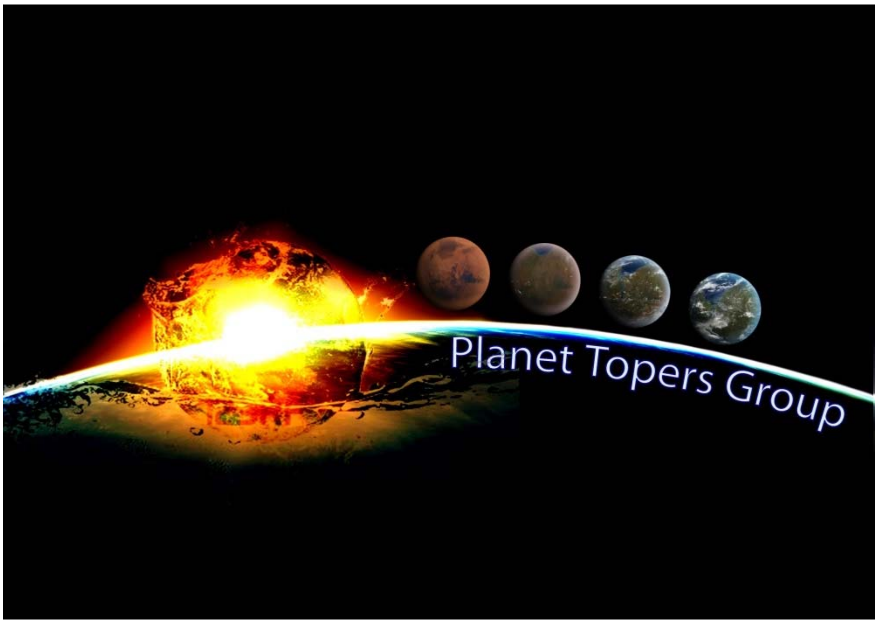
Interuniversity attraction poles - phase VII

Annual Scientific Report
October 2014 – September 2015

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 Network
ACE	Advanced Composition Explorer
AGEX	Asteroid Geophysical Explorer
AGU	American Geophysical Union
AIM	Asteroid Impact Mission
ALVL	Azimuth Lidort VLidort
AMELIA	Atmospheric Mars Entry and Landing Investigation and Analysis
AOTF	Acousto-Optical Tunable Filter
ASIMUT-ALVL	Radiative transfer modelling and spectrum retrieval in a non-scattering atmosphere (ASIMUT) and scattering atmosphere ((V)LIDORT)
BELA	BEpicolombo Laser Altimetry experiment
BELSPO	BELgian Science POlitics
BC	BepiColombo
BIF	Banded Iron Formation
BISA	Belgian Institute for Space Aeronomy
BX	BoXcar
CHUR	CHondritic Uniform Reservoir
Co-I	Co-Investigator
CLUPI	CLose-UP Photograph Imager
CHIC	Code for Habitability, Interior and Crust
CNES	Centre National d'Etudes Spatiales
Co-I	Co-Investigator
Co-PI	Co- Principal Scientist
COST	European Cooperation in Science and Technology
CLUPI	CLose-UP Imager
CrossDrive	Collaborative Rover Operations and Satellites Science in Distributed Remote and Interactive Virtual Environments.
DFMS	Double Focusing Mass Spectrometer
DLR	Deutsche Zentrum für Luft- und Raumfahrt
DREAMS	Dust characterization, Risk assessment and Environment Analyzer on the Martian Surface
EANA	European Astrobiology Network Association
EC	European Commission
EDM	ExoMars Entry Descend Module
EGU	European Geoscience Union
EMTGO	ExoMars Trace Gas Orbiter
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
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
GCM	General/Global Circulation Model
GEM	Global Environmental Multiscale
GaLA	Galilean moons Laser Altimeter
GSA	Geological Society of America
GSA	Geological Society of America Annual Meeting
HED	Howardite - Eucrite - Diogénite
HITRAN	HIgh-resolution TRANsmission molecular absorption)
HR	High Resolution
HRTEM	High Resolution Transmission Electron Microscopy
H-type	High iron abundance ordinary chondrite
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;
IM	Instrument Manager
IMCCE	Institut de Mécanique Céleste et de Calculs des Ephémérides
InSIGHT	Mars Interior exploration using Seismic Investigations, Geodesy, and Heat Transport
IR	InfraRed
ISRO	Indian Space Research Organization
ISSI	International Space Science Institute
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
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
NASA	National Aeronautics and Space Administration
NEXAFS	Near Edge X-Ray Absorption Fluorescence Synchrotron
NIPR	National Institute of Polar Research
NOMAD	Nadir and Occultation for MArs Discovery
NMI	Non-Magmatic Iron
OC	Ordinary Chondrite
ODY	Mars Odyssey
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
SAMBA	Search and Study of Antarctica Meteorites
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
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
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. General information:

Composition of the network, the name of all the partners of the network with their institution and their research unit.

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

2. Introduction:

Brief overview of the main scientific results

Early thermal evolution: Magma ocean Crystallization and Heat pipe mechanism

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. Furthermore, we continued our work on the heat pipe mechanism as an important mechanism for early planetary cooling. This finding can have important consequences for the initial distribution of compositional heterogeneities (including the volatile distribution) generated through the magma ocean fractional crystallization.

Mars: present thermal state and abundance of radiogenic heat sources

We found that the Urey ratio of Mars – 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.

Mars and Mercury: core material and evolution

A precise thermodynamic description of planet's core materials is of fundamental importance for understanding of the core evolution. We are using 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.

Mercury's magnetic field

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.

Present core state with snow and dynamo

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.

Convection code CHIC

We have extended the code CHIC to include compressibility and full 2D spherical convection and participated in several community benchmarks.

Convection in high-pressure ice

We have worked on the simulation of the thermal evolution of high-pressure ice layers that occur in water-rich planets 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, that may hinder material transport from bottom to surface of the ice layer.

Habitability of terrestrial planets: outgassing and plate tectonics

We have studied the geophysical limitations for terrestrial planets in terms of outgassing of greenhouse gases, which influences the possible habitability of these planets.

Tidal heating of terrestrial planets

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.

Characterization of water-rich exoplanets

Simulations have been performed to address the thermal evolution and possible habitability of water-rich exoplanets. 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 an adiabatic temperature profile, we have investigated the existence of a water layer inside the planet.

Quantitative study of the possible appearance of a lower ocean layer

We have simulated the physical states of the layers inside water-rich planets accounting for different initial temperatures and layer thicknesses. High- pressure ice 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.

Planetary atmospheres – trace gases

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.

On the mission Venus Express, the SOIR instrument was an IR spectrometer which allowed the detection of a broad series of species. CO_2, for instance, can be retrieved from very high altitude down to the cloud layer, i.e. from 170 km down to 70 km. Information on the aerosols can also be inferred from the background level of the spectra as well.

Similar studies of Mars have continued through the analysis of the SPICAM spectra. We have further developed a Global Circulation Models (GCM) and radiative transfer codes. Simulations based on these codes and allowing sensitivity studies have been performed in preparation of TGO. 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 (Mumma et al. 2009), smaller than the 300 years predicted by photochemical models (Summers et al. 2002). 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 BIRA-IASB. 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 BIRA-IASB GCM. The precise evolution of methane throughout the atmosphere after a surface release has also been simulated in our GCM and this study was recently submitted (Viscardy et al. 2016).

One of the recent developments to the BIRA-IASB GCM is the inclusion of radiatively active water ice clouds which allows a better representation of water vapour, trace gases and general circulation in the model simulations.

NOMAD

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 is planned in March 2016 from Baikonur in Kazakhstan.

Clathrate, climate and habitability of Mars

Clathrates or gas hydrates are crystalline compounds formed by the inclusion of gas molecules in the cavities of water molecules network 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.

Atmospheric models

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 were involved in high-level working group (ISSI workshop). With atmospheric models, we understand a repository of geophysical data accessible in terms of species, time, solar local time, longitude and latitude, etc.
The Mars GCM model was applied for continued support of observations by 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) (Daerden et al. 2015).

Atmospheric models – Modeling of the interaction between the surface and the atmosphere

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 BIRA-IASB, a 3D global circulation atmospheric model considering photochemistry.

Solar illumination, solar wind, magnetosphere and atmosphere interactions

The long-term evolution of the atmosphere of a planet depends on how material is lost from the atmosphere to space.

The BIRA-IASB Space Physics team continued in 2015 to look 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.

Ionospheric material escaping out into the magnetosphere will interact with the interplanetary medium. 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.

Venus: Atmosphere/mantle coupling

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. Mantle dynamics are 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 model he previously developed.

Mantle evolution as a consequence of an impact

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.

Effect of planetesimal volatile contents

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.

Impacts and volcanism

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 the thicker crust left from before the impact, added to newly created material.

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.

Impacts and Convection

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.

Early impacts can degas the early mantle efficiently and desiccate it, leaving it dry for most of its history, which could have strong implication for 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 Myrs of the evolution, preventing it from becoming habitable.

Modelling of solar radiation erosion, impacts, and volcanism on atmosphere evolution – Application to Venus – Application to Mars

We have modeled asteroid and comet impacts on terrestrial planets (Venus-Mars). The first part of the process includes atmosphere erosion and loss of volatiles during the impacts. The second part deals with energy transmission to the mantle during the impact and modification of mantle convection patterns.

Hydrodynamic escape during the accretion phase

Work has been started on hydrodynamic escape during the accretion phase and 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.

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

In that frame 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 early evolution of biological innovations in the domain Eucarya in the early Mesoproterozoic of Australia (Roper Gp), and for the first time, their worldwide diversification to West Africa (El Mreiti Gp, Mauritania) and Central Africa (RDC Bushimay Spg) by the mid-Proterozoic
- 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 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.

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.

Influence of life on atmospheric evolution and vice versa

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.

Isotope cosmochemistry – meteorite analysis and lunar samples

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. Further, our studies need laterally resolved isotopic analysis. We have used several very performant tools/instruments to reach that goal: (1) laser ablation (LA), (2) 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) thermos-ionization mass spectrometer. The methods used have been improved (patent pending). Several samples have been investigated from the US Antarctic meteorite sample collection and from the collection of Antarctic meteorites curated by the Royal Belgian Institute of Natural Sciences. A case study has been performed for demonstrating the validity of Ca isotopes measurements in preparation to analysis of lunar samples that should be received soon. Analytical developments have also been made in parallel in order to efficiently removing isobaric interference for particular isotops.

Petrography/geochemistry of ejecta material

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.

Planetesimals – Meteorites achondrites

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. 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 the one 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 one (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.

Comets: Composition and Role of impacts

The BIRA-IASB Space Physics team is 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 that the D/H ratio is strongly different from Earth's, 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.

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

Following the proposition that plate tectonics may not have active during the Archean period (Debaille et al., 2013) 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.

Most important activities of networking

Activities organized as part of the IAP network

Planet TOPERS members have organized their first year meeting together with the Helmholtz Alliance meeting in Berlin; an additional executive 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 executive meeting has been organized as well on November 4th. Our 3d year meeting is held in ROB in January 2016 together with an Executive meeting.

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 (see meeting organization below)

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.

Outreach

The planet TOPERS have several press releases, TV interviews, radio interviews, paper press, and have given several public conferences (see below).

"Snow-ball effect"

Planet TOPERS Members participate in several calls and obtained several new contracts (see Section New contracts between October 2014 and September 2015 below).

Planet TOPERS Members have obtained new international responsibilities.

3. Description of the research completed

The work of the Planet TOPERS Consortium has been organized in WPs and the first results are here described in subdivisions corresponding to the different WPs. This separation is however more and more difficult as we are integrating our results all together and interacting between the groups and/or between the WPs.

WP 1: Internal Geophysics and Interaction with Atmosphere

WP 1.1: Interior modelling and consequences on thermal state and convection – WP 1.2: Interior modelling and consequences on the magnetic field

In this theme, it is remarkable to note that we have contributed with four chapters in Treatise of Geophysics (Sohl and Schubert, 2015; Breuer and Moore, 2015; Van Hoolst, 2015; Dehant and Mathews, 2015).

Early thermal evolution: Magma ocean Crystallization and Heat pipe mechanism

We have studied in particular on the early planetary evolution, i.e. the magma ocean solidification phase (Maurice et al. 2015a,b). In this study, we investigated the cooling and crystallization of a whole-mantle magma ocean and in particular the conditions for the onset of solid-state convection before complete mantle solidification. We have started to couple the magma ocean evolution with a 1-D atmosphere model via volatile outgassing (Nikolaou et al. 2015). Furthermore, we continued our work on the heat pipe mechanism as an important mechanism for early planetary cooling (Prinz et al. 2015). We have examined the distribution and influence of mantle water on the thermal evolution of Mars (Breuer et al., 2015) and the present-day Urey ratio of Mars (ratio between surface heat flow and heat produced by radioactive elements (Plesa et al., 2015). We have further modelled the mantle dynamics and thermal evolution of Mercury and studied the influence of lateral surface temperature variation on the gravity and topography field (Tosi et al, 2015b). To this end, we have improved and benchmarked our numerical code GAIA (Tosi et al., 2015a). We have further studied the water-rock differentiation and internal structure of Ceres in modelling accretion together with compaction by creep (Neumann et al. 2015).

For the magma ocean crystallization we show that, even for a rapidly decreasing surface temperature, a sufficiently high Rayleigh number guarantees the onset of solid-state convection prior to complete mantle crystallization. This finding can have important consequences for the initial distribution of compositional heterogeneities (including the volatile distribution) generated through the magma ocean fractional crystallization.

Mars: present thermal state and abundance of radiogenic heat sources

We found that the Urey ratio of Mars 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. If the thermostat effect is efficient, as expected for the Martian mantle, assuming typical Solar System values for the thorium-uranium ratio and a bulk thorium concentration, simulations show that the present-day Urey ratio is approximately constant, independent of model parameters. Together with an estimate of the average surface heat flux as determined by InSight, models of the amount of heat producing elements present in the primitive mantle can be constrained.

Mars and Mercury: core material and evolution

A precise thermodynamic description of planet's core materials is of fundamental importance for the interpretation of measurements provided by ongoing and future space missions (InSight...) as well as for the understanding of the core evolution. Thermoelastic properties and material melting properties are not independent. Data about those properties can be used together to build a thermodynamic model of core materials. Since sulfur is the ubiquitous light element in planetary cores, we have started to build a thermodynamic model of Fe-S by taking into account measured melting temperatures and high pressure and temperature density measurements of liquid and solid Fe and Fe-S alloys. Since density measurements of Fe-S alloys at Mars' and Mercury's core conditions are scarce, we have participated in a measurement campaign initiated by D. Antonageli (Institut de Minéralogie, de Physique des Matériaux et de CosmoChimie (IMPCM) in Jussieu) and G. Morard (IMPCM Jussieu) at the European Synchrotron Radiation Facility in Grenoble to measure the density of different liquid Fe-S alloys at high pressure and temperatures.

We have constrained Mercury's internal structure from its gravity field and rotation observation. With those data the radius of the core and its density can be determined precisely. However, the thermal state of the planet, the density of the mantle, and the radius of the inner core are almost not constrained. However, by seeking interior models that give rise to solid iron crystallization configurations and that do not preclude present day magnetic field generation, we have constrained the radius of the inner core.

The secular cooling of Mercury results in its global contraction. Studies about tectonic features revealed that Mercury's radius decreased by about 7 km. We have used this upper limit to constrain Mercury's present-day thermal state and internal structure. We have found that since the end of the large heavy bombardment event, the measured radial contraction implies that Mercury's core cooled by less than 200K and that its inner core cannot be significantly larger than 1000km.

Mercury's magnetic field

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 thermal evolution of the whole planet. In our approach we have assumed that the dynamo is principally driven by secular cooling, heat generated by solid iron crystallization, and gravitational energy released by sinking of iron-rich snow and upwelling of iron depleted fluid. Our result show that, given the estimates of the present day core-mantle boundary heat flow, a significant part of the liquid core is not convecting and as a consequence such our approach cannot explain the present day internally generated magnetic field. Likewise, early in Mercury's history, prior to the advent of solid iron crystallization, secular cooling alone cannot explain the measured almost 4 billion year old remnant crustal magnetization. Further investigations about other plausible driving mechanism are required in order to explain Mercury's past and present magnetic field.

Present core state with snow and dynamo

We have studied the various aspects of core crystallization and magnetic field generation of terrestrial planets (Breuer et al, 2015) and discussed in particular the iron snow regime of Ganymede as a mechanism for its present day dynamo (Rückriemen et al., 2015). In this regime, Fe-crystals first form at the core-mantle boundary and later settle to the deeper core due to their higher density (Fe-snow). We have investigated this scenario with a 1D core evolution model by varying the initial sulfur concentration, the core heat flux, and the thermal conductivity of the core.

We propose that Ganymede's dynamo is originated in the deeper, entirely liquid core below the iron snow zone. Such a dynamo is restricted by the period of time the snow zone needs to grow across the core. For the proposed dynamo in the deeper liquid core, we obtain necessary time periods of between 320-800 Myr and magnetic field strengths at the surface that match the observed value of 719 nT. Furthermore, a present dynamo below the snow zone suggests the absence of an inner core.

Convection code CHIC

For the simulation of the interior of terrestrial planets we developed the observatory code CHIC 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, mantle convection and related volcanic outgassing in terrestrial planets, and 1D thermal evolution of water-rich planets (described in the next section).

The convection code CHIC has been further developed to include compressible convection in the mantle, and is involved in a benchmark study for compressible mantle convection (Davies et al., in preparation). Self-consistent calculation of phase transitions and related latent heat release and consumption is another new module of CHIC. In collaboration with Attilio Rivoldini from the observatory, up-to-date equation of states for the calculation of thermodynamic properties have been added to the code for, silicate mantles, iron cores and water-ice layers. A project is currently realized with B. Journaux from the Université Grenoble Alpes addressing the possible convection in high-pressure ice including phase transitions and non-Newtonian rheology.

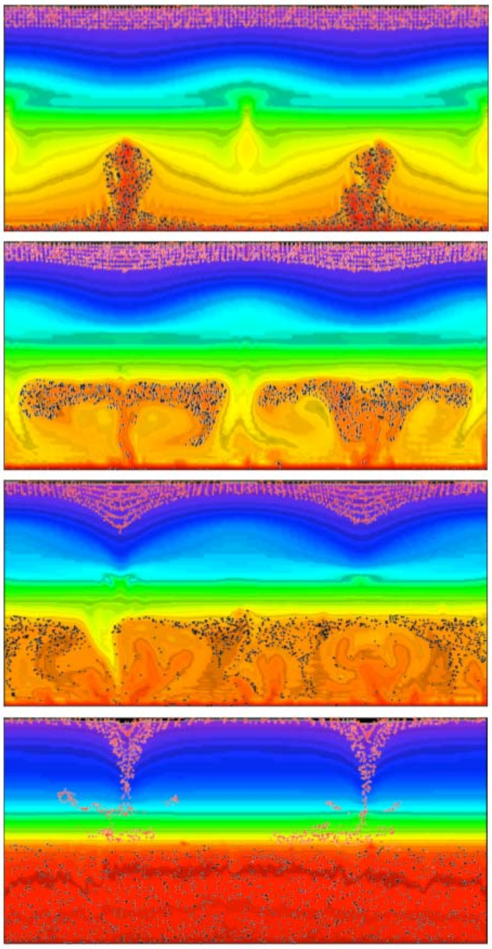


Figure 1: Ice convection using a diffusion rheology. Temperature field including material tracers for a 200km thick high-pressure ice sphere with phase transition between ice VI and ice VII at 0.05, 0.4, 1.3 and 11 Myr.

Mantle evolution as a consequence of an impact

We have taken into account the effects of meteorites in coupled atmosphere-mantle evolution simulations (see point in WP 2) by adapting each relevant part of the model. The impactors can bring volatiles as well as erode the atmosphere. Mantle dynamics are modified since the impact itself can also bring a large amount of energy to the mantle. A 2D distribution of the thermal anomaly due to the impact is used. The simulations showed that the impacts can lead to regional melting.

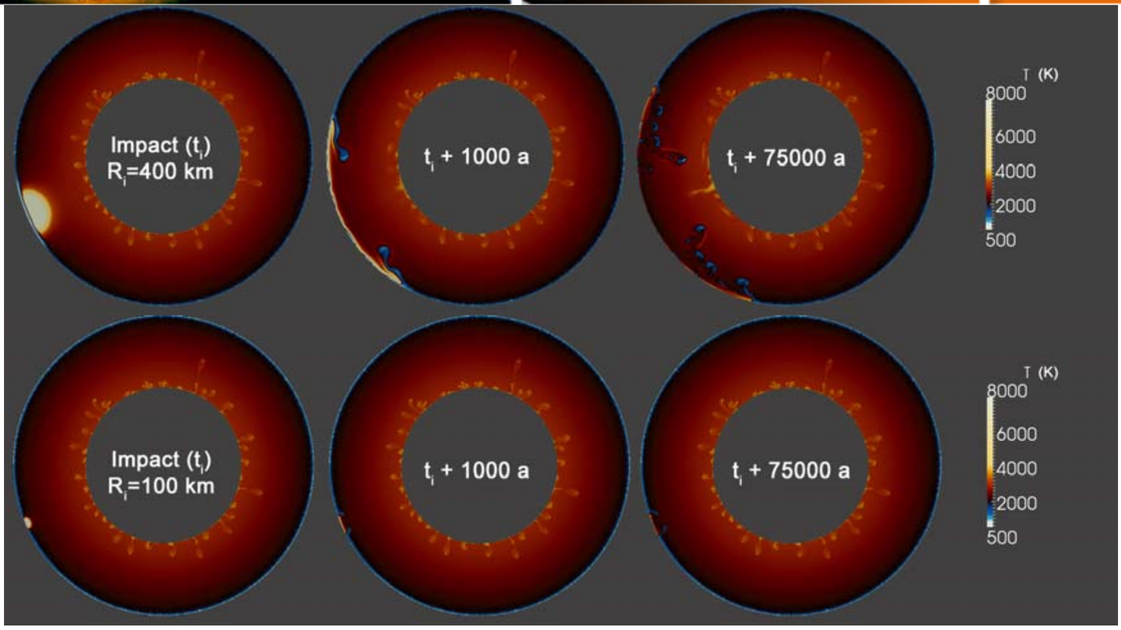


Figure 2: Illustration of the temperature anomaly occuring during and immediately after an impact, for two different impactors.

