Planetary science: a question of origins

Since ancient times, philosophers and scientists have scrutinized the night-sky, directly or indirectly, hoping to answer the question of our place in the universe. The invention of the telescope and the discovery of Jupiter’s four largest moons by Galileo in 1610 heralded a new era, where the combination of observations and theory led to major advances in our understanding of the solar system. However, despite more and more powerful telescopes, the planets and their moons long remained mysterious and far-away objects.

This situation changed dramatically in the second half of the 20th century, with the development of spacecraft capable of travelling to our planetary cousins to study them close-up. The early 1960s saw the first flybys of Venus, and since that time, over one hundred space-based missions have been launched to the vast majority of the major bodies of the Solar System, from Mercury to Neptune.

Over the last ten years, space-based exploration of the Solar System has increased enormously, with more and more sophisticated orbiters and landers being sent to Mars, Venus and Saturn, not forgetting our own Moon.

This intense period, rich in unprecedented scientific data, has led to immense progress in our perception of the origin and evolution of the solar system and the objects it contains, from a completely new view of the history of water at the surface of Mars, to the discovery of strangely familiar landscapes on Titan, one of Saturn’s icy moons, whose surface is shaped by methane rain.

Technical and scientific teams at the Observatoire Midi-Pyrénées are taking part in a large number of these adventures, often playing key roles in the conception and construction of onboard instruments, or in the scientific interpretation of the results obtained. These numerous successes have resulted from efficient collabora-
Studying planetary science at the University of Toulouse:

Research in planetary science covers a huge range of fields, from the conception and construction of on-board instruments, to the deployment and up-keep of seismic networks, not to mention laboratory and numerical simulations in fields as varied as thermodynamics, nuclear spectroscopy, plasma physics, and the dynamics of geophysically relevant fluids in general. There are several Master programmes in Toulouse that are directly relevant to these areas of research, in particular the Earth science and the astrophysics research masters (M2R STPS and M2R ASEP), the Master Pro, techniques spatiales et instrumentation, as well as the courses proposed by the department ‘Mesures Physiques’ at the IUT Technical School.

Looking even further into the future, the group is also actively preparing for the next generation of missions, in particular to study the moons of Jupiter (ESA’s JUICE mission) and the deployment of the first ever seismometer at the surface of Mars (InSight mission of NASA).

Planetary science is a rapidly evolving field, the discovery of an ever increasing number of planets around stars other than the Sun and the eternal question of the origin of life, is leading to new interactions with other fields of research, from astrophysics to biology. This melting pot of ideas and scientific disciplines shows that it is more important than ever to explore how our planet formed, and how the life that appeared there originated.

Missions

The last ten years has seen an exceptional crop of results for the group in Toulouse, from missions such as Cassini/Huygens around Saturn, Cluster which has studied the interactions between solar wind and the Earth’s magnetosphere, and the American and European missions to Mars (Mars Odyssey, Mars Exploration Rovers and Mars Express). The future is looking just as bright with several high profile and ambitious projects firmly on track, many of which carry major instrumental contributions from the group in Toulouse, in particular Mars Science Laboratory (of NASA), which was launched in December 2011, MAVEN (NASA), which will leave for Mars in 2013, BepiColombo (of the European Space Agency), which will leave for Mercury in 2017 and the Solar Orbiter mission (from ESA), which has just been selected for a launch towards the Sun in 2017.

The GPPS group boasts over 100 members, including researchers, technical staff and PhD students/post-docs, and it has numerous links with the French national space agency (CNES). As illustrated in the following pages, the members of the group treat all the principal constituents of a planet, from the deepest (core/mantle) to the farthest from the centre (magnetosphere/ionosphere), always looking to understand the physical and chemical processes at work.

The creation of this group, unique in France, opens the possibility of providing a unified vision of different planetary bodies, allowing the reconstruction of their geological history, and highlighting the diversity and particular features of each object, contributing to a better understanding of the Solar System as a whole.
Planetary interiors

Seismic noise analysis has been used to reveal the internal structure of our planet, and this method is now being applied to other planets.

