9.2 Interior Structure and Evolution of the Terrestrial Planets

A. Context and state of the art

The internal structure of the terrestrial planets is a relict of a large number of geologic processes that started early in solar system formation and which continue to operate up to the present day. Some of these processes were quick and violent, such as those associated with the earliest stages of planetary accretion and the initial differentiation into a core, mantle and crust. Other processes, such as those associated with the transfer of heat from the interior to the surface by mantle convection and volcanism, have shaped the planets through the expanse of geologic time. The exogenic process of impact cratering, whose cumulative effects have gradually decreased over time, has also continued to shape planetary surfaces through punctuated catastrophic events.

The processes that led to the current structure of our home, Earth, are reasonably, though imperfectly known. The composition and size of the major chemical reservoirs (crust, mantle, and core) are relatively well constrained, and the manner by which internal heat is lost to space via plate tectonics is understood from both observational of modeling perspectives. For the other terrestrial planets, however, our understanding is considerably more limited, and many first-order questions remain unresolved. As examples:

- What is the thickness and composition of the crusts of Mercury, Venus, the Moon, and Mars?
- Might large impacts have excavated through the entire crust, exposing mantle materials at the surface?
- How has the thickness of planetary lithospheres varied in space and time as the planets cooled?
- At what depths do the major phase transitions occur in the mantles of Mars and Venus, and how do these affect mantle convection and plume dynamics?
- What is the size of the metallic cores of Mercury, Mars, and the Moon? And what are the abundances of light alloying elements such as sulfur, carbon, and silicon in the liquid portion of their cores?
- Do Mercury, Venus, Mars and the Moon possess a solid inner core? And is core crystallization the source of energy that powered the martian and lunar dynamos?

To address these and other question, this project will rely heavily on data that will be collected by future planetary missions. Members of this research project are involved in several NASA and ESA planetary missions as co-investigators, collaborators, and project leads. Participation with past planetary instruments and missions includes NASA's lunar gravity mapping mission GRAIL and the ESA/ISRO Chandrayaan-1 X-ray spectrometer. Upcoming missions include NASA's InSight geophysical mission to Mars, a magnetometer on a Google X-prize mission to the Moon, the laser altimeter on ESA's BepiColumbo mission to Mercury, and the laser altimeter and gravity experiments on ESA's JUICE mission to Jupiter. In addition to these, we are leading a proposal to place a geophysical station on the farside of the Moon that will be submitted to ESA's next call for medium-sized missions (M5). We are also involved with several projects at the proposal level, such as a lunar sample return mission (MoonRise), a lunar geophysical network, and a mission to the metallic asteroid Psyche.

This project will make use of several diverse datasets, including seismic measurements, in situ heat flow data, gravity, topography, and magnetic field data. These measurements are sensitive to a variety of depth ranges in the planet, and are sensitive to a planet's structure, composition, and temperature. For simplicity, we will take a two-pronged approach to the internal structure of a planet and focus on (1) the lithosphere, which includes the crust and upper mantle, and (2) the deep mantle and core. This division into two depth ranges is related to the different depth sensitivities of the available data, and the different timescales and processes that are involved with modifying each of the two regions.

B. Structure of the crust and lithosphere

The crust is an important indicator of the processes involved not only with the initial differentiation of a planet, but also the importance of later volcanic construction, tectonic deformation, and impact events. The crust is the most accessible portion of a planet, and a wealth of sample and remote-sensing data exist that constrain the age and composition of the surfaces of bodies like the Moon and Mars. To determine the deep structure of the crust, however, it is necessary to rely on geophysical data, such as gravity, topography, magnetic field, and heat flow.

Our past studies of planetary crusts have relied on a synergistic approach that combines remote sensing, sample, and geophysical data. As a demonstration, we consider our recent work with the Moon. Using high-resolution gravity data obtained from NASA's Gravity Recovery and Interior Laboratory mission (GRAIL), we have determined not only the average thickness of the lunar crust, but also how it varies laterally (Figure 1). When combined with constraints on crustal composition derived from sample and remote sensing data, the bulk abundance of refractory elements in the Moon and Earth were shown to be same, which has important consequences for theories of Moon formation (Taylor and Wieczorek 2015). Lateral variations in crustal thickness (Wieczorek et al. 2013) show that the crust is extremely thin within the interiors of several impact basins that formed during the first 600 million years of solar system evolution. The basins appear to be larger on the nearside than on the farside, which is a consequence of the Moon's asymmetric thermal evolution (Laneuville et al., 2014) and the influence of temperature on the excavation and collapse stages of the cratering process (Miljković et al. 2013). Furthermore, we have shown that atypical outcrops of dunite are associated only with two impact craters were the crust is predicted to be absent. Simulations of the impact cratering process show that these deposits are likely to represent exposures of the lunar mantle (Miljković et al. 2015).