Large impacts transfer large amounts of energy to the mantle of planets. We simulate this by adding a thermal anomaly corresponding to the zone affected by the impact to the mantle. The convection code then reacts to this anomaly and modifies convection patterns accordingly. Melting occurs as temperatures at the impact point are high. The direct effects of the impact are visible for a few ten thousand years.

The immediate effect of such an impact modifies the in-depth temperature profile of the mantle for less than 1 Myr. Melt generation and near-surface effects last longer. Global scale melting and crust emplacement is expected.

We have observed short term and long term effects of the impacts on planetary evolution. While small (less than kilometer scale) meteorites have a negligible effect, large ones (up to around 100 km) are able to bring volatiles to the planet and generate melt first at the sub-impact location and, later on, due to the volcanic events they triggered, composition (and temperature) anomalies that change considerably the mantle dynamics.

Hydrodynamic escape during the accretion phase

Large (500km) impact occuring at 0.005 Gyr are common events during the accretion phase (Figure 2). The thermal anomaly created is very large. A large amount of melt is created, as shown on this composition evolution figure (a). Degassing due to this melting is strong and a large amount of water is released into the atmosphere, leading to increased surface temperatures (b). Corresponding vertical temperature profiles are shown (c) before and after impact. Strong early escape removes this excess of volatiles over severals tens of million years.

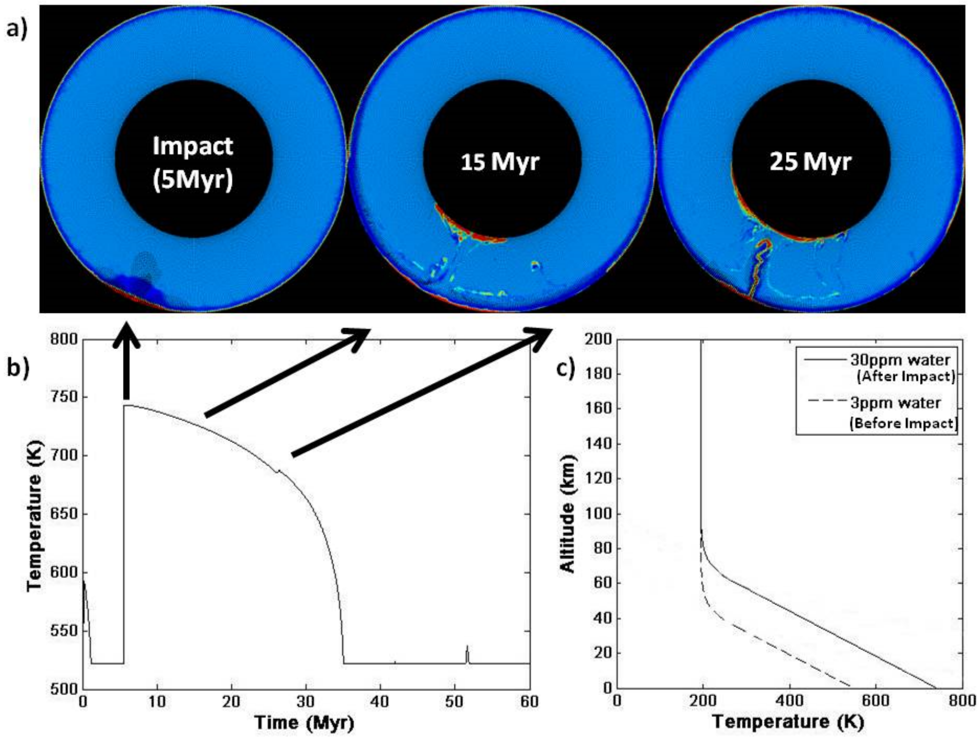


Figure 3: Coupled evolution of the atmosphere and mantle of Venus in the case of an early impact (5 Ma). (a) Composition of the mantle of Venus at three different times at and after the impact. Red colour represents basaltic rocks, while light blue is fertile and dark blue depleted mantle material. (b) Evolution of the Surface temperature of Venus. Thick black arrows indicate which part of the temperature profile corresponds to which stage of the simulation shown in (a). (c) Simple vertical temperature profile of the atmosphere before and just after the impact.

Impacts and Convection

The composition anomaly created during the impact is the cause of later activity (downwelling) at the same spot 20 Myr after the impact. With minimal erosion, melting has a dominant effect after impact due to degassing (affecting surface conditions) and crust generation for later mantle dynamics.

Basaltic material is formed immediately at the impact location and emplaced there, forming a thicker crust. As it cools down with time and as surface temperatures decrease it will trigger several million years later downwellings of cooler material into the hot mantle. In turn this event leads to more melting and renewed volcanic activity.

Typically, we observe that during the evolution subsequent to a large impact (>400 km radius) roughly half of the activity takes place at or near the impact location, with 20% close to the antipodal position and 30% distributed over the rest of the surface.

These features (both antipodal and linked to the thermal anomaly) are related to the extent of the upper mantle affected by the thermal anomaly and the region where it can destabilize early crust or form new basaltic material. Three processes lead to this situation: (i) The larger impacts will completely remove early crust from most of the surface, preventing the formation of subsequent downwellings in those regions for an extended period of time. (ii) Some regions (far from the impact) are also less affected by the anomaly and exhibit thicker, colder and older crust, which will later form downwellings. (iii) Finally, melting will occur at the impact site itself, renewing the basaltic layer and causing most activity there. In the end, more basaltic material is emplaced at the impact point and near the antipodal position than at any other location on the surface of the planet.

The use of the coupled model rather than a fixed 740 K surface temperature (uncoupled) favors this repartition of activity and downwellings. Uncoupled models rarely show a specific focusing of activity at the same locations coupled models do. The coupling allows for lower surface temperatures, which tends to favor a mobile lid regime that is enhanced by these lateral differences in upper mantle structures and tends to sustain itself.

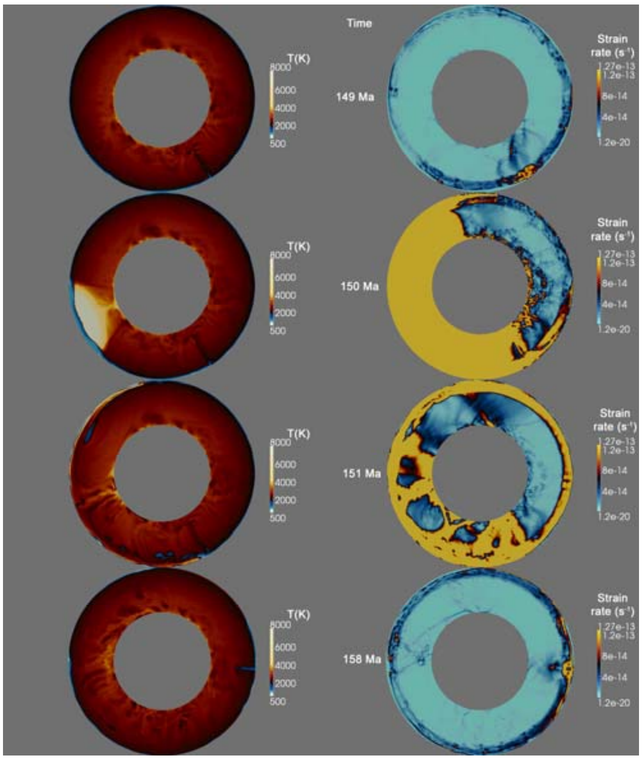


Figure 4: Temperature and strain rate fields in the mantle of Venus after an 800km radius impact in the lower left cadrant of the annulus. At the impact location, the thermal anomaly and subsequent rising plume are visible. At the antipodal position, later downwelling can also be seen. Strain rates show 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.

A significant amount of volatiles can be released on a short timescale. Depending on the timing of the impact, this can have significant long term effects on the surface condition evolution. Atmospheric erosion caused by impacts, on the other hand, and according to recent studies seems to have a marginal effect on the simulations, although the effects of the largest impactors is still debatable.

The timing of the impact has a small influence on the final surface temperature of the planet. However, it has a strong influence on the evolution of the surface temperature between 3.5 and 1.5 Ga, Thus affecting surface conditions AND mantle (feedback). A large impact could lead to bypassing completely the low surface temperature period and thus make a strong difference for mantle convection evolution.

Large impacts can affect long term evolution of terrestrial planets through their influence on key periods of the history of the body and trigger changes due to the atmosphere/mantle feedback.

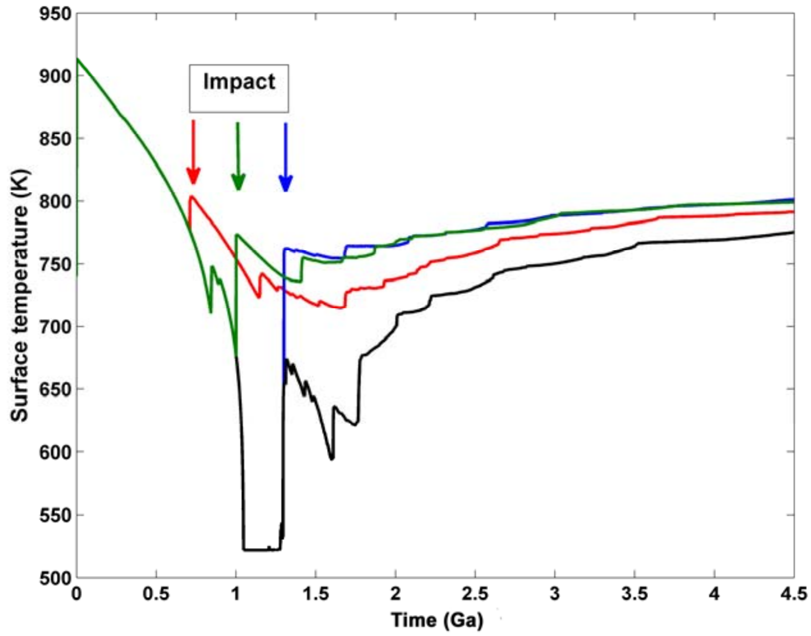


Figure 5: Long term effects of large impacts depending on their timing. Reference case without impact is in black line.

Impacts and volcanism

A second example shown in Figure 6 focuses on the Late Veneer (LV) era. We can observe that the evolution of surface conditions is completely modified by the occurrence of a major impact early on. Indeed, the late evolution is marked by surface temperature reduction by 60-100 K for the case including an impact. Looking into more detail, we see that the "low temperature era" common to those simulations starts a few tens to a hundred Ma later than in cases without an impact event. It also extends for 500 Ma longer until 2.5-2 Ga ago instead of 3-2.8 Ga. During that era, fewer spikes of higher surface temperatures can be observed. Even after temperatures have risen again, the rate of increase is small and values stay lower than in models featuring an impact. Melt production (volcanic activity) shows that the early evolution of the impact case is dominated by melt produced by the impact itself.

In summary, the impact leads to massive degassing and depletion of the mantle very early on by (i) directly melting a large portion of the upper mantle and (ii) enhancing early volcanic activity (during the era 4-3 Ga ago). The consequences are a depleted upper mantle that is more difficult to melt later on and a major loss of volatiles early on, when they are efficiently lost to space. In contrast, the simulation without an impact releases volatiles later on, over an extended period of time, with late spikes of activity ensuring replenishment of water in the atmosphere.

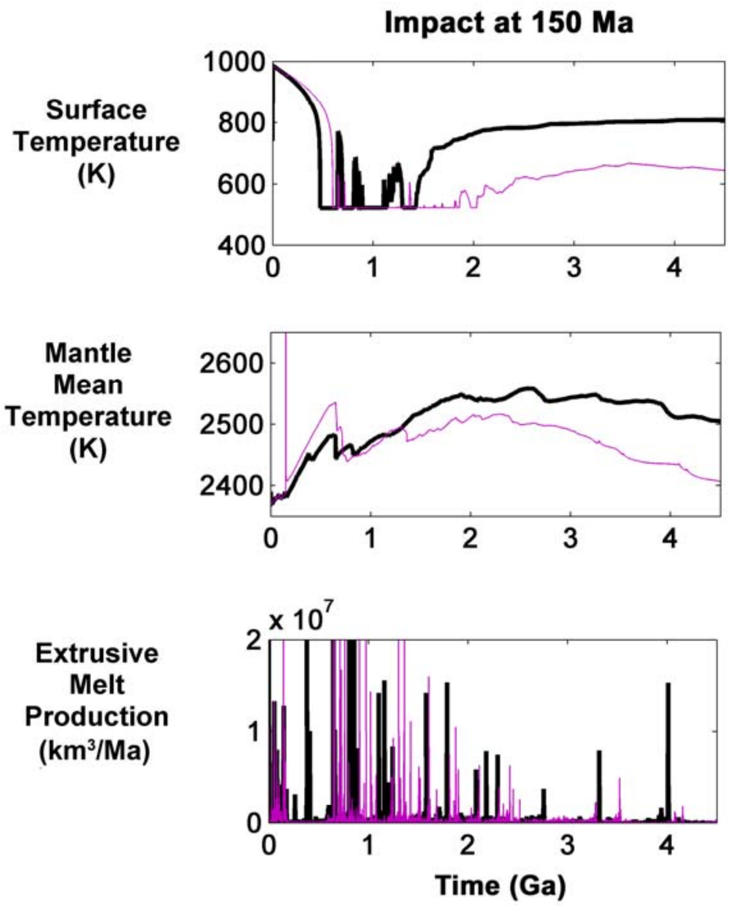


Figure 6: Comparison between the evolution of a reference case (black) without impact and a LV impact (purple) occurring 4.4 Ga ago with a 800 km radius impactor. Surface temperature evolution, mean mantle temperature and extrusive melt production rate are plotted.

Effect of planetesimal volatile contents

Initial condition is a very important parameter for all long term evolution simulations. In the case of habitability and surface conditions, the amount of water and its emplacement is a major challenge. We aim at obtaining new clues on how volatiles were distributed during accretion and quantify their early history. We develop our hydrodynamic escape process numerical model to study the history of volatiles during accretion and monitor the evolution of volatile and water abundance on the planetesimals during the later phases of accretion. As has been shown by several studies, the bulk of the water and volatiles delivered to terrestrial planets in the solar system is obtained between 70-200 Myr after the start of the accretion by a small number of large, high velocity impacts from objects coming from the outer solar system.

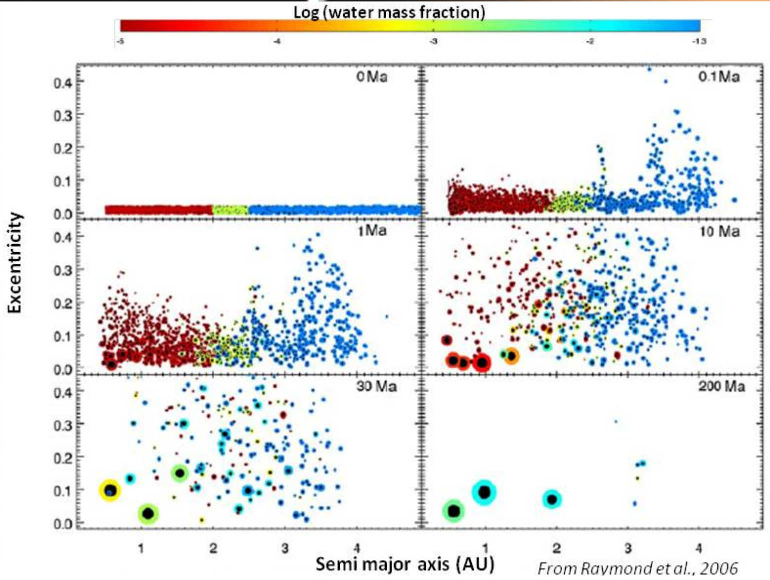


Figure 7: simulation of planetary system formation including water and volatile accretion.

We test several scenarios of accretion by tracking the water inventory of these outer system objects. Hydrodynamic escape is the main escape process during that time and it is affected by the change in distance to the sun with time as the impactor enters the inner solar system. We also take into account the evolution of the mass of the impactor as it accretes more material during its transit.

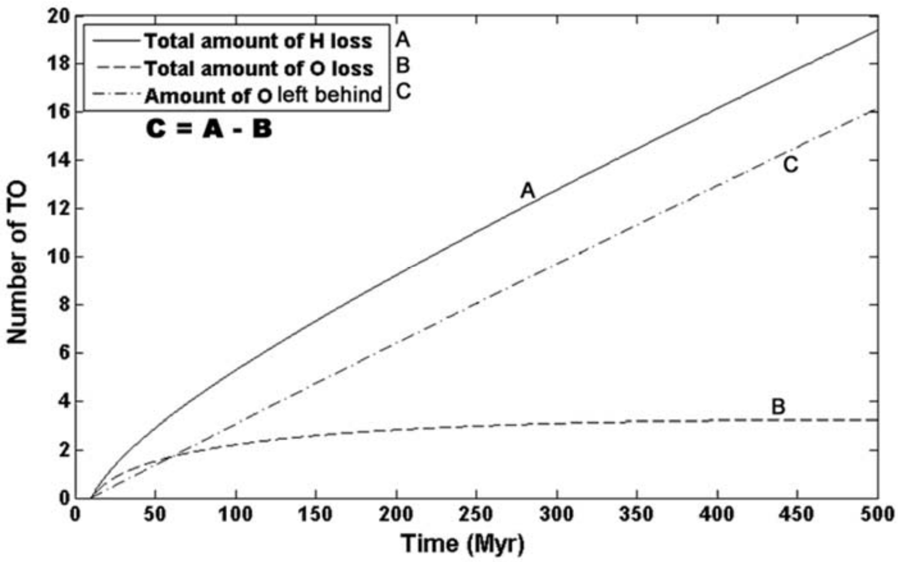


Figure 8: Simulation of the early escape of hydrogen and oxygen from the atmosphere of Venus, placing constraints on the length of the escape and initial water inventory of the planet.

Convection in high-pressure ice

H_2O is one of the most abundant molecules in our galaxy and is present in a large variety of planetary environments. In the last few years an increasing number of exoplanet discoveries suggested the existence of a new kind of planetary bodies very rich in H_2O that explain the low density of some relatively small planets. They may contain a large H_2O-based icy mantle, up to thousands of kilometers thick, possibly overlaid by a liquid ocean.

With such thermodynamic conditions the solid mantle would be dominated by dense high pressure ice polymorph, stable beyond the Giga-Pascal (i.e. ice VI, ice VII or ice X). This thick ice mantle may represent a physical barrier for chemical exchange between the rocky core and the uppermost ocean. This is why the ocean of such planets is regarded as bad candidates for hosting habitable environment that would require inputs of nutrients.

We model the possible material transport through high-pressure ice layers in water-rich planets. The model focusses on the influence of phase transitions on the convective patterns, where we apply physical properties of high pressure ice. We investigate if (or under which circumstances) the transport path through the ice may be blocked by phase-transition induced multi-layer convection in the high-pressure ice layer.

Our model either use a diffusion or dislocation creep rheology, whereas the first rheology is often used in high-pressure ice studies (see Figure 1), but dislocation creep is the favoured mechanism from laboratory rheology studies for high-pressure ice. Our simulations suggest that a dislocation creep rheology does not allow for efficient convection due to small strain rates, which we did show over a large parameter space. To allow for convection in the high-pressure ice layer in water-rich bodies as Ganymede, other convection drivers need to be considered. A possible influence is expected for molten material at the base of the high-pressure ice layer (which may penetrate the ice and lower the local viscosity) or due to chemical diffusion from lower-density salts provided by the silicate mantle.

Habitability of terrestrial planets: outgassing and plate tectonics

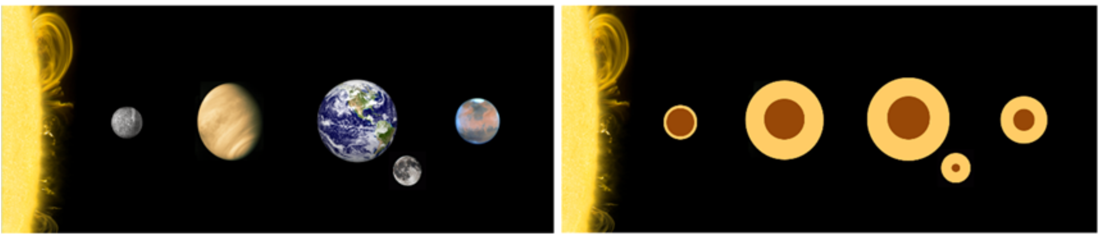


Figure 9: Variety of masses and interior structures for the terrestrial bodies in the inner Solar System.

