comet impacts on the atmosphere evolution of a planet and the influence on habitability, and to prepare the next missions for Mars exploration as well as for the exploration of the icy moons of the solar system. 15 October 2013-14 October 2016.

Planet TOPERS members from BISA are also part a BELSPO bi-lateral project between Belgium (BISA) and **India** (ISRO and other research centers). In the frame of this project, Belgian and Indian researchers collaborate for the different space missions to Mars.

Planet TOPERS Members are participating in Tournesol (France-Belgium) collaboration. ULB in particular is working with a well-known group of Aix-en-Provence and VUB, with Paris-Tech. Univ.

4.3. Durability of the IAP – Continuation of the network

The multi-disciplinary concept and understanding of habitability is certainly a **hot topic** for the next decade (see Sections 4.1.1 and 4.1.4). The roadmaps and objectives mentioned in Sections 4.1.1.2–4.1.1.6, as well as the perspectives of the **new space missions** (see Section 4.1.1.1) dedicated to astrobiology of terrestrial planets such as ExoMars, focused on comets or asteroids such as AIM (not yet adopted but where 5/7 Planet TOPERS are involved), or centered on exoplanets such as CHEOPS or PLATO, strongly indicate the major importance for our teams and for Belgian research in general to **continue to work as a network** in the next IAP-phase.

Planet TOPERS has addressed themes related to planetary habitability and requiring an integrated approach, which couples the evolution and internal dynamics of a planet, through various processes such as volcanism, outgassing, and dynamo-induced magnetic field with the evolution, dynamics and chemistry of a planet's atmosphere. We have characterized the early Earth and extreme life and some of their biosignatures, providing some answers to the above **roadmap** objectives highlighted in red. The continuation of the network in the next IAP phase is justified by the present advancement of our work, the exciting results obtained, and those that will be obtained in the remaining period of our IAP. While a series of questions have been solved, as usual in science, a series of additional new questions have emerged.

Further advances in our own objectives and first avenues for future work will be discussed during the Azores international workshop entitled "*Geoscience for understanding habitability in the solar system and beyond*" that we organize in September 2017. Within our 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, on early life and on planetary evolution. A particular important issue is the difference in evolution between the Earth and Mars. Several processes responsible for differences in planetary evolution have been identified, but many **fundamental questions remain to be further addressed**: (1) What is the relation between (plate) tectonics and atmospheric evolution? What is the role of the global carbon and water cycles therein? 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 planetary interiors, crust, oceans, hydrosphere, and 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 the 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 further discussions of the pros and cons of different hypotheses are needed. In the coming years a lot of efforts in these directions will be made and a state-of-the-art of these questions will be derived from the workshop we organize in the Azores, which will assess the answers and work avenues in a constructive and critical way.

The general aim of our next proposal will be close to the vision of our present IAP project explained in Section 1.3 and on our website http://iuap-planet-topers.oma.be/scientific_concept_and_overall_planning.php. 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. The next phase IAP proposal will further address 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.

In the current IAP phase, Planet TOPERS members have concentrated their work on life in the Solar System, its characterization, its (detectable) signatures, and the general understanding of habitability of terrestrial planets. We have also studied the interior structure and interior dynamics of terrestrial exoplanets, super-Earths, and ocean planets. We think that this theme needs to be further intensively studied in view of the upcoming space missions and ground telescope observations, and in view of the roadmaps. Recent breakthroughs have put exoplanetology, the study of exoplanets and their host stars, at the forefront of modern astrophysics, planetary sciences, and astrobiology (see for instance the AstRoMap roadmap presented in Section 4.1.1.5 and the ESA and NASA roadmaps presented in Sections 4.1.1.1 and 4.1.1.6 respectively), notably because they bring us closer than ever to an answer to the tantalizing question **"is there life around other stars?"**. In this exciting context, current efforts are focusing on the detection of habitable planets (host star properties, planets in habitable zone, planetary structure, atmospheric composition), with as 'Holy Grail' the study of **Earth-analogs** and the search for **traces of life in their atmospheres**. We will therefore continue to work on **modeling the interior** and **exchange with a possible atmosphere** for **exoplanets** (in particular for those larger than Earth) in the next IAP-phase.

For many recent and planned astronomy missions, the focus in the next 5 to 10 years will be on the detection of Earth-like planets. In relation with what is done in Belgium, the main efforts will be on exoplanets either in the habitable zone as detected by the space telescopes (Kepler, PLATO, CHEOPS) and transiting cool M-dwarfs because of their favorable star/planet contrast that should make possible their detailed characterization with current technology (see for instance recent discovery http://www.eso.org/public/news/eso1615/ by the Belgian TRAPPIST telescope).

The proposed future WPs for the network in the next IAP-phase will include members of the **community of exoplanetary research** in Belgium. Our affiliated partner Anne-Sophie Libert and her team at Namur University extensively study the orbital dynamics of extrasolar systems to improve the habitability definition via a project with two of Planet TOPERS partners (name: ExtraOrDynHa). This project will end at the end of 2016 and we all would benefit from incorporating the team in our IAP, in addition to incorporating teams in exoplanet community such has KULeuven.

We intend to keep developing the research themes of our five WPs and add one WP related to exoplanet observations and their interpretation. This 6th WP will directly benefit from the experience gained during the first 5 years of Planet Topers, and we expect from the start an interesting synergy and numerous exchanges with the initial 5 WPs.

5. OUTPUT

5.1. IAP publications

List the 10 most relevant publications or co-publications directly related to the achievements of the IAP project as a whole.

Dehant V., D. Breuer, P. Claeys, V. Debaille, J. De Keyser, E. Javaux, S. Goderis, Ö. Karatekin, T. Spohn, A.-C. Vandaele, F. Vanhaecke, T. Van Hoolst and V. Wilquet, 2012, "From meteorites to evolution and habitability of planets.", Planetary and Space Science,72, 3-17, DOI: 10.1016/j.pss.2012.05.018. → ROB + BISA + VUB + ULB + UGent + ULg + DLR

Noack L., Godolt M., von Paris P., Plesa A.-C., Stracke B., Breuer D., and Rauer H., 2014, "Constraints on planetary habitability from interior modeling.", Planetary and Space Science, special issue 'Planetary evolution and life', 98, 14-29. → ROB + DLR

Martin C., Debaille V., Lanari P., Goderis S., Vandendael I., Vanhaecke F., Vidal O., and Claeys Ph., 2013, "REE and Hf distribution among mineral phases in the CV-CK clan: a way to explain present-day Hf isotopic variations in chondrites.", Geochimica Cosmochimica Acta, 120, 496-513. → VUB - ULB- UGent

Noack L., and Breuer D., 2014, "Plate tectonics on rocky exoplanets: Influence of initial conditions and rheology.", Planetary and Space Science, special issue 'Planetary evolution and life', doi: 10.1016/j.pss.2013.06.020, 98, 41-49. → ROB - DLR

Gargaud M, Amils R, Cernichicaro Quintanilla J, Cleaves HJ, Irvine WM, Pinti D, Rouan D, Spohn T, Tirard S, Viso M (Chief Eds.), Albarede F, Arndt N, Javaux EJ, Prantzos N, Stahler S, Raymond S, Ehrenfreund P, Charnley S, Encrenaz T, DW Latham, Kaltenegger L, Kobayashi K, Horneck G, Bersini H, Gomez F (Eds.), 2015, Encyclopedia of Astrobiology, 2nd Edition

Springer, 2550 p. → ULg – DLR

Chernonozhkin, S. M., Goderis, S., Lobo, L., Claeys, Ph., Vanhaecke, F., 2015, Development of an isolation procedure and MC-ICP-MS measurement protocol for the study of stable isotope ration variations of Nickel, Journal Analytical Atomic Spectrometry, 30, 1518-1530, DOI: 10.1039/C5JA00080G. → VUB – UGent

Pittarello L.L., Baert K., Debaille V., Claeys Ph., 2015, Screening and classification of ordinary Chondrite by Raman Spectroscopy, Meteoritics and Planetary Science, 50, 10, 1718-1732, DOI: 10.1111/maps.12506. → VUB – ULB

Van Roosbroek N., Debaille V., Pittarello L., Goderis S., Humayun M., Hecht L., Jourdan F., Spicuzza M., Vanhaecke F., & Claeys Ph., 2015, The formation of IIE iron meteorites investigated by the chondrule-bearing Mont Dieu meteorite. Meteoritics & planetary science, 50, 1173-1196, doi:10.1111/maps.12463. → VUB – UGent – ULB

Vandaele A. C., Neefs E., Drummond R., Thomas I. R., Daerden F., Lopez-Moreno J.-J., Rodriguez J., Patel M. R., 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., and Wolff M., 2015, "Science objectives and performances of NOMAD, a spectrometer suite for the ExoMars TGO mission.", Planetary and Space Science, 119, 233-249, DOI: 10.1016/j.pss.2015.10.003. → ROB – BISA

Noack L., D. Höning, A. Rivoldini, C. Heistracher, N. Zimov, B. Journaux, H. Lammer, T. Van Hoolst and J.H. Bredehöft, 2016, "Water-rich planets: how habitable is a water layer deeper than on Earth?" Icarus, accepted, DOI: 10.1016/j.icarus.2016.05.009. → ROB + DLR

Remark:

- A complete list of publications is already provided in the scientific activity reports of the first three years of the project.
- The complete list of the recent publications (not included in the activity reports of the first three years) is provided in Annex 1 of this review report.
- The list of our publications is provided on http://iuap-planet-topers.oma.be/publications.php.
- We have several publications in press in a special issue of Life and Evolution of Biospheres (OLEB), of which we are as well Editors and related to one of the COST ORIGINS workshop (Porto, Portugal, 2014).

5.2. Outreach, dissemination and impact to society

As planets and habitability are themes that the public likes very much, the Consortium had several outreach activities.

5.3. Press releases

- ESA News – 1 October 2012: « BISA work on a curious cold layer in the atmosphere of Venus »
- BISA News - 1 October 2012: "A curious cold layer in the atmosphere of Venus" and the article
- IASB News - 1 October 2012: "Une couche froide intrigante dans l'atmosphère de Vénus" and the article
- BIRA News - 1 October 2012: "Een verbazend koude laag in de atmosfeer van Venus" and the article
- Polar Research News - 28 February 2013: "Antarctic Scientists discover a 18kg-meteorite"
- IRSNB - 28 February 2013: "Météorite de 18kg découverte en Antarctique exceptionnellement exposée au Musée des Sciences Naturelles"

- KBIN - 28 February 2013: "Meteoriet van 18kg ontdekt op Antarctica uitzonderlijk tentoongesteld in Natuurwetenschappen Museum"
- RBINS - 28 February 2013: "Meteorite of 18kg discovered in Antarctica exceptionally exposed to the Museum of Natural Sciences
- ESA News - 8 November 2013: "ExoMars lander module named Schiaparelli"
- BISA News - 8 November 2013: "ExoMars lander module named Schiaparelli"
- IASB News - 8 November 2013: "L'atterrisseur de ExoMars est baptisé Schiaparelli"
- BIRA News - 8 November 2013: "ExoMars-lander is Schiaparelli gedoopt"
- BISA News - 1 March 2014: "New laboratory measurement of CH4 lines" and the complete article
- BISA News - 10 April 2014: "Venus Express: 8 years in orbit !"
- IASB News - 10 April 2014: "Venus Express: 8 années en orbite !"
- BIRA News - 10 April 2014: "Venus Express: 8 jaren in orbit !"
- EGU press Conference - 27 April-2 May 2014: "Fingerprints of life: from the early Earth to outer space", with participation of Lena Noack and Emmanuelle Javaux.
- BISA News - 17 July 2014: "Planetary Aeronomy Team paper highlighted: Venus Express took a plunge into the Venus atmosphere"
- IASB News - 17 July 2014: "Venus Express a fait un plongeon dans l'atmosphère de Vénus"
- BIRA News - 17 July 2014: "Venus Express nam een duik in de atmosfeer van Venus"
- Science Direct - Press release/Highlights - August 2014: "Biological enhancement of weathering and erosion as discovered by DLR team of researchers modelling early Earth"
- IASB News - 4 August 2014: "Une primeur ! Rendez-vous de Rosetta avec une comète - La Belgique est à bord"
- BIRA News - 4 August 2014: "Primeur! Rosetta's rendez-vous met een komeet - België is aan boord"
- IRSNB - 4 November 2014: "La météorite antarctique de retour au Muséum"
- KBIN - 4 November 2014: "Antarctische meteoriet keert terug naar Museum"
- RBINS - 4 November 2014: "Antarctic Meteorite Returns to Our Museum"
- BISA - 27 February 2015: "First Science Results from Rosetta" in French and in Dutch, public and press event at the Planetarium
- BISA - 20 March 2015: "NOMAD" in French and in Dutch
- BISA - 29 October 2015: "First detection of molecular oxygen in a comet by Rosetta" in French and in Dutch, public and press event at the Planetarium
- BISA - 3 March 2016: "Du belge à bord de la mission ExoMars de l'ESA"
- BISA - 3 March 2016: "Belgische toptechnologie klaar voor vertrek naar planeet Mars"
- BISA - 3 March 2016: "Du belge à bord de la prochaine mission ExoMars de l'ESA"
- Mars.aeronomie: "ExoMars launch with huge media echo"

5.4. Press conferences

During EGU, we participated as main interveners in a Press Conference on "Fingerprints of life: from the early Earth to outer space" related to the two scientific sessions BG8.1 and PS8.1/BG8.2. The Press Conference was filmed but only stayed one year on the web. The content was highlighted in several journals. IUAP Planet TOPERS members Emmanuelle Javaux (University of Liège) and Lena Noack (Royal Observatory of Belgium), together with a colleague from the Canada (Kurt Konhauser, University of Alberta) gave a press conference at the EGU (European Geophysical Union) in Vienna (at the Press Centre, located in the Austria Center Vienna) on Thursday, 1st May 2014, at 11:00 on "Fingerprints of life: from the early Earth to outer space".

