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The Moon That Thinks It's A Planet

Editorial

14 January 2005 was a slow news day: nothing happened that justified an eye-catching headline. Hence, a calm day for the newspapers. Yet, a small note amongst all the daily trivialities meant relief from a seven year nightmare for numerous space scientists and engineers all over the world: Huygens had safely landed on Titan.

Titan: the sorcerous name for an enigmatic moon in the outer solar system, more than one billion kilometres away. Huygens, a small space probe named in honour of Dutch scientist Christiaan Huygens, built by the European space community, had been seven years underway towards its remote destination Titan together with its US-American mate Cassini, commissioned to enter a literally unknown world.

The challenges were numerous: Titan's distance from Earth is so great that radio signals need one and a half hour to reach Earth and any corrective measure would need the same time again before becoming effective. Thus, there is no chance of intervening from Earth during the final critical moments when the probe approaches its destination with cosmic speed: a fully automatic mode of operation was required. Furthermore, is the surface of Titan liquid or solid? How cold is it there? No one knew. Huygens had to cope with all imaginable scenarios and in fact, it mastered its job excellently, imperturbably until the end of its short life on the surface, 72 minutes after touchdown. All these and many further challenges remain in the memories of the people who made the dream a reality.

One of the Huygens mission's leading scientists is Professor John Zarnecki, former Director of the Centre for Earth, Planetary, Space & Astronomical Research at the Open University, Milton Keynes, England. He was the Principal Investigator of the Surface Science Package of Huygens, a suite of instruments that probed the moon's atmosphere during descent and the surface properties after landing. It is with great pleasure that we present our readers today with his review of what an armada of scientists have found out since Huygens landed on Titan, eleven years ago.

Even though Titan surprises us with its many similarities to our planet, its climate does not really qualify it as an alternative: the surface temperature is some 200 °C degrees lower than on Earth! Anyhow, we wish our readers a pleasing lecture about one of the fascinating worlds in which our solar system is so incredibly rich.

Hansjörg Schlaepfer
Cinuos-chel, October 2016

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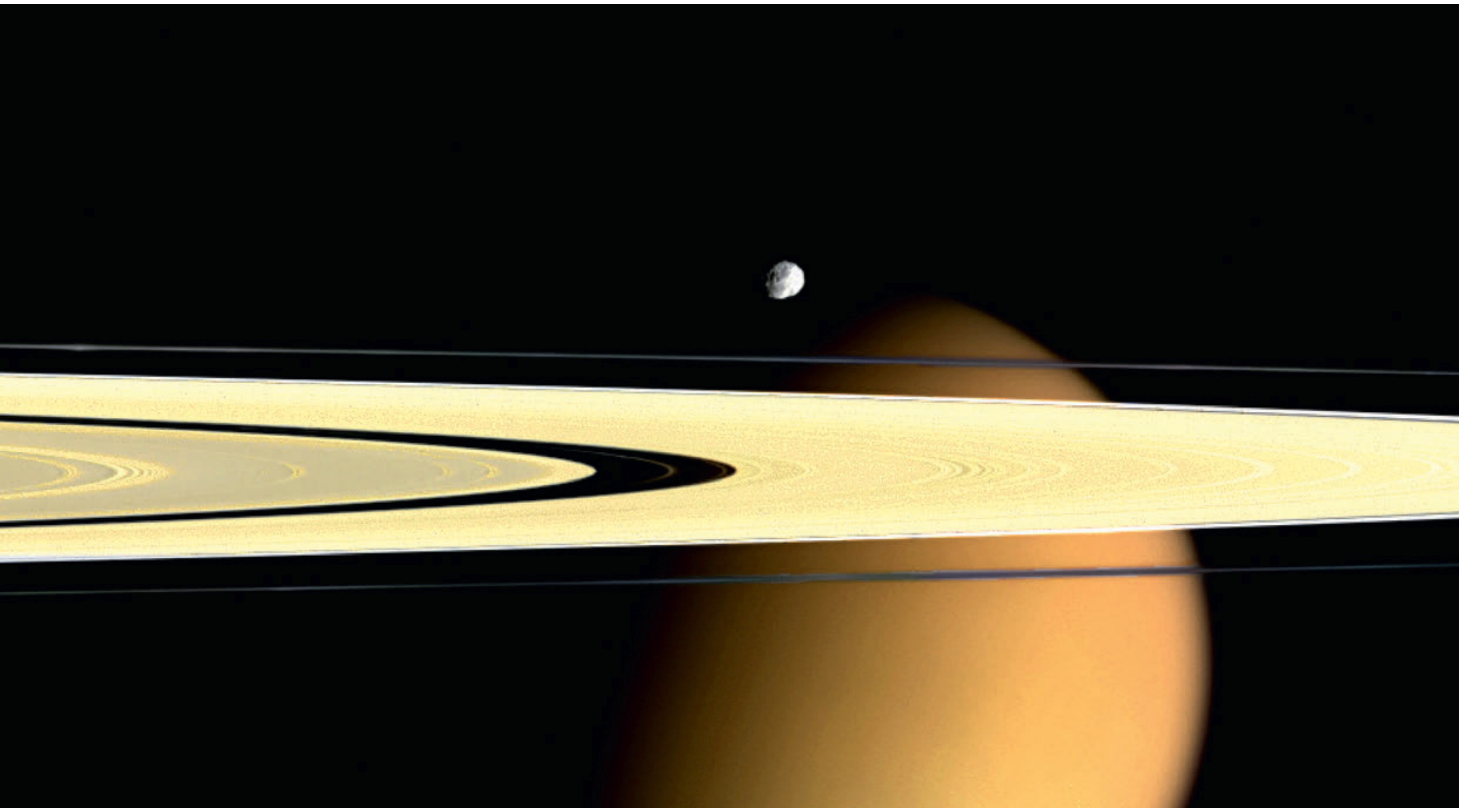
The Moon That Thinks It's A Planet: Titan[1]