When looking at the terrestrial bodies in the Solar System, we can see a wide range of planet masses and interior structures for "Earth-like" planets, see Figure 9. The exoplanets that have been discovered so far and for which both mass and radius are known, suggest an even wider diversity (www.exoplanets.eu). It is therefore necessary to investigate the influence of mass and radius on the geophysical surface processes of terrestrial planets.

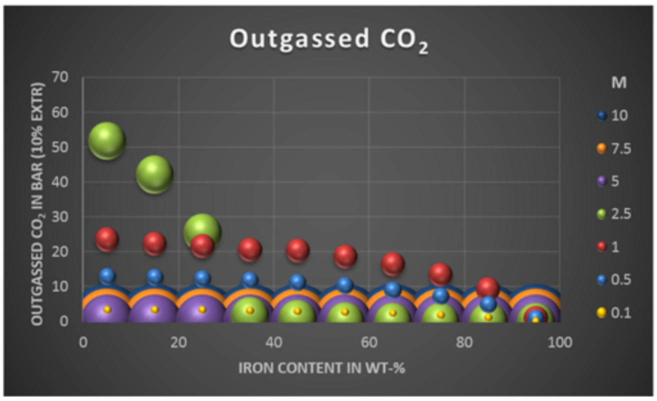


Figure 10: Melt depletion for terrestrial planets of different mass and composition after 4.5 Gyr for Earth-like initial conditions and heat sources.

Our research studies show that both plate tectonics and volcanic activity are strongly influenced by the interior structure, the energy budget and the mass of a planet (for both terrestrial planets and water-rich planets). Mantle silicates can melt if the temperatures are high enough to overcome the solidus melting temperature, which strongly depends on the pressure and therefore on the mass of a planet.

Stagnant-lid planets with large masses (or a high iron-content similar to Mercury, Kepler-10b or CoRoT-7b) for example may not be able to build up a dense atmosphere, which has important consequences for the interpretation of exoplanet mass-radius data and can help to constrain the interior structure of rocky planets, see Figure 10. A paper on this study is currently in preparation for submission.

In another project with Caroline Dorn from the Univeristy of Bern, we test different interior structures (depending on different mantle compositions, using for example different Mg and Fe amounts) that lead to a predefined mass and radius of a terrestrial planet within a confidence interval between 0.5% and 5%. With CHIC we then determine the influence of the different interior structures on the outgassing behavior to investigate if the unknown composition and core size of a planet influences the likelihood to outgas a dense CO_2 atmosphere.

Our first results show that the mantle depletion in volatiles and hence the outgassed amount of CO_2 does not significantly depend on the exact interior composition (within the limits of our study assumptions), see Figure 11. An exoplanet for which the mass and radius are determined with a

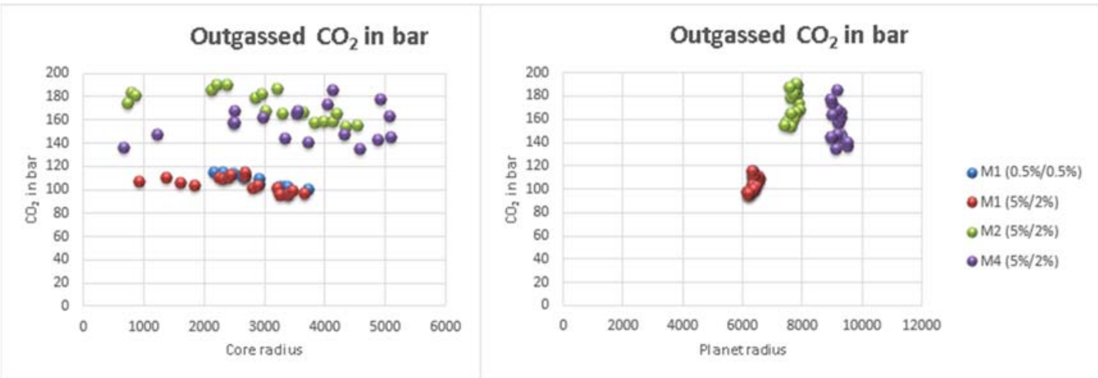


Figure 11:Outgassed CO_2 for planets of 1, 2 and 4 Earth masses with different compositions leading to a pre-defined radius and mass with either 0.5% or 2/5% accuracy. Even though the core radius strongly varies for all models, the amount of outgassed CO_2 is only slightly influenced. We find that a thin mantle is completely depleted in volatiles, a deep mantle is only partially depleted and an inhomogeneous mantle chemistry is obtained.

high accuracy and which is therotically in the habitable zone can indeed be characterized as potentially habitable (i.e. able to deliver a dense-enough atmosphere needed especially at the outer boundary of the habitbable zone).

Tidal heating of terrestrial planets

In the framework of an internship project, tidal heating was implemented in the CHIC code together with the student Jérémie Godret and with the help of Michael Beuthe from the ROB.

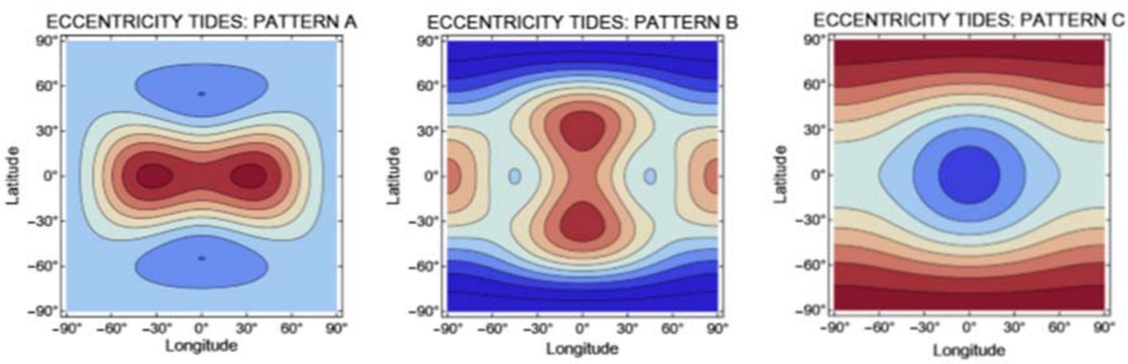


Figure 12: Eccentricity tides patterns, from Beuthe (Icarus, 2013)

The model is based on the formulation derived in the paper by Beuthe (Icarus, 2013) and allows for 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. The model considers also spatial patterns of tidal heating, see Figure 12.

The model will be used to model the tidal heating effects on exoplanets as modeled by n-body simulations at the Université de Namur by Anne-Sophie Libert and Emeline Bolmont. Another co-operation is possible for the simulation of the star-planet tidal-dissipation interactions and their effects on the interior with Florian Gallet from the Université de Génève.

Characterization of water-rich exoplanets

This research addresses the characterization, modelling, thermal evolution and possible habitability of water-rich exoplanets. To obtain consistent profiles for the depth dependent pressure, density, gravity and mass, we solve the Poisson equation for the gravity and the hydrostatic pressure equation for pre-defined mass and composition (in terms of iron, silicates and water). For the density, equations of state are applied. The interior structure model is described in detail in Noack et al. (2015, INFOCOMP) and Noack et al. (Icarus, in review). The thermal evolution is modeled with a 1D parameterized model. Both models are part of the CHIC code.

The interior structure of water-rich planets cannot be determined uniquely, even if mass and radius of the planet are known exactly. On the other hand, additional information as moment of inertia are not available for exoplanets. Even without the possible additional influence of a possible extended atmosphere, accurate mass and radius determinations do not lead to a unique determination of the interior structure.

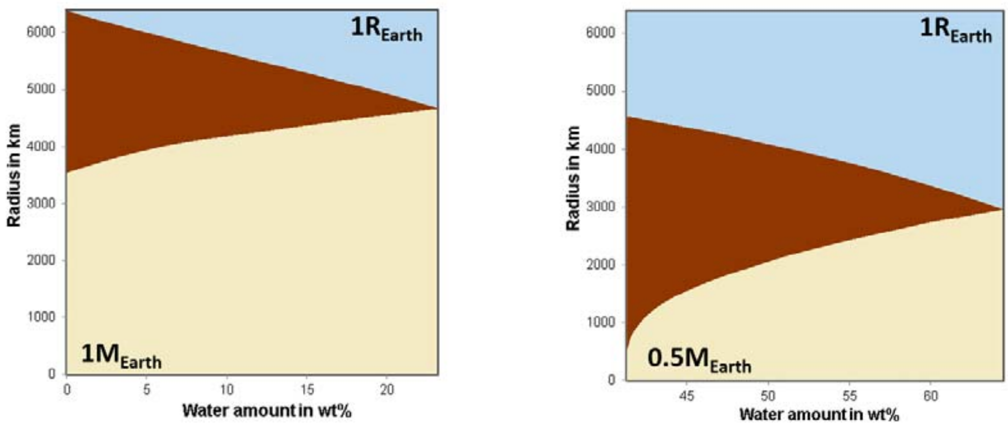


Figure 13: Possible interior structures for an Earth-size planet with one or half an Earth mass.

Figure 13 shows two example cases for a planet of one Earth radius and either half an Earth mass or one Earth mass. In both cases it is assumed that mass and radius are known exactly, the core is assumed to consist of liquid iron, the mantle is composed of Mg-silicates, and an adiabatic temperature profile is assumed.

For both investigated masses, a deep water layer cannot be excluded, only in the less-dense case (assuming that there is no extended atmosphere), the planet has to contain a large amount of water. In this case, a characterization of the planet is possible, but not for the Earth-like mass (as long as surface temperature allows for either ice or liquid water at the surface).

Quantitative study of the possible appearance of a lower ocean layer

For the simulation of water-rich planets, several parameters (as initial temperatures or layer thicknesses) are unknown. In our quantitatve study, we therefore investigated first which parameters have the largest influence on the appearance of a lower ocean, which appears at the bottom of a high-pressure ice layer, if it is molten from beneath from heat flowing out of the mantle. We find that the surface temperature has the largest influence on the thickness of water layers, for which a lower ocean can still form between the high-pressure ice layer and the silicate mantle. For higher surface temperatures, not only entirely liquid oceans are possible for deeper water shells, also a liquid ocean can form under high-pressure ice layers of hundreds of kilometer thickness (for a 1 Earth-mass planet). Deeper down, the lower ocean can still appear episodically at the water-mantle boundary (WMB).

In order to classify the potential habitability of the lower ocean, we introduce five different regimes for a water layer (as shown for an example simulation using a surface temperature of 290K and Earth-like interior structure and parameters in Figure 14):

- 100% O - a liquid ocean without high-pressure ice
- 100% OIO - a liquid lower ocean (ocean-ice-ocean struc-ture)
- < 100% OIO - a periodically occurring liquid ocean (liquid more than 50% of the time)
- <50% OIO - a periodically occurring liquid ocean (liquid less than 50% of the time)
- 0% OIO - no lower ocean, the water layer always has an ocean-ice structure

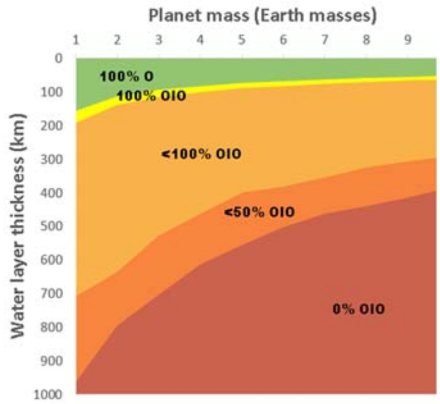


Figure 14: Lower ocean appearance regimes for different planet masses and water layer depths.

To evaluate the percentage of lower ocean appearance over time, we run all simulations (here for different water amounts and planet masses) for 1 Gyr (initialisation phase) and average the lower ocean appearance time for another Gyr. The borders between the different regimes are determined with an accuracy of 5%.

We also investigated the main paramters influencing the existence of volcanic activity and silicate crust formation. Under deep water layers, the high pressure from the overlying water layer can inhibit melting in the mantle. The main parameters influencing the maximal water layer depth, for which melting is still possible, are indeed the parameters influencing the mantle energy budget, which are the amount of radioactive heat sources and the initial upper mantle temperature. Plate tectonics also has a strong influence on the existence of volcanism. Crustal parameters (initial thickness or heat sources enrichment factor) as well as the ice rheology (i.e. the isolating effect of the ice shell on the mantle) have only a small influence on melting processes in the interior and the formation of crust.

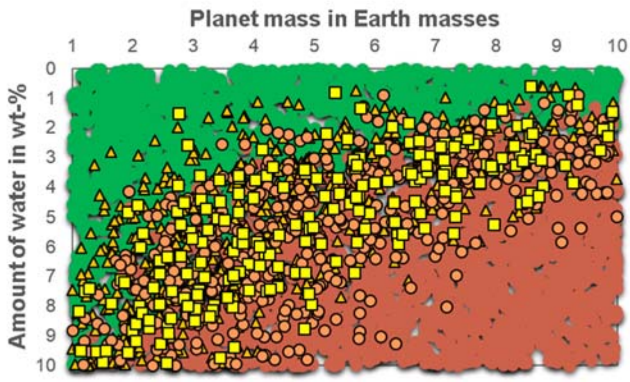


Figure 15: Monte Carlo quantitative study for different planet masses and amounts of water. Green markers stand for liquid water layers, red for high-pressure ice that cannot be molten from beneath. The yellow markers in-between denote cases where a second, lower ocean forms, orange stands for episodic appearance of the lower ocean.

We conducted a Monte-Carlo quantitative study in which we randomly selected initial and rheology parameters as well as the planet composition. Figure 15 shows the habitability regimes over planet mass and water amount sorted into three habitability classes:

H1: habitable (color green in Figure 14 and Figure 15), the water-layer is completely liquid,

H2: restricted habitable (color yellow), an ice layer forms, which is located between two ocean layers, and

H3: likely inhabitable (color red), the lower part of the water-ice-layer is frozen, and at the WMB no liquid water is available

In addition, mixed H2/H3 cases are depicted in Figure 15, where light orange points refer to a lower ocean appearing more than half of the time, and dark orange for less than half of the time.

WP 1.3: Internal and external volatile content in particular Carbon Dioxide (CO_2), Sulfur dioxide (SO_2), methane (CH_4) and water (H20) and planetary evolution

Planetary atmospheres – trace gases

BIRA-IASB was responsible (PI) for the SOIR instrument onboard the ESA mission Venus Express. The Venus Express mission sadly ended in Dec. 2014 after all its fuel had been used. The SOIR instrument was 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 analysed 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" (see Publication list).

The analysis of the aerosols has also 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.

BIRA-IASB has been participating to 3 ISSI International teams which were considering three different aspects of the Venus atmosphere: its structure (temperature), the presence of SO_2 and its relation to the clouds. The last meeting was held in Feb. 2015. Review papers on these issues are being prepared and close to submission.

Study of Mars has continued through the analysis of the SPICAM ultraviolet spectra, leading to the PhD thesis presentation of Yannick Willame (Willame, 2015). 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 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 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 XX) and also the surface albedo.

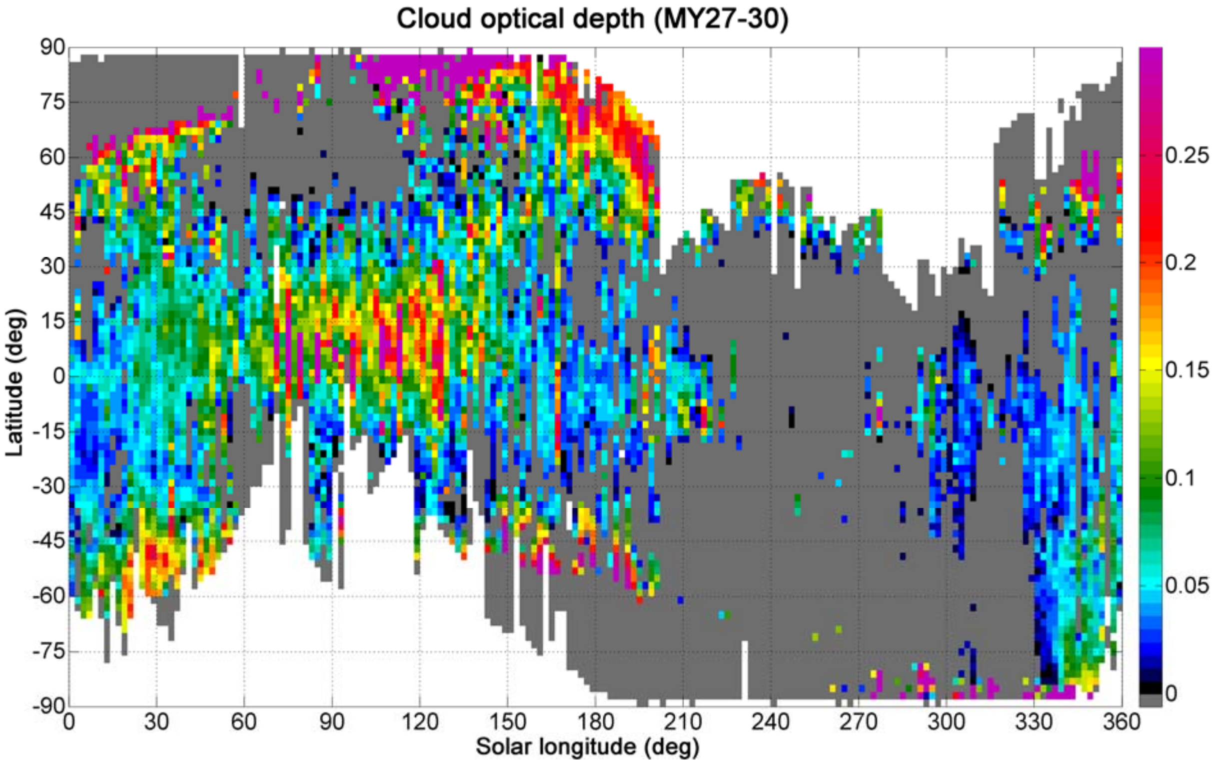


Figure 16: Seasonal evolution of the zonally averaged cloud opacity. The values are also averaged on the four Martian years of the dataset (from MY: 26.9 to 31.0). The white areas correspond to regions where no measurements were performed, the grey background represents the measurement coverage and the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

NOMAD

NOMAD (Nadir and occultation for Mars Discovery) – a UV-VIS and IR spectrometer suite on the ExoMars TGO 2016 has been delivered on time to ESA. It has been mounted on the TGO s/c and is now in Baikonur awaiting the launch which is foreseen on March 14, 2016. The instrument has been subject to a lot of tests and a calibration session. The data are still under analysis. In the mean time we have started some investigation of the expected sensitivity of the instrument. 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. This was the subject of 2 papers, one being already published (Vandaele et al, 2015), the second being under review (Thomas et al., submitted).

Knowing the expected SNR, it is also 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 associated paper (Robert et al, subm.) has been submitted for publication. As for the SO and LNO solar occultation results, detection limit values are specified for different orders (spectral intervals) for the LNO nadir simulations. The Optimal Estimation Method was used to characterize the detection limits achievable with the LNO channel in nadir observation mode for 17 molecules. 50 factors, from 0.001 to 100 were applied to initial values (see Table 2 in the paper Robert et al). Random noise was added to the simulated spectra in order to create a batch of 100 spectra per factor per molecule. Using that methodology, we know what to expect from the retrieval, i.e. the retrieved density should equal the initial density value times the factor considered in that particular case. The retrievals were run with ASIMUT-ALVL using a random a priori value of 30% around the solution and a variability of 10%. 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 for the 5000 retrievals, i.e. 50 factors times 100 spectra, were plotted (red dots in Figure 17). The detection limits were determined using the DOFS values. The results for CH_4 is shown in Figure 17.

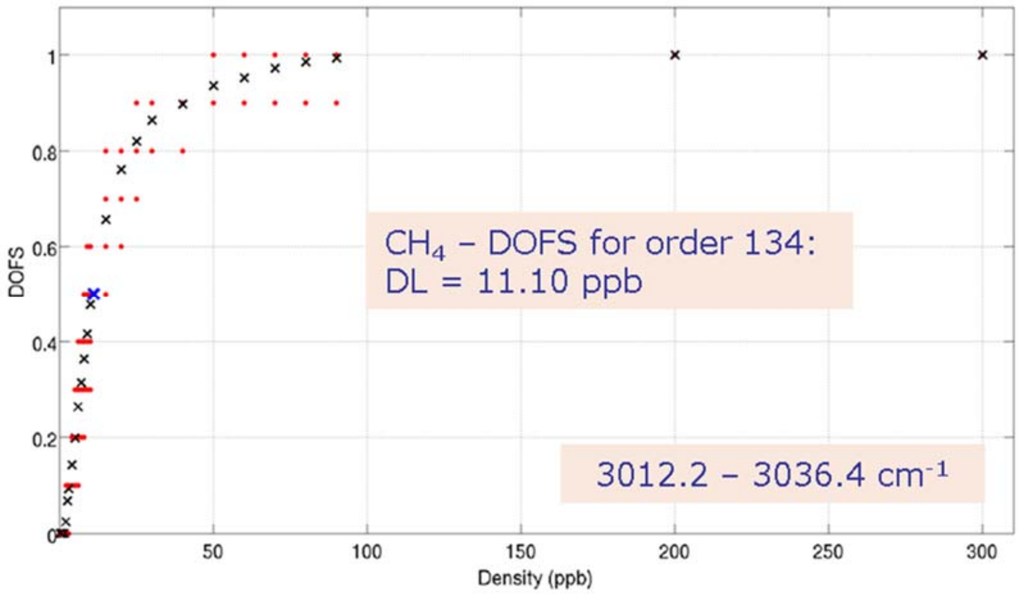


Figure 17: Degree of freedom for Signal of the retrievals in the LNO diffraction order 133 (2989.416 - 3013.415 cm^{-1}) and order 134 (3011.893 - 3036.072 cm^{-1}) for CH_4. The red dots correspond to each individual retrieval. The black crosses represent the averages of the DOFS for each considered factor. The blue cross indicates the value of DOFS=0.5 hence the value of the detection limit in abscissa, in ppb.