Tomography is an echography of the Earth’s interior, and relies on measuring seismic waves from earthquakes. These waves are reflected at interfaces and their velocity depends on the temperature and physical properties of the medium. In this way, in-depth analysis of seismic records can provide detailed information about the structure of the Earth’s interior, and now, other planets too.

**Spectacular resolution**

Studies of the Earth’s internal structure and dynamics are currently experiencing rapid development in many countries with the deployment of dense arrays of seismometers. Recently, the PYROPE experiment (PYRenean Observatio- nal Portable Experiment) deployed around 60 broadband seismometers in the Pyrenees and in western France. The project involves 25 researchers (geologists and geophysicists) from seven institutes in France and Spain. This project will provide detailed images of deep structures beneath the Pyrenees and provide in-depth information concerning the formation of this mountain range.

Seismology is also a useful tool for exploring the interior of other planets. However, sources of seismic waves are required, and not all planetary bodies show the same, abundant seismic activity as Earth. In this case, records of background “noise” provide an alternative way of probing a planet’s interior without earthquakes and the deep structure of planets can thus be explored, even in the absence of plate tectonics.

**Grain size variations in the inner core**

The inner core of Earth is one of the most enigmatic parts of our planet. This solid body found at the centre of the globe, with a radius of 1220 km, grows from the crystallization of molten iron in the outer liquid core. Information on the structure of the inner core is mainly obtained from the propagation of seismic waves that reveal a strange hemispherical structure at the top of the inner core. Velocity and attenuation of seismic waves are correlated and appear weaker on one hemisphere (facing Peru) than the other (facing Indonesia). This correlation is unusual. The reverse occurs in the mantle!

A possible explanation for these results is a variation of the grain size of crystals of iron from one side of the inner core to the other. To interpret such a large contrast of grain size between the two hemispheres, researchers from IRAP have proposed that the inner core experiences a continuous west-east translation, resulting in permanent crystallization on the western face and melting on the eastern one. That fact that grains of iron are expected to grow with time during this translation provides a plausible explanation for the unusual seismic properties of Earth’s deepest reservoir.

**Insight into other planets**

Do the other terrestrial planets possess an inner core? Do they even have a core? If so, what is its size? The detailed analysis of spacecraft trajectories while in orbit provides some information, but these data sources are limited.

For the Moon, the presence of a core has only just been resolved by a recent seismological study performed in collaboration with IRAP and IPG Paris. This work used 40 year old seismological data from the Apollo missions to find seismic waves reflected on top of the core. In this way, the radius of the Moon’s core has been calculated to be 380±40 km. This insight into the internal structure of the Moon allows us to better understand the giant impact that formed the Earth-Moon system, and the chemical composition of our planet and its satellite.

For Mars, orbital data suggest that the red planet possesses a core, but its density and size are not precisely known. In order to answer these questions, the scientific and technical teams of IRAP and OMP are working on the NASA Insight mission, a project that aims to deploy the first ever seismometer on the surface of Mars. This sensor will allow unprecedented determination of Martian seismicity and internal structure, and why not, provide the first direct constraint on the size of its core.

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Are Martian volcanoes still active?

Space-based exploration of rocky bodies in the solar system has led to a remarkable increase in our knowledge of the geology, mineralogy and composition of planetary surfaces, thanks to advanced remote sensing techniques, such as infrared and optical hyperspectral sensors and gamma ray spectrometers. These data provide invaluable insight into the geological history of planets such as Mars, supplying a means to link surface characteristics to internal workings of the planet.

For example, for planetary bodies as large as the Earth, Mars or the Moon, deep movements driven by mantle convection lead to partial melting of rocks at depth. The magmatic liquids produced may migrate to the surface where they may be observed as lava flows and/or volcanoes.