Other press conferences have been organized in the frame of the experiments/instruments where we are involved, such as the Rosetta mission, the TGO launch etc.

The **Rosetta** events were covered by ESA (see e.g. http://sci.esa.int/rosetta/, http://www.esa.int/spaceinvideos/Videos/2015/06/Replay_of_Rosetta_conference) but we also organized a Press Conference in Belgium, related to the inauguration of a special Rosetta exhibit at the Euro Space Center, Redu, Belgium, which included a presentation by De Keyser J. on "Les comètes, Rosetta, et l'Institut d'Aéronomie Spatiale de Belgique.", 27 February 2014.

The **TGO** launch event was covered by ESA but as there is a Belgian instrument onboard the spacecraft, there was a press conference organized by BISA at the Space Pole in Uccle, which included a presentation of E. Neefs on "The NOMAD instrument" and from the NOMAD industrial partners, 14 March 2015, and a press conference organized by BISA at related to the inauguration of a special MarsExpress exhibit at the Euro Space Center, Redu, Belgium, which included a presentation by Vandaele Ann Carine. on "La mission ExoMars" and from the NOMAD industrial partners, 10 March 2015.

We plan a Press Conference for the Schiaparelli module landing newt September.

5.5. Written press

- LaLibre -7 August 2012: Interview of Véronique Dehant, "Curiosity en mode martien"
- L'Avenir (Alain Wolwertz) - 7 August 2012: Interview of Véronique Dehant, "Curiosity va débuter la lecture de Mars"
- LeSoir (Frédéric Soumois) - 22 August 2012: Interview of Véronique Dehant, "Mars commence à livrer ses mystères à Curiosity"
- ULg Culture - August 2012: Interview of Emmanuelle Javaux "En quête de signatures de vie..."
- ULg News, 15ème jour du mois (ULg), n°216 ERC Grants - September 2012: Interview of Emmanuelle Javaux, "le sommet de l'excellence scientifique en Europe"
- Le Soir - 20 January 2012: Une météorite martienne au Maroc, interview of Vinciane Debaille
- La libre Belgique - 29 January 2012: Quel est le lieu idéal pour trouver des météorites ?, interview of Vinciane Debaille
- Le Soir (Frédéric Soumois) - 28 November 2012: A la chasse à la météorite sur la glace antarctique, interview of Vinciane Debaille
- Le Soir - 27 January 2012: les météorites belges de l'antarctique sont rentrées au pays, interview of Vinciane Debaille
- L'avenir.net - 28 February 2013: "Une météorite de 18 kg trouvée par des chercheurs belges en Antarctique"
- Le Vif - 28 February 2013: "Une météorite de 18 kg trouvée par des chercheurs belges en Antarctique"
- 7sur7 - 28 February 2013: "Une météorite de 18 kg trouvée par des chercheurs belges en Antarctique"
- rtbf.be - info - 28 February 2013: "Des chercheurs belges ont trouvé une météorite de 18 kg en Antarctique"
- Le Figaro - 28 February 2013: "Météorite de 18 kg en Antarctique"
- Globalpost - 28 February 2013: "Scientists find one of Antarctica's largest meteorites"
- BFMTV - planètes - 28 February 2013: "Antarctique: des scientifiques découvrent une météorite de 18 kg"
- Canada.com - 28 February 2013: "International scientists find 40-pound meteorite in eastern Antarctica"
- Edmonton Journal - 28 February 2013: "International scientists find 40-pound meteorite in eastern Antarctica"
- Montreal Gazette - 28 February 2013: "International scientists find 40-pound meteorite in eastern Antarctica"
- The Vancouver Sun - 28 February 2013: "International scientists find 40-pound meteorite in eastern Antarctica"
- News.com - 28 February 2013: "Scientists find large Antarctica meteorite"
- The Daily Telegraph - 28 February 2013: "Scientists find large Antarctica meteorite"
- SKYE weather - 28 February 2013: "Big Meteorite Discovered in Antarctica. An expedition netted 425 meteorites in 40 days, with a total weight of 165 pounds"
- Science Daily - 28 February 2013: "Antarctic Scientists Discover 18-Kilogram Meteorite"

- News - Princess Elisabeth Antarctica - Polar Research Station - 28 February 2013: Interview of Vinciane Debaille, “Meteorite Hunter”
- La Recherche - February 2013: interview E. Javaux, “les macrofossiles de 2.1 milliards d’années, Gabon”
- News - Princess Elisabeth Antarctica - Polar Research Station - 28 February 2013: “Scientists at Princess Elisabeth Antarctica Discover 18kg Antarctic Meteorite”
- The Huffington Post - 3 March 2013: “Huge Meteorite Found In Antarctica, Largest Discovered There In 25 Years”
- De Standard - 12 March 2013: “Belgische wetenschappers ontdekken 18 kilo zware meteoriet op Antarctica”
- Conférence de la ville de Verviers - 26 March 2013: “L'eau et la vie dans l'univers: un trésor essentiel à la vie”, Jehin E, Javaux EJ, Magain P, Gillon M.
- La Libre Belgique - 2 July 2013: “Terre et Mars, un peu cousines”, interview of Vinciane Debaille
- La Libre Belgique - 31 August 2013: De l’eau sur Terre grâce aux comètes, interview of Vinciane Debaille
- Le Soir - 2 July 2013: Quand la Terre ressemblait à Mars, interview of Vinciane Debaille
- La Libre Belgique - 18 May 2013: Mission en antarctique travail en milieu hostile, interview of Vinciane Debaille
- La Libre Belgique - 01 March 2013: Découverte d’une météorite de 18 kg en antarctique, interview of Vinciane Debaille
- BIOFUTUR spéciale édition - Juillet-août 2013: Interview of Emmanuelle Javaux, “Les premières traces de vie”
- DeltaNews - 14 November 2013: Interview of D. Höning, “Did Early Life Build Earth's Continents?”
- NewScientist - 25 November 2013: Interview of D. Höning, “Early life built Earth's continents”
- Science Connection - May 2014: Interview of Véronique Dehant concerning the IUAP, in English, in French, in Dutch
- LeSoir - 16 June 2014: Interview of Vinciane Debaille, “La Lune viendrait de la Terre… et de Theia”
- La Libre Belgique - 4 August 2014, J. De Keyser, Interview with La Libre Belgique newspaper about Rosetta and BISA's role.
- BELGA news agency - 4 August 2014, J. De Keyser, F. Dhooghe, and R. Maggiolo, Press release concerning Rosetta's arrival at 67P/Churyumov-Gerasimenko and BISA's role in the science, sent out to the Belgian press. Picked up by the BELGA news agency, who combined our story with the ESA press release, and published in several newspapers (Het Laatste Nieuws, Het Belang van Limburg, LeSoir, Het Nieuwsblad, De Standaard).
- METRO newspaper - 5 August 2014, J. De Keyser, F. Dhooghe, R. Maggiolo, Short press story in the METRO newspaper (Dutch and French), “België staat voor ontmoeting met komeet” / “La Belgique a rendez-vous avec une comète”.
- Bruxelles News - 14 August 2014, J. De Keyser, Short press story in "Bruxelles News" about Rosetta's arrival at 67P, and BISA's role.
- DailyScience 29 October 2014: "Bienvenue dans la zone d’habitabilité", interview of Véronique Dehant by Christian Du Brulle
- Newsletter of the European Low Gravity Research Association - 7 November 2014, J. De Keyser, Interview for the Newsletter of the European Low Gravity Research Association about Rosetta and the landing of Philae on 67P/Churyumov-Gerasimenko.
- Het Laatste Nieuws - 12 November 2014, J. De Keyser. Interview for newspaper "Het Laatste Nieuws" about the landing of Philae on 67P/Churyumov-Gerasimenko.
- LaLibre - 12 October 2014: Interview of Véronique Dehant by Sophie Devillers, “Quand notre Terre perd la boussole...”
- L’Avenir - 27 November 2014: Vinciane, chercheuse de météorites, interview of Vinciane Debaille

- La libre Belgique - 24 November 2014: À la chasse aux météorites, interview of Vinciane Debaille
- La libre Belgique - 11 March 2014: The Atomia Price, interview of Vinciane Debaille
- LeSoir - 12 and 13 November 2014: Interview of Emmanuelle Javaux, “Philae on Rosetta : comètes, histoire du système solaire et origine de la vie”.
- Magazine d'Uccle - 17 November 2014, J. De Keyser, Interview concerning Rosetta and Philae's landing by Chr. Du Brulle for the Magazine d'Uccle.
- La Libre Belgique - 31 December 2014, pp 20-21. “Une nouvelle méthode pour détecter les extraterrestres”, interview of Emmanuelle Javaux et Yaël Nazé par S. Devillers
- LeSoir - 13 March 2015 : “Possibilité de vie sur lunes glacées de Jupiter”, interview of Emmanuelle Javaux
- Le Soir - 25 March 2015 : “La Belgique va chercher des traces de vie sur Mars –NOMAD and ExoMars ”, interview of Valérie Wilquet
- SpaceNews - 19 mai 2015: “La Belgique à la recherche de traces de vie sur Mars”
- Brussels Studies - 6 July 2015; article related to Philippe Claeys’ recent publication about how incoherence in cartographic data between Brussels, Flanders and Wallonia complicates water management in Brussels. It is based on an article published in the journal “Brussels Studies”
- L'Avenir - 25 July 2015: Interview of Lena Noack on "Nouvelle exoplanète : une Terre 2.0?" by Céline Demelenne
- L'Avenir - 12 August 2015: Interview of Johan De Keyser on "Du belge au plus près de l'astre solaire” and "On fait fonctionner un appareil à 300 millions de km de la Terre"
- CineTeleRevue - 25 September 2015: Interview of Veronique Dehant and Vinciane Debaille by Frederic Seront after the vision of the Premiere of the film The Martian.
- LaLibre - 29 September 2015 : Interview of Véronique Dehant by Sophie Devillers « Sur Mars, les conditions de vie sont réunies»
- LeSoir, Interview of Veronique Dehant by Laetitia Theunis, 30 September 2015.
- LaLibre - Dailymotion - 1 October 2015: Interview of Ozgur Karatekin by Sophie Devillers « le film Seul sur Mars vu par un planétologue de l'Observatoire de Belgique »
- LaLibre - 6 October 2015: Interview of Ozgur Karatekin by Sophie Devillers « En 4 scènes, "Seul sur Mars" vu par la science »
- La Libre Belgique - 29 October 2015: Interview of Johan De Keyser about first detection on molecular oxygen with Rosetta at 67P/Churyumov-Gerasimenko
- Le Vif - 30 October 2015: "Une station spatiale sur Mars?" by journalist Rosanne Mathot
- Le Vif - 1 November 2015: “De la vie sur Mars? ” by journalist Rosanne Mathot
- Le Vif - 44 - 30 October 2015: “Mars - La nouvelle Terre promise” by journalist Rosanne Mathot
- Le Vif - 44 - 30 October 2015: “Mars - La stratégie de la Belgique” by Journalist Christophe Leroy
- LeSoir - 10 October 2015 : “Seul sur Mars”, interview of Emmanuelle Javaux
- Le vif l’Express (suppl. web) - 10 October 2015 : “Seul sur Mars”, interview of Emmanuelle Javaux
- Het Belang Van Limburg – 18 October 2015: comments on dating the migration of Homo sapiens out of Africa by Philippe Claeys.
- UCL News 13 November 2015: "Véronique Dehant, Docteur Honoris Causa de l'Observatoire de Paris"
- BELSPO News 13 November 2015: "Observatoire royal de Belgique : Véronique Dehant, Docteur Honoris Causa de l’Observatoire de Paris"
- BELSPO News 13 November 2015: "Koninklijke Sterrenwacht van België : Véronique Dehant, Doctor Honoris Causa van het Observatoire de Paris"
- BELSPO News 13 November 2015: "Royal Observatory of Belgium : Véronique Dehant, Doctor Honoris Causa of the Paris Observatory"
- DailyScience - 4 Jan 2016: on NOMAD and ExoMars, interview of Ann Carine Vandaele