		SO	LNO	
		Solar Occultation	Solar Occultation	Nadir
CH_4	0-60 ppb [a]	25 ppt	20 ppt	11 ppb
H_2O	~ 300 ppm (variable with season)[b]	0.2 ppb	0.15 ppb	31 ppb
HDO	D/H =5.6 SMOW[c]	0.7 ppb	0.7 ppb	0.8 ppm
CO	~ 557 ppm [d]	5 ppb	4 ppb	1.5 ppm
C_2H_2	< 2 ppb [g]	0.03 ppb	0.03 ppb	20 ppb
C_2H_4	< 4 ppb [g]	0.2 ppb	0.15 ppb	70 ppb
C_2H_6	< 0.2 ppb [e] < 0.7 ppb [g]	0.03 ppb	0.02 ppb	11 ppb
HCl	< 3 ppb [e] < 0.2 ppb [f] < 0.6 ppb [g]	0.03 ppb	0.025 ppb	31 ppb
HCN	< 5 ppb [g]	0.03 ppb	0.03 ppb	15 ppb
HO_2	0.1-6 ppb [i] < 200 ppb [g]	1 ppb	1 ppb	0.5 ppm
H_2S	< 200 ppm [h]	4 ppb	3 ppb	1.6 ppm
N_2O	< 100 ppb [h] < 90 ppb [g]	0.2 ppb	0.2 ppb	83 ppb
NO_2	< 10 ppb [h]	0.14 ppb	0.1 ppb	50 ppb
OCS	< 10 ppb [h]	0.3 ppb	0.3 ppb	122 ppb
O_3	~ 1 -500 ppmv (variable with season)[j]	2.5 ppb	1.5 ppb	0.8 ppm
H_2CO	< 4.5 ppb [e] < 3.9 ppb [g]	0.04 ppb	0.03 ppb	16 ppb

Table 1: Detection limits for SO and LNO channels.

All the detection limits in the IR, for the SO and LNO channels are given in Table 1. These have been obtained considering no aerosol loadings in the martian atmosphere.

WP 1.4: Clathrates and methane in the atmosphere of Mars

Clathrate, climate and habitability of Mars

In recent years, several detections of methane in the atmosphere of Mars were reported from Earth-based observations and from Mars orbiter observations. This gas has a non-uniform distribution involving an observed lifetime of 200 days, smaller than the 300 years predicted by photochemical models. We studied the effects of soil composition on the stability zone of methane clathrates in the Martian crust. Clathrates or gas hydrates are crystalline compounds formed by the inclusion of gas molecules in the cavities of water molecules network and are typically stable at high pressure and low temperature. In addition to the fields of energy, environment and industry, clathrates play an important role in the study of the formation and evolution of planets. Indeed, they may exist in many solar system bodies such as icy moons or cometary nuclei. These compounds may also be present on Mars today given the favorable thermodynamic conditions in the crust and the polar regions of the planet. The purpose of this work is to characterize 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. Our results also provide important clues about the evolution of Martian atmosphere, the presence of liquid water in the past of the planet and its habitability. It also provides valuable information about the current distribution of gases in the Martian atmosphere and will give theoretical support for current and future space missions (MAVEN, TGO).

Mars subsurface thermal model: We have developed a 1D subsurface thermal model of Mars including several layers of varying thickness with depth and properties (thermal conductivity, density…) that can be changed to correspond to those of Martian rocks at locations studied. The heat equation is solved at each time step with the Crank-Nicolson algorithm. The boundary conditions are given by the surface temperature and the heat flux. This code that is written in FORTRAN also takes into account the condensation of carbon dioxide at the surface.
Figure 18 shows daily average temperature profiles calculated at regular intervals on a Martian year for a homogeneous dry soil and a layered subsurface. For the latter, thermal properties are changed below 54 cm deep to correspond to those of ice-cemented soil. It can be seen that the amplitude of temperature oscillations is greater in dry soil than in ice-cemented soil. However, these oscillations reach a more important depth in the soil saturated with ice.

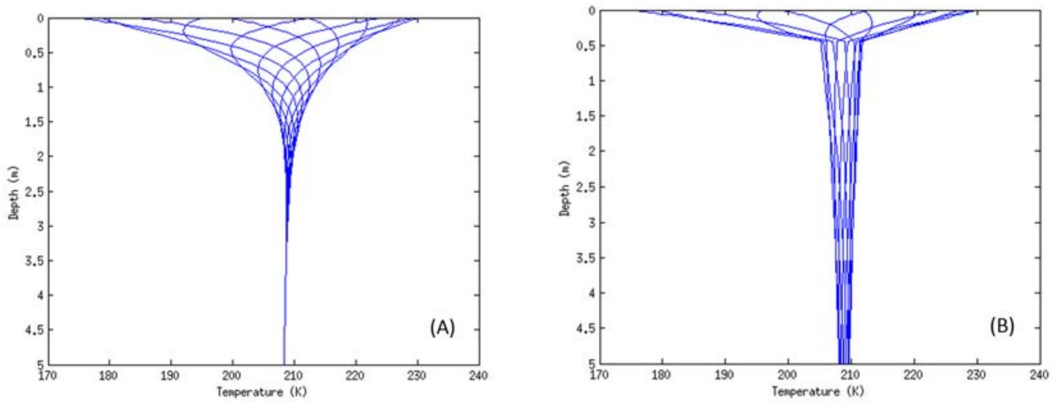


Figure 18: Example subsurface temperature profiles for a homogeneous dry soil (A) and a layered subsurface (B) for a latitude of 45 °N. Each curve is a diurnal average temperature profile calculated at regular intervals for a full Martian year. For the layered case, thermal properties are changed at and below 54 cm deep to correspond to those of ice-cemented soil.

Mass transport model: The ROB thermal model also includes the water vapour diffusion through porous regolith, which occurs due to differences in concentration, temperature and pressure. Thermodiffusion and barodiffusion are typically negligible and the model assumes that the mass flow is described by the Fick's law. When the water diffuses through the regolith during the Martian year, it can undergo phase transitions. The mass conservation equation takes into account the different phases of water: vapour, ice and adsorbed H_2O.

The determination of the diffusion coefficient depends on the pore radius. When the pore radius is greater than ten times the mean free path of the diffusing molecule, the normal molecular diffusion occurs and collisions between gas molecules dominate. In the case of Knudsen diffusion, collisions between gas molecules and the pore walls will dominate (the pore radius is less than about one tenth of the mean free path). It is important to note that the presence of ice in the pores will affect diffusion by reducing the pore size. Finally, when the mean free path is the same order as the pore size, which is the case for water vapor in the Martian subsurface, the two types of diffusion (Knudsen and Fickian) must be taken into account.

The boundary conditions of the model are given by the partial pressure of water at the surface (assumed or given by the observations) and a zero flux in the last subsurface layer. We have computed the accumulation of an ice layer from atmospherically derived water vapor during an annual temperature cycle, under simplified conditions. The model calculation assumes the same inputs as in Schorghofer and Aharonson (2005). A sinusoidal surface temperature and constant daytime partial pressure $p_0 = 0.1$ Pa are assumed and adsorption is not included. The diffusion coefficient is not ice dependent and is assumed to be $D = 0.1(T/200\ K)^{3/2}$ cm^2 s^{-1}. Other parameters are the thermal inertia I = 280 J m^{-2} K^{-1} s$^{-1/2}$ and the volumetric heat capacity $\rho_c = 1.28 \times 10^6$ J m^{-3} K^{-1}. The results are similar to those of Schorghofer and Aharonson (2005). A layer of frost migrates inward during the warming part of the cycle and begins to fill the subsurface with ice.

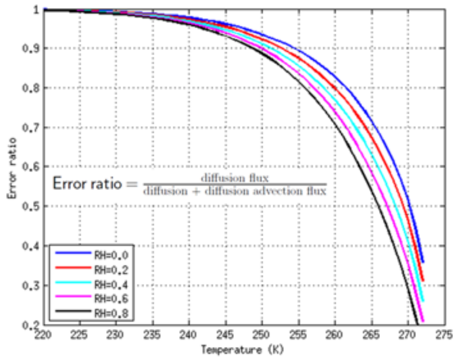


Figure 19: Error ratio under Mars conditions by ignoring diffusion advection from 220 to 273 K for various relative humidities (modified from Ulrich (2009)).

Influence of advection on water vapour transport: Advection and its influence on water vapour transport in Martian conditions have been studied. Indeed, the only use of Fick's law to calculate the flow in temperature and pressure conditions of Mars will result in an erroneous value (Ulrich, 2009). The total flow is the sum of the diffusive flow and advective flow and diffusion advection for water vapour will be negligible only if the mole fraction of water vapour is very low. Figure 19 shows the underestimation of water vapour flux under Mars conditions if advection is not taking into account. For a relative humidity of 0.8 and a temperature of 260 K, the flux calculated without advection is 30% less than the total flux. In addition, simulations showed that ice filling in pores is more important with advection than without.

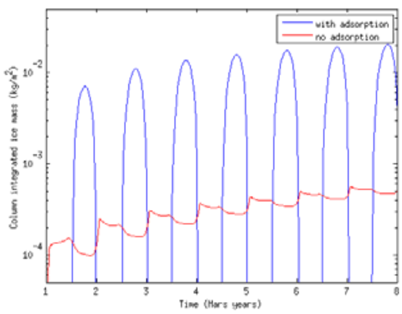


Figure 20: Ice accumulation as a function of time with a mean temperature of 190 K.

Influence of adsorption on water vapor transport: Adsorption at thermodynamic equilibrium is determined by the partial pressure of water and the temperature. The ROB model uses adsorption isotherms for palagonite (Zent and Quinn, 1997).

Figure 20 shows the total mass of ice in the Martian subsurface as a function of time with adsorption (blue) and with no adsorption (red). The change in the total mass of ice in the subsurface has greater amplitude with adsorption than without. The period and the slope of this variation are identical for both situations, which indicates the same net accumulation. However, the vertical profile of water vapour density and the quantity of water exchanged periodically are strongly affected by adsorption.

In ROB model, adsorption is supposed instantaneous but a time lag exists to reach equilibrium due to the intrinsic kinetics of the adsorption process. The equations taking into account the kinetics of adsorption were implemented in ROB model. However the determination of kinetic constants for adsorption and desorption in Martian conditions is quite difficult given the lack of experimental data on the subject. Several kinetic parameters known at given pressure and temperature (Beck et al., 2010; Chevrier et al., 2008; Zent et al., 2001) will be used in the model to characterize kinetics influence at constant pressure and temperature. Figure 21 shows the amount of adsorbed water as a function of time for different samples at 243 K and 0.1 Pa. The time needed to reach equilibrium is different for each sample.

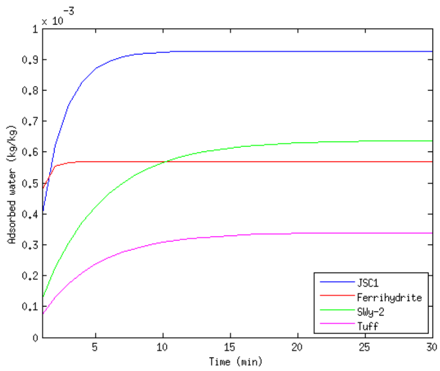


Figure 21: The amount of adsorbed water as a function of time for different samples at 243 K and 0.1 Pa. Kinetic constants and specific surface areas are taken from Beck et al. (2010) and Pommerol et al. (2009) respectively.

MSL observations: ROB model has been applied at MSL landing site to study the exchange of water between the subsurface and the atmosphere and MSL data (air pressure and water mixing ratio) were used to calculate the H_2O flux during MSL sols 15-17 (Savijärvi et al., 2015). On Figure 22, a flux less than zero represents H_2O passing from the atmosphere into the ground. During the night, the atmosphere is very stable near the surface and the regolith is slowly depleting the atmosphere of water vapour. In the morning there is a sudden pulse of water vapor in the subsurface. At this time, the atmosphere begins to become convective and there is an enrichment of water vapour in the lower atmosphere. As the temperature increases, desorption of water occurs causing soil vapour concentrations to increase. Around 10am, H_2O concentrations become higher than those of the atmosphere and the flow is reversed. This process continues throughout the day until the temperatures decrease.

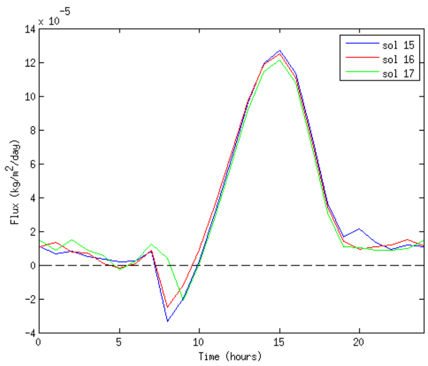


Figure 22: Water vapour flux between the atmosphere and the subsurface.

Methane transport: Methane transport in the Martian subsurface has been studied with a diffusive model. CH_4 may be trapped and released by clathrate hydrates, whose stability zone has been previously studied and was found starting from 50 m deep at the equator and 1 m deep at the poles. Figure 23 shows methane flux over time between the subsurface and the atmosphere due to the dissociation of 1 m^3 of CH_4 clathrates at different depths. The time between clathrate hydrates dissociation and the peak flux depends on source depth and the magnitude of the peak is higher for shallower source depth. In addition, the CH_4 flux decreases more rapidly after peak release for shallower source depth.

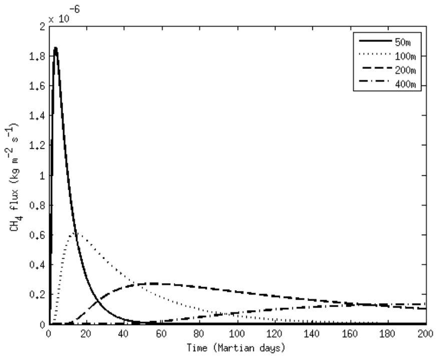


Figure 23: Methane flux over time between the subsurface and the atmosphere due to the dissociation of 1m^3 of CH_4 clathrates at 50, 100, 200 and 400 m deep.

The methane release due to destabilization of clathrate hydrates could provide a sudden flux of CH_4 into the atmosphere that could feasibly create a plume as observed by Mumma et al. (2009) but advection transport and effects of adsorption remain to be implemented in the methane transport model.

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

WP 2.1: Solar illumination, solar wind, magnetosphere and atmosphere interactions for determining the net loss of atmospheric material

Atmospheric models

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 were involved in high-level working group (ISSI workshop). With atmospheric models, we understand a repository of geophysical data accessible in terms of species, time, solar local time, longitude and latitude, etc.

The Mars GCM model was applied for continued support of observations by 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) (Daerden et al. 2015).

Atmospheric models – Modeling of the interaction between the surface and the atmosphere

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 BIRA-IASB, a 3D global circulation atmospheric model considering photochemistry..

Venus: Atmosphere/mantle coupling

Our work aims at producing a coupled code for the long term evolution of terrestrial planets, taking into account many different mechanisms that have a direct effect on surface conditions and habitability. It will be able to provide a precise and complete view of the planet's history from its solid part to outer fluid layers, including mantle convection, surface conditions and atmospheric escape, and considering the interactions between these layers/reservoirs. Our work demonstrates why these interactions are important in the long run and need to be considered when modeling terrestrial planets. Venus is chosen as a test subject due to its similarity to the Earth (bulk composition, formation…) and its massive atmosphere, which will enhance the coupling mechanisms.

In this work, we developed models in order to simulate the following mechanisms. The coupled model is also used to test how the different reservoirs interact with each other.

- Atmospheric escape (hydrodynamic): relevant during the early evolution (0-500 Ma), when Extreme UV flux leads to massive loss of hydrogen and oxygen. Noble gases are fractionated during that time.
- Atmospheric escape (Non-thermal): the main escape-mean during the bulk of the evolution. ASPERA data for present day are used, as well as modern numerical simulations of the different mechanisms.
- Atmospheric surface conditions and vertical profiles of pressure and temperatures relevant for exchange between reservoirs. A radiative-convective model is used for a grey atmosphere (considering total incoming energy, rather than differenciating between wavelengths), based on the greenhouse effect of water dand CO_2.
- Mantle dynamics and volcanism: providing temperature evolution and volcanic degassing of the mantle to the atmosphere. They are calculated with an adapted version of the state of the art StagYY code developed initially by Paul Tackley.
- Effects of meteoritic and cometary impacts on the atmosphere and the mantle of the planet.

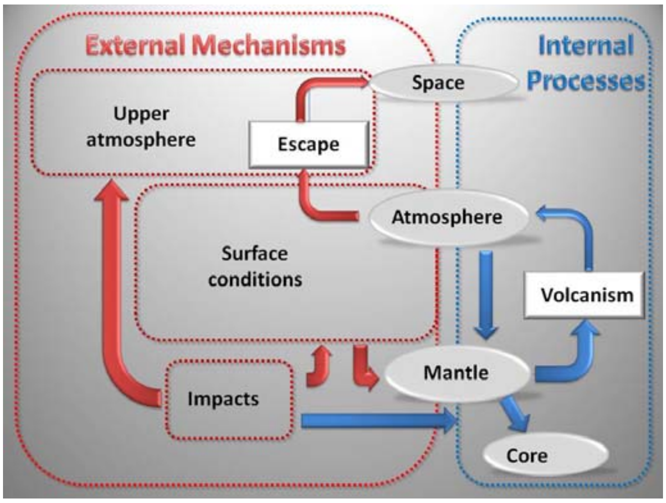


Figure 24: Mechanisms and feedbacks between layers in a terrestrial planet: current state of the model.

Modelling of solar radiation erosion, impacts, and volcanism on atmosphere evolution – Application to Venus

We worked on mechanisms that deplete or replenish the atmosphere: atmospheric escape to space and volcanic degassing of the mantle. These processes are linked to obtain a coupled model of mantle convection and atmospheric evolution, including feedback of the atmosphere on the mantle via the surface temperature.

Solar radiation erosion: During early atmospheric evolution the hydrodynamic escape is dominant, while for later evolution we focus on non-thermal escape, as observed by the ASPERA instrument on the Venus Express Mission. The atmosphere is replenished by volcanic degassing from the mantle, using mantle convection simulations based on those of Armann and Tackley (2012), and include episodic lithospheric overturns.

Convection and volcanism: The evolving surface temperature is calculated from the amount of CO_2 and water in the atmosphere using a grey radiative-convective atmosphere model. This surface temperature in turn acts as a boundary condition for the mantle convection model. Cédric Gillmann obtained a Venus-like behavior (episodic lid) for the solid planet and an atmospheric evolution leading to the present conditions.

CO_2 pressure is unlikely to vary much over the history of the planet; with only a 0.25-20% post-magma-ocean build-up. In contrast, water pressure is strongly sensitive to volcanic activity, leading to variations in surface temperatures of up to 200 K, which has an effect on volcanic activity and mantle convection. Low surface temperatures trigger a mobile lid regime that stops once surface temperatures rise again, making way to stagnant lid convection that insulates the mantle.

