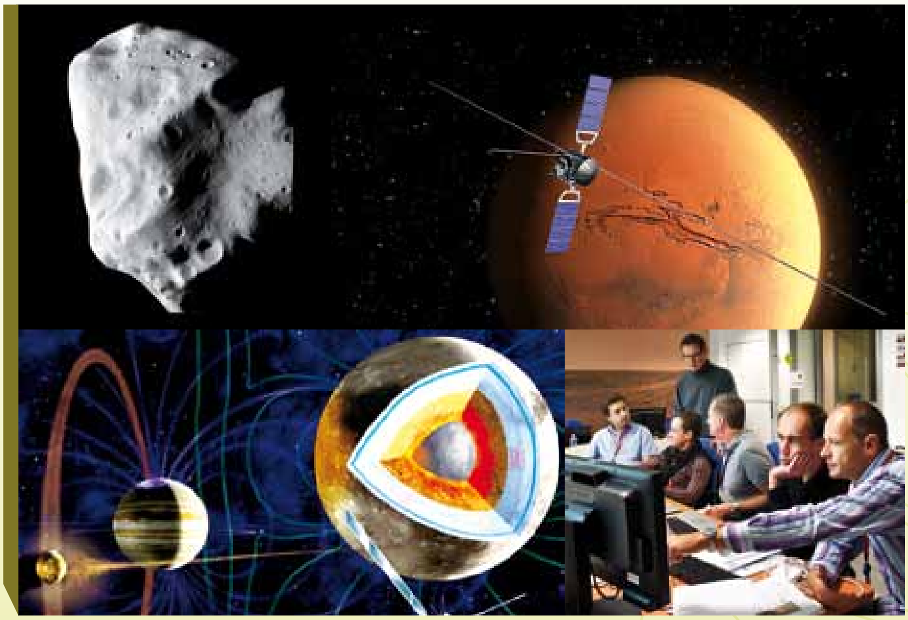
AUTHOR: F. Rocard

Solar System

[Fig. 1] [Fig. 2]



[Fig. 3] [Fig. 4]

[Fig. 1]
Asteroid (21) Lutetia at closest approach.
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[Fig. 2]
Mars Express has used its MARSIS radar to give strong evidence for a former ocean of Mars. The radar was deployed on the spacecraft in 2005 and has been collecting data from the subsurface ever since.
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[Fig. 3]
This illustration shows Jupiter and its large moons: Ganymede, Europa, Io and Callisto. © ESA/M. Carroll

[Fig. 4]
The French Instruments Mars Operation Centre (FIMOC), the MSL operation centre at CNES Toulouse.
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Rosetta: deciphering the Rosetta stone of our origins

The Rosetta spacecraft of ESA, launched on March 2, 2004, is en route to its target. On July 10, 2010, Rosetta flew by the asteroid 21-Lutetia at a distance of 3 142 km (Fig. 1). The 400 images revealed that Lutetia is a 120 x 100 km asteroid with a very high density and is very dry. A team from LESIA has suggested that Lutetia is a remnant of the numerous planetesimals and not a fragment of a large object. Eleven months later Rosetta entered in Deep Space Hibernation (DSH) for a period of 32 months. After a ten-year cruise and four gravity assists (Earth, Mars, Earth, Earth), the satellite will rendezvous with the Churyumov-Gerasimenko comet in 2014 and will then drop the PHILAE lander on its surface in November, thus chalking up two world firsts.
CNES coordinated all French contributions to the payload and lander, involving eleven instrumental and two technical contributions to the lander. CNES is in charge of the Science operation and navigation centre of PHILAE as part of the ground segment, in cooperation with DLR.

Mars Express

For more than eight years, the European probe Mars Express has been observing the red planet. It is a great success for Europe, being the first European mission devoted to this planet and has thus been extended until the end of 2012 and probably beyond.

New analysis of data sent back by the SPICAM spectrometer has revealed for the first time that the planet's atmosphere is supersaturated with water vapour. This surprising discovery by a team of LATMOS-UVSQ (Guyancourt) has major implications for understanding the Martian water cycle and the historical evolution of the atmosphere. It seems that previous models have greatly underestimated the quantities of water vapour at heights of 20-50 km, with as much as 10 to 100 times more water than expected at this altitude.

A team of scientists from LATMOS and IAS-CNRS (Orsay) have discovered a new type of light emission in the night of planet Mars, which helps to understand how the upper atmosphere is moving as a function of season. Using the OMEGA imaging spectrometer, they detected an emission at 1.27 µm, the tell-tale signature of the oxygen (O_2) molecule when it has just been formed from recombination of two oxygen atoms ($O+O \rightarrow O_2$).

A team led by scientists from IPAG (Grenoble) has mapped the dielectric properties of Mars polar regions using the MARSIS radar (Fig. 2). In the Southern hemisphere, a decrease of dielectric constant at high latitude has been interpreted as due to the presence of ice in the ground. In the North, the spatial variations of the dielectric constant show a strong correlation with the age and geological nature of the terrain. The low dielectric constant of the 'Vastitas Borealis' indicates its sedimentary nature.