- Athena – 26 February 2016: “Via Liège, NOMAD Belge autour de Mars”, article by Théo Pirard
- L’Echo – 11 March 2016: “NOMAD, le nez belge qui va renifler l'atmosphère de Mars“, article by Olivier Gosset
- Spacepage – 11 March 2016: “ExoMars Trace Gas Orbiter en Schiaparelli klaar voor lancering”, article by Kris Christiaens
- L’Echo – 12 March 2016: “Mission ExoMars | À la recherche de la vie extraterrestre“, interview of Véronique Dehant, Emmanuelle Javaux, Ann Carine, Vandaele and Arnaud Striepen by Mélanie Noiret
- De Morgen – 14 March 2016: “Belgische 'NOMAD' vertrokken naar Mars”
- Standaard – 14 March 2016: “De ExoMars op weg naar de Rode Planeet” article by JVT
- ZDNet – 14 March 2016: “ESA lanceert eerste fase in zoektocht naar leven op Mars” – article by Dries cludts
- Nieuwsblad.be – 14 March 2016: “Europese ruimtemissie zoekt naar sporen van leven op Mars”, article by JVA and JVT
- Metrotime – 14 March 2016: “Belgisch instrument NOMAD vertrokken naar Mars”
- Daily Science – 14 March 2016: “ExoMars 2016 : le grand voyage vient de commencer”, Article by Christian Du Brulle, with interviews and photos of Ann Carine Vandaele (BISA) and Ozgur Karatekin (ROB)
- Le Soir – 14 March 2016: “ExoMars: la fusée en quête de vie sur Mars a décollé (photos et vidéo)”, article by Chloé Monge-Cadet
- ScienceDaily – 14 March 2016: “ExoMars on its way to solve the Red Planet’s mysteries”
- Spacepage – 15 March 2016: “ExoMars ruimtesonde is op weg naar Mars”, article by Kris Christiaens
- Science News – 3 March 2016: "Scientists gear up to drill into ‘ground zero’ of the impact that killed the dinosaurs" by Eric Hand et derriere, la file Scientists gear up to drill into ‘ground zero’ of the impact that killed the dinosaurs - Science
- Smithsonian – 10 March 2016: “A giant planetary smashup may have turned venus hot and hellish”, Interview of C. Gillmann by Nola Taylor Redd
- Le Nouvel Observateur – L’Obs – 14 March 2016: « Cet asteroide géant qui aurait transformé Vénus en véritable enfer », Report on work by C. Gillmann by Jean-Paul Fritz.
- Bulletin 67 de l’Association Planète Mars (Mars Society France), April 2016. "MAVEN, à quoi ça sert ?”, Review of scientific results by the MAVEN probe by C. Gillmann.
- LeSoir - 2 May 2016: Interview of Lena Noack, “l’experte - Nous nous rapprochons d’une planète similaire à la Terre" by Violaine Jadoul
- Science et Avenir – May 2016: "Origine de la vie", interview of Emmanuelle Javaux by Azar Khalatbari
- Daily Science – 2 May 2016: les météorites belges recoltées en Antarctique menacées par la rouille, interview of Vinciane Debaille by Christian Du Brulle

5.6. Radio Interviews

- RTBF - La Première, Le Forum de Midi, 12h, Astronomie et exoplanètes - 17 January 2012: Interview of Emmanuelle Javaux, Michaël Gillon and Emmanuel Jehin (rediffusion of 20/12/2011)
- RTBF radio for Matin Première ‘l’invité de Matin Première’ – 19 January 2012: Interview of Vinciane Debaille
- Griffe de l'info - 28 March 2012: Interview of Veronique Dehant by Coralie Lemke
- RTBF radio for news - 7 August 2012: Interview of Veronique Dehant by François Kirsch, “Le robot Curiosity s'est posé avec succès sur la planète Mars”, Summary on the web by François Kirsch
- RTBF radio for Matin Première ‘l’invité de Matin Première’ - 7 August 2012: Interview of Veronique Dehant by Arnaud Ruyssen, on “Curiosity”
    - Questions from Arnaud Ruyssen and answers by Véronique Dehant
    - Questions from the auditor and answers by Véronique Dehant

  - Follow-on of the interview of Veronique Dehant by Arnaud Ruyssen: RTBF radio for "Le Forum de midi" - 9 August 2012 - Lien 2 - Lien 1
- DW for Actualités / International - 6 August 2012: Interview of Veronique Dehant by Perine Willame, "Mars a de la visite"
- RTBF LaPremière O Positif - 18 February 2013: les météorites en Antarctique, Interview of Vinciane Debaille
- 48FM - 13 March 2013: Interview of Emmanuelle Javaux, "Eau et vie sur Mars, découverte de la NASA"
- RTBF LaPremière Soir Première - 3 March 2013: Interview of Véronique Dehant by Arnaud Reyssen, "L'habitabilité de Mars - MarsOne"
- RTBF LaPremière O Positif - 22 March 2013: Interview of Emmanuelle Javaux et Emmanuel Jehin by Véronique Thyberghien and Yasmine Boudaka, "Printemps des Sciences", "L'eau dans l'univers"
- RTBF La Première NUWA - 7 May 2013: Interview of Vinciane Debaille
- RTBF radio, J. De Keyser, Interview about Rosetta's arrival at 67P for the News, 6 August 2014.
- RTBF radio for Matin Première 'l'invité de Matin Première' - 6 August 2014: Interview of Johan De Keyser by Sophie Braems, on "Rosetta and Philae"
- Radio 1 (Flemish radio), J. De Keyser, Interview about Rosetta's arrival at 67P for the News, 6 August 2014.
- Radio 1 (Flemish radio), J. De Keyser, F. Dhooghe, D. Devisscher, Interviews about Rosetta's arrival at 67P for "Vandaag", 6 August 2014.
- RTBF La Première radio, J. De Keyser, R. Boninsenga, and E. Jehin, Panel discussion aired live during the RTBF La Première radio program "Le Forum du Midi" about Rosetta's arrival at 67P, the role of space research, and the upcoming Perseid meteor shower, 7 August 2014.
- RTBF La première "Forum du midi" 12-13h - 12 November 2014: Interview of Emmanuelle Javaux, J.P. Swings, and E. Jehin, "Philae : comètes, histoire du système solaire et origine de la vie"
- RTBF Par A+B, Interview de Véronique Dehant par Benjamin Luypaert, 8 February 2015, 16h.
- RTBF La Première Radio News - 27 February 2015, "First science results from Rosetta", interviews of Johan De Keyser.
- VRT Radio - 27 February 2015, "First science results from Rosetta", interviews of Johan De Keyser.
- VRT Radio 2 - 27 February 2015, "First science results from Rosetta", interviews of Johan De Keyser.
- RTBF Par A+B, Interview de Vinciane Debaille par Benjamin Luypaert, 15 February 2015, 16h.
- Radio Vivacité « 5 à 7 » - 17 August 2015: Interview of R. Maggiolo on « les aurores polaires »)
- RTBF - La Première, Le Forum de Midi, L'eau sur Mars 12 à 12h20 – 30 September 2015: interview of Emmanuelle Javaux by F. Van de Meersche.
- Radio Vivacité - 28 September 2015: Interview of Elodie Gloesener by Julie Compagnon and Cyril.
- BelRTL Radio - 29 September 2015: Interview of Veronique Dehant by Pascal Vrebos
- RTBF radio Midi Première - Le Forum - 2 November 2015: "Quelle est la stratégie de la Belgique dans cette course technologique ?", interview de Christophe Leroy, Dominique Tilmans, Vladimir Pletser, where Mars' research of ROB and BISA are mentioned.
- RTBF - La Première, Le Forum de Midi, Philae on Rosetta : comètes, histoire du système solaire et origine de la vie, 12 à 12h20 – 12 November 2015: interview of Emmanuelle Javaux, Jean-Pierre Swings and Emmanuel Jehin by F. Van de Meersche.
- RTBF LaPremière Soir Première - 21 January 2016: Interview of Véronique Dehant by Arnaud Reyssen, "Planet Nine - la neuvième planète ?"

- RTBF - La Première - 14 March 2016: "Mars, des jeunes et des robots", interview of Elodie Gloesener and Bart Van Hove by Françoise Barré
- RTBF – 15 January 2016: “La mission ExoMars”
- Radio 1 – 23 February 2016: “Hoe wordt een ruimtesonde bestuurd en geland?”
- VRT (Flanders Main Radio Station) – 7 March 2016: interview of Philippe Claeys for the Morning Show, on The Iodp-Icdp Drilling of the Chicxulub Crater In Yucatan.

5.7. TV interviews

- RTBF TV for JT - 6 August 2012: Interview of Veronique Dehant by Lucie Dendooven: “MSL et habitabilité”
- RTL TV for RTL+ - 8 August 2012: Interview of Veronique Dehant by Vanessa Costanzo
- Telecast on Ketnet – 1 March 2013 – "Meteoriet"
- Telecast on De Redactie – Interview of Steven Goderis - 1 March 2013 – "Meteoriet gevonden tijdens expeditie Zuidpool"
- RTBF JT - 15 February 2013: Interview of Vinciane Debaille for the fall of the Chelyabinsk meteorite
- RTL JT - 16 February 2013: Interview of Vinciane Debaille for the fall of the Chelyabinsk meteorite
- TV RTC Liège - 12 March 2014: Interview of E. Javaux, “Printemps des sciences 2014”
- RTBF TV for JT - 13 March 2013: Interview of Véronique Dehant by Pascale Bollekens : Découvertes de nutriments dans le sol Martien – 13 March 2013
- RTBF TV for JT - 13 April 2013: Interview of Romain Maggiolo, “Une aurore boréale sera peut-être visible cette nuit”
- RTBF TV for JT - 13 April 2013: Interview of Romain Maggiolo, “Une aurore boréale visible dans le ciel de Belgique”
- Télé Bruxelles - 23 May 2013: Interview of Vinciane Debaille, on meteorites.
- RTBF Journal Télévisé, J. De Keyser, Contribution concerning Rosetta, 12 March 2014.
- RTL TVI television interview, J. De Keyser, on air in the 19:00 evening news, 5 August 2014.
- RTL TVI - 6 August 2014: Interview of Johan De Keyser and Mikael Beuthe, on “Rosetta”
- RTL television, J. De Keyser, F. Dhooghe, R. Maggiolo, E. Equeter, Interview about Rosetta's arrival at 67P for the News, 6 August 2014.
- VTM television, J. De Keyser and E. Equeter. Interview about Rosetta's arrival at 67P for the News, 6 August 2014.
- VRT television, J. De Keyser, E. Equeter, F. Dhooghe, Interview about Rosetta's arrival at 67P for the News, 6 August 2014.
- RTBF television, J. De Keyser, E. Equeter, F. Dhooghe, R. Maggiolo, Interview about Rosetta's arrival at 67P for the News, 6 August 2014.
- RTBF TV La Une JT 19h30 - 11 November 2014: Interview of R. Maggiolo, “Atterrissage de Philae”
- RTBF TV La Une JT 19h30 - 12 November 2014: Interview of E. Javaux, R. Maggiolo, E. Neefs, “Atterrissage de Philae”
- VRT television, J. De Keyser, Live commentary and interview by L. Scheire and B. Van Peer for Nerdland, parts of which were shown during Terzake, during the landing of Philae on 67P/Churyumov-Gerasimenko, organized by ESERO Belgium and University of Gent, Gent, 12 November 2014.
- VTM television, J. De Keyser, Interview about the landing of Philae on 67P/Churyumov-Gerasimenko for the News, 12 November 2014.
- RTBF TV La Une JT 19h30 - 13 November 2014: Interview of Vinciane Debaille pour l’inauguration d’une météorite antarctique de 18 kg au Musée royal des Sciences Naturelles de Belgique
- Télé Bruxelles (reportage) - 13 November 2014: Interview of Vinciane Debaille: « météorite en antarctique »

- VTM television - 14 November 2014, Interview of Johan De Keyser, about the survival possibilities of Philae on 67P/Churyumov-Gerasimenko for the News.
- RTBF La Une - 27 February 2015, interview of Johan De Keyser about "First science results from Rosetta".
- VTM - 27 February 2015, interview of Johan De Keyser about "First science results from Rosetta".
- RTBF - 24 March 2015: "NOMAD, futur instrument d'étude de l'atmosphère martienne, testé à Liège"
- ULg TV – Pause-Café, Interview of Emmanuelle Javaux, Remonter le temps jusqu'aux origines de la vie et explorer l'univers à travers les roches, and on YouTube.
- TeléBruxelles for the « M (Mag) de la rédaction » - 29 September 2015 : interview of Ozgur Karatekin by Murielle Berck.
- RTBF Television for JT - 28 September 2015: interview of Veronique Dehant by Pascale Bolekens.
- RTBF TV La Une JT 13h & 19h30 – 4 October 2015, Interview of Philippe Claeys regarding the mechanisms leading to the extinction of the dinosaurs
- RTBF La Une television news - 29 October 2015, Interview of J. De Keyser and R. Maggiolo about the first detection on molecular oxygen with Rosetta at 67P/Churyumov-Gerasimenko.
- RTL-TVI television news - 29 October 2015, Interview of J. De Keyser and R. Maggiolo about the first detection on molecular oxygen with Rosetta at 67P/Churyumov-Gerasimenko.
- TeléBruxelles for the « M (Mag) de la rédaction », météorite en antarctique - 26 November 2015 : interview of Vinciane Debaille
- TéléBruxelles (reportage) - 21 January 2016: Interview of Marie Yseboodt: « Planet Nine - la neuvième planète? »
- TVBruxelles bx1 - 14 March 2016: "L'instrument belge NOMAD en route pour Mars", Interview of Elodie Gloesener and Bart Van Hove by Pierre Beaudot and Yannick Vangansbeek
- RTBF - le JT - 14 March 2016: "La mission ExoMars 2016 a quitté l'orbite de la Terre", by Lucie Dendoven
- RTBF - le JT - 14 March 2016: "La mission ExoMars 2016 a quitté l'orbite de la Terre", Interview of Elodie Gloesener by Lucie Dendoven
- RTBF - le JT - 14 March 2016: "La mission ExoMars 2016 a quitté l'orbite de la Terre", Interview of Sévrine Robert by Lucie Dendoven
- RTBF - le JT - 14 March 2016: "La mission ExoMars 2016 a quitté l'orbite de la Terre", Interview of Eddy Neefs by Lucie Dendoven
- RTBF - le JT - 15 March 2016: "La mission russo-européenne ExoMars 2016 entame son voyage vers la planète rouge"
- Euronews – 25 February 2016: "Destination Mars, episode 2: The hunt for methane", interview of Ann Carine Vandaele (BISA)
- Euronews – 21 January 2016: "Destination Mars, episode 1: Searching for signs of life", interview of Jorge Vago (ESA)
- VTM-niews – 14 March 2016: "Belgische 'NOMAD' vertrekt naar Mars", interview of Eddy Neefs (BISA) by Baudewijn Van Spilbeeck
- De Redactie – VRT nieuws – 14 March 2016: "Missie Exo-Mars speurt naar leven op de rode planeet", interview of Eddy Neefs (BISA) and Lieve De Vos by Kaja Verbeke
- RTL Info – 14 March 2016: "Lancement de la mission ExoMars", interview of Philippe Antoine, Yannick Willame and Séverine Robert (BISA)
- RTBF Journal Televise 13h – 14 March 2016 (16'16"): "Journal Televise 13h", interview of Elodie Gloesener (ROB), Elke Sleurs, Olivier Dupont by L. Dendoven, R. Hoyois and D. Crozet

- BX1 Médias de Bruxelles – 14 March 2016: "L'instrument belge NOMAD en route pour Mars", Interview of Séverine Robert (BISA), Philippe Antoine by Pierre Beaudot and Yannick Vangansbeek
- Brusselnieuws.be – 14 March 2016: "Lancering ExoMars live te volgen"
- HLN.be – 14 March 2016: "Belgische 'NOMAD' vertrokken naar Mars"
- RTBF "Le Journal", Belgian French Television – 4 October 2015: "Mechanisms leading to the extinction of the dinosaurs", interview for the news (1 pm and 7 pm).
- RTBF television news – 12 January 2016: interviews of J. De Keyser and R. Maggiolo on the prospects for recontacting Philae.