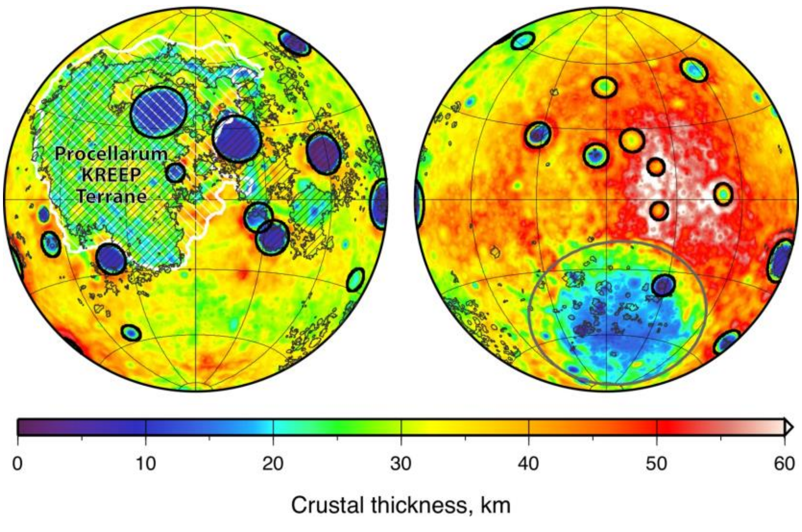

Figure 1. Crustal thickness of the Moon derived from gravity and topography data. The crust has an average thickness of 38 km, and it is thinned by 10s of km in the interiors of ancient impact basins that are several hundreds of km in diameter. The Procellarum KREEP Terrane is a region on the nearside hemisphere (left) that is enriched in heat producing elements, and the hotter temperatures in this province are responsible for the larger sizes of impact basins located on the nearside. The giant 2000-km diameter South Pole-Aitken basin on the farside hemisphere (right) is the largest and oldest recognize impact structure in the solar system.

In addition to relying on gravity and topography data, we have also been using magnetic field data of the Moon to place constraints on impact processes and the history of the lunar dynamo. Our analyses show that the highest intensity magnetic anomalies are associated with the northern half of the South Pole-Aitken impact basin. This is the largest impact structure on the Moon, and simulations show that a moderately oblique impact (corresponding to the average impact angle of 45°) would deposit considerable quantities of the projectile in the downrange direction. Given that the primordial crust of the Moon contains extremely low abundances of metallic iron (which is the main magnetic mineral on the Moon), the strongest magnetic anomalies are likely the result of exo-lunar materials that were delivered to the Moon later in its evolution (Wieczorek et al. 2012). By modeling the direction of magnetization in the crust, we are currently in the process of reconstructing the geometry and orientation of the Moon's ancient core-generated magnetic field, and the duration over which the core dynamo operated.

In this project, we will expand upon our work that was largely developed for the Moon, and apply this to other planetary bodies, such as Mercury, Venus, Mars, and the icy satellite of Jupiter, Ganymede. For Mercury, these investigations will focus on determining the thickness and composition of the crust, as well as the elastic thickness, which is an indication of the planet's heat flow. These investigations will make use of recently acquired data from NASA's Messenger spacecraft, and will be in preparation for higher resolution data that will be acquired by ESA's BepiColombo mission. For Mars, we will make use of not only recent improvements in the gravity field, but also from new seismic constraints on crustal structure and thickness that will be acquired at the InSight landing site in late 2018. For Venus, we will make use of modern spatio-spectral localization techniques (Wieczorek 2007) to investigate how the lithospheric thickness (and thermal regime) of this planet varies from beneath the volcanic rises to continental plateaus. Finally, in preparation of the JUICE mission, we will begin to develop techniques for analyzing the gravity and topography of Jupiter's icy satellite Ganymede, which is expected to be considerably different in character with respect to the silicate planets.