by Prof. John Zarnecki, Professor of Space Science, The Open University, Milton Keynes, England and International Space Science Institute, Bern

Prologue

This issue of *Spatium* picks up a subject that *Spatium* no. 15 addressed in November 2005[2]: Titan and the Huygens Mission. That early report appeared a few months after the successful landing of the European Space Agency's Huygens probe on Saturn's largest moon Titan, a staggering 1,500 million kilometres away **(Fig. 1)**. At that time, the science community was just starting to browse the wealth of data that Huygens had downloaded. In the meantime, the stream of science data did not cease, rather, NASA's Cassini orbiter continued circling the Saturnian system providing a further cornucopia of data. The current issue of *Spatium* summarizes some major findings scientists all over the world have gained so far while the reader is kindly referred to *Spatium* 15 for technical information on the Cassini–Huygens twin spacecraft and its unique trajectory to the outer Solar System.

Fig. 1: The yellowish moon Titan seen here by NASA's Cassini orbiter behind Saturn's A rings (in white) and F ring (in blue). Near the rings and appearing above Titan is Epimetheus, a small moon that orbits just outside the F ring. The dark space in the A ring is called the Encke Gap, the domain of the minute moon Pan. (Credit: ESA/NASA).



[1] This text is based on a talk by Prof. John Zarnecki for the Pro ISSI audience on 28 October 2015. It was prepared by Dr. Hansjörg Schlaepfer and reviewed by Prof. Zarnecki.

[2] See *Spatium* no. 15: Titan and the Huygens Mission by Nicolas G. M. Thomas, November 2005.

Introduction

The Cassini-Huygens mission was conceived in the early 1990s. That was at a time when our knowledge of Titan was scarce due to its enormous distance from Earth. Ground-based observations had yielded no more than some blurry pictures, and the images gained by Pioneer 11 in 1979 and the two Voyager fly-bys in 1980 and 1981 respectively, could not improve the situation drastically. A thick opaque atmosphere obscures the moon **(Fig. 2)**, and it was not known therefore, whether Huygens would land on a liquid or solid surface. This compelled the mission planners to take a broad variety of scenarios into account.

In contrast, one thing was clear: the atmosphere is a complex chemical laboratory producing an astounding variety of organic molecules. Its major constituent is nitrogen, as is the case with the Earth's atmosphere. In addition, one finds methane (CH_4), a gas that on our planet is produced by biological processes. Would this mean that the methane is a sign of present life on Titan? As methane is destroyed in time spans of 50 million years by the solar ultraviolet radiation under the conditions prevailing on Titan that was an obvious, albeit far-reaching conclusion. The presence of methane makes an active source of fresh gas necessary that continuously replenishes the amount lost. Furthermore, under the temperature and pressure regime prevailing on Titan's surface, methane is a liquid fuelling speculations about lakes and seas covering Titan, just like on Earth. In short, the methane mystery marked Titan as a prime target for a daring space mission amongst all the objects in the outer Solar System.

Now, after the spectacular in-situ measurements made by the Huygens lander and the numerous fly-bys executed by Cassini in the meantime, our portrait of this enigmatic world has sharpened considerably and the intriguing similarities with our planet have become even more astonishing than before.