At the Observatoire Midi-Pyrénées, geologists, physicists, geochemists and planetary scientists have been working together closely over the last ten years, spurred on by the increasing amount of high quality data now available from space-based explorations of the Solar System. Mars has been one of the main planets studied, thanks to numerous European and American-led missions to the red planet. Images from the HRSC (High-Resolution Stereo Camera) aboard the Mars Express spacecraft have greatly modified our view of Mars’ volcanic history. A group of researchers from IRAP has contributed to the discovery of a large volcanic province that has been very active over the last 200 million years with extremely recent eruptive events in regions that are only a few million years old. Such ages are extremely young on geological time-scales, suggesting that volcanism on Mars may not be entirely over.

**Hot spots**

Remote sensing observations also offer the possibility to detect the presence of certain minerals crystallizing within lava flows, using hyperspectral imagery in the visible and near-infrared parts of the electromagnetic spectrum. However, determining various mineral species within a rock may hide that of other, equally relevant ones. Using a numerical inversion method validated in the laboratory, the regional occurrence of the mineral olivine in lava flows in the central part of a major volcanic edifice called Syrtis Major has been established from the data of the OMEGA instrument aboard Mars Express by a team from IRAP. The presence of olivine is characteristic of basaltic liquids resulting from relatively large degrees of partial melting, suggesting a geological context akin to “hot spots” on Earth, such as Iceland or Hawaii.

Mars cools slower than Earth

Concerning the chemistry of these volcanic rocks, several researchers from IRAP have been involved in the analysis of data provided by the Gamma Ray Spectrometer aboard the Mars Odyssey probe (NASA). The objective of this instrument is to produce maps of the abundance of several key chemical elements, such as iron, silicon, and thorium. These elements are of interest because they are particularly sensitive to the conditions in which magmas formed. Using data from 12 volcanic provinces of various ages, it was possible to identify chemical variations that could explain how Martian mantle temperatures have evolved over the last three billion years. These results may be used to show that the Martian mantle has cooled over time, but that this cooling is slower than that on Earth, a difference that is probably linked to the existence of plate tectonics on Earth, but not on Mars. This work offers a framework to understand the complex mineralogical evolution recently revealed by orbital spectroscopy, as well as the persistence of volcanic activity mentioned above.

The Martian globes show the position of 12 volcanic provinces, six of which are young (in red) and six that are older than 3.6 billion years. Studying these provinces and the concentrations of iron, silicon and thorium in volcanic rocks allowed the researchers to estimate how the interior of the red planet has cooled over time.

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Could there be water on other planets?

Mineralogical observations of planet surfaces, together with laboratory experiments and thermokinetic modelling, can provide valuable information on the presence of water in the distant past. Although such an approach is possible in the case of Mars, it is more difficult to apply to Venus.

In the case of Mars, spectroscopy and orbital imagery allow us to define three main geological time-periods, which, on the basis of their mineralogy, appear to be associated with quite distinct surface conditions. Terrains belonging to the oldest period (Noachian) were subject to a wet environment, similar to that of Earth’s, followed by a period when surface fluids were very rich in sulphur (the Hesperian Period), finally leading to dry, cool and oxidizing surface conditions that would appear to have lasted over the last three billion years or so (the Amazonian Period). Robotic ground exploration, with increasingly mobile and better-equipped rovers, has made it possible to obtain much more precise information on the chemical and mineralogical composition of the landing sites. Thanks to results obtained from the highly sulphate-enriched rocks analysed by NASA’s Opportunity rover in Meridiani Planum, the OMP have tackled the question of Hesperian weathering from the geochemistry point of view. Based on numerical modelling of fluid-rock interactions, it can be shown that these rocks were formed under extremely acidic conditions, but with very little water and extremely short weathering times on the geological scale.

Water in abundance

The scientific community is now focusing on the older periods of Martian history when water could have been present in abundance. These favourable conditions could have led to the emergence of living organisms, a hypothesis that has guided the choice of study sites and instrument payloads for NASA’s Curiosity robot (planned to arrive on Mars in August 2012).