5.8. YouTube

- Movie about the project UPWARDS - Understanding Planet Mars
- Movies about the ROB team in UPWARDS
- Movies about the BISA team in UPWARDS
- YouTube – 7 March 2016: "ExoMars science" - interview of Nicolas Thomas and Ann Carine Vandaele (BISA) by European Space Agency, ESA
- YouTube – 12 October 2015: "EuroVenus News - Ann-Carine Vandaele at EPSC 2015" - by Ann Carine Vandaele, EuroVenus News
- YouTube – 26 February 2016: "Destination Mars : la quête du méthane." by Ann Carine Vandaele, EuroNews
- YouTube – 26 February 2016: "Destination Mars, episode 2: The hunt for methane." by Ann Carine Vandaele, EuroNews
- YouTube – 24 September 2013: "NOMAD - UVIS selector mechanism vibration testing", by BISA
- YouTube – 27 January 2015: "NOMAD - Electrical Calibration Test Time Lapse", by BISA
- YouTube – 11 December 2015: "NOMAD – Ann Carine Vandaele", by BISA
- YouTube – 11 December 2015: "NOMAD - Valérie Wilquet", by BISA
- YouTube – 11 December 2015: "NOMAD - Lori Neary", by BISA
- YouTuve – 27 May 2015: "The NOMAD instrument on-board ExoMars", by Loic Trompet, SAC Planetary GIS Workshop
- YouTube – 25 March 2016: « Biosignatures et indices de la vie » - by Emmanuelle Javaux, Société Française d'Exobiologie
- YouTube – 23 March 2016: « Modes de fossilisation et premières traces de vie » - by Emmanuelle Javaux, Société Française d'Exobiologie
- YouTube – 19 December 2014: « Des origines de la vie à l'exploration de l'univers » - by Emmanuelle Javaux, Pause café de l'Université de Liège
- YouTube – 12 December 2014: « De l'étude des roches ancestrales à l'exploration spatiale » - by Emmanuelle Javaux, Pause café de l'Université de Liège
- YouTube – 21 November 2013: « How to keep your feet dry in Brussels ? » - by Philippe Claeys, Nuit du Savoir sur Bruxelles - Nacht van de Kennis over Brussel
- YouTube – 7 Aout 2012: « Véronique Dehant - planètologue s/ Mars dans Matin Première »
- YouTube – 4 February 2013: « Habiter sur Mars ? » - by Véronique Dehant, Académie royale de Belgique
- YouTube – 4 November 2014: « Évolution et habitabilité du système solaire 1/2 » - by Véronique Dehant, Académie royale de Belgique
- YouTube – 4 November 2014: « Évolution et habitabilité du système solaire 2/2 » - by Alessandro Morbidelli, Académie royale de Belgique
- YouTube – 27 January 2015: « Habitabilité et détection des Exoplanètes (1/2) » - by Valérie van Grootel, Académie royale de Belgique

- [YouTube – 27 January 2015: « Habitabilité et détection des Exoplanètes (2/2) » - by Anne-Sophie Libert, Académie royale de Belgique]
- [YouTube – 24 February 2015 : « Rosetta et la science des comètes (1/2) » - by Emmanuel Jehin, Académie royale de Belgique]
- [YouTube – 24 February 2015 : « Rosetta et la science des comètes (2/2) » - by Johan De Keyser, Académie royale de Belgique]
- YouTube – 1 October 2015 : « Habiter sur une lune du système solaire ? » - by Véronique Dehant, Académie royale de Belgique (soon on web)
- [YouTube – 29 September 2015 : « Eau sur Mars: les réponses aux 7 questions que vous vous posez » - by Véronique Dehant, L'actu en débat, LeSoir]
- [YouTube – 3 March 2015: « Intervention au Sénat – La recherche au niveau fédéral » by Véronique Dehant, frame Senate debate on « Quel avenir pour la recherche scientifique en Belgique »]

5.9. Blogs, tweets, and webstories

The VUB-ULB team together with a Japanese team from the National Institute of Polar Research (Tokyo) searched the blue ice fields around PE (Princess Elizabeth) station in Antarctica for meteorites from December 2012 to February 2013. More than 400 new and unique samples were collected and in particular an 18kg specimen, the largest found on the Southern Continent since 1988. This attracted quite a bit of media coverage worldwide (http://iuap-planet-topers.oma.be/outreach.php). The blog (http://antarctica.oma.be/) of this expedition also received a lot of attention (statistics of the attendees are shown in Figure 56). The 18kg-meteorite found in Antarctica (see Figure 49) was shown at the Antarctic Treaty Consultative Meeting, on May 25-26, 2013, in Brussels.

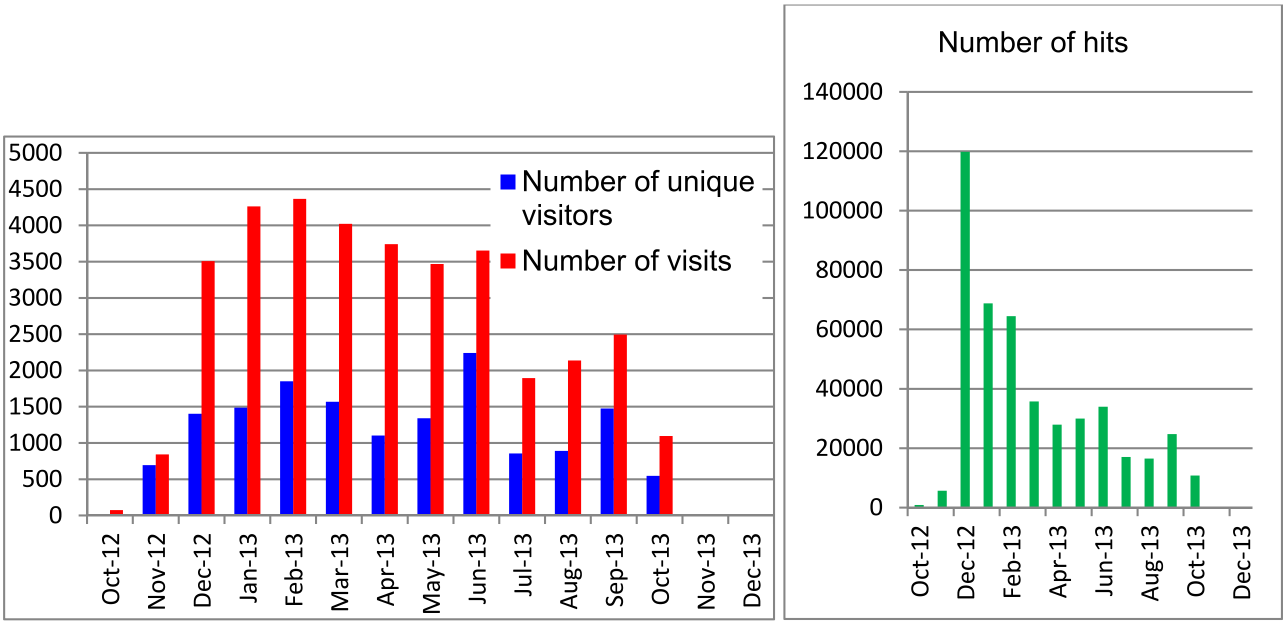


Figure 56: Statistics on the blog of the Antarctica expedition.

In addition to being information for the outside world, this Antarctica blog was really useful as a team building event.

We also made two other blogs, for the PhobosGround mission (failure at the launch), the MSL launch, and participated into the Trace Gas Orbiter blog of ESA (http://blogs.esa.int/rocketscience/ and http://blogs.esa.int/rocketscience/2016/03/22/exomars_twitter_collection/) and the Antarctica blog of the US mission http://caslabs.case.edu/ansmet/category/14-15/ (see all exchanges around page 5, 6 and 7, with photos where Vinciane Debaille appears at http://caslabs.case.edu/ansmet/2014/12/02/more-on-clothing-distribution/, http://caslabs.case.edu/ansmet/2014/12/07/most-of-the-group-during-our-shakerdown/, and http://caslabs.case.edu/ansmet/2014/12/11/hello-phineas/).

We also created several web stories on the ESA Rosetta blog:

- Concerning the Comet's coma composition and related to the paper of M. Hässig, K. Altwegg, H. Balsiger, A. Bar-Nun, J.J. Berthelier, A. Bieler, P. Bochsler, C. Briois, U. Calmonte, M. Combi, J. De Keyser, P. Eberhardt, B. Fiethe, S. A. Fuselier, M. Galand, S. Gasc, T. I. Gombosi, K.C. Hansen, A. Jäckel, H. U. Keller, E. Kopp, A. Korth, E. Kührt, L. LeRoy, U. Mall, B. Marty, O. Mousis, E. Neefs, T. Owen, H. Rème, M. Rubin, T. Sémon, C. Tornov, C.-Y. Tzou, H. Waite, P. Wurz. Comet's coma composition varies significantly over time, http://blogs.esa.int/rosetta/2015/01/22/comets-coma-composition-varies-significantly-over-time/, 22 January 2015.
- Concerning the detection of molecular nitrogen and related to the paper of M. Rubin, K. Altwegg, H. Balsiger, A. Bar-Nun, J.J. Berthelier, A. Bieler, P. Bochsler, C. Briois, U. Calmonte, M. Combi, J. De Keyser, F. Dhooghe, P. Eberhardt, B. Fiethe, S. A. Fuselier, S. Gasc, T. I. Gombosi, K.C. Hansen, M. Hässig, A. Jäckel, E. Kopp, A. Korth, L. LeRoy, U. Mall, B. Marty, O. Mousis, T. Owen, H. Rème, T. Sémon, C.-Y. Tzou, H. Waite, P. Wurz. Rosetta makes first detection of molecular nitrogen at a comet, http://blogs.esa.int/rosetta/2015/03/19/rosetta-makes-first-detection-of-molecular-nitrogen-at-a-comet/, 19 March 2015.
- Concerning the detection of argon and related to the paper of H. Balsiger, K. Altwegg, A. Bar-Nun, J.-J. Berthelier, A. Bieler, P. Bochsler, C. Briois, U. Calmonte, M. R. Combi, J. De Keyser, P. Eberhardt, B. Fiethe, S. A. Fuselier, S. Gasc, T. I. Gombosi, K. C. Hansen, M. Hässig, A. Jäckel, E. Kopp, A. Korth, L. Le Roy, U. Mall, B. Marty, O. Mousis, T. Owen, H. Rème, M. Rubin, T. Sémon, C.-Y. Tzou, J. H. Waite, P. Wurz. ROSINA detects Argon at 67P/Churyumov-Gerasimenko, http://blogs.esa.int/rosetta/2015/09/25/rosina-detects-argon-at-comet-67pc-g/, 25 September 2015.
- Concerning the detection of molecular oxygen and related to the paper of A. Bieler, K. Altwegg, H. Balsiger, A. Bar-Nun, J.-J. Berthelier, P. Bochsler, C. Briois, U. Calmonte, M. Combi, J. De Keyser, E. F. van Dishoeck, B. Fiethe, S. A. Fuselier, S. Gasc, T. I. Gombosi, K. C. Hansen, M. Hässig, A. Jäckel, E. Kopp, A. Korth, L. Le Roy, U. Mall, B. Marty, O. Mousis, T. Owen, H. Rème, M. Rubin, T. Sémon, C.-Y. Tzou, J. H. Waite, C. Walsh, P. Wurz. First detection of molecular oxygen at a comet. ESA web story, http://www.esa.int/Our_Activities/Space_Science/Rosetta/First_detection_of_molecular_oxygen_at_a_comet, 28 October 2015.