[Fig. 5]

[Fig. 5] - The 150 km GALE crater where MSL will land in August 2012. During the mission the rover will climb the mountain in the centre of the crater. Curiosity will first pass over a very old clay layering and then through a younger sulfate layer during the nominal 2 year mission.
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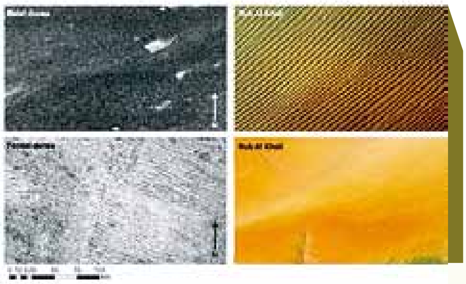
wider areas in between, suggesting less abundant dune material in this region

[Fig. 6]



[Fig. 6] - Dunes on Saturn's moon Titan and on Earth.
Two different dune fields on Titan: Belet (top left) and Fensal (bottom left), as imaged by Cassini's radar.
The image also shows two similar dune fields on Earth in Rub Al Khali, Saudi Arabia. Fensal is at higher latitude and elevation than Belet and clearly shows thinner dunes with brighter and wider areas in between, suggesting less abundant dune material in this region.
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This finding provides new geophysical evidence that the top layer of the Northern plains is of sedimentary origin, deposited when large amounts of liquid water were flowing through the outflow channels and carrying water and sediments onto the plains in water and sediments.

Cassini Solstice mission

The Cassini mission has been continuing to observe Saturn's system since its arrival there in July 2004. French scientists, involved in almost every one of the twelve instruments, are the second biggest scientific community after the Americans. A team led by scientists from LATMOS-UVSQ has studied the Radar data of the Cassini mission. They measured the dunes on Titan and have shown that they are 100 km long, 1 to 2 km wide and 100 m high (Fig. 3). Their findings show that the size of the Titan dunes evolved with latitude and elevation. They are distributed mainly near the equatorial region between + and – 30° of latitude, but they are less abundant toward the North probably because of a seasonal effect. The higher in elevation, the thinner are the dunes. A dry climate is more favourable for the dunes to grow and evolve.
The second extension of the programme, called the 'Cassini Solstice Mission' has been accepted on the grounds that it allows us to observe Saturn's system during half a kronian year in order to study the seasonal effects on the planet but also on Titan. The final stage of the mission foresees that the trajectory of Cassini will pass between the rings and Saturn before ending with a controlled entry into its atmosphere in the autumn of 2017.

Mars Science Laboratory, en route to Mars

MSL was launched successfully on 26 November 2011 and is due to land on 6 August 2012 in the Gale crater. France has contributed to the ChemCam (IRAP) and SAM (LATMOS) instruments.
The FIMOC (French Instruments Mars Operation Centre), the MSL operation centre at CNES Toulouse (Fig. 4), will be training along with JPL during the last few months in order to be ready when the rover lands on Mars on the floor of the Gale crater (Fig. 5) at the beginning of August. This crater was chosen because clay minerals have been detected there.

These minerals, discovered by the French OMEGA spectrometer in 2005, are the key evidence that Mars, early in its history, was warm and wet with abundant liquid water running on its surface.

BepiColombo aims for Mercury in 2022

Due to technical difficulties, ESA recently announced that the launch will be delayed until August 2015 with an arrival around Mercury planned for January 2022.
Since 2005, CNES and the CNRS laboratories have been pursuing their development of the scientific payloads for the MPO and MMO orbiters. The flight model of the French UV spectrometer, PHEBUS, led by LATMOS laboratory, is expected to be delivered to ESA late this year.

JUICE, an ambitious mission to Jupiter and its Moons

After a competition between a mission to Saturn (Titan Saturn System Mission, ex Tandem) and EJSM (ex Laplace), both French initiatives, ESA and NASA decided on 18 February 2009 that the L-class mission towards a giant planet would be EJSM. After the cancellation of the NASA orbiter (JEO: Jupiter Europa Orbiter) which was to study Europa and Io, the ESA orbiter (renamed JUICE, JUpiter ICy moon Explorer) intended to study Ganymede and Callisto, has been redesigned (Fig. 6). JUICE will perform two flybys of Europa and will have a high inclination phase to enable it to study the Jupiter magnetosphere. CNES is supporting several French teams who are preparing for their contribution to the payload. The mission was selected by SPC early in May 2012, the announcement. of opportunity for the selection of the payload will follow this summer.

Genesis, Sun and Planets Constructed Differently

A study led by a CRPG-CNRS team on nitrogen isotopic ratio revealed that in comparison to Earth's atmosphere, nitrogen in the sun and Jupiter has slightly more ^{14}N, but 40 percent less ^{15}N. Both the sun and Jupiter appear to have the same nitrogen composition. The implication is that objects in the solar system did not form out of the same solar nebula materials of which the sun was formed. Data on the solar wind ions collected by Genesis spacecraft and brought back to Earth in 2004 was analysed.