C. Deep interior structure from seismology

Whereas gravity, topography and magnetic field data are ideally suited for investigating the structure of the crust and lithosphere, seismic data are perhaps the best suited for investigating the deep interior of a planet. To date, seismic data have been acquired only on the Moon as part of the Apollo missions, but soon, the first seismic measurements will be made on Mars as part of NASA's InSight mission that will land in late 2018. The InSight seismometer has been developed by the French space agency and our group is involved with this mission at both the collaborator and co-investigator level. Furthermore our group is heavily involved in several mission proposals to place seismometers on the Moon.

The interior structure of Mars is today only poorly known. Without seismic constraints, inversions of the deep structure are highly non-unique. The composition of the mantle has been only weekly constrained by a handful of basaltic meteorites from this planet, it is not known if the pressures in the deep mantle are sufficient to reach the perovskite transition, the radius of the liquid core is poorly known, and it is entirely unknown if Mars has a solid inner core. As part of the InSight scientific team, we are currently developing methods for investigating the characteristics of Martian seismic signals by numerical simulation of seismic wave propagation in various proposed 1D and 3D elastic and anelastic models of Mars. This work aims to quantify the detection levels of Martian seismic signals, the seismic characteristics of marsquakes, meteorite impacts, noise generated by dust storms, and atmospheric signals. Following the collection of data, this project will focus on two investigations: We will investigate the interior structure of Mars using a variety of seismic methods, and we will investigate how the coupling between the atmosphere and surface affects the measured seismic and infrasound signals.

The focus of our first project will be on investigating the interior structure of Mars from the InSight seismic data. This will include investigating normal-mode spectra for interior structure, measuring differential travel times of major seismic arrivals for source location, and the characterization of surface-wave dispersion. Prior to launch, we will be performing numerical simulations of seismic wave propagation using the spectral-element method to constrain the characteristics of martian seismic signals. This will make use of the 3D open source spectral-element software package SPECFEM3D_GLOBE, originally developed by Komatitsch & Tromp (2002), which will take into account topography, attenuation, gravity, rotation, self-gravitation and ellipticity (Bozdag et al. 2011). As an example, of this approach, Figure 2 shows the effect of attenuation on synthetic seismograms. Using this code, we will investigate the effects of interior structure on the seismic signals expected from marsquakes, meteorite impacts, and dust storms. At a later stage, we will adopt the code to work with the Apollo seismic data.

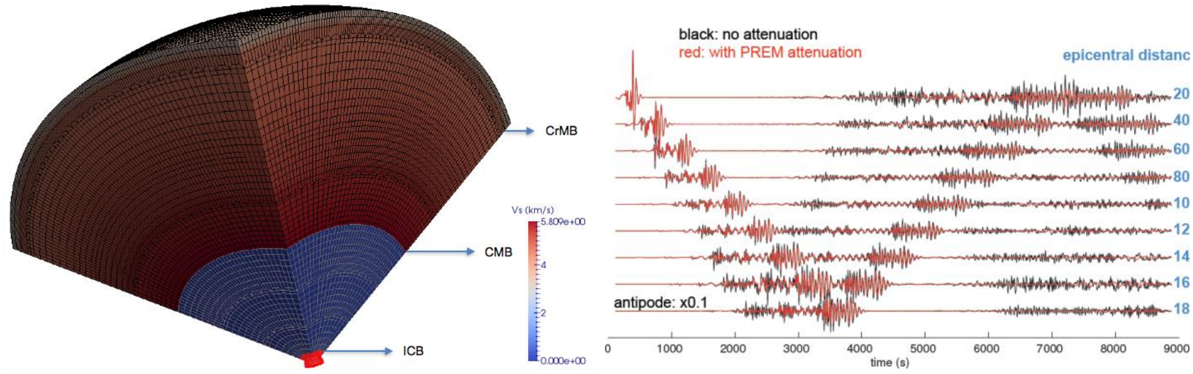

Figure 2. (left) 3D Mesh used for simulating seismic wave propagation that includes first-order seismic discontinuities. (right) Simulated seismograms (vertical component) using the SPECFEM3D_GLOBE package with and without attenuation. The moment tensor solution of the 2011 Virginia earthquake was used as a source (Mw=5.8, depth=12 km), and the PREM attenuation model was adopted to Mars in the anelastic simulations. Seismograms are filtered between 20 to 400 s where multi-orbit Rayleigh waves are clearly observed.