Among the suite of instruments aboard, this robot carries the ChemCam laser probe, developed in Toulouse by scientific and technical teams at IRAP and the CNES, in partnership with the Los Alamos National Laboratory in the USA. ChemCam can perform chemical analyses by laser spectroscopy on a surface less than a millimetre in diameter, at distances of up to seven metres from the rover! This capability will be an invaluable aid in quantifying the mineralogy at the surface of Mars. Furthermore, because of the short nature of the analysis (a few seconds) and its ability to measure far from the rover, ChemCam will also serve as a “scout” for the other instruments onboard Curiosity, identifying remote samples of potential interest for detailed study. Clay minerals will be priority targets, because they are the most likely places to find remains of life, thanks to the fact that these minerals maintained favourable conditions before the influx of sulphur produced acids much stronger than H$_2$CO$_3$.

Intense volcanism

On Venus, observations from space are very difficult because of the dense CO$_2$-rich atmosphere, the high-altitude clouds and extreme temperatures at the surface (470°C), which particularly hinder ground exploration where the lifetime of the instruments does not exceed three hours at most. Nevertheless, we know that the surface has been shaped by intense volcanic activity and complex atmospheric sulphur chemistry. The rare observations made on the surface by the Soviet Venera missions suggest chemical weathering phenomena. The possible existence of hydrated minerals at the surface implies an active water cycle at some time in the past, but the current dry atmosphere of Venus poses some fundamental chemical questions that are being addressed at the IRAP by the development of an experimental chamber reproducing conditions on the surface of our sister planet. At present, this facility allows us to simulate basalt-atmosphere interactions, and, in the long term, will lead to in-situ analyses of weathered rocks by LIBS and Raman spectrometry. These instruments are proposed by IRAP for the payload of a NASA-based mission (SAGE) presently being studied.

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Ionized environments of terrestrial planets

The solar wind can strip planets of their gas and dust, and even water.

Unlike the Earth, planets with no intrinsic magnetic field, like Mars and Venus, are under direct attack from the solar wind, which is emitted from the solar corona. The solar wind comes in the form of a cold plasma, dense and moving at high speeds of around 1.5 million kilometres per hour. Mars and Venus have an atmosphere and their interaction with the solar wind produces an induced magneto tail, like the extended tail of comets. The atmospheres of Mars and Venus are thus subject to intense erosion by the solar wind. Models predict a very important cumulative effect over a timescale of a billion years, potentially capable of dissipating a dense primitive atmosphere, which is needed to maintain water in liquid form.

The case of Mercury is different since this planet has an intrinsic magnetic field but has no significant atmosphere. Its interaction with the surrounding plasma results in surface ablation of materials under the influence of the solar medium to produce the outer atmosphere/exosphere of the planet.

Quantification of atmospheric escape from Mars and Venus

In cooperation with the Space Research Institute of Kiruna in Sweden, IRAP built the mass spectrometers placed on board the first European planetary missions Mars Express (MEX) and Venus Express (VEX). Contrary to predictions, MEX measurements show that, while the Martian atmosphere escape is important (1.2 \(10^{24}\) ions/s) at solar minimum, it probably cannot explain the disappearance of the primitive oceans of the planet. Indeed, even taking into account the evolution of the Sun and related UV/charged particle fluxes over several billion years, the cumulative effect of the Sun, calculated from data of Mars Express and observation of «young suns» can only explain the disappearance of a few centimetres of water from the surface of the planet. Other phenomena must be invoked (for example, escape at very low energies and cataclysmic events to name but two). Or water might be hidden in yet undiscovered tanks.

With regards to Venus, the Venus Express mission has allowed for the first estimate of atmospheric erosion during solar minimum. The outflow of energy ions between 10 eV and 25000 eV was measured for hydrogen and oxygen. These rates lie in a ratio close to two, indicating that the planet’s surface is no longer oxidizing. The actual escape rates are very similar to rates previously estimated by the American Pioneer Venus mission during periods of high solar activity, which indicates that atmospheric losses from Venus depend only weakly on solar activity.