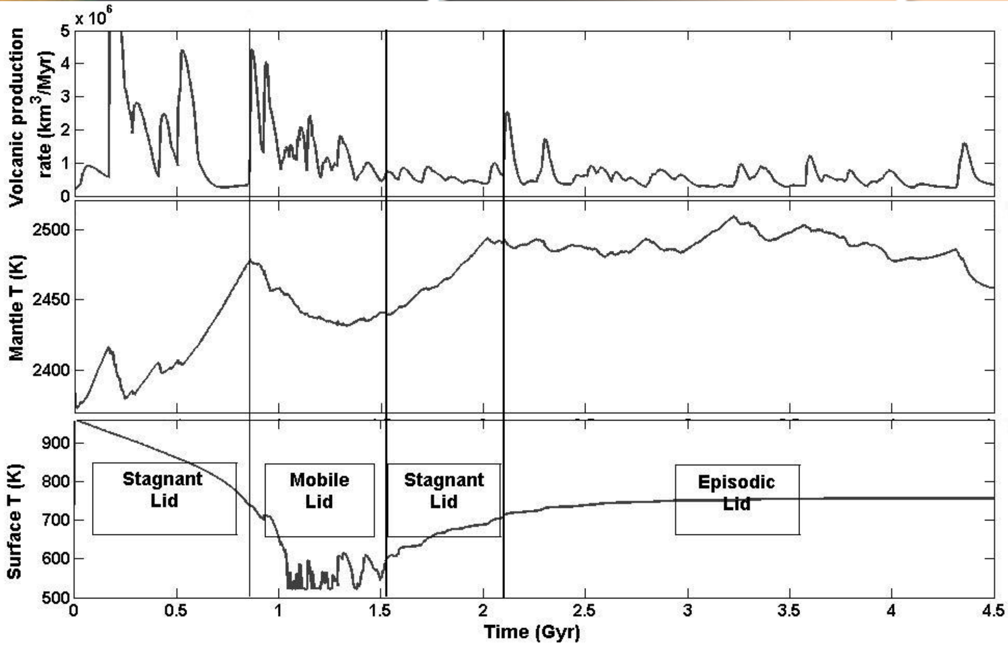
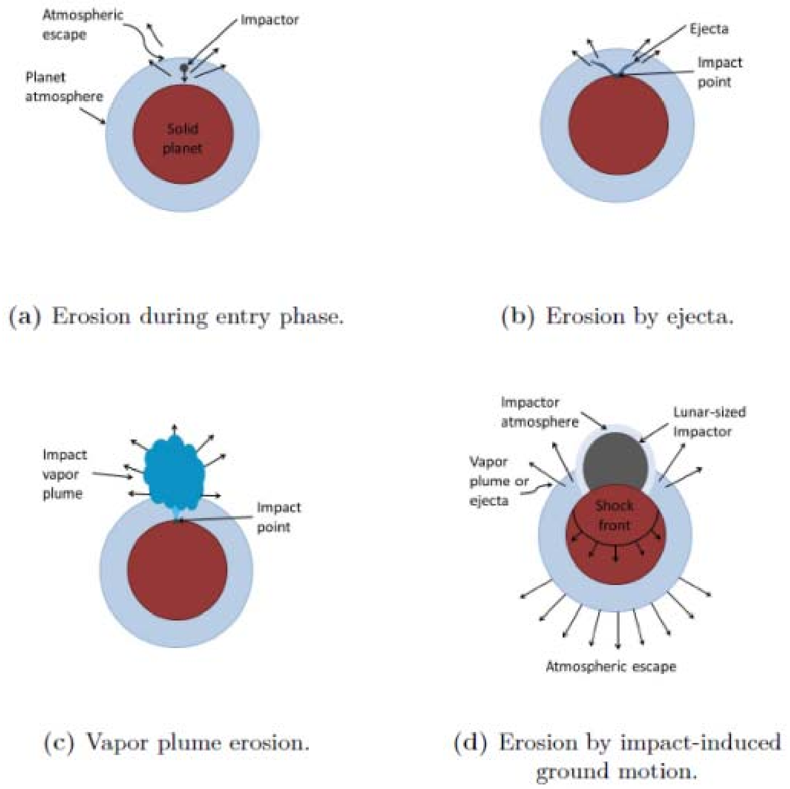


Figure 25: Comparative evolution of volcanic production rate, surface temperature and volume averaged mantle temperature with time for the reference case. Also indicated are the different convective regimes. The transition from mobile lid to stagnant lid is progressive. Early evolution (before 700Myr) follows an episodic, but mostly stagnant, lid pattern.

Impacts: Models studying the erosion of the planetary atmospheres due to ground movement induced by impacts have been either limited to case studies of a single impact or they were considering the impact erosion of the atmosphere after the formation of the planet, when impactor bodies are significantly smaller compared to their size during planetary accretion.



(a) Erosion during entry phase. (b) Erosion by ejecta. (c) Vapor plume erosion. (d) Erosion by impact-induced ground motion.

Figure 26: Mechanisms for the impact erosion of the atmosphere illustrated.

We have incorporated a model for erosion from meteorite impacts into the existing framework of the long term evolution model he previously developed. Due to large uncertainties in the simulation of the effects of large impacts, two different cases have been taken into account.

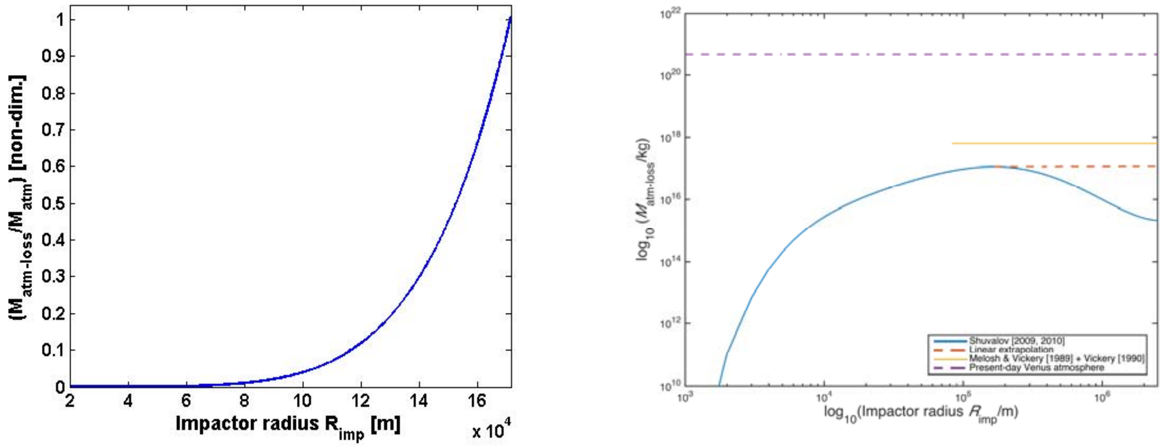


Figure 27: Two possible evolutions of atmosphere erosion by impactor with increasing impactor radius. Left hand panel shows large erosion increases with a model similar to Ahrens, 1993 and right hand panel shows much smaller erosion based on recent modelling by Shuvalov (2009, 2010) and the tangent plan model.

The earlier studies indicated that impact erosion is always a very efficient mechanism. Contrary recent and more advanced work by other authors came to the opposite conclusion that even giant impacts generally contribute to the volatile budget of the target body, except in extreme cases in which the impactor velocity is significantly higher than the mutual escape velocity or in which the surface is liquid.

The discrepancy between the results was shown to be due to the mathematical criterion for atmosphere loss used by the previous workers assuming incipient loss instead of complete loss. The contribution of transient silicate vapour to the primordial atmosphere was until now only considered in a single model. This study indicates that the contribution of silicate vapour to the atmosphere could help to suppress hydrodynamic loss as the mean molecular weight of the atmosphere is increased.

Modelling of solar radiation erosion, impacts, and volcanism on atmosphere evolution – Application to Mars

We have done preparation work to apply the project to Mars condition in a collaboration with François Forget's team in Paris. As opposed to Venus atmosphere where the vertical axis is the most important when studying atmosphere evolution due to its density and the planet's orbital parameters, on Mars, the 2D horizontal direction is more significant as strong changes in temperature and other parameters can occur across the surface. Additionnally, impacts are shown to have important effects on surface conditions. We therefore planed to combine those aspects in this new study. The main parts of the project include expertise relative to subsurface processes (see part on clathrates), software previously developed at ROB for surface conditions of Mars (by L. Pham and O. Karatekin), our work on Martian condition evolutions (Gillmann et al., 2009, 2010, 2012), evolution of the interior of the planet and long term surface conditions using the StagYY code and climate studies using the Mars Global Circulation Model developed by F. Forget at IPSL, Paris. We have begun to run test simulations on the effects of meteoritic impacts on the surface of Mars and their long term consequences as well as simulations of surface conditions evolutions to allow for the later calculation of surface climate at different times by the MGCM.

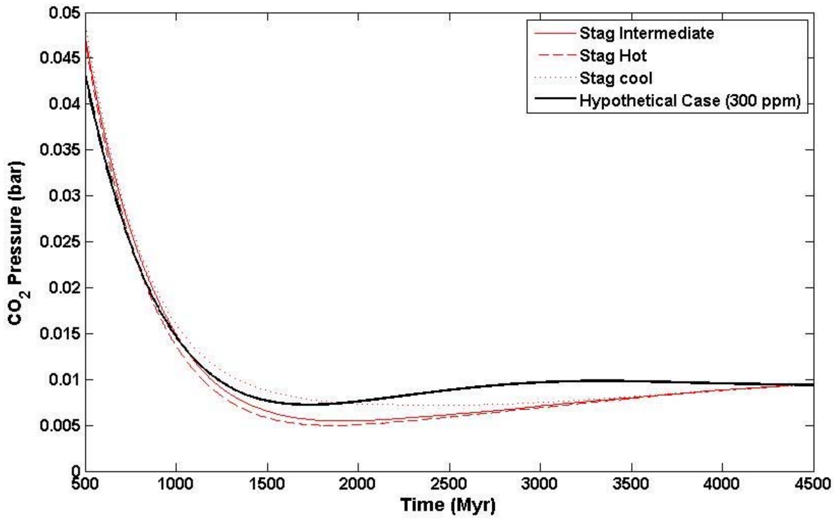


Figure 28: simulation of martian evolution for CO_2 partial pressure in the atmosphere (constituting the bulk of the atmosphere) over the last 4 Gyr using different initial states.

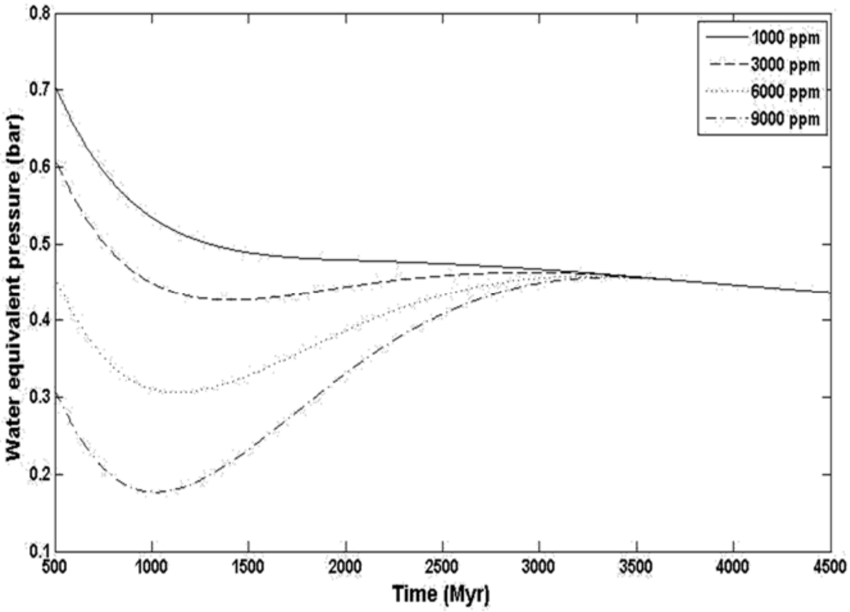


Figure 29: Water content at the surface of Mars (atmosphere and ice shelves) during the last 4 billion years reconstructed from present observation and modeling of volcanism and volatile escape.

Modelling of the interaction between solar radiation and the atmosphere

ASIMUT was developed at BIRA-IASB for Earth monitoring studies and extended to Venus and Mars. To better take into account the effect of the aerosols, ASIMUT has been coupled to LIDORT (ASIMUT-ALVL). The program is being tested within the inter-comparison exercise of radiative codes that is being organized within the NOMAD consortium. An online version of the program is now accessible through a dedicated web interface. The code has been improved to accommodate new instruments: OMEGA and PFS on board Mars Express (comparison exercise in the frame of the H2020 UPWARDS project) and to the NOMAD instruments. Different aspects are being implemented to consider and take advantage of the high number of data that will soon be available. For example, the possibility to use Look up Tables has been implemented, to reduce the analysis time.

Mass and energy transport at the magnetopause

The escaping material from the ionosphere is a major contributor to the mass residing inside the Earth's magnetosphere. The magnetosphere interacts with the interplanetary medium, so that there can be mass exchange between both. The transfer of mass and energy largely occurs at the magnetopause.

Only recently, with the advent of formation-flying multi-spacecraft missions such as Cluster and the associated multi-point data analysis tools, has it become possible to compile magnetopause statistics that are both extensive and sufficiently precise. A large-scale statistical analysis (Haaland et al., 2014) finds that there is a dawn-dusk asymmetry in the magnetopause thickness, with a median magnetopause thickness of around 1400 km at dawn and around 1150 km at dusk, both thicker than earlier reported dayside magnetopause thicknesses of 500-1000 km. The dawn-dusk difference is well below the typical range of the thickness variation, but nevertheless significant.

In 2015 we have conducted a study to examine the possible origin of this difference. The internal structure of the magnetopause is determined by the typical plasma properties in the magnetosheath and the magnetosphere on either side, which by themselves may show dawn-dusk asymmetries. Crucial also is the presence of a magnetic field rotation across the discontinuity, dictated by the ever-changing orientation of the interplanetary magnetic field. The flow shear across the magnetopause progressively increases from zero near the subsolar point to essentially the undisturbed solar wind flow speed along the tailward flanks. We have examined in particular the situation at the dawn and dusk flanks. We have used a particular kinetic tangential discontinuity model to determine the structure of the Chapman-Ferraro layer. The study – currently under review – describes how the magnetopause equilibrium structure is affected by the electric field inside the magnetopause, which in turn is related to the dawn-dusk difference in magnetosheath flow orientation. While the results of the calculations depend on the specific assumptions made in the model about the magnetosheath and magnetospheric particle populations, the drift speeds, and the transition lengths in the discontinuity, the robust conclusion remains that a dawn-dusk asymmetry is present in view of the interplay between the convection electric field and the Chapman-Ferraro electric field. The simulations confirm that the dawn magnetopause tends to be thicker than the dusk magnetopause by 15-25%. Of course, the external sources of asymmetry will play a role as well. See Figure 30.

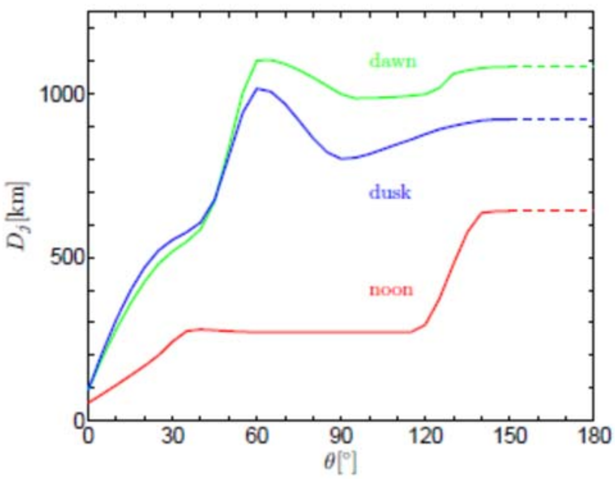


Figure 30: Magnetopause current layer thickness **Dj** as a function of magnetic field rotation angle θ. (De Keyser et al., 2015, accepted)

Magnetospheric mass circulation

The work on magnetospheric mass circulation was continued at a slow pace. No major progress was made.

Polar cap arcs and ionospheric ion outflow

Polar cap arcs are a class of auroral arcs occurring above the polar ionosphere. They can be of significant importance for ionospheric erosion as they occur at very high latitude where upflowing ionospheric ions are unlikely to be returned to the ionosphere. We collaborated to studies investigating the formation mechanism of large-scale polar cap arcs (Mailyan et al. 2015; Fear et al. 2015) and continued the analysis of multi-instrument observations of small-scale polar cap arcs (Hosokawa et al. and Maggiolo et al., in preparation).

Maes et al. (2015) published a paper in the beginning of the year, based on the work of 2013-2014, about the effect of solar illumination on the ion outflow in polar cap arcs. They show that the ion upflow from the polar ionosphere is strongly modulated by solar illumination and that the dependence manifests itself as two regimes, stronger upflow above a sunlit ionosphere and lesser above a dark ionosphere. The transition between both happens at a solar zenith angle higher than 90°. This work demonstrates that solar illumination strongly impacts ionospheric outflow, in particular for heavy ions, something that is confirmed by other studies.

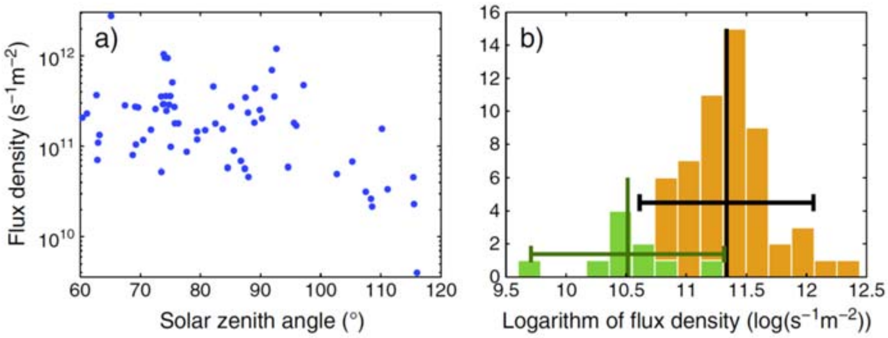


Figure 31: (a) The escaping O^+ flux densities observed in a number of polar cap arcs by Cluster versus the SZA of the ionospheric foot point. (b) The histograms of the logarithm of the O^+ flux densities in orange/green for the events with SZA lower/higher than 100°. The vertical black/green line gives the mean of the orange/green distribution; the horizontal lines show the 1.96σ interval. (Maes et al., 2015).

Inspired by these results, this year we investigated what would be the effect of solar illumination on the cold ion outflow (polar wind) from the whole magnetic polar cap. To do this we made a simplified model of polar cap ion outflow with two distinct regimes, sunlit and dark, neglecting all other possible natural spread. The model calculates the area of the magnetic polar cap which is sunlit and which is dark, as well as the resulting outflow. We show that the outflow exhibits diurnal and seasonal variations. Even when the outflow from both hemispheres is combined, there are still seasonal and diurnal variations. We also incorporate the asymmetry in the magnetic field between the northern and southern hemisphere and find that this adds an extra effect to the outflow. A paper is in preparation.

We have used the Cluster data set from André et al. (2015) to study the dependence of the ion outflow on solar illumination and season in order to look observationally for north-south asymmetries in the outflow. This data set uses a new observational technique to determine the cold ion outflow originating in the polar cap, which is normally very difficult to measure. A dependence on the solar zenith angle of the origin of the measured ions was found, showing that the outflow is controlled by solar illumination. The data also shows a seasonal dependence, which is expected because the solar zenith angle of the origin of the ions also depends on the seasons. Finally, there is also an asymmetry in the observed flux between north and south, both in the average flux and in the spread of the flux. However, due to the limitations of this data set, it is not completely clear whether this is really an effect from the north-south asymmetry or a seasonal effect. A paper is planned.

A book chapter entitled "Auroral arcs and ion outflow" has been finalized (Maggiolo, 2015). This chapter is part of the AGU book "Auroral Dynamics and Space Weather" and summarizes our current knowledge of ionospheric ion outflow associated with auroral emissions.

L. Maes is active within an International Space Science Institute group that investigates effects in the atmosphere and near-Earth space due to the north-south asymmetry in Earth's magnetic field. In 2015, he organized a session at the 2015 AGU fall meeting about ion outflow, and prepared for such a session at the upcoming 2016 EGU General Assembly.

WP 2.2: Sources of abiotic atmospheric gases: volcanism and impacts

See WP 1.3: Internal and external volatile content in particular Carbon Dioxide (CO_2), Sulfur dioxide (SO_2), methane (CH_4) and water (H_20) and planetary evolution

WP 2.3: Relation between atmosphere and cryosphere

Long term atmosphere evolution with temperature allowing a cryosphere is also treated in WP1.3.

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

WP 3.1: Identification and Preservation of life tracers in early Earth and analog extreme environments

The research objectives of the ULg team focuses on:

1) The **identification of Early traces of life** and their **preservation** conditions, in Precambrian rocks of established age

2) The characterization of their **biological affinities**, using **innovative approaches** comprising micro to nanoscale morphological, ultrastructural and chemical analyses of fossil and recent analog material

3) The determination of the **timing of major steps in evolution**. In particular, we aim to decipher **two major and inter-related steps in early life evolution and the rise of biological complexity**: the evolution of cyanobacteria, responsible for Earth oxygenation and ancestor of the chloroplast, and the evolution of the domain Eucarya.

4) The determination of **causes of observed pattern of evolution** in relation with the environmental context (oxygenation, impacts, glaciations, tectonics, nutrient availability in changing ocean chemistry) and biological innovations and interactions (ecosystems evolution).

5) The characterization of **habitability conditions** through space and time in the solar system and beyond.

To address these objectives, we are characterizing chemical and morphological biosignatures at the macro- to the micro-scale, and their mode of preservation, in Precambrian rocks and in modern analogs from extreme environments. We also study the geological context locally (age, environments, redox conditions) and globally (climate, tectonics, metamorphism) to better constrain the co-evolution of Earth and Life.

A) Modern analogs

Cyanobacteria are crucial microorganisms because they "invented" oxygenic photosynthesis, changing forever the chemistry of early Earth oceans and atmosphere and creating new ecological niches where complex life evolved. In this part of the project, we want to determine new biosignatures of cyanobacteria; to constrain the origin of oxygenic photosynthesis; and to pinpoint the origin of the chloroplast, resulting from an important symbiotic event that led to a large diversification of the eukaryotes.