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Solar System

Laboratory contribution

Seasonal evolution of the cloud cover above the north pole of Titan, the biggest moon of Saturn

Évolution saisonnière de la couverture nuageuse du pôle nord de Titan, la plus grosse lune de Saturne

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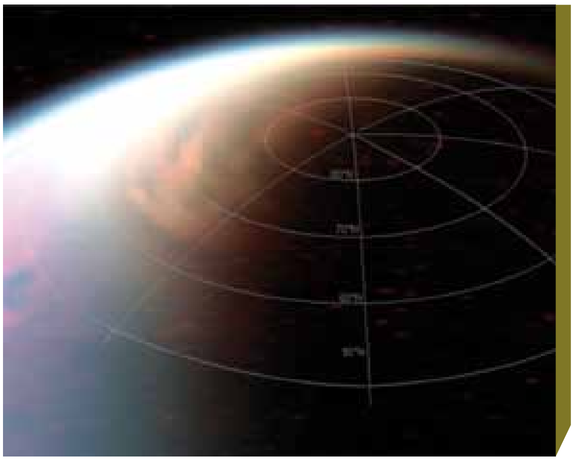
Abstract

Saturn's Moon Titan has a thick atmosphere with a meteorological cycle. Images acquired by the VIMS spectrometer onboard the Cassini spacecraft revealed that a giant cloud system covers the north pole of Titan. A seasonal evolution is observed.
Whereas the cloud system completely covered the north winter pole in 2006, it started to thin out and leave gaps as Titan approached equinox in 2009, revealing the underlying hydrocarbon sea known as Kraken Mare and surrounding lakes.

Résumé

Titan, une des lunes de Saturne, possède une atmosphère avec un cycle météorologique. Des images acquises par le spectro-imageur VIMS de la sonde Cassini montrent que le pôle nord de Titan est couvert, en hiver, par un vaste complexe de nuages qui évolue au cours des saisons. Alors que le système de nuages recouvrait entièrement le pôle en 2006, il commence à se désagréger à l'approche de l'équinoxe en 2009, laissant entrevoir la mer d'hydrocarbures « Kraken Mare » et les lacs environnants.

[Fig. 1]



Besides Earth, Titan is the only place in the solar system to be veiled by a thick atmosphere, with condensable species that form clouds, rain and lakes. This atmosphere, with a surface pressure close to the terrestrial value, contains primarily nitrogen and a few percent of methane.

The dissociation of methane and nitrogen by ultraviolet sunlight produces hydrocarbons and nitriles, which react to create more complex molecules as the origin of a photochemical haze. Titan's north polar latitudes, where the temperatures are the coldest during the winter season (2002-2009), provide a cold trap for several species produced by both chemistry and atmospheric transport processes, with strong winds blowing around the pole.

Clouds on Titan have been remotely observed by Earth-based telescopes since 1995 [1] [2][3][4] and since 2004 by the Cassini spacecraft [5][6][7][8][9]. Since then, they regularly appeared as convective methane clouds, on the south pole and on a belt located at ~40°S, with only few isolated occurrences observed in tropical regions. In addition to the discrete and optically thick methane clouds, the edges of a vast cloud system were detected north of 50°N latitude, up to the terminator at 68° latitude, in 2005 images [6]. This northern cloud was hypothesized, based on its altitude, mass and particle size to be an ethane cloud that capped the north pole, resulting from the winter downward mixing of photo-

[Fig. 1] - Image of the north polar cloud of Titan acquired with the Visual and Infrared Mapping Spectrometer (VIMS) onboard Cassini on 28 December 2006 (false color composite with the red, green and blue coded by the 5 µm, 2.78 µm, and 2.03 µm images). © NASA/JPL/Univ Arizona/LPGNantes

[Fig. 2]

[Fig. 2] - Series of false-color images obtained by VIMS between 2006 and 2009 when Titan was transitioning from northern winter to northern spring, and showing the evolution of the cloud cover over the north pole. The cloud appeared much thinner and patchier around the equinox in 2009, revealing the underlying northern seas and lakes of hydrocarbons. © NASA/JPL/Univ Arizona/LPGNantes

chemically produced species in the upper atmosphere [6][10]. Yet, as the north pole region was not illuminated, the cloud was not fully visible at the time of this detection. The first good opportunity to observe the half-lit north pole with the Visual and Infrared Mapping spectrometer (VIMS) onboard Cassini occurred on December 28, 2006 (Fig. 1). VIMS acquires hyperspectral images using a detector of 64x64 pixels in the spatial dimension. For each pixel of an image, a 352-channels spectrum is acquired in the range from 0.3 to 5.1 µm [11]. The extent and morphology of the north cloud was revealed for the first time in the image shown in Fig. 1 [12], confirming previous expectations [6]. Unlike Titan's southern clouds, this northern cloud appears diffusely spread over a very large area. The clouds extend from 64°N in latitude up to the north pole, and are surrounded by a hood down to latitudes of 55°N [13]. This range of latitudes also corresponds to the area where empty and filled lakes have been imaged by the RADAR instrument [14].