Fig. 2: Size comparison of Earth with the Moon (left) and Titan (right). Titan's diameter is 50% larger than Earth's Moon, and it is 80% more massive. It is the second-largest moon in the Solar System, after Jupiter's moon Ganymede, and is larger than the smallest planet, Mercury, although only 40% as massive. (Credit: NASA)

Exciting Titan

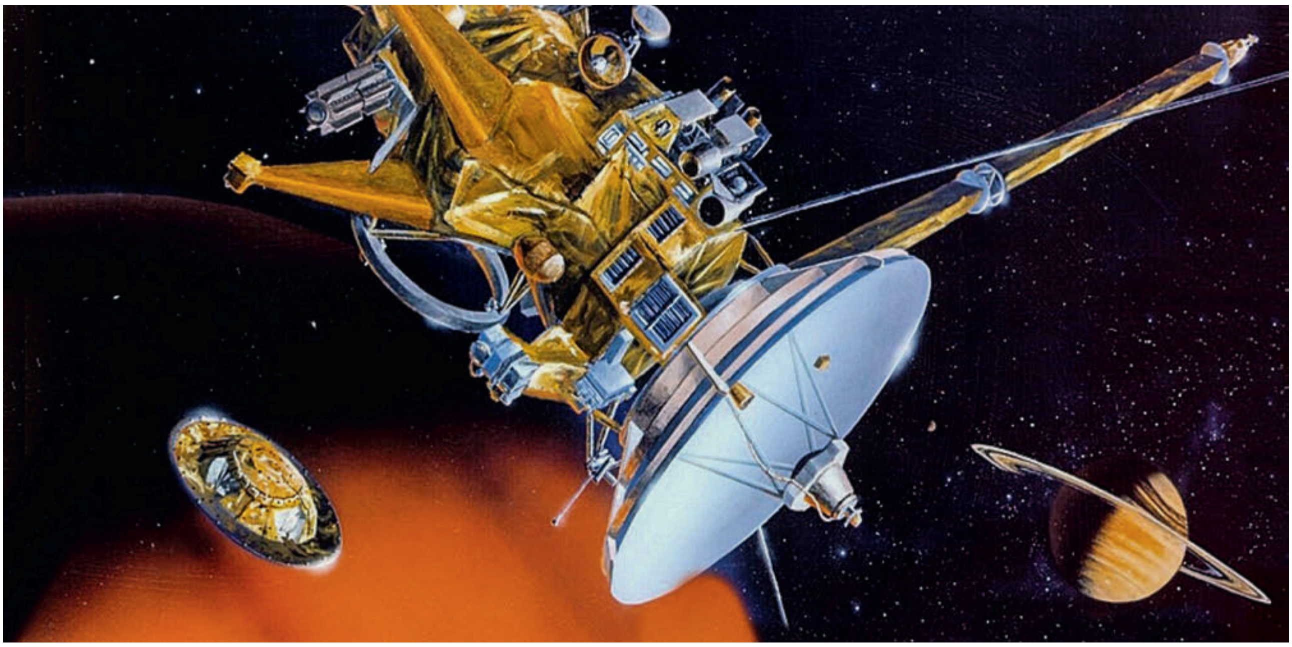
On Christmas Day 2004, Cassini's on board computer generated a short but nonetheless important signal. It activated the Swiss made spring and eject device, which had attached the Huygens probe safely to the Cassini main craft for the past seven years (see box to the right). The mechanism now provided the probe the required spin and velocity vector towards its final destination, Titan, still 4 million km away **(Fig. 3).** Twenty days later, Huygens reached Titan's outer atmosphere at a relative speed of 18,000 km/h, see **Fig. 4** overleaf. The heat shield reduced the velocity to 1,400 km/h allowing the probe to eject the first parachutes to further reduce the speed down to 300 km/h. At 160 km above ground, the heat shield and the back cover were jettisoned allowing the probe's instruments to fully take up their scientific tasks, which they executed with perfect precision.

Titan's Atmosphere

Titan is unique in many respects. It is the only moon in the Solar System that features a fully developed atmosphere consisting of more than just trace gases. It was known to the mission planners that Titan has a dense, opaque, aerosol-rich atmosphere consisting mostly of nitrogen mixed with methane and traces of some ten additional molecules. Probing the composition of this complex atmosphere at various altitudes and determining the temperature and pressure profile were

> **Swiss High Technology on Titan**
> The then Contraves Space Company, Zurich, together with the Vevey based APCO were responsible for three main subsystems of the Cassini-Huygens twin spacecraft: once released, the spin and eject device provided the Huygens probe with the required thrust towards its final destination Titan. The heat shield reduced the probe's speed during atmospheric entry while the back cover shielded the suite of science instruments during the seven years of interplanetary cruising.