We have completed the characterization of biosignatures from cyanobacterial mats growing in high UV Antarctic lacustrine habitat (Lepot et al., Geobiology 2014). We showed that cells and filamentous sheaths with pigments diagnostic of cyanobacteria (scytonemin) from modern mats could be preserved in 3000 years old siliciclastic sediments. Using electronic microscopy, Raman microspectroscopy and confocal fluorescent microscopy, we showed that preservation of these organic remains occurred through the precipitation of nanominerals (aragonite and clays). This study evidenced for the first time the preservation of cyanobacterial pigments in ancient sediments and their potential as taxonomic signatures in the geological record.

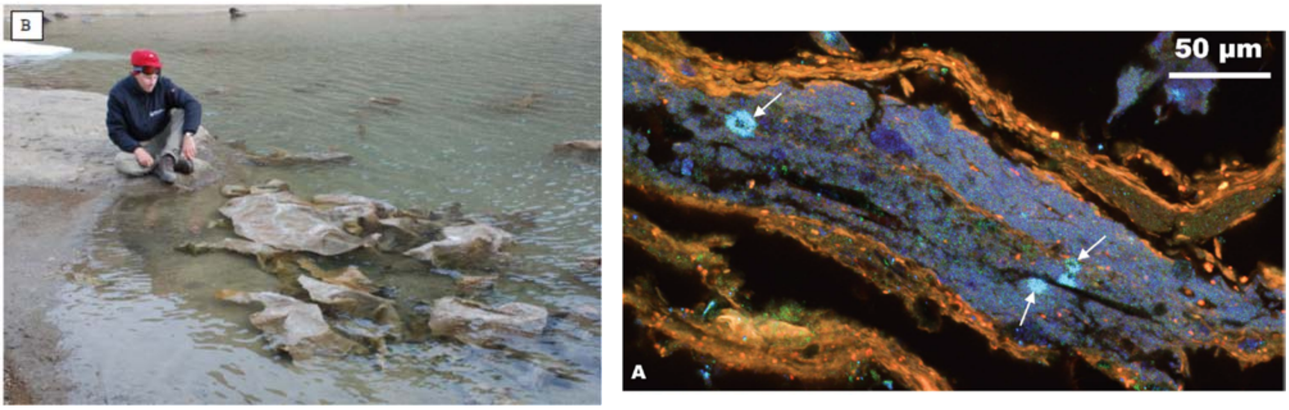


Figure 32: Microbial mats on the shore of a lake in Antarctica (left) and a confocal fluorescence microscopic image of the cyanobaterial mat with carbonates and clay minerals (right).

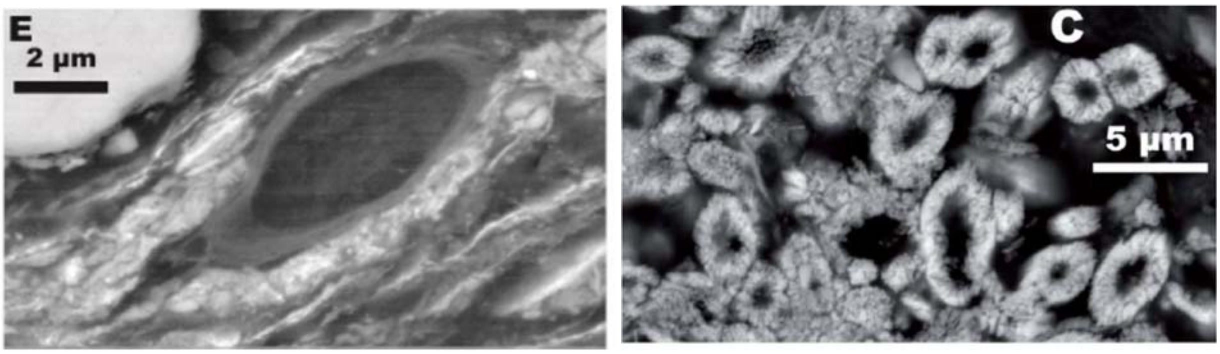


Figure 33: SEM images of cells incrusted by clay minerals (left) and nano-aragonites (right), in fossil samples of the microbial mats, from a drill core through sediments of the Antarctic lake.

We are also studying other pigment signatures of cyanobacteria in carbonate extreme environments. The cyanobacteria *Gloeocapsa* forms biofilms growing on carbonate walls from Belgium and in shoreline rocks from Croatia, and are exposed to high dessication and seasonal UV conditions. Identifications is made with optical microscopy, molecular analyzes, and pigment compositions with micro-Raman spectroscopy, in coll. with S. Golubic (Boston Univ.) and A. Wilmotte team (ULg) (Storme et al, Astrobiology 2015). Using the same techniques and electronic microscopy, we are also investigating biomineralization of carbonates by cyanobacteria in modern travertine deposits of the Hoyoux River (Belgium) (Postdoc J.Y. Storme, coll. A. Wilmotte, P. Compere, ULg; S. Golubic, Boston Univ.) (in prep).

Another ongoing study, in coll. With prof D Baurain (ULg) investigates the evolution and diversification of these crucial bacteria through molecular phylogenies and reevaluation of their fossil record (PhD L. Cornet, paper in prep.).

B) Early Earth-Proterozoic

We are interested by the interactions between the biosphere and the geosphere during this time period, between 1.8 and 0.8 Ga, called the "boring billion", marked by stratified oceans and fluctuating oxygenation conditions, and during which complex life (eukaryotes) started to evolve and diversify.

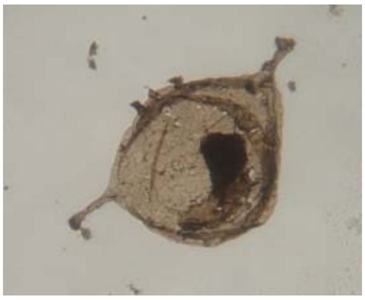


Figure 34: Picture of a 1.5 Ga protist, ~100 µm in diameter.

We are thus studying the oldest record and the evolution and diversification of eukaryotes through the Proterozoic, in rocks from:

- the 1.5 Ga Roper Group, Australia (see Figure 34).
  We have completed a detailed taxonomic analyzes of this assemblage,as well as characterized its paleoecology and discuss paleobiological innovations in the domain Eucarya (Javaux & Knoll, J Paleontology, in review).
- the 1.1 Ga Taoudeni Basin, Mauritania (IAP PhD J Beghin) (see Figure 35). J Beghin has a paper in review on the diversity and taxonomy of this exquisitely preserved microfossil assemblage. He also spent a month at the univ. of Leeds (UK) to determine the redox conditions using Fe speciation, in Prof S Poulton's laboratory who is the leader in this field and established the method. This is part of another paper on the paleoecology and possible link with redox conditions of early eukaryotes.

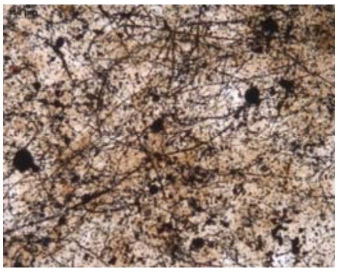


Figure 35: Picture of a microbial mat, ~5 mm across.

- the ~1.1-0.8 Ga Mbuyi-Mayi Supergroup, RDC (ERC PhD B.B. Kabamba, IAP Postdoc C. François, postdoc D Asael, coll. with MRAC). (see Figure 36). This study combines micropaleontology with geochronology (postdoc IAP C. François), chemostratigraphy (in coll. with Univ. Riverside, California), and analyzes of redox conditions using Fe and Mo isotopes (postdoc ERC D. Asael-now in Yale univ, IAP C François, coll. O. Rouxel, Ifremer, and S. Poulton, Univ. Leeds, UK) at high-resolution of sampling and on the same samples. This is crucial for the interpretation of data. A new IAP postdoc Camille François (PhD in IPGP, Paris) was hired to date the RDC drill cores using innovative geochronological techniques (U-Pb on monazite, zircons, Re-Os on sulfur in black shales[1]), and Sm-Nd datings on basaltic lavas, in collaboration with the ULB team. Several papers are in preparation.

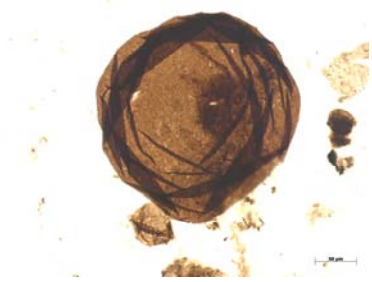


Figure 36: Picture of an organic-walled microfossil, about 80 µm in diameter.

- A new PhD student (Y. Cornet, ERC) is investigating the diversification of eukaryotes through the cryogenian, before and through the "snowball Earth" period, during which Earth was almost completely ice-covered. He is combining (optical and electronic) microscopic and microchemical methods to investigate the biological affinities of microfossils and to date branching events in the early evolution of protists (unicellular nucleated cells). A paper is in preparation, in coll with N Butterfield (Cambridge, UK).

[1] Shale is a fine-grained, clastic sedimentary rock composed of mud that is a mix of flakes of clay minerals and tiny fragments (silt-sized particles) of other minerals, especially quartz and calcite. The ratio of clay to other minerals is variable.

C) Early Earth-Archean

In collaboration with the ICDP project “cradle of life”, sampling of drill cores and fieldwork by E Javaux and ULB partner (Feb. 2013) and postdoc J.Y. Storme (Aug.-Sept 2014), permitted to characterize the organic matter preserved in different sedimentary facies of the 3.2 Ga Mapepe Fm, Barberton, South Africa (see Figure 37). To do so, the ERC Postdoc (J.Y. Storme) is using micro-raman spectroscopy and pyrolysis (coll. S. Derenne, Univ. Paris) (paper in prep.).

Figure 37: Barberton area.

In coll. with a Japanese team led by Dr.K Sugitani (Nagoya) and with Dr. K Lepot (Univ. Lille 1), and using TEM, SEM, micro-Raman spectroscopy and C isotope analyzes, we also characterized intriguing complex microfossils in 3.45 Ga rocks from the Streeley Pool Fm, Australia (Sugitani et al., Geobiology, 2015). Evidence for the endogenicity, syngenicity, and biogenicity was revealed for these large spindle-shaped microfossils forming chains, and preserved in shallow-water and occasionally evaporitic environments.

Data from the studies summarized above and other analyzes of cell cultures and fossil and rock collections are compiled to build a searchable Infra-Red (Figure 38, left picture) and Raman (Figure 38, right picture) spectroscopic database of minerals and organic signatures.

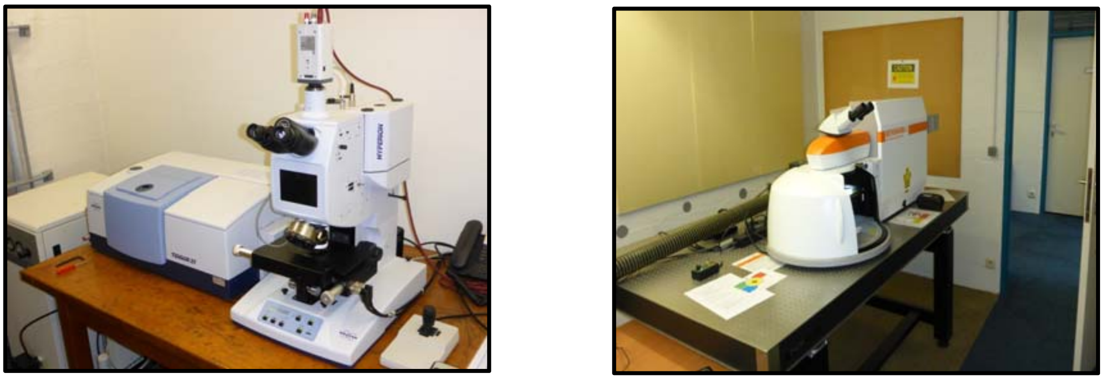


Figure 38: the ULg micro-spectroscopy labs: micro-FTIR spectrometer with Bruker Hyperion 2000 (left) and InVIA Renishaw confocal micro-Raman spectrometer (right) equipped with 3 lasers (514, 632 and 785 nm).

All PhDs and postdocs of the lab are using these non-destructive spectroscopic techniques to investigate in situ the distribution and composition of organics and minerals of their samples (rocks, living cells, isolated microfossils) in preserved context and make chemical maps at the micron or sub-micron scales. We are also refining methods for thermometry using Raman spectroscopy analyzes of organics in cherts[2] and in shales[12], and comparing with metamorphic grades defined from mineralogy.

Examination of possible abiotic processes mimicking biological processes and products is also carried out to identify real biosignatures that could be used for the detection of life in early Earth and extraterrestrial record.

All these studies led to several presentations at international meetings and several papers are in

[2] Chert is is a fine-grained silica-rich microcrystalline, cryptocrystalline or microfibrous sedimentary rock that may contain small fossils.

preparation (see publications below).

WP 3.2: Implication of life tracers preservation for in situ detection on Earth and other planets

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

The studies described in WP 3.1 of early life traces and their preservation has implications for in situ detection on Earth and other planets, and the conditions for planetary habitability.

Our study of the high UV Antarctic habitat showed the production of pigments and particular nanocarbonates by cyanobacteria and, even more interestingly, their preservation in ancient sediments. 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. Our characterization of organic-walled microfossils in Proterozoic and Archean shales and chert also evidenced the exquisite preservation of microorganisms and microbial mats. We are especially interested by the preservation of organic remains in clay minerals in early earth samples and possibly analog to those deposited during the Noachian on Mars.

The results 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. Indeed, the rovers are using a combination of macro-to microscopic tools to characterize the geological context and possible habitability of local Martian areas and lithologies, such as panoramic cameras, close-up imager (like the future CLUPI-a ExoMars instrument to which we participate), microscopes, IR and RAMAN microspectrometers to identify minerals and possible (abiotic or biotic) organics, and mass spectrometers measuring C isotopes. 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, as proposed for the ExoMars rover equiped with a drill. Our collection of well characterized fossil-rich and fossil-barren rocks can serve as reference to test instruments and landing and sampling strategies for future missions.

The studies described in WP 3.1 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. This is part of our contribution to the IAP PLANET TOPERS where we collaborate with astrophysicist, geophysicists, and geochemists, and ERC ELiTE, but also the topic of the new NASA Astrobiology Institute project "Alternative Earths" where we have been invited as external collaborator. 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 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. Our characterization of new cyanobacteria biosignatures will be used in the ancient rock record to reassess previously reported possible fossil of cyanobacteria and to extend or constrain their record. Molecular phylogenies, also ongoing, provide another approach to characterize the diversification of cyanobacteria. Other redox proxies include geochemical and geological analyses and are used worldwide in the Proterozoic and Archean rock record to constrain the chemical evolution of Earth early ocean and atmosphere. Another interesting atmospheric biosignatures, besides O_2 and O_3, is methane. Carbon isotopes analyzes of organics as old as 2.8 Ga and perhaps 3.5 Ga reveal strong fractionation in early Earth record, interpreted as evidence for the evolution of methanogens and methanotroph prokaryotes. Biological and geologically produced methane might be discriminated using this proxy if the carbon reservoir and the geological context are well characterized.

We also collaborate to the studies of habitability conditions in exoplanetary systems with astrophysicists from ULg (Speculoos project) and ORB and U Namur (FRFC ExtraOrDynHa).

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 could have evolved into a state with smaller continent coverage and a dryer mantle than observed today. On the other hand, Earth's biosphere provides enhanced weathering, erosion and sediment sedimentation. An increased rate at which sediments are subducted in turn might induce more water to be retained, potentially impacting processes in subduction zones (see Höning et al., 2014; Höning and Spohn, 2015).

WP 4: Accretion and evolution of planetary systems

WP 4.1: Isotope cosmochemistry

The first work package in WP4 is aiming at method development of isotopic systems to be used within the other packages of WP4. The direct applications may not yet be fully visible for two reasons: (1) methodology development takes time, and there is a learning period before the newly acquired instruments are fully operational, and (2) the interface between the development aspect and the application aspect starts later.

Elemental composition of iron meteorites

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. We have used laser ablation (LA) in combination with inductively coupled plasma - mass spectrometry (ICP-MS) to obtain 2-dimensional multi-element maps of the olivines present in main group pallasites (PMG). Multivariate statistical analysis of these laterally resolved multi-element data was relied on to reveal mineral- and parent body-scale processes that lead to the inhomogeneous distribution of elements in these olivines.

In addition to the information on minor element concentrations, also the isotopic compositions of selected elements in various differentiated meteorites can be used to constrain the early Solar System processes. Fe and Ni are some of the most abundant elements in the Solar System. Analytical protocols for high-precision isotopic composition of these two transition metals using multi-collector ICP-MS (MC-ICP-MS) were developed and deployed for isotopic analysis of a set of iron and stony-iron meteorite samples. Emphasis was put on the spatially resolved isotopic analysis of iron meteorites, and on the isotopic characterization of adjacent metal and silicate phases in PMG, mesosiderites, and non-magmatic silicate-bearing iron meteorites. Sampling of the phases of interest was accomplished via microdrilling.

To further extend our capabilities in terms of laterally resolved isotopic analysis via MC-ICP-MS, we have used the combination of femtosecond LA and MC-ICP-MS for the isotopic analysis of Fe in PMG and pallasites. This instrumentation is available at the Institute of Mineralogy, Leibniz University Hannover, Germany (prof. Dr Stefan Weyer and Dr Ingo Horn) and a cooperation between UGent-VUB and the Leibniz University Hannover was initiated. Fe isotopic analysis of major (olivine, kamacite/taenite metal) and minor (schreibersite, troilite) mineral phases of PMG and iron meteorites was performed with a spatial resolution down to 45 µm.

The samples investigated originate from the US Antarctic meteorite sample collection, recovered by the Antarctic Search for Meteorites (ANSMET) program, funded by NSF and NASA. These samples were characterized and are curated by the Department of Mineral Sciences of the Smithsonian Institution and Astromaterials Curation Office at NASA Johnson Space Center. A collection of ordinary chondrites was provided by the Royal Belgian Institute of Natural Sciences; it belongs to the collection of Antarctic meteorites, recovered through a joint collaboration with the Japanese National Institute of Polar Research (NIRP).

Method development

Despite the LA-ICP-MS set-up and ablation cell available at UGent being commercially state-of-art, the relatively slow washout leads to a very low sample throughput in elemental mapping, thus also degrading analytical quality as sensitivity tends to vary over such long periods. Using computer fluid dynamics, the A&MS unit has developed a novel type of ablation cell (patent pending) in which any turbulence is avoided, thus 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. While its added value has been demonstrated unequivocally, the ultrafast ablation cell developed now needs to be adapted such that also its flexibility is improved, by enabling it to hover over a larger sample surface. To further extend the possibilities of elemental mapping with LA-ICP-MS, we have recently also optimized sampling and data handling protocols. We have demonstrated that a lateral resolution below the laser beam diameter can be realized by combining overlapping laser craters and mathematical deconvolution protocols, thus demonstrating the best ever spatial resolution in the so-called far field regime.

Development of Ca isotopes measurements by Maria Valdes in order to measure the Ca isotope composition on lunar samples from the Apollo program

A case study has been performed for demonstrating the validity of the method (and presented at the Goldschmidt Conference in August 2015). The lunar samples have been granted by the CAPTEM in spring 2015 upon a rebuttal that was sent in September 2015. The lunar samples have been received in January 2016. The goal of the study will be to track the establishment of different reservoirs within the lunar mantle, and the mixing between them (see WP4.3).

Study of the average ^{142}Nd of the solar system

In the frame of the ERC starting grant “ISoSyC” to Vinciane Debaille, a thermo-ionization mass spectrometer has been acquired at ULB for performing high precision ^{142}Nd measurements. Following the first promising tests, chondritic samples (ordinary chondrites, for the first for this type of measurements from Antarctica, collection of the Royal Belgian Institute for Natural Sciences) have been measured by Rosalind Armytage. Results have been presented at the Goldschmidt Conference in August 2015. Analytical development has also been made for increasing the yield in Nd while efficiently removing the Ce causing isobaric interference. This improvement phase is still in development.

Participation in campaign

- Invited participation of Vinciane Debaille to the ANSMET campaign (American Antarctic search for Meteorites) from December 2014 to end of January 2015. This field campaign has permitted a great exchange of experience between the different procedures for collecting meteorites in Antarctica implemented in Japan and USA.
- Participation of Vinciane Debaille to a field campaign in Chile for collecting meteorites in the Atacama Desert (French expedition) in November 2015. The advantage of hot deserts over

Antarctica is the fact that the amount of extra-terrestrial materiel per area unit is preserved, so it is possible to estimate how much meteorites fall on earth every year. A strew field has been mapped, and very ancient surfaces permitted the collection of 200 meteorites. On the other hand, hot desert meteorites are much more altered and their isotope compositions should be used with caution.