We created a webstory and tweet as well during the event of Trace Gas Orbiter launch at http://mars.aeronomie.be/en/exomars/webstory.htm. Twitter - ExoMars_NOMAD

5.10. Policy brief

At the level of BELSPO policy, V. Dehant participated into a Senate debate/session on « Quel avenir pour la recherche scientifique en Belgique », 3 March 2015, with the title “La recherche au niveau fédéral” and where the IAP were defended. The presentations and the debate were recorded and are available on http://video.senate.be/video_archive/events/20150303/index_clips_fr.html.

In that same topic, we have as well produced an interview for Science Connection IAP in three languages:

- In French: “Les pôles d’attraction interuniversitaires (PAI) – La Recherche Interdisciplinaire : Un Moteur Puissant”, pp 15-17: http://www.belspo.be/belspo/organisation/Publ/pub_ostc/sciencecon/43sci_fr.pdf
- In Dutch: “Interuniversitaire attractiepolen (IUAP) – Interdisciplinair Onderzoek: Een Krachtige Motor”, pp 15-17: http://www.belspo.be/belspo/organisation/Publ/pub_ostc/sciencecon/43sci_nl.pdf
- In English: “The Interuniversity Attraction Poles (IAP) – Interdisciplinary Research: A Powerful Driver”, pp 15-17:

http://www.belspo.be/belspo/organisation/Publ/pub_ostc/sciencecon/43sci_en.pdf

5.11. Press events

Press events were organized in relation to the exhibitions (see Section 5.12, e.g. – on October 14, 2014, Inauguration of the permanent exhibit at the RBINS displaying the 18 kg meteorite found in Antarctica by the ULB-VUB Planet Topers), to the launches or landing of spacecraft (see Section 5.4, e.g. Philae landing or Mars Express TGO launch), or associated with Press releases (see Section 5.3). We also had an important press events related to the Planet TOPERS findings during congresses (during EGU and EPSC).

We also did a press event for the inauguration at ULB of the new lab with the new high-resolution MC-ICP-MS Nu-Plasma and the TIMS Triton Plus dedicated to understand the evolution of the solar system.

Our field trips in Antarctica have also been highlighted (web-based) for the press and in the press.

Some of our results published in the scientific literature have also been highlighted (web-based):

- November 2012, DLR Team: Dark material on Vesta from the infall of carbonaceous volatile-rich material. Localized dark and bright materials, often with extremely different albedos, were recently found on Vesta's surface. The range of albedos is among the largest observed on Solar System rocky bodies. Nature. See http://www.nature.com/nature/journal/v491/n7422/full/nature11561.html
- July 2013, ULB team: Stagnant-lid tectonics in early Earth revealed by ^{142}Nd variations in late Archean rocks. A team of geologists led by the Université libre de Bruxelles (Belgium), and from Macquarie University, University of Houston, University of California in Davis and Lunar and Planetary Institute reveal that the Earth may have been very different in the past compared to what we can see now. See http://gtime.ulb.ac.be/News.html
- January 2013, VUB team: Reduced plumage and flight ability of a new Jurassic paravian theropod. From China The discovery of a new bird-like theropod dinosaur of the Jurassic from China. Nature Communications. See http://www.nature.com/ncomms/journal/v4/n1/full/ncomms2389.html
- January 2015, DLR Team: The organic-rich surface of comet 67P/Churyumov-Gerasimenko as seen by VIRTIS/Rosetta. The VIRTIS (Visible, Infrared and Thermal Imaging Spectrometer) instrument on board the Rosetta spacecraft has provided evidence of carbon-bearing compounds on the nucleus of the comet 67P/Churyumov-Gerasimenko. However, no ice-rich patches are observed, indicating a generally dehydrated nature for the surface currently illuminated by the Sun. Science. See http://science.sciencemag.org/content/347/6220/aaa0628
- January 2015, BISA Team: Time variability and heterogeneity in the coma of 67P/Churyumov-Gerasimenko. Comets contain the best-preserved material from the beginning of our planetary system. Their nuclei and comae composition reveal clues about physical and chemical conditions during the early solar system when comets formed. ROSINA (Rosetta Orbiter Spectrometer for Ion and Neutral Analysis) onboard the Rosetta spacecraft has measured the coma composition of comet 67P/Churyumov-Gerasimenko with well-sampled time resolution per rotation. Measurements were made over many comet rotation periods and a wide range of latitudes. These measurements show large fluctuations in composition in a heterogeneous coma that has diurnal and possibly seasonal variations in the major outgassing species: water, carbon monoxide, and carbon dioxide. These results indicate a complex coma-nucleus relationship where seasonal variations may be driven by temperature differences just below the comet surface. Science. See http://science.sciencemag.org/content/347/6220/aaa0276
- January 2015, BISA Team: 67P/Churyumov-Gerasimenko, a Jupiter family comet with a high D/H ratio. The provenance of water and organic compounds on 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 deuterium-to-hydrogen (D/H) ratios in the reservoirs for comets and Earth's oceans. Here, we report the direct in situ measurement of the D/H ratio in the Jupiter family comet 67P/Churyumov-Gerasimenko by the ROSINA mass spectrometer aboard the European Space Agency's Rosetta spacecraft, which is found to be

(5.3 ± 0.7) × 10-4—that is, approximately three times the terrestrial value. Science. See http://science.sciencemag.org/content/347/6220/1261952

- September 2015, DLR team: Churyumov-Gerasimenko – mystery of the 'rubber duck' shape solved. Shaped like a rubber duck – this was the talk upon the discovery of Comet 67P/Churyumov-Gerasimenko's surprising shape in July 2014. Scientists were amazed at the celestial body's extraordinary shape, which was revealed by the European Rosetta spacecraft. Nature. See http://www.nature.com/nature/journal/v526/n7573/full/nature15511.html
- July 2015, DLR Team: Thermal and mechanical properties of the near-surface layers of comet 67P/Churyumov-Gerasimenko. Thermal and mechanical material properties determine comet evolution and even solar system formation because comets are considered remnant volatile-rich planetesimals. Using data from the Multipurpose Sensors for Surface and Sub-Surface Science (MUPUS) instrument package gathered at the Philae landing site Abydos on comet 67P/Churyumov-Gerasimenko, we found the diurnal temperature to vary between 90 and 130 K. Science. See http://science.sciencemag.org/content/349/6247/aab0464
- July 2015, DLR Team: The landing(s) of Philae and inferences about comet surface mechanical properties. The Philae lander, part of the Rosetta mission to investigate comet 67P/Churyumov-Gerasimenko, was delivered to the cometary surface in November 2014. Here we report the precise circumstances of the multiple landings of Philae, including the bouncing trajectory and rebound parameters, based on engineering data in conjunction with operational instrument data. These data also provide information on the mechanical properties (strength and layering) of the comet surface. Science. See http://science.sciencemag.org/content/349/6247/aaa9816
- July 2015, DLR Team: The structure of the regolith on 67P/Churyumov-Gerasimenko from ROLIS descent imaging. The structure of the upper layer of a comet is a product of its surface activity. The Rosetta Lander Imaging System (ROLIS) on board Philae acquired close-range images of the Agilkia site during its descent onto comet 67P/Churyumov-Gerasimenko. These images reveal a photometrically uniform surface covered by regolith composed of debris and blocks ranging in size from centimeters to 5 meters. Science. See http://science.sciencemag.org/content/349/6247/aab0232
- September 2015, DLR team: The diurnal cycle of water ice on comet 67P/Churyumov-Gerasimenko. Observations of cometary nuclei have revealed a very limited amount of surface water ice, which is insufficient to explain the observed water outgassing. The paper report observations of water ice on the surface of comet 67P/Churyumov-Gerasimenko, appearing and disappearing in a cyclic pattern that follows local illumination conditions, providing a source of localized activity. This water cycle appears to be an important process in the evolution of the comet, leading to cyclical modification of the relative abundance of water ice on its surface. Nature. See http://www.nature.com/nature/journal/v525/n7570/full/nature14869.html
- October 2015, BISA Team: Abundant molecular oxygen in the coma of comet 67P/Churyumov-Gerasimenko. The composition of the neutral gas comas of most comets is dominated by H_2O, CO and CO_2, typically comprising as much as 95 per cent of the total gas density. In addition, cometary comas have been found to contain a rich array of other molecules, including sulfuric compounds and complex hydrocarbons. Here we report in situ measurement of O2 in the coma of comet 67P/Churyumov-Gerasimenko, with local abundances ranging from one per cent to ten per cent relative to H_2O and with a mean value of 3.80 +/- 0.85 per cent. Our observations indicate that the O_2/H_2O ratio is isotropic in the coma and does not change systematically with heliocentric distance. This suggests that primordial O2 was incorporated into the nucleus during the comet's formation, which is unexpected given the low upper limits from remote sensing observations. Current Solar System formation models do not predict conditions that would allow this to occur. Nature. See http://www.nature.com/nature/journal/v526/n7575/full/nature15707.html
- December 2015, DLR team: Ammoniated phyllosilicates with a likely outer Solar System origin on (1) Ceres. Studies of the dwarf planet (1) Ceres using ground-based and orbiting telescopes have concluded that its closest meteoritic analogues are the volatile-rich CI and CM carbonaceous chondrites. Water in clay minerals, ammoniated phyllosilicates, or a mixture of $Mg(OH)_2$ (brucite), Mg_2CO_3 and iron-rich serpentine have all been proposed to exist on the surface. Nature. See http://www.nature.com/nature/journal/v528/n7581/full/nature16172.html

- January 2016, DLR team: Exposed water ice on the nucleus of comet 67P/Churyumov–Gerasimenko. From the discovery of water at the surface of the comet. A comet is largely composed of water ice and water vapor predominates in its 'atmosphere' – the coma that forms as it nears the Sun. However, very few examples of water ice have previously been observed on the surface of a comet. Now, scientists using the Visible and Infrared Thermal Imaging Spectrometer (VIRTIS) instrument carried by the Rosetta spacecraft have detected water ice on two areas of the surface of Comet 67P/Churyumov-Gerasimenko. Nature. See http://www.nature.com/nature/journal/v529/n7586/full/nature16190.html

5.12. Exhibitions

One of the Planet TOPERS, BISA, has organized two exhibitions in Redu, one on Rosetta (launched with a press event on 27 February 2014) and one on ExoMars (launched with a press event on 10 March 2014). They were announced to the general public by press releases and press conferences were organized.

Another member of Planet TOPERS, ULg, was member of scientific committee for the public exhibition "Darwin" at La Villette, Paris, Dec. 2015-August 2016 (commissaire: G. Lecointre).

ULg was also co-author of the COST ORIGINS travelling exhibition "river of time".

5.13. Booklet

- Dehant V., 2012, "Habiter sur Mars ?", livre de l'Académie en Poche, Ed. Académie royale de Belgique, 96 pages.
- Dehant V., 2015, "Habiter sur une lune du système solaire ?", de l'Académie en Poche, Ed. Académie royale de Belgique, 141 pages.

5.14. Encyclopedia

Planet TOPERS have contributed to the Encyclopedia of Astrobiology, 2nd Edition Springer, by Gargaud M, Amils R, Cernichicaro Quintanilla J, Cleaves HJ, Irvine WM, Pinti D, Rouan D, Spohn T, Tirard S, Viso M (Chief Eds.), Albarede F, Arndt N, Javaux EJ, Prantzos N, Stahler S, Raymond S, Ehrenfreund P, Charnley S, Encrenaz T, DW Latham, Kaltenegger L, Kobayashi K, Horneck G, Bersini H, Gomez F (Eds.), 2550 p. (2015):

- Gargaud M, Albarede F, Arndt N, Cleaves K, Gounelle M, Javaux EJ, Pinti D, Raymons S, 2015. Chronological history of life on Earth. In Gargaud et al, 2015. Encyclopedia of Astrobiology, 2nd Edition Springer.
- Javaux E.J., 2014 Acid maceration, in Gargaud et al., Encyclopedia of Astrobiology Springer 1p
- Javaux E.J., 2015. Acritarchs, in Gargaud et al., Encyclopedia of Astrobiology Springer 2p
- Javaux E.J., 2015. Amoebae, in Gargaud et al., Encyclopedia of Astrobiology Springer 1p
- Javaux E.J., 2015. Appearance and early evolution of eukaryotes, in Gargaud et al., Encyclopedia of Astrobiology Springer 3p
- Javaux E.J., 2015. Acid maceration, In Gargaud et al, 2015. Encyclopedia of Astrobiology, 2nd Edition Springer 1p
- Javaux E.J., 2015. Belcher Group Microfossils, in Gargaud et al., Encyclopedia of Astrobiology Springer 1p
- Javaux E.J., 2015. Biomarkers, biosignatures, traces of life in Gargaud et al., Encyclopedia of Astrobiology Springer 2p
- Javaux E.J., 2015. Bitumen, in Gargaud et al., Encyclopedia of Astrobiology Springer 1p
- Claeys Ph., 2015. Chicxulub crater, in Gargaud et al., Encyclopedia of Astrobiology Springer 2p
- Javaux E.J., 2015. Dubiofossil, in Gargaud et al., Encyclopedia of Astrobiology Springer 1p
- Spohn T., 2015. Dynamo, in Gargaud et al., Encyclopedia of Astrobiology Springer 4p
- Javaux E.J., 2015. Fossil, in Gargaud et al., Encyclopedia of Astrobiology Springer 1p
- Javaux E.J., 2015. Gunflint microbiota, in Gargaud et al., Encyclopedia of Astrobiology Springer 4p
- Spohn T., 2015. Heat Flow, in Gargaud et al., Encyclopedia of Astrobiology Springer 3p