Mechanisms of particle acceleration in ionized environments

The physical mechanisms responsible for the escape of planetary material and for its acceleration have been identified. On-going studies in different regions on Mars and Venus indicate that the main acceleration mechanism is linked to the strong magnetic tension prevailing in the region of the anti-solar induced magneto tail of the planets, as well as to a polarized electric field. In a second, outermost area, the ions are accelerated by the solar wind electric field and an electric field linked to charge separation. Thus, the atoms of the exosphere, ionized by solar wind impact, are accelerated by the interplanetary electric field.

Future studies

From 2014, researchers from IRAP will have access to data from the US mission MAVEN (Mars Atmosphere and Volatile Evolution) to which they provided an electron spectrometer. MAVEN aims to study the mechanisms responsible for the disappearance of the atmosphere of Mars. The launch of the probe is scheduled for late 2013.

IRAP has also provided two electron detectors for the first European mission to explore Mercury, BepiColombo, that will be launched in 2014. When it reaches Mercury in 2022, it will experience temperatures of up to 350°C and generate data for a year, with a possible extension for another year. BepiColombo is a coordinated mission between ESA and the Japanese Space Agency, JAXA. IRAP is also participating in scientific groups responsible for the preparation of the mission and the numerical simulation of Mercury’s environment.
T he two largest gas planets of the Solar System have attracted considerable attention over the last few decades with several major robotic space-based missions sent, or planned to be sent, to explore them and their local environment. Saturn’s system has been studied in detail since June 2004 (and will be until 2017) by the NASA/ESA Cassini-Huygens mission. The NASA Juno mission will insert into a polar orbit around Jupiter in 2016, while the ESA JUICE (JUpiter ICy Moon Explorer) mission is currently under study for a launch in 2022.

**Magnetospheres of Jupiter and Saturn**

In the magnetic cavities (magnetospheres) of giant planets such as Jupiter and Saturn, plasma sources are abundant. These may be created by the solar wind, in the atmosphere of the planets, in their ionosphere, or by their moons (in particular Io at Jupiter and Enceladus at Saturn). The situation is significantly more complex than even that on Earth, where external (solar wind) and internal sources (ionosphere/atmosphere) are similar. As a result, the magnetospheres of the giant planets contain uniquely diverse regions compared with those observed elsewhere in the Solar System. Understanding these regions, their equilibrium and dynamics, and their coupling via the transfer of mass, momentum, and energy at their interfaces is challenging.

One of the key problems consists in understanding how the various plasmas feed the entire magnetosphere, diffuse radially, are accelerated and finally recombine. Using multi-instrument data from Cassini, scientists at IRAP have revealed the role played by the interchange instability in the transport of plasma and its redistribution in the Saturnian magnetosphere. This centrifugal instability, of the “Rayleigh-Taylor” type, had been expected in the fast rotating magnetospheres of giant planets, but never proven. It is similar to the convective instability in planetary atmospheres that enables adjacent layers of gas to mix under the action of gravity.

**Titan’s induced magnetosphere and Ganymede’s mini-magnetosphere**

Discovered by the Dutch astronomer Huygens in the 17th century, Titan is one of Saturn’s moons and is unique in our solar system because of its large size (it has a diameter larger than that of Mercury). Thanks to its atmosphere, it is the densest among the known moons with a surface pressure 1.5 times larger than that at the Earth’s surface.

The Cassini-Huygens mission has unearthed numerous secrets about Titan, in particular concerning its methane cycle. This molecule is present in the near-surface/atmosphere of Titan in gas, liquid and solid forms, having a cycle similar to that of water on Earth (but with methane rain and snow this time!). In addition, Titan’s atmosphere is characterized by a complex chemistry between hydrocarbons and nitriles, making it a real factory for heavy organic molecules, which are the first steps towards the appearance of life. Scientists at IRAP have shown that the interaction between Titan and the plasma environment surrounding Saturn heats up Titan’s upper atmosphere, leading to certain atoms escaping. This creates energetic neutral atoms that can be imaged like photons by the INCA instrument onboard Cassini, ionizing the neutral atmosphere, thus initiating the complex chemistry described above, and forcing the entry of Saturn’s magnetic field into Titan’s ionosphere where it may be retained and preserved.