WP 4.2: Role/effects of meteorites and comets impacts

Petrography/geochemistry of ejecta material

To pursue ongoing efforts to understand ejecta distribution during large impact, we have conducted spatially resolved trace element analyses on fresh, unaltered microtektite glasses linked to the Cretaceous–Paleogene (K–Pg) boundary Chicxulub crater and on their surrounding alteration phases. Using the unique approach of LA-ICP-MS, we studied 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. At the Beloc locality (Haiti), the glass population is dominated by the presence of yellow high-Ca glass and black andesitic glass formed by admixture of carbonate/dolomite/anhydrite platform lithologies with crystalline basement. These glasses alter according to the well-established hydration–palagonitization model postulated for mafic volcanic glasses. REEs become progressively leached from the glass to below the detection limit for the applied spot size, while immobile Zr, Hf, Nb, and Ta passively accumulate in the process exhibiting both inter-element ratios and absolute concentrations similar to those for the original glass. In contrast, The Arroyo El Mimbral locality (NE Mexico) is characterized by abundant green glass fragments high in Si, Al and alkalis, and low in Mg, Ca, Fe. Low Si black glass is less abundant though similar in composition to the black glass variety at Beloc. The alteration pattern of high-Si, Al green glass at the Mimbral locality is more complex, including numerous competing reaction processes (ion-exchange, hydration, dissolution, and secondary mineral precipitation) generally controlled by the pH and composition of the surrounding fluid. All green, high-Si, Al glasses are hydrated and variably enriched in Sr, Ba, and Cs, indicating preferred adsorption from seawater during hydration. Refining the geochemical signature of (altered) melt lithologies may advance our current understanding of glass stability in the natural environment and provide insight into the origin and emplacement of ejecta material during crater formation (Belza et al. Geochimica et Cosmochimica Acta 152 (2015) 1–38).

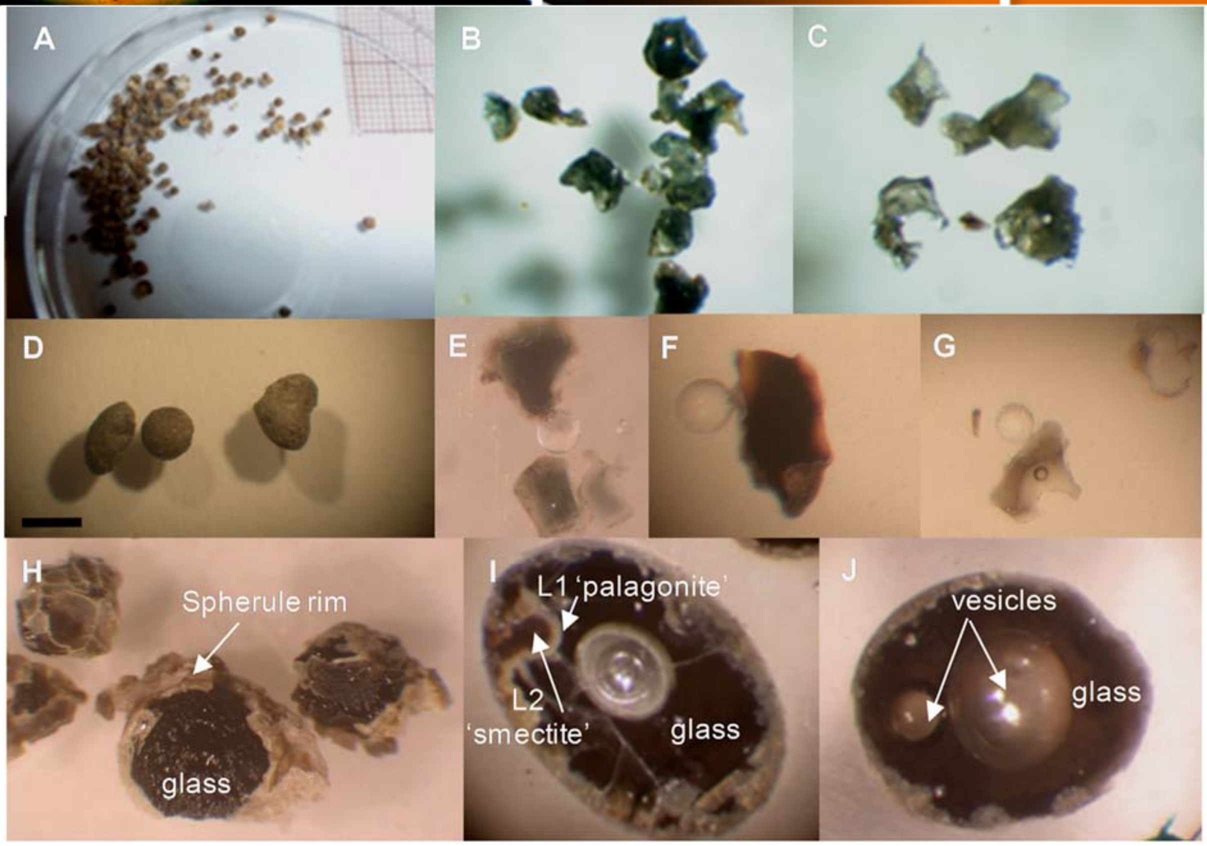


Figure 39: (A and D) Spherules separated from the Arroyo El Mimbral locality. Green glass fragments represent the most abundant variety, followed by black glass. (B and C) Note scalloped nature of the glass fragments. (E–G) Polished green (E), red (F) and black glass (G) from Mimbral. (H) Spherules from 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.

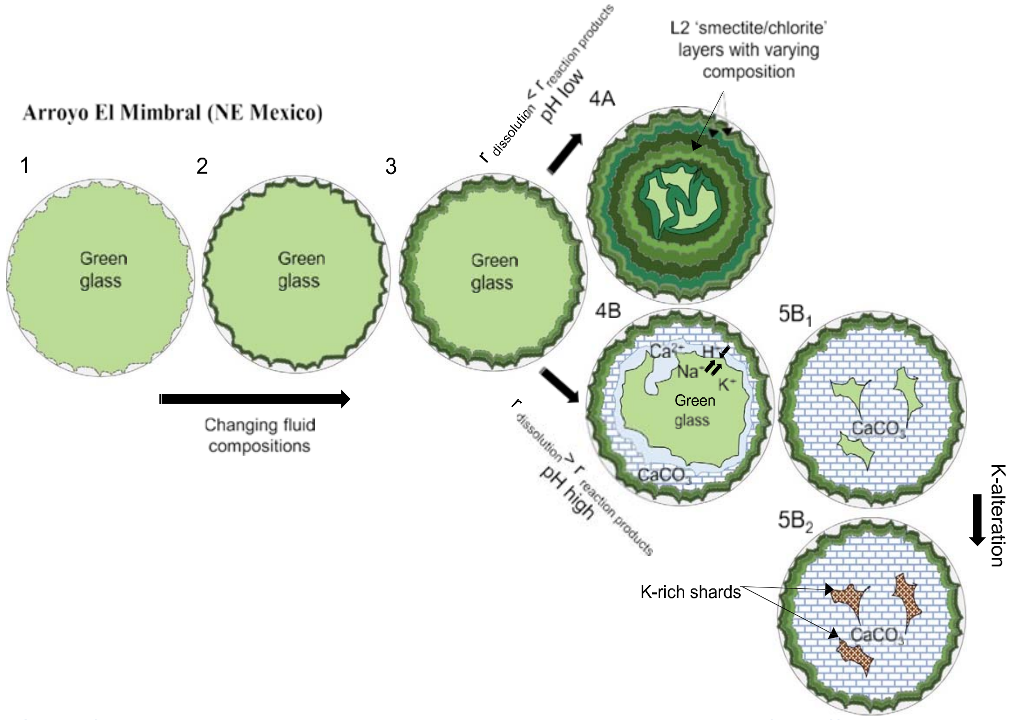


Figure 40: Simplified sketch showing the postulated alteration mechanism for different glass types. Beloc (Haiti): Black/yellow glass: hydration and formation of a 'palagonite' L1-layer enriched in Al, Fe and Ti. Arroyo El Mimbral (NE Mexico): Green glass undergoes several competing reaction processes, dominated by ion exchange, dissolution, water-diffusion and formation of secondary reaction products (hydration–palagonitization). Small, parallel alteration lamellae form when ion-exchange/secondary precipitation is the dominating alteration mechanism, usually under low pH conditions (1–4A). At high pH, dissolution dominates over ion-exchange and the glass will simply dissolve. The formation of secondary calcite rapidly cements the voids and remaining glass pieces in the spherules, often maintaining relict glass pieces in the spherules interior (4B, 4B1).

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. In the case of the El'gygytgyn (Chukotka, Arctic Russia) recently drilled by the ICDP program (2009), siliceous volcanic rocks were excavated. Several chemical and petrologic attempts, other than dating individual clasts, have been considered to distinguish impact melt from unshocked volcanic rock of the targets, but none has proven reliable. Here, we propose 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. Specifically, impact melt rocks display low cathodoluminescence intensity, whereas unshocked volcanic rocks from the area typically show high luminescence. This high luminescence decreases with the degree of shock experienced by the individual clasts in the impact breccia, down to almost undetectable when the groundmass is completely molten. This might apply only to El'gygytgyn, because the luminescence in volcanic rocks might be due to devitrification and recrystallization processes of the relatively old (Cretaceous) target rock with respect to the young impactites (3.58 Ma). The alteration that affects most samples from the drill core does not have a significant effect on the cathodoluminescence response. In conclusion, cathodoluminescence imaging and spectra, supported by Raman spectroscopy, potentially provide a useful tool for in situ characterization of siliceous impactites formed in volcanic target. (Pittarello et al. 2015, MAPS, 50, Nr 11, 1954–1969).

In meteorite research, the VUB and ULB team published a new, fast, cheap and accurate method for the classification of ordinary chondritic meteorites, which represent the vast majority of the extraterrestrial material reaching the Earth. We propose Raman spectroscopy as an alternative technique to determine the end-member content of olivine and pyroxene in ordinary chondrites, by using the link between the wavelength shift of selected characteristic peaks in the spectra of olivine and pyroxene and the Mg/Fe ratio in these phases. The existing correlation curve has been recalculated from the Raman spectrum of reference minerals of known composition and further refined for the range of chondritic compositions. Blind tests with ordinary chondrites of different provenance, weathering, and shock stages have confirmed the potential of the method. Pittarello et al. 2015, Meteoritics & Planetary Science, 50, 1718-1732).

The shock metamorphism of the mineral olivine in meteorites was also studied at very fine scale in collaboration with the group of Prof. D. Schryvers at the University of Antwerp, which are experts in transmission electron microscopy. This study might help to constrain impact events in the history of meteorites. In shock veins, olivine clasts with a complex structure, with a ringwoodite rim and a dense network of lamellae of unidentified nature in the core, have been reported in the literature. A highly shocked (S5-6), L6 meteorite, Asuka 09584, which was recently collected in Antarctica by a Belgian– Japanese joint expedition, contains this type of shocked olivine clasts and has been, therefore, selected for detailed investigations of these features by transmission electron microscopy (TEM). Petrographic, geochemical, and crystallographic studies showed that the rim of these shocked clasts consists of an aggregate of nanocrystals of ringwoodite, with lower Mg/Fe ratio than the unshocked olivine. The clast's core consists of an aggregate of iso-oriented grains of olivine and wadsleyite, with higher Mg/Fe ratio than the unshocked olivine. This aggregate is crosscut by veinlets of nanocrystals of olivine, with extremely low Mg/Fe ratio. The formation of the ringwoodite rim is likely due to solid-state, diffusion-controlled, transformation from olivine under high-temperature conditions. The aggregate of iso-oriented olivine and wadsleyite crystals is interpreted to have formed also by a solid-state process, likely by coherent intracrystalline nucleation. Following the compression, 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. (Pittarello et al. 2015, Meteoritics & Planetary Science 50, Nr 5, 944–957).

WP 4.3: Chronology of differentiation processes (core segregation, magma ocean, mantle overturn and early to recent volcanism) in the Solar System

Chronology of differentiation processes (core segregation, magma ocean, mantle overturn and early to recent volcanism) in the Solar System

- Study of 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.

The model developed implies up to 20% of partial melting of only the metallic phase. This could correspond to a temperature of 1300°C. In addition, we observed loss of volatile elements. These observations could be reconciled either with an impact inducing differentiation, either with simple metamorphism within an asteroid, followed by evaporative loss of some material into space. In addition, the use of the Al-Mg radioactive chronometer has allowed refining the age of two types of primitive achondrites thought to come from the same parent body: the acapulcoites and the lodranites. More specifically, the acapulcoites formed 1.7 ± 0.4 Ma after CAI (Ca-Al-rich Inclusion) formation while the lodranites formed 4.6 ± 1.8 Ma. These results will allow us to refine the thermal history of asteroids during the early stages of the formation of the solar system.

- Study of the differentiation of 4-Vesta.

Our final investigations indicate that a clear age difference is observed between the three main lithologies of the asteroid 4-Vesta. The basaltic eucrites correspond to the onset of a basaltic crust at the surface of the asteroid at 2.73 ± 0.93 Myr. Then, magmas sampling the same source in the asteroid went underplating the initial crust, and took longer for solidifying from 4.78 to 8.21 Myr. Finally, the diogenites are much younger, and cannot be dated using this system. However, we show that the source of diogenites is clearly distinct from the one of eucrites. According to this, we privilege the hypothesis of the diogenites being formed as plutons intruding the crust of Vesta, and being possibly contaminated by the eucritic crust.

- Study of ureilites.

Ureilites are very peculiar achondrites, sharing primitive characteristics (i.e. heterogeneous oxygen isotope signatures) with igneous one (as being mantle residue after partial melting). In addition, their high content in graphite make them resembling the carbonaceous chondrites. As such, the differentiation process(es) of the ureilite parent body (UPB) remains an unsolved problem. Using Al-Mg radioactive chronometers and Zn isotopes, we demonstrated that the process of smelting is a viable process for explaining all those process. This process involves the reaction, at the very beginning of the partial melting of the UPB, of silicate magma with the graphite pre-existing. A violent redox reaction then occurred, resulting in three phases: a metal phase, a silicate phase and a gaseous phase. Zinc isotopes can be fractionated in the gaseous phase. In addition, the very small degree of partial melting needed for having this reaction prevented the homogenization of the UPB. Finally, such an explosive reaction likely fragmented the UPB that re-accretionated. Smelting is now a process existing on Earth within industries for extracting metallic ores, but is also seems to be a possible process during planetary differentiation.

- Study of the formation of IIE3 non-magmatic iron meteorites.

Those iron meteorites are quite mysterious, as they contain silicate inclusions and their chemical composition does not correspond to a normal fractional crystallization path. Several processes have been involved for explaining the existence of those iron meteorites, that can be mainly divided within two different groups: a endogenic model and exogenic model. In the first model, an asteroid is heated, triggering the segregation of metal and silicate. However, this process is so efficient that it is not clear why the separation was not perfect. The exogenic model involves melting triggered by impact, but many people were reluctant to believe that this process could lead to partial differentiation. The investigations we made clearly indicated that shock features are present within two investigated samples: Mont Dieu and Netschaevo. In addition, our observations of Netschaevo show that this meteorite is not simply a primitive member of the IIE NMI meteorites, but instead a breccia[4] containing various silicate inclusions showing different degrees of thermal metamorphism. A breccia is also typical of impact. This study clearly shows that the beginning of planetary differentiation can be induced by impact.

Comet activities

As Co-Investigators on the ROSINA-DFMS mass spectrometer on ESA's Rosetta mission currently visiting comet 67P/Churyumov-Gerasimenko, we have worked on understanding some intricacies of the instrument. De Keyser et al. (IJMS, 2015) have solved a problem with the mass spectrometer ion optics, by developing a numerical technique that is capable of removing an artefact from the mass spectra at m/Z = 16, 17, 18, which include information on a number of important species.

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[3] The iron meteorites of the IIE chemical type are octahedrites of various coarseness, most of which contain numerous inclusions of recrystallized stony silicates. See https://en.wikipedia.org/wiki/IIE_iron_meteorite

[4] Breccia is a rock composed of broken fragments of minerals or rock cemented together by a fine-grained matrix that can be similar to or different from the composition of the fragments. See https://en.wikipedia.org/wiki/Breccia

We briefly review some of the DFMS discoveries that we have participated in.

- The volatile material on the comet surface is heterogeneous (Hässig et al., 2015). This implies that there was some mixing in the protoplanetary disk (to bring together planetesimals with different compositions) but not too much (otherwise composition would have become uniform).
- The D/H ratio in comet H_2O is about 3 times the value in the Earth's oceans, indicating that comet impacts on Earth are unlikely to have contributed much water to Earth's inventory (Altwegg et al., 2014).
- We have done considerable work in helping to assemble an inventory of volatiles (LeRoy et al., 2015).
- The first-ever detection of N_2 in a comet (Rubin et al., 2015), suggesting that N_2 became trapped in comet ices at a low formation temperature of ~40 K.
- The first-ever detection of Ar in a comet (Balsiger et al., 2015), leading to a similar conclusion.
- The DFMS mass spectrometer onboard the Rosetta spacecraft detected for the first time the presence of significant levels of O_2 in a cometary coma (~4% on average, occasionally up to 10%) [Bieler et al., 2015]. This was completely unexpected, as O_2 is quite reactive and had never been seen before. In order to identify the origin of this O_2 we have modelled the interaction between cosmic rays and comets. We showed that this interaction can indeed produce large amounts of O_2 from H_2O ice in the topmost ~10 meter soil of cometary nuclei. The results are subject to considerable uncertainties, e.g. concerning the possible diffusion of O_2 within the porous ice. As 67P is a relatively young comet, and thus weakly eroded, this mechanism might be the source of cometary O_2 detected by Rosetta. We have also conducted a study about how the presence of O_2 would impact the emission of the red and green lines (Cessateur et al., 2015, accepted).
- Models of comet illumination and sublimation appear to be able to explain the fluxes seen by DFMS (and other instruments on Rosetta) (Bieler et al., 2015; Tenishev et al., 2015, under review).
- DFMS provides information about the refractory composition at the comet surface. During the early phase of the mission, at 3.5 AU from the Sun, comet activity was very limited, so that the solar wind could reach the surface and sputter material off the comet, so that Ca, K, Si, Na could be measured (Wurz et al., 2015).

While DFMS is making all these discoveries, it becomes obvious that these place strong constraints on models of the solar system formation process, on the interactions between planetesimals as they formed, and on the consequences of impacts, e.g. on early Earth. It will, however, take some time to absorb all these.

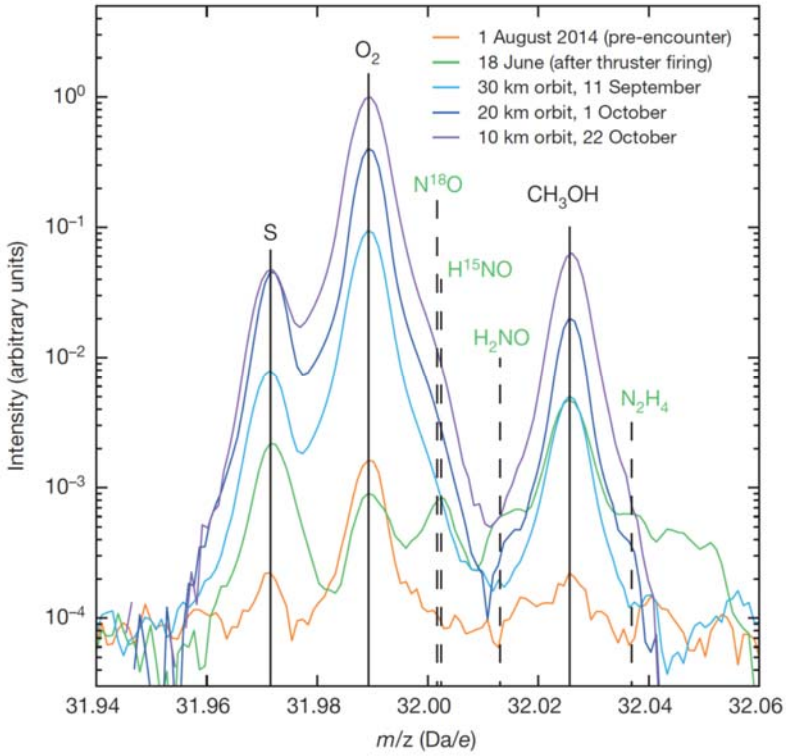

Figure 41: Typical spectra obtained with Rosetta/DFMS around mass-over-charge 32, showing the molecular oxygen peak (from Bieler et al., Nature, 2015).

WP 4.4: Onset of plate tectonics and recycling of the crust and possible implication for life sustainability

Plate tectonics, mantle overturn, and isotopic measurements

Following the proposition that plate tectonics may not have active during the Archean period (Debaille et al., 2013) we investigated the West African Craton to understand if we can observe indicators of plate tectonics, such as subduction zones chemical signatures. This project was initiated in the frame of the IUAP, and a field trip occurred in 2013. Up to now, mainly the basaltic rocks have been investigated. They show no indication of subduction zone component, and instead sample a depleted mantle resembling present-day oceanic plateaux. More acidic rocks were also investigated during a master thesis. On the contrary, they show TTG affinities that have been often attributed to subduction of hot oceanic crust. 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. This is intriguing because it has recently been proposed that oceanic plateaux could trigger subduction (Gerya et al., 2015, Nature). This hypothesis is compatible with the model proposed in 2013 by Debaille et al., where subduction was only active over short periods of time in a mainly stagnant regime.

4. Network organization and operation

Activities organized as part of the IAP network (Oct. 1st, 2014 to Sept. 31st, 2015)

The research and interactions between the teams were built during the kick-off meeting as well as the first and second annual joint meetings organized at DLR with the Helmholtz Alliance "Planetary Evolution and Life" and at ULg. There was an **Executive meeting** on November 27, 2015, as well as the **third scientific meeting**, organized at ROB. However, this meeting has been postponed due to the Level 4 security level against terrorism. 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 benefit from the **Astrobiology FNRS Contact Group** with Emmanuelle Javaux as President and Véronique Dehant as Secretary. The annual meeting 2015 is held jointly with our third scientific meeting. 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".