The focus of our second project will be to study the mechanisms of coupling between the interior and atmosphere on Mars. The existence of such coupling was revealed on Earth by the identification in seismograms of "air-coupled" Rayleigh surface waves that were related to atmospheric explosions from volcanic eruptions as well as from meteorite air blasts. Conversely, crustal motions due to large earthquakes trigger infrasound waves that are detectable by pressure sensors and ionospheric sounders at teleseismic distance (Rolland et al. 2011, 2013). On Mars, the Insight seismometer will be accompanied by a pressure sensor that can be used to detect atmospheric acoustic and gravity waves that are related to seismic activity. These infrasound measurements can be used to provide additional constraints for event source localization and characterization. More fundamentally, our study of the propagation of acoustic and gravity waves triggered by meteor impacts or large marsquakes will allow a better understanding of the non-linear effects related to strong attenuation mechanisms and large horizontal winds. Finally, we will further investigate orbital ionospheric radio-sounding and imaging methods in order to probe from an orbital platform the interior structure of Venus, which may be the next target of the 13th NASA discovery mission to be selected by the end of the year.

References:

Bozdag, E., J. Trampert, J. and J. Tromp (2011). Misfit functions for full waveform inversion based on instantaneous phase and envelope measurements. *Geophy. J. Int.*, **185**, 845870. doi:10.1111/j.1365-246X.2011.04970.x.

Laneuville, M., M. A. Wieczorek, D. Breuer, J. Aubert, G. Morard, T. Rückriemen (2014). A long-lived lunar dynamo powered by core crystallization, *Earth Planet. Sci. Lett.*, **401**, 251-260, doi:10.1016/j.epsl.2014.05.057.

Miljković, K., M. A. Wieczorek, G. S. Collins, M. Laneuville, G. A. Neumann, H. J. Melosh, S. C. Solomon, R. J. Phillips, D. E. Smith and M. T. Zuber (2013). Asymmetric distribution of lunar impact basins caused by variations in target properties, *Science*, **342**, 724-726, doi:10.1126/science.1243224.

Miljković, K., M. A. Wieczorek, G. S. Collins, S. C. Solomon, D. E. Smith, M. T. Zuber (2015). Excavation of the lunar mantle by basin-forming impact events on the Moon, *Earth Planet. Sci. Lett.*, **409**, 243-251, doi:10.1016/j.epsl.2014.10.041.

Rolland L. M., Lognonné P. and Munekane H. (2011). Detection and modeling of Rayleigh waves induced patterns in the ionosphere, *J. Geophys. Res.*, **116**, A05320.

Rolland, L. M. Vergnolle, J.-M. Nocquet, A. Sladen, J.-X. Dessa, F. Tavakoli, H. Reza Nankali, and F. Cappa (2013). Discriminating the tectonic and non-tectonic parts in the ionospheric signature of the 2011, Mw=7.1, dip-slip Van earthquake, Eastern Turkey, *Geophys. Res. Lett.*, L50544.

Taylor, G.J, and M. A. Wieczorek (2014). Lunar bulk chemical composition: a post-Gravity Recovery and Interior Laboratory reassessment, *Phil. Trans. R. Soc. A*, **372**, 20130242, doi:10.1098/rsta.2013.0242.

Wieczorek, M.A. (2007). Gravity and topography of the terrestrial planets, *Treatise on Geophysics*, **10**, 165-206, doi:10.1016/B978-044452748-6/00156-5.

Wieczorek, M. A., G. A. Neumann, F. Nimmo, W. S. Kiefer, G. J. Taylor, H. J. Melosh, R. J. Phillips, S. C. Solomon, J. C. Andrews-Hanna, S. W. Asmar, A. S. Konopliv, F. G. Lemoine, D. E. Smith, M. M. Watkins, J. G. Williams, M. T. Zuber (2013). The crust of the Moon as seen by GRAIL, *Science*, **339**, 671-675, doi:10.1126/science.1231530.

Wieczorek, M.A., B. P. Weiss, and S. T. Stewart (2012a). An impactor origin for lunar magnetic anomalies, *Science*, **335**, 1212-1215, doi:10.1126/science.1214773.