An evolution of the cloud cover with the seasons has then been observed. Fig. 2 displays a time series of a selection of the most resolved VIMS global views of the north pole acquired between December 28, 2006 and June 6, 2009, when Titan was transitioning from northern winter to northern spring [12]. In 2006, the north polar cloud appeared dense and opaque. But in VIMS images obtained around the 2009 equinox, when the sun was directly over Saturn and Titan's equators and northern winter was turning into spring, the cloud appeared much thinner and patchier. It should be noted that starting from 2008, it seems that the north cloud begins to break up in some places, leaving a zone which appears much less opaque than the surroundings at ~70°N. The images in March and April 2009 confirm this observation. The north cloud is at this time much less widespread than in previous observations, showing a very diffuse and patchy cloud pattern, and revealing the underlying Kraken Mare. Kraken Mare corresponds to the largest exposure of liquids in the northern regions. It is therefore interesting to note that starting from the equinox, it will be directly possible to investigate the composition of liquids in the northern regions using infrared spectroscopy. A dedicated observation has been designed at closest approach during the T69 flyby in June 2010, providing a very detailed view of Ligea Mare and its connexion with Kraken Mare [15].

The predictions of the Titan global climate model (GCM) [10] are at first order consistent with the presence of this northern cloud system at latitudes higher than 60°N, and with its observed temporal evolution. The reversal of the pole-to-pole circulation, which is predicted to occur after the equinox during the spring/fall seasons, will lead to significant changes in the cloud cover, and possibly the underlying lake distribution, which will be monitored with the Cassini spacecraft up to 2017.

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Solar System

Laboratory contribution

Titan's dunes

Les dunes de Titan

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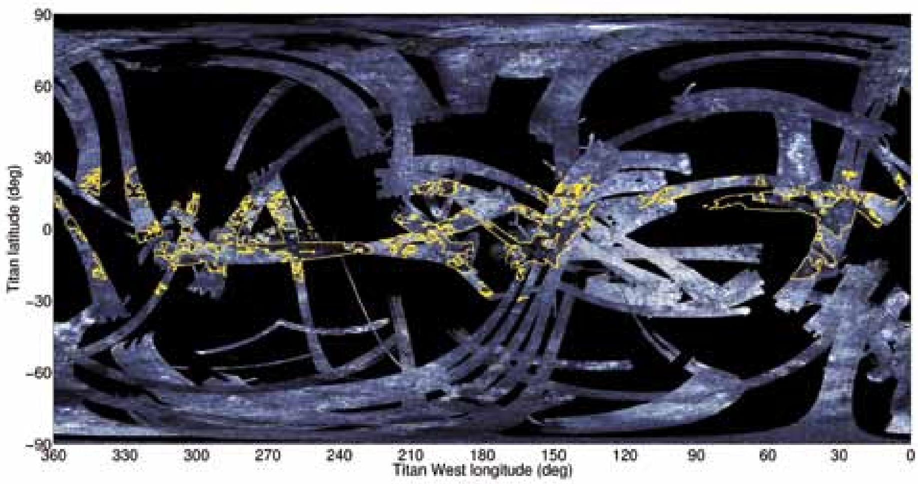
Abstract

Fields of linear dunes cover a great portion of the equatorial belt of Titan, the biggest satellite of Saturn. Dunes point to the mobility and processing of sediments – they are the telltale signatures of wind at work. As such, they provide crucial insights into the geology and climatic history of the only satellite in the solar system that has a substantial atmosphere.

Résumé

Des champs de dunes linéaires couvrent une portion importante de la ceinture équatoriale de Titan, le plus gros satellite de Saturne. Signatures du vent à l'œuvre et de l'érosion de la matière sédimentaire, elles fournissent des informations précieuses sur la géologie et les climats passés et présents du seul satellite du système solaire possédant une atmosphère substantielle.



[Fig. 1]

Thousands of dunes observed on the surface of Saturn's moon Titan were one of the greatest surprises uncovered by the Cassini spacecraft. Although dunes occur on the Earth, Mars and Venus, their discovery was unexpected on Titan where solar heating and cooling were thought to be not significant enough to generate substantial winds [1]. Dunes were first imaged in February 2005 by the SAR (Synthetic Aperture Radar) onboard Cassini [2]. As the mission continues, more dunes are unveiled. Titan's dune fields are mainly confined to the equatorial belt, almost strictly within ±30° latitude, and nearly encircle the globe (Fig. 1). They likely cover as much as 13% of Titan's surface which corresponds to an area of ~10 million km² that is roughly the area of the United States [3].

Dune fields are in fact, with the exception of seemingly featureless plains, the dominant landform on Titan. Cross-cutting relationships indicate that there are among the youngest features on the surface of the satellite, though whether they are still active is unclear. Nearly all of Titan's dunes are linear in form: they extend parallel to each other with long straight crests. They are generally a few kilometers wide, hundreds of kilometers long and tens of meters high. They are very similar in size and morphology to the giant linear dunes found on Earth in the Namibian, Saharan, and Saudi Arabian deserts [4]. On Earth, and by extension Titan, several conditions must be met in order to develop dunes: 1) a supply of sand-sized sediments, 2) winds strong enough to transport these sediments from source zones and 3) collection areas offering climatic and topographic conditions favorable to sand deposition and far from sediment removal or a trapping systems such as expanses of liquid or rough surfaces [5]. Furthermore, dune dimension and shape reflect the meteorological and geological boundary conditions in which they have formed and evolved. Dunes thus hold important clues for Titan's climate and surface processes.