Informal meetings were also organized to discuss specific questions or to celebrate some of the medals and prizes awarded to Planet TOPERS members (see below), such as breakfast between members of the executives, Christmas party, summer party etc.

Figure 42: Cake at the Christmas party on 11 December 2015, representing the Martian surface and Mars' interior – author: Rose-Marie Baland.

Activities organized at International level (from Oct. 1st, 2014 to Sept. 31st, 2015)

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

There were several presentations at Geological Society of America Annual Meeting (November 1-4, 2015, Baltimor, Maryland, USA, & October 19-22, 2014, Vancouver, Canada), at the Lunar and Planetary Science Meeting in The Woodlands, Texas (March 2015), at the 38th Symposium on

Antarctic Meteorites - The Sixth Symposium on Polar Science, Tokyo, Japan (November 16-19, 2015), at the 77th annual meeting of the Meteoritical Society, Casablaca, Maroco (September 8-13, 2014), at the 78th annual meeting of the Meteoritical Society, Berklely, USA (July 27-31, 2015), at the Goldschmidt Conference – 25th anniversary, Prague, Czech Republic (August 16-21, 2015), at the 46th Lunar and Planetary Science Conference LPSC2015, Houston, USA (March 16-20, 2015), at the 12th International Symposium on Antarctic Earth Science – ISAES, Goa, India (July 13-17, 2015), at the 37th Symposium on Antarctic Meteorites - The Fifth Symposium on Polar Science, Tokyo, Japan (December 2-5, 2014), at the 38th Symposium on Antarctic Meteorites - The Sixth Symposium on Polar Science, Tokyo, Japan (November 16-19, 2015), at the American Geophysical Union Meeting (December 14-18, 2015, San Francisco, USA), at European Geoscience Union Meeting (April 7-12, 2013, in Vienna, Austria), at European Planetary Science Congress EPSC 2015, Nantes, France (September 27-October 2, 2015), at European Planetary Science Congress EPSC 2014, Centro de Congressos do Estoril, Cascais, Portugal (September 7-12, 2014), at the Planet Formation and Evolution 2014, Kiel University (September 8-10, 2014), at the Company of Biologists, Wiston House, Sussex, UK (March 8-11, 2015), at the EU EuroScience Open Forum ESOF2014 conference, Copenhagen,DK (June 21-26, 2014), at the 2015 Aquatic Sciences Meeting 'Aquatic Sciences: global and regional perspectives - North meets South', Grenada, Spain (February 22-27, 2015), at the the 18th Australian Organic Geochemistry Conference AOGC2014 (November 30-December 2, 2014), at the 4th International Paleontological Congress PALASS, Mendoza Argentina (September 28-October 3, 2014), at the ESF-EMBO Symposium Biology of Plastids, Pulstusk, Poland (June 21-26, 2014), at the ESF-EMBO Symposium Biology of Plastids, Heidelberg, Germany (June 21-23, 2015), at the Origins 2014 meeting, the second joint international conference the International Society for the Study of the Origin of Life ISSOL & the International Astrobiology Society and Bioastronomy, Nara, Japan (July 5-11, 2014), at the 15th International Symposium on Phototrophic Prokaryotes ISPP, Tubingen, Germany (August2-6, 2015), at the 14th European Astrobiology Conference, European Astrobiology Network Association EANA2014, Edinburgh, Scotland (October 13-16, 2014), at the 15th European Astrobiology Conference, EANA2015, Noordwijk, the Netherlands (October 6-9, 2015), at the COST Life-Origins (TD1308) meeting (Porto, Portugal, 22-27 March 2015), at the 12th international planetary probe workshop (Cologne, Germany, June 13-14, 2015), at the Fifth International Conference on Advanced Communications and Computation (Brussels, Belgium, 21-26 June 2015), at the 12th annual meeting of AOGS (Singapore, Republic of Singapore, August 2-7, 2015), at the XIVth International Workshop on Modelling of Lithosphere and Mantle Dynamics (Oleron Island, France, 31 Aug-5 Sep 2015), at the 6th Moscow Solar System Symposium, (6M-S3, Moscow, Russia, October 5-9, 2015), at the XIVth International Workshop on Modelling of Lithosphere and Mantle Dynamics (Oleron Island, France, 31 Aug-5 Sep 2015), AAS/DPS meeting #47 (Gaylor Harbor, MD, USA, November 8-13, 2015)….

Planet TOPERS members were invited as lecturers to **several international thematic schools**, e.g. on Astrobiology [AbGradE 2014] (Astrobiology Graduates in Europe), Edinburgh, UK (October 10-11, 2014).

International radiancy (from October 1st, 2014 to September 31st, 2015)

Meeting Organization

Planet TOPERS members were responsible for the organization of several 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, Özgür 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, Özgür 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.

Thanks to three Planet TOPERS members, (1) Özgür Karatekin, being **President** of the Planetary and Solar System Sciences division, (2) Lena Noack, being the **Young Scientists Representative** of the Planetary and Solar System Sciences Section of EGU, and (3) Emmanuelle J. Javaux, being **Secretary** of EGU Biogeosciences section “Early life and astrobiology”, we had much visibility.

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**) 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.

Medals, Prizes, Awards

Several Members of Planet TOPERS have received Prizes or Awards between October 2014 and September 2015:

- IUAP Planet TOPERS members Emmanuelle Javaux (University of Liège) became Member of the Royal Academy of Belgium. 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:
  for more information, click here
  (http://www.academieroyale.be/cgi?lg=fr&pag=774&tab=87&rec=1757&frm=0)
  and for the photo gallery, click here
  (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.

- Emmanuelle Javaux received a Francqui Foundation Research Professorship (2013-2016).
- Emmanuelle Javaux became Director of UR GEOLOGY, ULg.
- 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.

Website and Ftp

The planet TOPERS website is at http://planet-topers.oma.be/. It contains:

- Home (where the latest news are displayed)
- Objectives
- Partners
- Definition of Habitability
- Scientific Concept and Overall Planning
- Useful Links (including 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
- Executive meetings
- Helmholtz Alliance
- Internal (WG) meetings
- Kickoff meeting
- Reports - Lists publications & presentations
- Outreach
- Project
- WP1 2 3 4 5: This is and will be the most active part of our ftp.

Visitors

In addition to several short-term visitors in each institutions, Planet TOPERS Members have had long-term visitors:

- At ROB in June-August 2015: Jérémie Godret (ELISA, EcoLe d'Ingenieur des Sciences Aerospatiales),
- At ROB in June-August 2015: Dr. Caroline Dorn (ETH Zurich),
- At VUB, Maxim Castrillejo-Iridoy (Autonomous University of Barcelona), Summer – Fall 2015, research stay to use analytical facilities.

- At VUB, Dr. Edina Prondvai, (Eötvös Loránd University, Dept. of Physical & Applied Geology, Hungary) regular visits for µXRF study of dinosaur eggshell: 30-31.10.2014; 8-16.12.2014; 04-05.05.2015
- At VUB, Dr. Matthias Van Ginneken (Imperial College, London) spent 1 week (2-6.03.2015) at AMGC to discuss micrometeorites.

Outreach

Websites

The coordinator is maintaining a website where all activities and results are mentioned.

Press releases

- 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

TV Interviews

- 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, http://www.rtbf.be/video/detail_de-l-oxygene-decouvert-autour-de-la-comete-tchouri?id=2055287.
- TeléBruxelles for the « M (Mag) de la rédaction », météorite en antarctique - 26 November 2015: interview of Vinciane Debaille.

Radio Interviews

- 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.
- CEPULB-antenne de Nivelles - 27 March 2015: Interview of Vinciane Debaille,on « Météorites en Antarctique: archives de notre système solaire »
- 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.

Written Press

- 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...”.

- 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 Yael 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
- Space News - 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 - 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, Written press, Interview of Veronique Dehant by Laetitia Theunis, 30 September 2015.
- 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,.

Public Conferences

- 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.
- Dehant V. and Morbidelli A., "Évolution et habitabilité du système solaire.", Cours Collège Belgique, Académie des Sciences, Palais des Académies, 4 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.
- Debaille V and E. Javaux, "Tectonique des plaques dans le système solaire : implications pour l'évolution de la Terre et pour l'origine et la diversification de la vie.", Cours Collège Belgique, Académie des Sciences, Palais des Académies, 13 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 Womens Association IAWA, November 6, 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., 2014, « Tectoniques des plaques dans le système solaire et évolution de la terre», conference collège Belgique, Académie, November 13, 2014.
- Debaille V., "Hisotry of Belgian meteorites and history of meteorites in Belgium", national Symposium organised in the frame of the Belspo BELAM project, 14 November 2014.
- Javaux E., "Pause café" with Emmanuelle Javaux, ILe lungo, December 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.
- 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.

- 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.
- 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, "Organisation 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), BIRA-IASB, 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, BIRA-IASB, Brussels, May 20, 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.

Public book

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

Movies on YouTube

- movie about the project UPWARDS - Understanding Planet Mars
- movies about the ROB team in UPWARDS
- movies about the BISA team in UPWARDS

Other/New contracts between October 2014 and September 2015

One Planet TOPERS Member participates in the **H2020** COMPET 8 project **EURO-CARES**, which has started now. 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). http://www.euro-cares.eu/

Ann Carine Vandaele (BISA) and Özgür 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 project has started now. 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

One Planet TOPERS Member (Vandaele A.C.) has obtained an **FNRS-PDR** 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).

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 34 beneficiary institutions from 19 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 visualisation 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 centre. BISA is putting their Venus data, spectra, atmospheric profiles & composition. This provides visibility and it is thus important to participate. Even models can be put there. The infrastructure provides help to those who want to use that site as depository. See http://europlanet-vespa.eu/call.shtml.

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, manely 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 core like inertial waves and instabilities inside the liquid core, are also valid in other terrestrial planets having a liquid core like Mars, Vnus, and Mercury.

Planet TOPERS members have developed an **instrument** that has been **selected** for the ExoMars 2018 platfome. This instrument is called LaRa (Lander Radioscience). LaRa uses X-band[5] 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 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.

[5] 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

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. The mission AIM will be proposed to the Council of the European Space Agency in November 2016 for implementation.

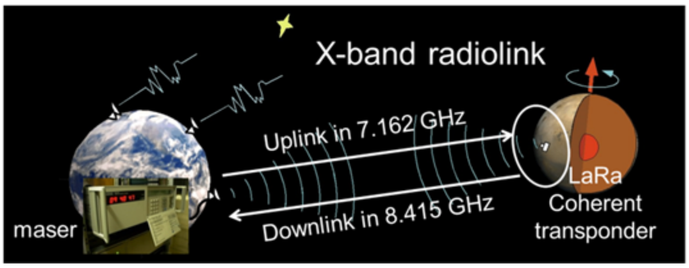

Figure 43: LaRa principle.

Planet TOPERS Members have started **brain-be projects** funded by BELSPO Belgian Science Policy:

- Brain Network project METRO (Meteor Trajectoires and their origin), PI Johan De Keyser (IASB-BIRA), partners: VKI, 15/12/2014 - 15/03/2019
- 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 pioneer project LOTIDE (Localized Tidal Heating on Enceladus), PI: Mikael Beuthe (ROB), 15/12/2014 - 15/03/2017
- Brain Network project. AMUNDSEN (Antarctic Meteorites Curation, Digitalization And Conservation), (Co-PI: Ph. Claeys-VUB and Vincinae Debaille-ULB), 2015-2017
- Re-Opening Of The Bernissart Iguanodon Crime Scene, (Co-Pi: Ph. Claeys), 2015-2018.

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

- "Mars Atmospheric Entry Decent Landing Radio Link Analysis for ExoMars' AMELIA investigation", PI: Özgur 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 Sébastien Le Maistre (ROB),
- "Rosetta/DFMS data analysis" for A. Gibbons, PI: J. De Keyser (BIRA-IASB Space Physics Division).

Frank Vanacker and his team at UGhent have developed a novel type of ultrafast ablation cell and mass spectrometer (A&MS) unit 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.

A Planet TOPERS Member (E. Javaux) participates in an **International ISSI Bern & Bejing 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.

Planet TOPERS Members have been participating to 3 ISSI International teams which were considering three different aspects of the Venus atmosphere: its structure (temperature), the presence of SO_2 and its relation to the clouds. The last meeting was held in Feb. 2015.

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

A Planet TOPERS Member (E. Javaux) is member of the **international advisory committee 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.

BISA was part of the consortium submitting the Alfven+ magnetospheric mission mission proposal in response to the ESA Cosmic Vision M4 call, a mission aimed at studying auroras, including auroral escape. During 2015 we learned that this proposal was not selected. Preparations were made for a new attempt in 2016 in response to ESA M5 Cosmic Vision opportunity. BISA was part of the consortium submitting the Nitrogen Traceing Observatory (NITRO) mission proposal in response to the **ESA Cosmic Vision M4 call**, a mission aimed at measuring the nitrogen escape (as well as that of other species). During 2015 we learned that this proposal was not selected. Similar attends were done at ROB. Preparations were made for a new attempt as the Nitrogen and Oxygen Budget ExpLorer (NOBEL) that will be submitted in 2016 in response to **ESA M5 Cosmic Vision opportunity**. Other participations are foreseen in particular to the Europa penetrator and the Venus missions.

Contracts that have been obtained in the frame of Planet TOPERS previously and still running

During the first year of the IUAP, two Planet TOPERS Members have 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. In summary:

- Emmanuelle Javaux got an **ERC** (ELITE, for Early Life Traces, Evolution & Implications for Astrobiology), on early evolution of life on Earth, 2013-2018)
- Vinciane Debaille got an **ERC** called ISoSyc: Initial solar system composition

During this year, another ERC Grant has been obtained! An ERC Advanced Grant, obtained by Véronique Dehant. See above.

Planet TOPERS Members (O. Karatekin, V. Dehant, Vandaele A.C., 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 Member (Ph. Claeys, PI) has obtained a budget from Institute for the encouragement of Scientific Research and Innovation of Brussels (Innoviris), 2014-2016, Osiris - Tracing Metropolitan Brussels Water Routes: 209.975 €.

Planet TOPERS Member Ph. Claeys (Co-Pi) has obtained **FWO funding** (2015-2018) for "The origin of glasses: melts, metals and motive", FWO-Research Foundation Flanders FWO-G0C4315N: 94.200€.

Planet TOPERS members are part a **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.

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**' of the Federal Science Policy to rejoin our research network.

Several EU projects submitted by Planet TOPERS (BISA) members are running:

(1) FP7 'CrossDrive': to create a virtual environment to better merge data from different missions to Mars; BISA.
(2) FP7 'EuroVenus': to better exploit the Venus Express results and ground-based observations of Venus; BISA.
(3) FP7 'ESPaCE': to build ephemerides of moons in the solar system; ROB.
(4) H2020 'UPWARDS': to prepare the next missions to Mars, to the understanding planet Mars with advanced remote-sensing datasets and synergistic studies; BISA and ROB.
(5) H2020 'EURO-CARES' (COMPET 8) project dedicated to create a roadmap for the implementation of a European Extra-terrestrial Sample Curation Facility (ESCF); ULB.

Four planet TOPERS Members, Emmanuelle Javaux, Philippe Claeys, Véronique Dehant, 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, 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 are also working group leaders (Early and extreme life, and Planetary habitability, respectively). V. Dehant is Monitoring Process Coordinator for ORIGINS. The start of this Action was 15/05/2014 and the end of Action will be 14/05/2018. We got several meetings yet. In particular this last year, we had a 1st Conference in Porto, Portugal, 22-27 March 2015 and a Core Group Meeting in Budapest, Hungary, 28-29 October, 2015.

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.

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).

Similarly, one other Planet TOPERS Member (Vandaele A.C.) 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).

Johan De Keyser is involved in a **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. **Modeling of atmospheric and cometary erosion processes -** Production of missing atomic and molecular data. FNRS project (Research Project T.107314, 205 kEUR, 2 FTE-year, involving ULB, BIRA-IASB, UCL, UMons), 1 July 2014 - 30 June 2016.

ULB does also participate in an **FNRS-New equipment** on analytical/isotopic analysis (PI: N. Mattielli from ULB Planet TOPERS team). Name: **AIMS**: Advanced Isotopic Multitracing Spectrometry.

Planet TOPERS Member Ph. Claeys has obtained **FWO funding** (2015-2018) for the development of µXRF and high resolution elemental mapping. He also became lid of the Science Advisory Board of the International Scientific Drilling Program (ICDP). Former Planet Toper Dr. Janos Kodolanyi moved to the Max Plank Institute for Chemistry, Mainz, Germany. This opens a new avenue of collaboration and guarantee access to the NanoSIMS instrument at the MPI. Dr. Seann McKibbin received a 3 years FWO Post-doctoral fellowship. Seann will continue to work on Planet Toper related topics.

Dr. Arnaud Mahieux (BISA) has received a **post-doctoral grant from the FNRS** (Chargé de Recherches - 2013-2015).

Planet TOPERS Members (Ph. Claeys and E. Javaux) have run some of their projects within the **ICDP** (International Continental Scientific Drilling Program).

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 amenable 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.).

Emmanuelle Javaux continued her work as Collaborator of a selected team of the **NAI** (NASA Astrobiology Institute) of which the PI is Tim Lyons of the University of California, on the theme "Alternative Earths: Explaining Persistent Inhabitation on a Dynamic Early Earth", see http://nai.nasa.gov/teams/can-7/ucr/.

Other/New International Responsibilities since IAP

Özgür Karatekin (ROB) is **President** of Planetary Science Section of EGU. Lena Noack (ROB) is the **Early-Career Scientists (ECS) Representative** of the Planetary and Solar System Sciences Section of EGU and has been elected the **EGU-wide ECS Representative** from 2016-2017. Cédric Gillmann and Elodie Gloesener take also part of the **Planetary Science outreach activities**. Emmanuelle J. Javaux is **Secretary** of EGU Biogeosciences section "Early life and astrobiology".

Lena Noack (ROB) is the AbGradE representative within the EANA network and is member of the Advisory Committee of the UK Centre for Astrobiology based at the University of Edinburgh.

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

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), Cluster (quartet of satellites as a space plasma microscope); NASA: MGS, Pathfinder Rover on Mars, ODY, MRO, MER, MSL, ACE, InSIGHT).

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), Surface Platform (experiment LaRa), BepiColombo to Mercury (experiments MORE, BELA, and SIMBIO-SYS), JUICE (experiments 3GM, MAJIS, GaLA, J-MAG, and PRIDE), AIM (experiment AGEX); NASA: MAVEN, InSIGHT (experiments SEIS and RISE), MSL2020), Exoplanets (CHEOPS and PLATO).

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
- 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.

Participation in exhibition

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

5. Publications

List of publications from each team

ROB

PEER REVIEWED

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Karatekin Ö., 2014, "Tidal Flows in Titan's Largest Sea Kraken.", Cassini Project Science Group (PSG #63), ESTEC/ESA, June 23-27, 2014. *Forgotten in last-year report*

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List of co-publications

ROB – BISA – VUB – ULB – UGhent – ULg – DLR

<u>PEER REVIEWED</u>

2014 (not in previous report)

Arridge C.S., Achilleos N., Agarwal J., Agnor C. B., Ambrosi R., André N., Badman S. V., Baines K., Banfield D., Barthélémy M., Bisi M.M.,Blum J., Bocanegra-Bahamon T., Bonfond B., Bracken C., Brandt P., Briand C., Briois C., Brooks S., Castillo-Rogez J., Cavalié T., Christophe B., Coates A.J., Collinson G., Cooper J.F., Costa-Sitja M., Courtin R., Daglis I.A., de Pater I., Desai M., Dirkx D., Dougherty M.K., Ebert R.W., Filacchione G., Fletcher L.N., Fortney J., Gerth I., Grassi D., Grodent D., Grün E., Gustin J., Hedman M., Helled R., Henri P., Hess S., Hillier J.K., Hofstadter M.H., Holme R., Horanyi M., Hospodarsky G., Hsu S., Irwin P., Jackman C.M., Karatekin Ö., Kempf S., Khalisi E., Konstantinidis K., Krüger H., Kurth W.S., Labrianidis C., Lainey V., Lamy L.L., Laneuville M., Lucchesi D., Luntzer A., MacArthur J., Maier A., Masters A., McKenna-Lawlor S., Melin H., Milillo A., Moragas-Klostermeyer G., Morschhauser A., Moses J.I., Mousis O., Nettelmann N., Neubauer F.M., Nordheim T., Noyelles B., Orton G.S., Owens M., Peron R., Plainaki C., Postberg F., Rambaux N., Retherford K., Reynaud S., Roussos E., Russell C.T., Rymer A.M., Sallantin R., Sánchez-Lavega A., Santolik O., Saur J., Sayanagi K.M., Schenk P., Schubert J., Sergis N., Sittler E.C., Smith A., Spahn F., Srama R., Stallard T., Sterken V., Sternovsky Z., Tiscareno M., Tobie G., Tosi F., Trieloff M., Turrini D., Turtle E.P., Vinatier S., Wilson R., and Zarka P., 2014, "The science case for an orbital mission to Uranus: Exploring the origins and evolution of ice giant planets.", Planetary and Space Science, 104, pp. 122-140, DOI: 10.1016/j.pss.2014.08.009. → ROB – DLR

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