Finally, in 1996, the NASA mission Galileo at Jupiter discovered that Ganymede, the largest moon in the solar system, has its own magnetic field and thus forms a mini-magnetosphere inside the giant magnetosphere of Jupiter. Researchers at IRAP are currently developing numerical models to characterize the charged particle populations existing inside this mini environment. These will help them design specially-adapted instruments and subsequently propose these for the JUICE mission in a response for a call-to-tender expected in 2012.

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Space Weather

Being able to predict magnetic storms emanating from the Sun will allow us to protect our electricity grids and communication networks.

Sunspots
Sunspots are observed in areas in which particle and magnetic flux eruptions occur on the Sun. The ejected particle flow carries an intense magnetic field and propagates in the heliosphere where it forms giant bubbles of plasma, often weighing billions of tons. These bubbles are called “coronal mass ejections” and can stretch across large distances (as far as half the Sun-Earth distance or more). The Sun is characterised by an 11-year activity cycle. For the last four centuries or so, the principal indicator of this activity has been the number of sunspots observed on the Sun’s surface.

Terrestrial perturbations
Geomagnetic storms triggered by coronal mass ejections lead to significant perturbations in the near-Earth environment, from the magnetosphere to the ionosphere and even on the ground. These perturbations can cause communication system failures, electrical black-outs over large areas and GPS system malfunction. They can also adversely affect civil and military aviation.

Being able to predict these storms depends on our ability to understand the chain of events (initiation, propagation and coupling with the geomagnetic field) that governs Sun-Earth interactions. Scientists in the IRAP laboratory are thus largely focusing on the study of the fundamental physical processes that occur in the near-Earth environment, including magnetic reconnection, shocks, turbulence, and other particle acceleration mechanisms that, for instance, produce the northern lights (auroras). This subject area, which consists of developing tools to predict conditions in the near-Earth environment and that of other planets as a function of solar activity, is called “space weather”. And since it also has practical applications, it is a rapidly growing field of research.

Such studies require various approaches, from theory and modelling to observations. The GPPS group at IRAP is strongly involved in all these domains, and particularly in the instrumentation part. The group has built particle instruments for numerous past (Interball, Giotto, Double Star), current (Cluster, THEMIS, STEREO, DEMETER) and future (MMS, Solar Orbiter, Bepi-Colombo, Maven) space missions.

STEREO mission
In 2006, the STEREO mission was launched to observe the initiation, propagation and impact of solar eruptions in the heliosphere. STEREO is composed of two distant satellites with particle instruments onboard that were built at IRAP. This multipoint observation capability, combined with the high-quality imaging and in-situ measurements made onboard, allowed researchers to track coronal mass ejections all the way from the Sun to the Earth without interruption for the first time. STEREO data have also been used to demonstrate, for example, the ubiquity of the magnetic reconnection process in the solar wind and the ability of this process to erode coronal mass ejections during their propagation in the heliosphere. The magnetic erosion that occurs at the front of these structures alters the nature and the amount of plasma that interacts with Earth’s magnetosphere. In addition to scientific results related to the ejection and interaction of these structures in the heliosphere, recent work has also highlighted the ability to provide end-to-end monitoring (through imaging) and thus to effectively predict the arrival and intensity of the largest of these structures at Earth.

The significant effort in terms of instrumentation in our group is accompanied by activities to ensure the long-term availability of all data acquired over the years and to develop added value scientific tools and “virtual observatories” in the framework of the Centre de Données de la Physique des Plasmas (CDPP; cdpp.cesr.fr).