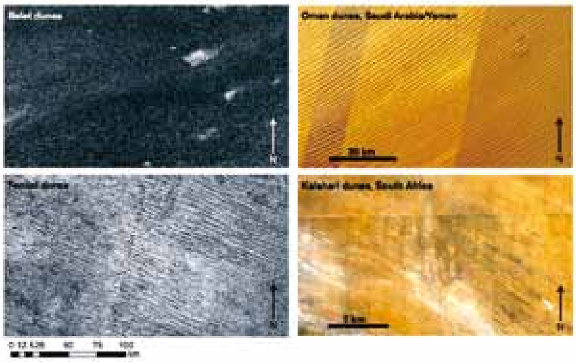
Dunes point to the processing of sediments on Titan. Cassini spectroscopic and microwave radiometry observations have shown that the composition of Titan's sand is most probably dominated by solid organics rather than water ice [6][3]. Dune material would then be the product of atmospheric photochemistry. However the process by which sub-micron haze particles aggregate into sand grains (presumably ~0.3 mm [2]) are still unknown. Most likely mechanisms imply the erosion (fluvial, aeolian or by seepage of liquid hydrocarbons from the subsurface) of surficial sedimentary layers made of organics precipitated out of the atmosphere and uniformly deposited at the surface.

Dunes are also the telltale signatures of wind at work. The surface winds that sculpted the linear dunes on Titan were likely triggered by the annual cycle of meridional 'Hadley' flows like on Earth but also, to a smaller extent, by the atmospheric gravitational tides due to Saturn [8]. Because of Titan's thick atmosphere and low gravity, winds as strong as 1-2 m/s appears to be sufficient to transport the probably fairly light sand-sized particles. Based on the orientation of the linear dunes and the way they divert and reconnect around topographic obstacles, these winds probably blow from west to east [9].

SAR images have revealed regional variations among Titan's dunes [10]. These variations betray regional contrasts in terms of the sand supply, sand availability (actual sediment delivery to the dune system) or wind transport capacity. As illustrated by Fig. 2, in some regions, dunes are closely-spaced and separated by radar-dark inter-dune areas (upper left panel) while, in other places, dune fields exhibit narrow dunes and bright inter-dune zones (lower left panel). The sand volume is probably reduced in the latters. The brightening of the inter-dune areas, in particular, suggests a thinner sand cover. Further, there seems to be a definite trend towards narrower or more widely separated dunes and thinner interdunal sand cover in both elevated and higher northern latitude terrains [10]. The altitudinal control of dunemorphometry indicates that sand sources most probably occur in lowlands. The latitudinal preference could result from a gradual increase in the soil wetness toward the North due to the asymmetric seasonal forcing associated with Titan's current orbital state. Summers are indeed shorter but more intense in the south [11]; if the northern terrains are wetter, they are probably less favourable to dune development. This should reverse every ~40 000 years (Croll-Milankovitch cycle).

It remains that the variations observed among Titan's dunes are relatively small which suggests that they were all built at the same time, forming a single generation. The sparse dune-like radar-bright features recently detected at Titan's mid-to-high latitudes, however, may be fossil dunes and thus provide insights into more ancient climates [12].

[Fig. 2]



[Fig. 1] - Mosaics of the Cassini SAR (Synthetic Aperture Radar) swaths overlaid on an ISS (Imaging Science Subsystem) base map. Dunes field are outlined in yellow. They are confined to the Equatorial belt.

[Fig. 2] - Images of dune fields on Titan (left) and on Earth (right). The Oman dunes are similar in morphometry to Titan's Belet dunes while the Kalahari dunes, which are located in an area limited in sediment availability, bear a striking ressemblance with the Fensal's dunes. Fensal is both at higher latitude and altitude than Belet.

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Solar System

Laboratory contribution

Dielectric map of the Martian polar regions and the nature of Northern circum-polar plains

Cartographie diélectrique des pôles martiens et la nature des plaines circumpolaires Nord

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Abstract

The dielectric properties of Mars polar regions were mapped by the MARSIS radar on board Mars Express. In the southern hemisphere, a decrease of dielectric constant at high latitude is interpreted by the presence of ice in the ground. In the North, the spatial variations of the dielectric constant show a strong correlation with the age and geologic nature of the terrains. The low dielectric constant of the « Vastitas Borealis » attests of its sedimentary nature.

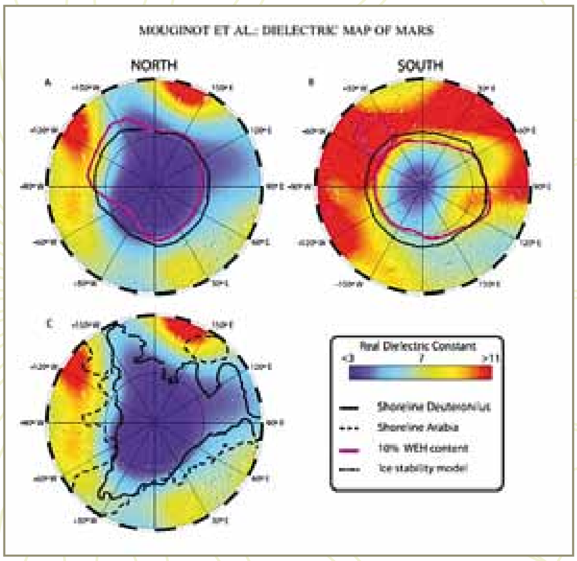
Résumé

Le radar Marsis de la sonde Mars Express a permis la cartographie des propriétés diélectriques des régions polaires martiennes. Au Sud, une diminution de la constante diélectrique à haute latitude est expliquée par la présence de glace dans le sous-sol. Au Nord, les variations spatiales des propriétés diélectriques montrent une forte corrélation avec l'âge et la nature géologique des terrains. La faible constante diélectrique de la formation « Vastitas Borealis » atteste de sa nature sédimentaire.