- Claeys Ph., 2015. Impact melt-rock, in Gargaud et al., Encyclopedia of Astrobiology Springer 1p
- Claeys Ph., 2015. Impactite, in Gargaud et al., Encyclopedia of Astrobiology Springer 1p
- Spohn T., 2015. Interior structure, in Gargaud et al., Encyclopedia of Astrobiology Springer 7p
- Claeys Ph., 2015. Iridium, in Gargaud et al., Encyclopedia of Astrobiology Springer 1p
- Javaux E.J., 2015. Kerogen, in Gargaud et al., Encyclopedia of Astrobiology Springer 1p
- Claeys Ph., 2015. KT Boundary, in Gargaud et al., Encyclopedia of Astrobiology Springer 2p
- Claeys Ph., and Morbidelli A., 2015. Late Heavy Bombardment, in Gargaud et al., Encyclopedia of Astrobiology Springer 1p
- Javaux E.J., 2015. Microfossils, in Gargaud et al., Encyclopedia of Astrobiology Springer 2p
- Jaumann R., 2015. The Moon, in Gargaud et al., Encyclopedia of Astrobiology Springer 3p
- Javaux E.J., 2015. Morphological Biomarkers, in Gargaud et al., Encyclopedia of Astrobiology Springer 5p
- De Vera J.P., 2015. Panspermia, in Gargaud et al., Encyclopedia of Astrobiology Springer 3p
- Javaux E.J., 2015. Pseudofossil, in Gargaud et al., Encyclopedia of Astrobiology Springer 1p
- Stamenković V., Sohl F., 2015. Rheology of planetary interiors, in Gargaud et al., Encyclopedia of Astrobiology Springer 3p
- Stamenković V., 2015. Serpentinization, in Gargaud et al., Encyclopedia of Astrobiology Springer 2p.
- Claeys Ph., 2015. Shocked Quartz, in Gargaud et al., Encyclopedia of Astrobiology Springer 1p
- Spohn T., 2015. Tides, in Gargaud et al., Encyclopedia of Astrobiology Springer 7p
- Claeys Ph., 2015. Tektites, in Gargaud et al., Encyclopedia of Astrobiology Springer 1p
- Javaux E.J., 2015. Ultrastructure, in Gargaud et al., Encyclopedia of Astrobiology Springer 1p

We also contributed to the Encyclopedia of the Solar System, by Eds. Tilman Spohn, Doris Breuer, and Torrence V. Johnson, 2014, 1336 p, Elsevier Inc., 3d edition, DOI: 0.1016/B978-0-12-415845-0.00018- 9.

- Dehant V., and Van Hoolst T., 2014, “Rotation of terrestrial planets.”, in: Encyclopedia of the Solar System, Chapter 8, pp. 159-184.
- Tosi N., Breuer D., and Spohn T., 2014, “Evolution of Planetary Interiors.”, in: Encyclopedia of the Solar System, Chapter 9, pp. 185-208.
- Van Hoolst T., and Rivoldini A., 2014, “Interior Structure and Evolution of Mars.”, in: Encyclopedia of the Solar System, Chapter 18, pp. 379-396.
- Hiesinger H., and Jaumann R., 2014, “The Moon.”, in: Encyclopedia of the Solar System, Chapter 18, pp. 493-538.
- Banerdt B., Dehant V., Grimm R., Grott M., Lognonné P., and Smrekar S., 2014, “Probing the Interiors of Planets with Geophysical Tools.”, in: Encyclopedia of the Solar System, chapter 55, pp. 1185-1204.
- Oberst J., Gwinner K., and Preusker F., 2014, “Exploration and Analysis of Planetary Shape and Topography using Stereogrammetry.”, in: Encyclopedia of the Solar System, chapter 55, pp. 1223-1234.

We also contributed to the Treatise on Geophysics, by Ed. Gerald Schubert, Elsevier Inc., 2nd edition, 5604 p, ISBN: 9780444538024.

- Dehant V., and Mathews P.M., 2015, “Earth Rotation Variations.”, Treatise on Geophysics, Volume 3 (Ed. T. Herring): Geodesy, Section 3.10.
- Spohn T., 2015, “Physics of Terrestrial Planets and Moons: An Introduction and Overview.”, Treatise on Geophysics, Volume 10 (Ed. T. Spohn): Planets and Moons, Section 10.01, pp. 1-22.
- Sohl F., and Schubert G., 2015, “Interior Structure, Composition, and Mineralogy of the Terrestrial Planets.”, Treatise on Geophysics, Volume 10 (Ed. T. Spohn): Planets and Moons, Section 10.02, pp. 23-64.
- Van Hoolst T., 2015, “The rotation of the terrestrial planets.”, Treatise on Geophysics, Volume 10 (Ed. T. Spohn): Planets and Moons, Section 10.04, pp. 121-151.

- Breuer D., and Moore W.B., 2015, "Dynamics and Thermal History of the Terrestrial Planets, the Moon, and Io.", Treatise on Geophysics, Volume 10 (Ed. T. Spohn): Planets and Moons, Section 10.08, pp. 255-305.
- Helbert J., Hauber E., and Reiss D., 2015, "Water on the Terrestrial Planets.", Treatise on Geophysics, Volume 10 (Ed. T. Spohn): Planets and Moons, Section 10.11, pp. 367-409.
- Southam G., Westall F., and Spohn T., 2015, "Geology, Life, and Habitability.", Treatise on Geophysics, Volume 10 (Ed. T. Spohn): Planets and Moons, Section 10.14, pp. 473-486.
- Hussmann H., Sotin C., and Lunine J.I., 2015, "Interiors and Evolution of Icy Satellites.", Treatise on Geophysics, Volume 10 (Ed. T. Spohn): Planets and Moons, Section 10.18, pp. 605-635.

5.15. Patents

UGent patent application PCT/EP2015/07 1525, based on EP14185463.8 for an ultrafast ablation chamber.

5.16. Involvement in societal issues

We have been involved in some discussions concerning the women in science:

- Javaux E.J., 2012, "How did I become a scientist. Green light for Girls.", Mol, Belgium – 20 November 2012.
- Dehant V., 2014, "`Challenges and opportunities for women leadership in Europe and USA: View of a Scientific Researcher.", Speech for the joint meeting of Women in Aerospace WIA-Europe and the International Aviation Women Association IAWA, November 6, 2014.

We (V. Debaille and V. Dehant) have been involved in the ASBL "Cles pour l'Univers" http://www.astro.ulb.ac.be/~cplu/accueil-fr.html ("Keys to the Universe", association) of which the objectives are to bring scientific culture elements in places where the usual communication channels happen only rarely: children hospitals, deaf and dumb homes, prisons etc. These professional scientists commit to share their knowledge to this specific audience and already have teaching experience for non-specialists and of all ages. The emotional charge contained in these talks are tremendous.

We have also participated in debate related to philosophical, societal, and political issues:

- Dehant V., « Intervention au Sénat – La recherche au niveau fédéral », Senate debate on « Quel avenir pour la recherche scientifique en Belgique », 3 March 2015.
- Claeys Ph., « How to keep your feet dry in Brussels? », Nuit du Savoir sur Bruxelles - Nacht van de Kennis over Brussel, 21 November 2013.
- Claeys Ph., 2016, "Wetenschappen en technologie: de toekomst, jouw toekomst! – Science et technologie: le future, votre future !", Invited speaker at Science and technology day organized for high school students by the Comité National de Chimie/Nationaal Comité Chemie and the Solvay group on the Solvay Campus in Brussels, April 16, 2016.

Debates on the origin of life, and TV or radio interviews are reported in Sections 5.17 and 5.5-5.9.

5.17. General public conferences

We have dedicated time to public conferences and in particular were organizing or were invited to give lectures at the prestigious Collège de France or Collège Belgique (these conferences are highlighted in the list below).

- Van der Auwera J. and Dehant V., "Compréhension de l'évolution des planètes telluriques par la minéralogie.", Cours **Collège Belgique**, Académie des Sciences, Palais des Académies, 25 September 2012.
- Dehant V. and Bibring J.P., "Histoire de Mars révélée par les satellites artificiels.", Cours **Collège Belgique**, Académie des Sciences, Palais des Académies, 25 September 2012.
- Sohl F., 2012, "Mars - Ziel der Raumfahrt (Mars - a space flight target).", Planetarium of the Observatory of Schwerin, Further Education College "Ehm Welk", Schwerin, Germany – 5 October 2012.

- Sohl F., 2012, "Die Suche nach der zweiten Erde (The search for a second Earth).", Planetarium of the Observatory of Schwerin, Further Education College "Ehm Welk", Schwerin, Germany – 6 October 2012.
- Sohl F., 2013, “Rocky Exoplanets.”, Colloquium of the field of geosciences, Berlin, Germany – 7 February 2013.
- Wilquet V. Vandaele and A.C., 2013, "Passage de Vénus en 2012 : des cythérographes à Venus Express.", Soc. Royale d’Astronomie, de météorologie et de Physique du Globe, Brussels – 14 February 2013.
- Sohl F., 2013, “Solid exoplanets.”, MExLab Student Seminar, MIIGAiK Extraterrestrial Laboratory (MExLab), Moscow, Russia – 4. March 2013.
- Jehin E., Javaux E.J., Magain P., Gillon M., 2013, "L’eau dans l’univers.", Grande conférence Liégeoise. Verviers – 26 March 2013.
- Dehant V., 2013, “Rotation de la Terre et des planètes.”, Cours au **Collège de France** dans le cadre de la Chaire "Développement durable Environnement, énergie et société", du Prof. Anny Cazenave – 8 April 2013.
- Dehant V., 2013, “Habiter sur Mars ?”, Conférence organisée par le Kot Astro – 24 April 2013.
- Vandaele A.C., 2013, “Exploring Venus.”, organized by the Royal Society of Chemistry, Brussels – 26 November 2013.
- De Winne Frank, Dehant V., Willame Y., and Wilquet V., 2013, “Mars uncovered.”, event-debate at the Planetarium of the Royal Observatory of Belgium, session of questions and answers with in the frame of the World Space Week 2013 – 4 October 2013.
- Claeys Ph., « How to keep your feet dry in Brussels? », Nuit du Savoir sur Bruxelles - Nacht van de Kennis over Brussel, 21 November 2013.
- Rückriemen T., D. Breuer and T. Spohn, 2013, “Key characteristics of the iron snow regime in Ganymede's core.”, MExLab Student Seminar, MIIGAiK Extraterrestrial Laboratory (MExLab), Moscow, Russia – 4 March 2013.
- Debaille V., 2013, "Météorites en Antarctique : archive de notre système solaire.", Maison communale de Tourinnes-La-Grosse – 7 novembre 2013.
- Debaille V., 2013, "Sciences en Antarctique", Institut Sainte Marie d’Arlon – 6 December 2013
- Claeys Ph., Series of lecture for high potential (IQ > 130) secondary school students in Flanders: Brightspark: "Planeet Aarde 4.5 miljard jaar voortdurend in verandering" organised by VZW BEKINA (www.bekina.org). (1) Hoe het begon? – 2 October 2013; (2) T-Rex vs. Meteoriet – 16 October 2013; (3) Klimaatverandering in stalagmieten – 6 November 2013; (4) Poster maken en diploma-uitreiking – 16 January 2014.
- Debaille V., 2013, "Sciences en Antarctique", Institut Sainte Marie d’Arlon, 6 December 2013.
- De Keyser J., "Les comètes, Rosetta, et l'Institut d'Aéronomie Spatiale de Belgique.", Presentation given at the press conference on the inauguration of a special Rosetta exhibit at the Euro Space Center, Redu, Belgium, 27 February 2014.
- Javaux EJ, “Des nouvelles de la planète Mars.”, Université du 3ème âge, ULg, 27 February 2014.
- Javaux EJ, “Des nouvelles de la planète Mars." Chênée, AGAB. 7 March 2014.
- Javaux EJ, “A la recherche des premières traces de vie Université de Liège, 12 March 2014. (WEBTV)
- Dehant V., 2014, “Planètes ou lunes habitables dans le système solaire.”, conference for Connaissance et Vie, Namur, 11 March 2014.
- Jehin E., Javaux E.J., Magain P., Gillon M., "L’eau dans l’univers.", Grande conférence Liégeoise, Verviers, 26 March 2014.
- Aerts C., and Dehant V., 2014, “Planètes Habitables dans notre Système Solaire et dans la Galaxie : connection avec l’Astérosismologie ? / Leefbare planeten in ons Zonnestelsel en in de Melkweg: Verband met Asteroseismologie?", conference for Fondations Universitaires, March 31, 2014.
- Dehant V., 2014, “Mars est-elle une planète habitable ? L'a-t-elle été ? Y a-t-il d'autres planètes ou lunes habitables ?”, conference for Association des Anciens Saint-Boniface-Parnasse, May 15, 2014.