D. International collaborations

This research project will support the scientific exploitation of data obtained from ongoing and future missions, as well as the preparation for planetary missions that will launch in the coming decade. Though our funding for these missions comes from the French Space Agency (CNES), these missions are an inherently international endeavor The NASA GRAIL mission has led to strong institutional collaborations with the *Jet Propulsion Laboratory (JPL)* and the *Massachusetts Institute of Technology (MIT)*. The NASA InSight mission (led by JPL) is international, with critical pieces of hardware being furnished by CNES, ETH, and the German space agency (DLR). The laser altimeters that will be flown on BepiColombo and JUICE include partnerships with DLR, the University of Bern, and the Japanese space agency. In addition to these institutional collaborations, as part of these missions, we have forged close ties with numerous participating scientists within the United States, Europe and Japan. Previous post-docs and students that were funded to support these missions were largely non-French, and they have obtained permanent jobs in non-French laboratories. Supporting our participation in ongoing and upcoming planetary missions will allow us to attract the best talent to Nice and the Observatoire de la Côte d'Azur.

E. List of people involved in the project

Mark Wieczorek (CNRS Directeur de Recherche, laboratoire Lagrange)
Lucie Rolland (Maître de Conférences, GéoAzur)
Ebru Bozdag (Chaire d'Excellence, GéoAzur)
Agnès Fienga (Astronome, GéoAzur)
Contact : Mark.Wieczorek@oca.eu

F. Most significant publications of the team

Taylor, G.J, and M. A. Wieczorek (2014). Lunar bulk chemical composition: a post-Gravity Recovery and Interior Laboratory reassessment, *Phil. Trans. R. Soc. A*, **372**, 20130242, doi:10.1098/rsta.2013.0242.

Wieczorek, M.A. (2007). Gravity and topography of the terrestrial planets, *Treatise on Geophysics*, **10**, 165-206, doi:10.1016/B978-044452748-6/00156-5.

Wieczorek, M.A., B. P. Weiss, and S. T. Stewart (2012). An impactor origin for lunar magnetic anomalies, *Science*, **335**, 1212-1215, doi:10.1126/science.1214773.

Wieczorek, M. A., G. A. Neumann, F. Nimmo, W. S. Kiefer, G. J. Taylor, H. J. Melosh, R. J. Phillips, S. C. Solomon, J. C. Andrews-Hanna, S. W. Asmar, A. S. Konopliv, F. G. Lemoine, D. E. Smith, M. M. Watkins, J. G. Williams, M. T. Zuber (2013). The crust of the Moon as seen by GRAIL, *Science*, **339**, 671-675, doi:10.1126/science.1231530.

Zhu, H., E. Bozdag, D. Peter, and J. Tromp (2012). Structure of the European upper-mantle revealed by adjoint tomography, *Nature Geosciences*, doi:10.1038/NGEO1501.

H. Short CV of participants

Mark Wieczorek (CNRS Director of Research, laboratory Lagrange) specializes in using geophysical data to decipher the interior structure and geologic evolution of the terrestrial planets. He is a co-investigator on NASA's lunar gravity mapping mission GRAIL, NASA's martian geophysical station InSight, and the laser altimeters that will be flown on the ESA BepiColombo and JUICE missions. He is a former editor-in-chief of the *Journal of Geophysical Research Planets*, and has published over 66 scientific papers (H-index 31).

Lucie Rolland (CNAP Associate Professor) specializes in natural hazards monitoring using space geodesy (GNSS precise positioning and ionospheric sounding). She is chair of the study group *Ionospheric and Atmospheric Coupling processes and phenomena* in subcommission 4.3 of the International Association of Geodesy and co-investigator of the International Space Science Institute team *Understanding Solid Earth/Ocean-Ionosphere coupling*. She has published 17 referred publications.

Ebru Bozdag (Chaire d'Excellence, Geoazur) specializes in global seismology, 3D wave simulations and full-waveform inversion. She was a collaborator (2013-2014) and then co-investigator (2015-2016) of the INCITE Awards of Oak Ridge National Lab to run global full waveform inversions on their "Titan" system and the co-investigator of the CAAR program (2015) to continue global inversions on Oak Ridge's next generation supercomputer "Summit" that will be ready before 2018.

Agnès Fienga (Astronomer, GéoAzur) is an expert in planetary ephemerides. She is a co-PI of INPOP planetary ephemerides, a member of the French space agency expert council on fundamental physics, a co-investigator of the 3GM radio science experiment on ESA's JUICE mission, a member of the ESA BepiColombo Science Working Group, and a former co-editor of *Celestial Mechanics and Dynamical Astronomy*. She has more than 30 referred publications.