Ground penetrating radars offer a unique opportunity to characterize the nature and structure of planetary subsurfaces at depths that cannot be reached by other remote-sensing techniques. We have processed data collected by the MARSIS/Mars Express radar [1] during 3 years to retrieve a global reflectivity map of Mars at a frequency of 5 MHz. The first reflection of the electromagnetic wave is influenced by both the topography of the surface and the average properties of the first 50 to 100 meters below the surface. Accurate simulations of the influence of surface topography on the radar reflectivity have been performed using the MOLA altitude map in order to isolate and subtract topographic effect from the reflectivity map [2]. As a result, we obtain a map that characterizes the spatial variations of the dielectric constant of the subsurface materials. This dielectric constant, epsilon, is influenced by the physical and chemical properties of the subsurface. In the case of Mars, this value is essentially influenced by the density of the rocks and the presence and amount of water ice.

Comparative analysis of the dielectric maps for the Northern and Southern polar regions [3] reveals an intriguing difference between the two hemispheres (Fig. 1). In the South, we observe a strong decrease of the dielectric constant poleward of 60°, from values around

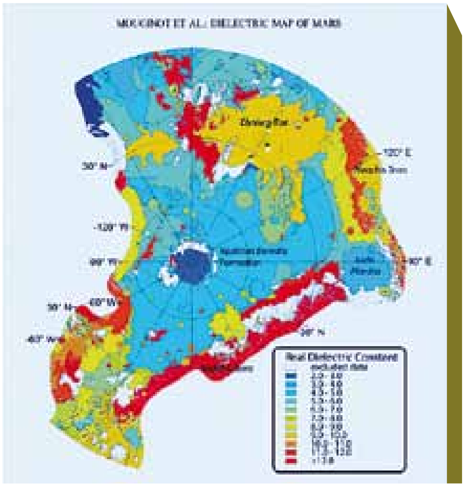
[Fig. 1]



8 or 9, typical of dense igneous rocks, to values as low as 4 or 5 near the pole. The observed pattern of dielectric constant shows a good consistency with the theoretical distribution of ground water ice in equilibrium with the current climate [4].
In addition, there is also a good match between the MARSIS map and the map of hydrogen concentration in the first meter of the subsurface obtained by the Neu-

trons and Gamma-ray spectrometers on board Mars Odyssey [5]. The agreement between independently measured datasets and theoretical calculations leads to a robust conclusion about the cause of the decrease of dielectric constant: the presence of water ice in the ground, either deposited by diffusion of water vapor from the atmosphere or as remnants from deposition during a past episode of high obliquity.

The situation appears very different in the North where the surface dielectric map clearly differs from the distribution of ground-ice observed by GRS. The MARSIS map displays a pattern of low reflectivity in three similarly sized lobes or branches extending toward lower latitudes in the regions of Amazonis Planitia (150°W), Chryse Planitia (30°W) and Utopia Planitia (100°E). This pattern of low dielectric values is generally consistent with the global topography and the extent of the Vastitas Borealis Formation (VBF), a geological formation that covers most of the Northern plains. It has been proposed in the past that the VBF is a sedimentary unit, consisting of material eroded from the Martian highlands, transported by the large outflow channels and deposited over the Northern plains [6][7]. The channels activity declined and eventually stopped around the Hesperian/Amazonian transition. Simultaneously, intense volcanic activity has affected the Northern plains, as attested by numerous geologic features [8]. Concomitant fluvial and volcanic activity certainly resulted in a complex stratigraphy of sedimentary and igneous rocks. The low dielectric constant measured over the VBF can only be explained by the presence of very large amounts of water ice, a high porosity of the rocks, or a combination of these. In any case, the dielectric map points towards a sedimentary nature for the VBF.
In order to further investigate the relationships between the observed dielectric constant and the nature and age of the geological formations, we have calculated the average dielectric constant of the different units defined by [9]. Fig. 2 shows the results of this analysis.



[Fig. 2]

[Fig. 1] - Dielectric maps of the Northern (A,C) and Southern (B) polar regions of Mars measured by MARSIS. The contour-line of 10% Water Equivalent Hydrogen (WEH) in the shallow subsurface [5], the current theoretical stability limit of ground ice [4] and the putative paleo-shorelines in the North [7] are overlaid onto the MARSIS map. Figure taken from [3].

[Fig. 2] - Composite geologic and dielectric map of Mars Northern plains. The map is color-coded to indicate the MARSIS mean dielectric constant of each geological unit identified by [4]. Figure taken from [3].