- De Keyser J., Presentation to secondary school groups of the Rosetta exhibit for the Open Doors of the Space Pole, Brussels, 10 October 2014.
- Debaille V., la conquête de la Lune, in the frame of the exhibition “Tous vers la Lune avec Tania” http://www.expolune.be/ à Parentville 11 October 2014.
- De Keyser J., Dhooghe F., and Maggiolo R., “Een komeet ontdekken met Rosetta.”, Public lecture during the Open Doors of the Space Pole, Brussels, 11-12 October 2014.
- Gillmann C., “Pourquoi Vénus est-elle si différente de la Terre ?”, Public lecture during the Open Doors of the Space Pole, Brussels, 11-12 October 2014.
- Dehant V., 2014, “Planètes ou lunes habitables dans le système solaire.”, conference for the Rotary Club, Namur, 27 October 2014.
- Javaux E. and López-Garcia P., Conférence au **Collège Belgique** “Origine et évolution des eucaryotes (1/2) : Origine et diversité des eucaryotes.", 21 October 2014.
- Javaux E. and Baurain D., Conférence au **Collège Belgique** “Origine et évolution des eucaryotes : Évolution des eucaryotes : l’éclairage de la phylogénie moléculaire et de la paléobiogéologie (2/2)", 23 October 2014.
- Dehant V., “Évolution et habitabilité du système solaire. (1/2)", Cours **Collège Belgique**, Académie des Sciences, Palais des Académies, 4 November 2014.
- Morbidelli A., “Évolution et habitabilité du système solaire. (2/2)", Cours **Collège Belgique**, Académie des Sciences, Palais des Académies, 4 November 2014.
- Debaille V., “Tectonique des plaques dans le système solaire : implications pour l’évolution de la Terre et pour l’origine et la diversification de la vie. (1/2)", Cours **Collège Belgique**, Académie des Sciences, Palais des Académies, 13 November 2014.
- Javaux E., “Tectonique des plaques dans le système solaire : implications pour l’évolution de la Terre et pour l’origine et la diversification de la vie. (2/2)", Cours **Collège Belgique**, Académie des Sciences, Palais des Académies, 13 November 2014.
- Van Grootel V., “Habitabilité et détection des exoplanètes. (1/2)", Cours **Collège Belgique**, Académie des Sciences, Palais des Académies, 18 November 2014.
- Libert A.S., “Habitabilité et détection des exoplanètes. (2/2)", Cours **Collège Belgique**, Académie des Sciences, Palais des Académies, 18 November 2014.
- De Keyser J., Dhooghe F., Maggiolo R., “Rosetta at the Belgian Institute for Space Aeronomy.”, Presentation during the Philae landing event organized by ESERO Belgium and University of Ghent, 12 November 2014.
- Dehant V., 2014, “`Challenges and opportunities for women leadership in Europe and USA: View of a Scientific Researcher.", Speech for the joint meeting of Women in Aerospace WIA-Europe and the International Aviation Women Association IAWA, November 6, 2014.
- Debaille V., “History of Belgian meteorites and history of meteorites in Belgium”, national Symposium organized in the frame of the Belspo BELAM project, 14 November 2014.
- Javaux E., "Pause-café" with Emmanuelle Javaux, Le lungo, December 2014.
- Dehant V., 2014, “Mars est-elle une planète habitable ? L'a-t-elle été ? Y a-t-il d'autres planètes ou lunes habitables ?”, conference for Association des Anciens Saint-Boniface-Parnasse, May 15, 2014.
- De Keyser J., Presentation to secondary school groups of the Rosetta exhibit for the Open Doors of the Space Pole, Brussels, 10 October 2014.
- Debaille V., la conquête de la Lune, in the frame of the exhibition “Tous vers la Lune avec Tania” http://www.expolune.be/ à Parentville 11 October 2014.
- De Keyser J., Dhooghe F., and Maggiolo R., “Een komeet ontdekken met Rosetta.”, Public lecture during the Open Doors of the Space Pole, Brussels, 11-12 October 2014.
- Debaille V., “Météorites en Antarctique”, école primaire Notre Dame des Champs, Uccle, October 2014.
- Javaux E., Conférence au **Collège Belgique** “Origine et évolution des eucaryotes : informations du registre fossile“, October 2014.
- Dehant V., 2014, “Planètes ou lunes habitables dans le système solaire.”, conference for the Rotary Club, Namur, 27 October 2014.

- De Keyser J., Dhooghe F., Maggiolo R., “Rosetta at the Belgian Institute for Space Aeronomy.”, Presentation during the Philae landing event organized by ESERO Belgium and University of Ghent, 12 November 2014.
- Debaille V., 2014, « La conquête de la Lune », conference in the frame of the exhibition « Tous à la conquête de la Lune », ULB-Parentville, November 10, 2014.
- Debaille V., “History of Belgian meteorites and history of meteorites in Belgium”, national Symposium organized in the frame of the Belspo BELAM project, 14 November 2014.
- Yseboodt M., and Van Hoolst T., 2014, “The long-period librations of large synchronous icy moons.”, Seminary 2014-2015 on “Structure and Dynamics of Earth-like Planets”, organized by B. Romanowicz, Chaire ‘Physique de l’intérieur de la Terre’, **Collège de France**, Paris, November 20-21, 2014.
- Rivoldini A., Van Hoolst T., and Noack L., 2014, “Insights into Mercury's interior structure from geodesy measurements and global contraction.”, Seminary 2014-2015 on “Structure and Dynamics of Earth-like Planets”, organized by B. Romanowicz, Chaire ‘Physique de l’intérieur de la Terre’, **Collège de France**, Paris, November 20-21, 2014.
- Dehant V., and Van Hoolst T., 2014, “Rotation and interior of terrestrial planets.”, Seminary 2014-2015 on “Structure and Dynamics of Earth-like Planets”, organized by B. Romanowicz, Chaire ‘Physique de l’intérieur de la Terre’, **Collège de France**, Paris, November 20-21, 2014.
- De Keyser J., 2015, “Rosetta et la comète Churyumov-Gerasimenko", Public lecture for the Cercle d'Astronomes Amateurs du Pays de Charleroi, Couillet, January 16, 2015.
- Rosenblatt P., 2015, “Les lunes de Mars : Phobos et Deimos.”, 24 heures Basiliennes d'Astronomie 2015, Baisieux, France, January 24, 2015.
- De Keyser J., 2015, “Rosetta en Philae op ontdekkingsreis naar een komeet.”, Public presentation organized by Mercator vzw en Bibliotheek Temse, Temse, Belgium, January 17, 2015.
- De Keyser J., 2015, “Komeetonderzoek met Rosetta: België is aan boord!”, Public lecture at Volkssterrenwacht MIRA vzw, Grimbergen, Belgium, February 14, 2015.
- De Keyser J. and Jehin E., 2015, “Rosetta et la science des comètes.", Public presentation in the frame of the **Collège Belgique** course on "Objets gelés du Système Solaire : Comètes et Lunes", Academy Palace, Brussels, 24 February 2015.
- Coustenis A., and Dehant V., 2015, “Les lunes de glace dans notre système solaire.", Public presentation in the frame of the **Collège Belgique** course on "Objets gelés du Système Solaire : Comètes et Lunes". Academy Palace, Brussels, March 26, 2015.
- Debaille V., 2015, Séance de questions avec Hubert Reeves, Foire du livre, March 2, 2015.
- De Keyser J., 2015, "Comet Catcher: The Rosetta Landing", invited presentation, commentary, and panel member regarding the movie at the Festival du Film Scientifique de Bruxelles, Université Libre de Bruxelles, Brussels, Belgium, March 23, 2015.
- Debaille V., 2015, « Météorites en Antarctique : archives de notre système solaire », Extension de l’ULB, Nivelles, March 27, 2015.
- De Keyser J., Dhooghe F., Maggiolo R., Gunell H., Cessateur G., and Gibbons A., 2015, “Chasing a comet with Rosetta.”, Presentation during the Asgard 2015 event, Space Pole, Brussels, April 23, 2015.
- De Keyser J., Dhooghe F., Gibbons A., Lefever K., and Mestdagh P., 2015, “Organization of an event on Comets, Rosetta and Mass-Spectrometry.”, in the frame of an ESERO Rosetta-event for students of Sint-Niklaas-Instituut (Anderlecht) and Sint-Barbara Instituut (Gent), BISA, Brussels, May 7, 2015.
- De Keyser J., Dhooghe F., Gibbons A., Cessateur G., Maggiolo R., and Gunell H., 2015, “Komeetonderzoek met massa-spectroscopie op Rosetta.”, Presentatie tijdens studiebezoek van de Universiteit Twente, BISA, Brussels, May 20, 2015.
- Dehant V., 2015, “Habiter sur une lune du système solaire ?", Public presentation in the frame of the **Collège Belgique,** Academy Palace, Brussels, October 1, 2015.
- Debaille V., 2015, “Météorites en Antarctique.”, conference in école primaire Notre Dame des Champs, Uccle, October 16, 2015.

- De Keyser J., 2015, “Komeetonderzoek met Rosetta: België is aan boord!”, Public presentation organized by Markante Dialogen vzw, Vormingscentrum Ghuislain, Gent, Belgium, November 9, 2015.
- Claeys Ph., 2015, « Évolution de la biogéosphère : l’origine de l’eau sur Terre », CEPULB, Centre Education Permanente de l’Université Libre de Bruxelles, Brussels, October 12, 2015.
- Javaux E.J., 2015, « qu’est-ce qu’une planète ou lune habitable ? », SAL, Liège, May 30, 2015.
- Dehant V., 2016, “ExoMars LaRa for understanding the habitability, interior and rotation of Mars.”, Conference at Space Tech, Brussels, April 29, 2016.
- Javaux E.J., 2015, « La vie ailleurs ? », conférence pour professeurs de secondaire, 53eme congrès des professeurs de science, ULg, Liège, August 25-27, 2015.
- Vandaele A.C., 2015, « Exomars : la future mission de l'ESA vers Mars. », Extension de l’ULB, Nivelles, Sept. 17, 2015.
- Vandaele A.C., 2015, « Pleidooi voor Mars » Gesprekavond – World Space Week, Expert in the Panel, Volkssterrenwacht Armand Pien, Ghent, Oct. 7, 2015.
- Gillmann C., 2016 “Le point sur Vénus et son évolution” Cercle d'Astronomes du Pays de Charleroi.

Each year Planet TOPERS participates in the “Printemps des Sciences” at UCL, ULB, ULg for instance.

Publicity have been done through the website, the newsletters, and emails to schools, astronomer associations, using most email lists that are available to the Consortium such as the planetarium email list, the Royal Academy of Belgium etc.

5.18. Website

Our website http://iuap-planet-topers.oma.be/ is also used as a window into our work and our group. Details are provided in Sections 3.1.8 and 3.3.3.

Links to other interesting websites are also given there (http://iuap-planet-topers.oma.be/useful_links.php).

5.19. PhD and postdoc training

In the table below we present the PhD students and the dates of the PhD defense. Several of them have PhD thesis directed in conjunction with two institutes. Those identified in bold were directly paid by the IAP. Those not in bold are contributing to the IAP.

Main institute	Secondary institute	Students (in bold those financed or partly financed by IUAP)	Date of PhD
ROB		**Sébastien Le Maistre**	2012
ROB		**Lê Binh San Pham**	2013
ROB		Antony Trinh	Expected 2016 or 2017
ROB		Bart Van Hove	Expected 2016 or 2017
ROB		Nicolas Gerbal	Expected 2019
ROB		Alexis Coyette	Expected 2018
ROB	BISA	**Elodie Gloesener**	Expected 2016 or 2017
ROB		Marie-Julie Péters	Expected 2019
ROB		Marie-Hélène Deproost	Expected 2019
VUB		Kevin De Bondt	Expected 2016
VUB		Rémy Mas	Out
VUB		Christina Makarona	Expected 2016
VUB		**Maité Van Rampelbergh**	2014
VUB		**David De Vleeschouwer**	2014

VUB	UGent	**Joke Belza**	2015
VUB	ULB	**Claudio Ventura**	Out
VUB		Niels De Winter	Expected 2018
VUB		Stef Vansteenberge	Expected 2018
VUB		Matthias Sinnesael	Expected 2019
VUB		Tom Goosse	Out
VUB		**Bastien Soens**	Expected 2019
ULB		Claire Duchemin	Out
ULB		**Geneviève Hublet**	2015
ULB		**Maria Valdes**	Expected 2018
ULB	VUB	**Nadia Van Roosbroek**	2015
ULg		**Jeremie Beghin**	Expected 2017
ULg		**Luc Cornet**	Expected 2017
ULg		Blaise Kabamba Baludikay	Expected 2017
ULg		Yohan Cornet	Expected 2018
UGent	VUB	**Stepan Chernonozhkin**	Expected 2016
UGent		Stijn Van Malderen	Expected 2017
UGent		**Thibaut Van Acker**	Expected 2019
UGent		Jefferson Santos de Gois	2016
BISA		Yannick Willame	Expected 2016
BISA		Loïc Trompet	Expected 2019
BISA		Arnaud Mahieux	2012
BISA		**Lukas Maes**	Expected 2016
BISA		Yannick Willame	2015
DLR		Achim Morschhauser	Expected 2016
DLR		Matthieu Laneuville	2013
DLR		Frank Walter Wagner	2014
DLR		Wladimir Neumann	2014
DLR	ROB	**Ana-Catalina Plesa**	2014
DLR		Tina Rückriemen	Expected 2016 or 2017
DLR		Dennis Höning	Expected 2016
DLR		Maxime Maurice	Expected 2018
DLR		Athanasia Nikolaou	Expected 2018

There were efforts of the network for the careers of the PhD and postdocs and first, we give here some training success stories (among others):

- Lara Lobo-Revilla (UGent) joined the A&MS group at UGent with a Marie Curie fellowship, focusing on the development of novel methods for provenance of ancient glass based on isotopic analysis of the metals it contains. Her stay at the UGent - A&MS group was extended via financing from the IUAP project. She then focused on isotopic analysis in the context of cosmochemistry and a systematic evaluation of a novel type of ICP-MS instrumentation (Mattauch-Herzog ICP-MS). Currently, Lara is Clarín Postdoctoral researcher at the University of Oviedo (Spain). For some projects, there is still a close collaboration with A&MS-UGent. Lara's body of work was awarded with the first JAAS (Journal of Analytical Atomic Spectrometry) Emerging Investigator Lectureship by the Royal Society of Chemistry (RSC).