Comparison between the nature of the geological units as inferred from geological mapping and the dielectric constant as measured by MARSIS demonstrates their correlation: units interpreted as sedimentary by [9] show low values of dielectric constant while units interpreted as volcanic show significantly higher dielectric values.
The MARSIS dielectric map provides new geophysical evidence that the top layer of the Northern plains is of sedimentary origin, deposited when large amounts of liquid water were flowing through the outflow channels and feeding the plains in water and sediments. Whereas MARSIS shows evidence for strong mechanical alteration of the igneous rock from which these sediments are formed, the absence of identification of alteration minerals in the VBF by orbital spectrometers [10][11] shows that the interaction between rocks and water was of short duration and/or at low temperature. Contrary to putative warmer and wetter Noachian environments, the cold and muddy oceans that episodically covered the northern plains at Hesperian were certainly not favorable environments for life.

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Solar System

Laboratory contribution

Isotope composition of solar wind nitrogen collected by the Genesis NASA mission

Composition isotopique de l'azote du vent solaire collecté par la mission Genesis de la NASA

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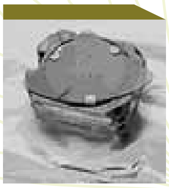
Abstract

The Genesis mission sampled solar wind ions to document the elemental and isotopic compositions of the Sun and, by inference, of the proto-solar nebula. Isotopic analysis of a Solar-Wind Concentrator target material shows that implanted solar wind N has a $^{15}N/^{14}N$ ratio of $2.18 \pm 0.02 \times 10^{-3}$ (≈ 40% poorer in ^{15}N relative to terrestrial atmosphere), which is the lowest value known for solar system objects. This result demonstrates the extreme N isotopic heterogeneity of the nascent solar system.

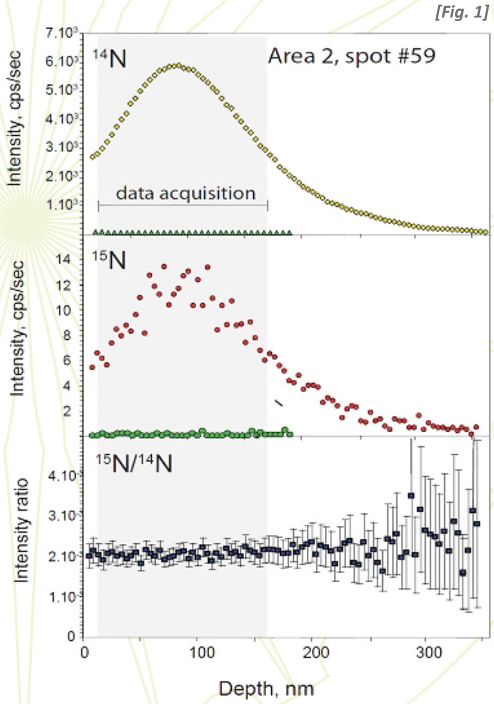
Résumé

La mission Genesis a échantillonné le vent solaire afin de documenter les compositions élémentaire et isotopique du Soleil et de la nébuleuse proto-solaire. L'azote solaire analysé au CRPG (Nancy, France) a un rapport isotopique $^{15}N/^{14}N$ de $2.18 \pm 0.02 \times 10^{-3}$ (≈ 40% plus pauvre en ^{15}N que l'atmosphère terrestre), ce qui est la valeur la plus basse enregistrée dans le système solaire. Ce résultat montre l'hétérogénéité extrême de la composition isotopique de N dans le système solaire naissant.

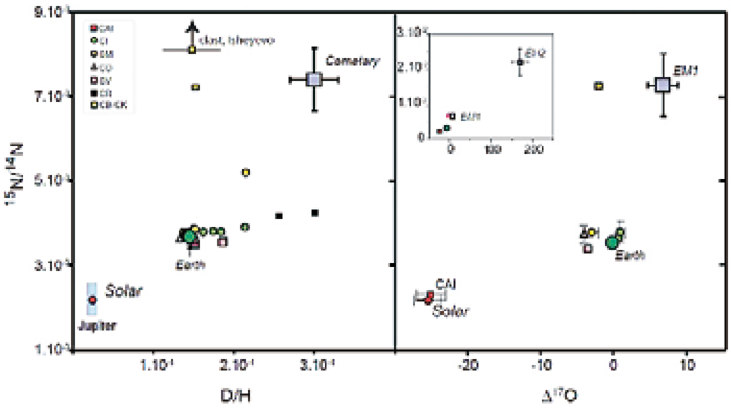


Matter in the solar system is very well homogenized, likely a result of efficient stirring in the highly turbulent nascent solar system. However, some of the light elements present large, sometimes extreme, variations of their isotopic ratios among different solar system objects and reservoirs. Nitrogen, the fifth most abundant element in the Sun, is particularly intriguing because its isotopic composition shows variations up to a factor of ≈ 6 in solar-system objects. Numerous attempts have been made over the last decades to determine the N isotopic composition of the Sun through the analysis of solar ions implanted in lunar soils, with limited success. The cause of such variations (whether resulting from processes internal to the solar system or inherited from a pre-solar history) remains unclear, in part because the initial isotopic compositions of these elements in the proto-solar gas are not known. In order to document the elemental and isotopic compositions of light elements, particularly O and N, the Genesis mission sampled solar wind (SW) ions in various target materials during 27 months at Lagrangian point L1 [1].