- At ULg, Camille François came from France and is financed by IAP and Dan Asael (came from Israel), Jean-Yves Storme (Belgium) were financed by ERC StG ELITE. Dan Asael has now a permanent position in Yale University as researcher and J.Y. Storme has a permanent job in a federal office in Brussels. Camille François is still with us.
- Dr. Steven Goderis was promoted to professor (10%) within the Chemistry Dept. at the VUB.

Lena Noack (ROB) is the Young Scientists Representative in our Steering Committee. She organizes get-together events for the early career scientists, she distributes to them the information concerning schools, meetings, opportunities. She is as well the Early-Career Scientists Representative of EGU and involved in the Astrobiology Graduates in Europe (AbGradE) association (see http://eana-net.eu/AbGradE/about.html). More information on AbGradE are provided in Sections 3.3.4 and 4.1.1.2.

EANA and other organizations do produce on their website conferences available for the young scientists. Through the ABC-Net lecture courses, a live teleteaching program is available on the web; it was performed by EANA in cooperation with ESA, interconnecting several European universities (see http://eana-net.eu/education.html).

Network-driven activities for PhD students and postdocs are described in Section 3.3.4 and possible training schools were our PhD students and postdocs could participate in Section 3.2.9.

In addition, our lectures at the different universities were open to all the IAP PhD students and postdocs.

5.20. Young emerging research teams (if applicable)

The young emerging teams (ULB, ULg, and BISA – as identified in the proposal in 2012) of the network have been fully integrated in the network and have contributed to the results of the IAP. Their success can be measured as ULB – Vinciane Debaille – and ULg – Emmanuelle Javaux – have obtained an ERC Grant; and BISA – Ann Carine Vandaele became Principal Investigator of the NOMAD instrument on ExoMars.

ANNEX 1: Recent publication list

The list of the recent publications related to the IAP-project (not included in the activity reports of the first three years) is shown below. The complete list of publications is on our website:

http://iuap-planet-topers.oma.be/publications.php

List of publications from each team (between November 2015 and May 2016)

ROB

PEER REVIEWED

Baland, R.-M., Yseboodt, M., and Van Hoolst, T., 2016, “The obliquity of Enceladus”, Icarus, 268, pp. 12-31, DOI: 0.1016/j.icarus.2015.11.039.

Beuthe, M., 2015, “Tides on Europa: The membrane paradigm.”, Icarus, 248, pp. 109-134, DOI: 10.1016/j.icarus.2014.10.027.

Cadeck, O., Tobie, G., Van Hoolst, T., Choblet, G., Massé, M., Mitri, G., Lefèvre, A., Behounkova, M., Bourgeois, O., Baland, R.-M., Trinh, A., 2016, “Enceladus’s internal ocean and ice shell constrained from Cassini gravity, shape and libration data”, Geophys. Res. Lett., in press.

Cockell, C.S., Bush, T., Bryce, C., Direito, S., Fox-Powell, M., Harrison, J.P., Lammer, H., Landenmark, H., Martin-Torres, J., Nicholson, N., Noack, L., O'Malley-James, J., Payler, S.J., Rushby, A., Samuels, T., Schwendner, P., Wadsworth, J., and Zorzano, M.P., 2016, “Habitability: A Review”, Astrobiology, 16(1), pp. 89-117.

Coyette, A., Van Hoolst T., Baland R.M., and Tokano T., 2016, “Modeling the polar motion of Titan”, Icarus 265, pp. 1-28, DOI: 0.1016/j.icarus.2015.10.015.

Dehant V., Baludikay B.K., Beghin J., Breuer D., Claeys Ph., Cornet Y., Cornet L., Debaille V., De Keyser J., El Atrassi F., François C., Gillmann C., Gloesener E., Goderis S., Hidaka Y., Höning D., Javaux E., Karatekin Ö., Maes L., Maurice M., Mattielli N., McKibbin S., Neumann W., Noack L., Pittarello L., Plesa A.C., Robert S., Spohn T., Storme J.-Y., Valdes M., Vandaele A.C., Vanhaecke F., Van Hoolst T., Wilquet V., and the PLANET TOPERS group (see http://iuap-planet-topers.oma.be/partners.php), 2016, “PLANET TOPERS: Planets, Tracing the Transfer, Origin, Preservation, and Evolution of their ReservoirS.”, COST Life-Origins (TD1308) meeting on ‘Missions to Habitable Worlds’, Budapest, Hungary, 28-29 October, 2015, OLEB, in press.

Domagal-Goldman, S.D., K.E. Wright, K. Adamala, M. Antonio, L.A. de la Rubia, J. Bond, L. Dartnell, A. Goldman, I. Lima, K. Lynch, M.-E. Naud, K. Singer, X. Abrevaya, R. Anderson, G. Arney, D. Atri, A. Azua-Bustos, J. Bowman, W. Brazelton, G. Brennecka, R. Carns, A. Chopra, J. Colangelo-Lillis, C. Crockett, J. DeMarines, E. Frank, C. Frantz, E. de la Fuente, D. Galante, J. Glass, D. Gleeson, C. Glein, C. Goldblatt, R. Horak, L. Horodyskyj, B. Kacar, A. Kereszturi, E. Knowles, P. Mayeur, S. McGlynn, Y. Miguel, M. Montgomery, C. Neish, L. Noack, S. Rugheimer, E. Stueken, P. Tamez-Hidalgo, S.I. Walker, 2016, “Astrobiology Primer 2.0”, Astrobiology, accepted.

Dumberry M., and Rivoldini A., 2015, “Mercury’s inner core size and core-crystallisation regime.”, Icarus, 248(3), pp. 254-268, DOI: 10.1016/j.icarus.2014.10.038.

Gillmann C., Golabek G.J., and Tackley P.J., 2016, “Effect of a single large impact on the coupled atmosphere-interior evolution of Venus.”, Icarus, 268, pp. 295-312, DOI: 10.1016/j.icarus.2015.12.024.

Grebowsky J., Fast K., Talaat E., Combi M., Crary F., England S., Ma Y., Mendillo M., Rosenblatt P., Seki K., Stevens M., and Withers P., 2015, “Science Enhancements by the MAVEN Participating Scientists.”, Space Science Reviews, Vol. 195, issue 1-4, pp. 319-355, 2015.

Kereszturi, A. and Noack, L., 2016, “Review on the role of planetary factors on habitability”, Origins of Life and Evolution of Biospheres, accepted.

Le Gall A., Malaska M. J., Lorenz R. D., Janssen M. A., Tokano T., Hayes A. G., Mastrogiuseppe M., Lunine J. I., Veyssière G., Encrenaz P., Karatekin Ö., 2016, "Composition, seasonal change, and bathymetry of Ligeia Mare, Titan, derived from its microwave thermal emission.", Journal of Geophysical Research: Planets, 121(2), pp. 233-251, DOI: 10.1002/2015JE004920

Noack, L., Rivoldini A., and Van Hoolst T., 2016, "CHIC - Coupling Habitability, Interior and Crust: A new Code for Modeling the Thermal Evolution of Planets and Moons", International Journal On Advances in Systems and Measurements, accepted.

Pham L.B.S., and Karatekin Ö., 2016, "Scenarios of atmospheric mass evolution on Mars influenced by asteroid and comet impacts since the late Noachian.", Planetary and Space Science, 125, pp. 1-11, DOI: 0.1016/j.pss.2015.09.022.

Van Hoolst T., 2015, "The rotation of the terrestrial planets.", Treatise on Geophysics, Vol.10: Planets and Moons, 2nd edition, Ed. Gerald Schubert, Section 10.04, ISBN: 9780444538024.

Vincent D., Karatekin Ö., Vallaeys V., Hayes A.G., Mastrogiuseppe M., Notarnicola C., Dehant V., and Deleersnijder E., 2016, "Numerical study of tides in Ontario Lacus, a hydrocarbon lake on the surface of the Saturnian moon Titan.", Ocean Dynamics, DOI: 10.1007/s10236-016-0926-2.

BOOK

Dehant V. and Mathews P.M., 2015, "Precession, Nutation, and Wobble of the Earth.", Cambridge University Press, ISBN: 9781107092549, 536 pages, See www.cambridge.org/9781107092549.

Dehant V., 2015, "Habiter sur une lune du système solaire ?", de l'Académie en Poche, Ed. Académie royale de Belgique, 141 pages.

SUBMITTED OR IN PREPARATION

Gillmann, C., Karatekin O., Wallemacq Q. and Claeys Ph. Impact-induced heating effects on the surface conditions of early Mars. (in prep.)

BISA

PEER REVIEWED

Altwegg K., Balsiger H., Bar-Nun A., Berthelier J. J., Bieler A., Bochsler P., Briois C., Calmonte U., Combi M., De Keyser J., Eberhardt P., Fiethe B., Fuselier S., Gasc S., Gombosi T. I., Hansen K. C., Hässig M., Jäckel A., Kopp E., Korth A., LeRoy L., Mall U., Marty B., Mousis O., Neefs E., Owen T., Rème H., Rubin M., Sémon T., Tzou C.-Y., Waite H., Wurz P., 2015, "67P/Churyumov-Gerasimenko, a Jupiter family comet with a high D/H ratio.", Science, Volume 347, Issue 6220, article id. 1261952, DOI: 10.1126/science.1261952.

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ANNEX 2: Scientific paper on the Highlights of Planet TOPERS

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

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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 (core, mantle, crust, atmosphere, hydrosphere, cryosphere, (and space)) considering interactions and feedback mechanisms. Here we present the first results after two 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 Figure 57.

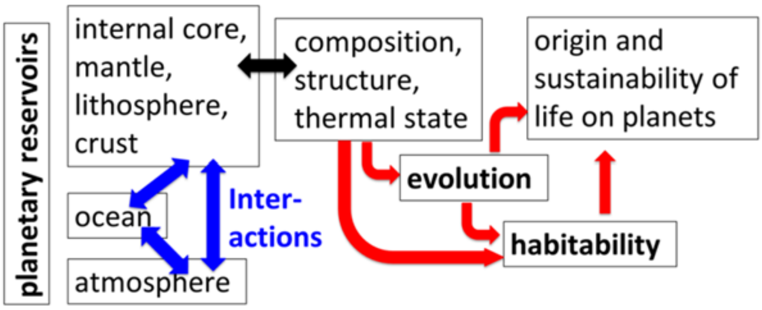

Figure 57: Sketch on the themes involved in Planet TOPERS. Note that "planets" includes the Earth.

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 and including, 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 coupled models of the individual reservoirs developed by the different partners. 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 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, atmosphere, hydrosphere, cryosphere, (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 bio-signature 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 Pole 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 international 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

(1) 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 planetesimals varies from the most evolved structure, in which an iron core exists below a silicate mantle 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., 2014), 21Lutetia instead, has potentially experienced little differentiation with an interior compacted by sintering below a porous layer (Neumann et al., 2013).

(2) 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., 2013; 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, 2014b). 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 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., in prep.) and potential links between chondritic starting materials and achondritic products (Goderis et al., 2015; Van Roosbroek et al., 2015).

(3) Plate tectonics onset, stagnant lid, and 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). 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.

(4) 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. 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., in prep.).

(5) Role of water on volcanism and convection/thermal history/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.

(6) 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., 2015) have been used in the analysis of meteorites and micrometeorites that sample early Solar System planetesimals, especially as chondritic, achondritic, and iron meteorites (McKibbin et al., 2013; Wittmann et al., 2013; McKibbin and Claeys, 2014; Goderis et al., 2015) and in the analysis of impact rocks, both terrestrial (Goderis et al., 2013a, 2013b; Belza et al., 2015; Simonson et al., 2015) and extraterrestrial (Van Roosbroek et al., 2015). These studies of meteoritic and ejecta materials shed light on the impact crater and the overlying turbulent vapor 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.

(7) 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 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., 2015; 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 described 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. 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., 2015d).

(8) 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 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 differences between Earth, Mars, and Venus atmosphere would thus be due to the presence of a strong magnetic field on Earth contrary to Mars and Venus, which have no comparable planetary magnetic field, even if recent observations challenge the idea that planetary magnetic fields offer 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. 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. For later evolution, non-thermal escape becomes the main process but remains low.

(9) 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 ocean 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., accepted). The simulations show that the high-pressure ice layer can be re-molten from below at the water-mantle boundary due to heat loss from the interior. Depending on the thickness of the ice layer, a stable or episodic second, lower ocean can form.

(10) 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 (see Hässig et al., 2013, 2014; Altwegg et al., 2014). While it is still rather early to draw many conclusions, we highlight here one of the first results that we obtained with the DFMS science team: 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.

(11) 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., in review; Javaux and Knoll, in review). We also performed a coupled geochronological study, in particular on diagenetic minerals to better constrain the age of fossiliferous Proterozoic successions (Francois et al., 2015).

(12) Influence of life on atmospheric evolution and vice versa:

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 might evolve to a smaller continent coverage and a dryer mantle than is observed today. On the other hand, a biosphere on the Earth could provide enhanced erosion and sediment deposit, which in turn might induce more water to be retained, potentially impacting the processes in subduction zones (see Höning et al., 2014; Höning and Spohn, 2015).

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