[Fig. 1]



[Fig. 2]



[Fig. 1] - Left: Concentrator SiC target mounted on its ion probe holder. Right: Example of depth profile of ^{14}N and ^{15}N concentrations as a function of depth (from surface on the left hand side to interior on the right hand side) within the target material. The lower part of the diagram represents the evolution of the $^{15}N/^{14}N$ isotopic composition with depth (from [2]).

[Fig. 2] - Co-variations of D/H and $\Delta^{17}O$ isotope compositions (the latter representing mass-independent fractionation of oxygen isotopes) with $^{15}N/^{14}N$ ratios among solar system objects and reservoirs (small symbols correspond to different classes of primitive meteorites; data refs. in [2]). All isotope variations can be understood as resulting from enrichments in the heavy and rare isotopes of H, O, N of the proto-solar nebula gas. Processes responsible for such enrichments are likely to have taken place in the nascent solar system through UV light-matter interactions or low temperature ion-molecule reactions, or both (from [2]).

We have analyzed precisely the isotopic composition of SW N by secondary ion mass spectrometry using the Cameca 1280HR2 instrument recently installed at CRPG Nancy, France [2]. SW ions were collected by implantation into a silicon carbide (SiC) quadrant of the target of the Genesis Solar Wind Concentrator, an electrostatic mirror that increased the fluence of some SW elements by a factor up to ~50. Both ^{14}N and ^{15}N data define simple bell-shaped distributions as a function of depth which peak ~80 nm below the target's surface (Fig. 1), as expected for SW implantation. Our measurements yield a $^{15}N/^{14}N$ ratio for the SW of $2.178 \pm 0.024 \times 10^{-3}$ (95% confidence level), corresponding to $\delta^{15}N = -407 \pm 7‰$ relative to the terrestrial reference value. Our estimate for the $^{15}N/^{14}N$ ratio of the bulk Sun, after correction for solar processing and propagation of all errors, is $2.268 \pm 0.028 \times 10^{-3}$ (95% conf.; $\delta^{15}N = -383 \pm 8‰$). This corrected $^{15}N/^{14}N$ ratio is a proxy for that of the proto-solar nebula (PSN). It is much lower than the ratio in the terrestrial atmosphere (3.676×10^{-3}), but is identical to that measured in Jupiter's atmosphere $^{15}N/^{14}N = 2.3 \pm 0.3 \times 10^{-3}$] [3] within the relatively large errors in the Jupiter ratio.

Because the PSN is the most ^{15}N-depleted, and the most gas-rich, reservoir in the solar system, we propose that the N isotope variations among solar system bodies result from variable mixing between a ^{15}N-poor gaseous component, and solids rich in nitrogen-15. Observed H, N and O isotopic variations are consistent with variable mixtures of a PSN component with components rich in heavy and rare isotopes, respectively D, ^{15}N and $^{17,18}O$ (Fig. 2). Alternatively, these enrichments might have resulted from interactions between photons and matter (e.g., photochemistry, ion-molecule reactions) that took place before, or during, formation of the solar system.

The existence of a common origin for these strong D-, ^{15}N-, ^{17}O- and ^{18}O- enrichments is a key question. The agreement of the solar and Jupiter's outer atmosphere $^{15}N/^{14}N$ is of considerable importance because Jupiter's atmosphere is enriched in N/H by about a factor of 3 (along with Ar, Kr, Xe, C, and S) compared to the solar photospheric elemental ratios [4]. These enhancements are usually interpreted as indicating that Jupiter is a mixture of solar nebula gas (the source of H and He) and outer solar system planetesimals [the source of the other, less volatile, elements]. If this interpretation is correct, then only about ¼ of the N in Jupiter is of nebula origin. Nevertheless, Jupiter has preserved the solar $^{15}N/^{14}N$, requiring that the N in the planetesimal contribution had low $^{15}N/^{14}N$, with only very small contributions from the very high $^{15}N/^{14}N$ observed in cometary HCN and CN [5]. Thus either the model for the origin of Jovian volatiles is not correct or the cometary HCN-CN $^{15}N/^{14}N$ may not be representative of outer solar system, possibly even cometary, matter. Nitrogen isotopic variations in meteorites provide a new cosmochemical tracer for understanding chemical and thermodynamical heterogeneities during condensation, dust aggregation and coalescence, and parent body processing. They were partially molten. Our result also has implications for the origin of volatile elements in terrestrial planets. These elements have similar N and H isotopic compositions to those of the sources of some chondritic materials (Fig. 2). Mixing between a D-rich, ^{15}N-rich component as observed in some comets with a solar reservoir (Fig. 2) cannot account for the relative homogeneity (ignoring factors of 1.5 or less) of N and H isotopic ratios of inner planets and meteorites. Instead this homogeneity suggests relatively efficient stirring and mixing of at least three (N, H) components in the inner solar system.

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