Fig. 3 Probing the Saturnian system: NASA's Cassini spacecraft is shown here in the centre a few moments after the release of ESA's Huygens probe (to the lower left) heading toward its ultimate destination Titan in the lower background. (Credit: NASA)



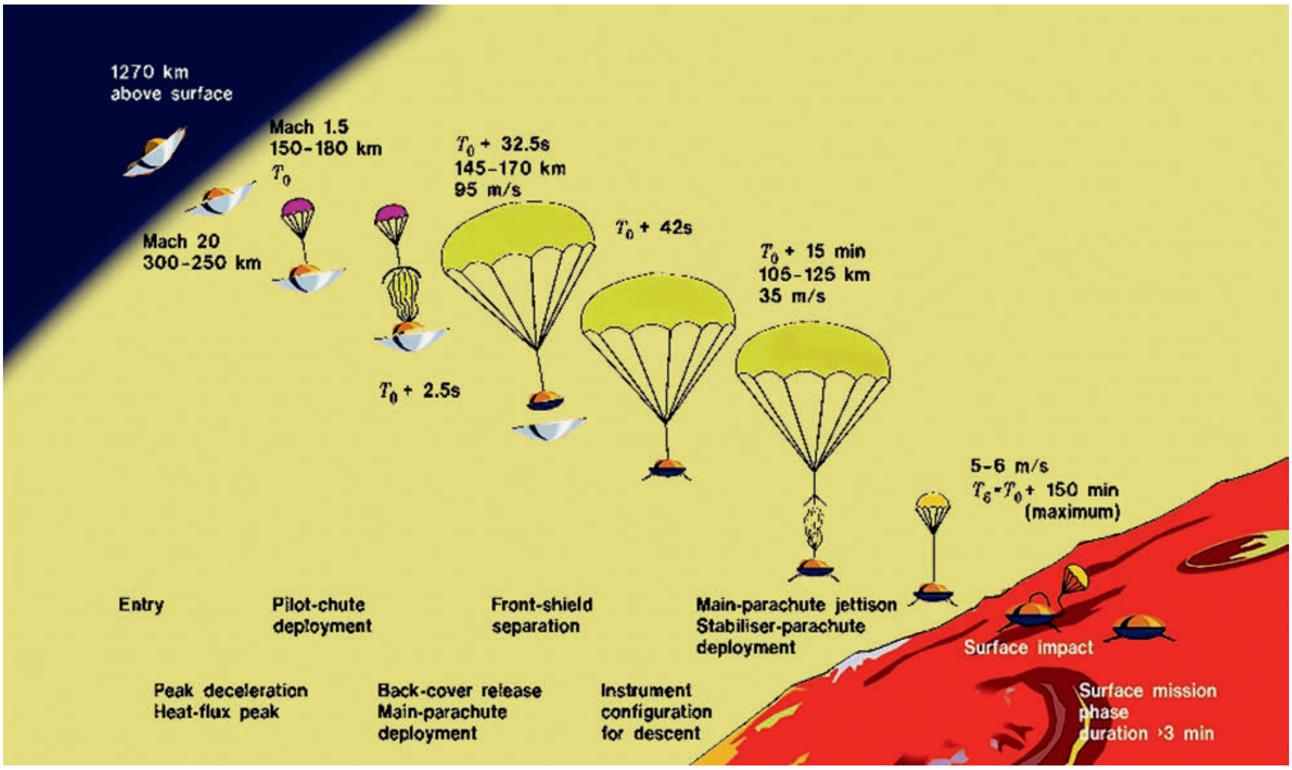


Fig. 4: Huygens' landing sequence: The probe dived at a speed of 18,000 km/h into the atmosphere's outer layers at an altitude of 1,270 km. The large heat shield served to reduce the entry velocity down to 1,400 km/h at about 150 km altitude. At this moment, Huygens' onboard computer ordered the ejection of the pilot parachute, which in turn opened the first main parachute, as well as the ejection of the back cover. At a velocity of 95 m/s, the front shield is jettisoned and replaced by a small stabilizer parachute that allows the probe to drift slowly through the atmosphere. Upon surface impact, the probe sat calmly on the moon's surface at an ambient temperature of –180 °C. For about 70 minutes, it remained active before falling into an eternal silence. The radio signals from Titan need some 1.5 hours to reach our planet. This precludes controlling the descent sequence from Earth and makes a fully automatic mode of operation a must. (Credit: after an ESA image)

therefore amongst Huygens' chief objectives.

Atmospheric Temperature and Pressure Profiles

The main instrument for probing the temperature and pressure during descent was the Huygens Atmospheric Structure Instrument (HASI). In contrast to expectations, the atmosphere turned out to be highly stratified **(Fig. 5).** Above 500 km, the average temperature was in the order of –100 °C with strong variations of some 20 °C due to inversion layers. Below, the temperature increased rapidly, reaching a maximum of –87 °C at 250 km. Further down, the temperature decreased steadily again throughout the stratosphere, reaching a minimum of –203 °C at the boundary between the stratosphere and the troposphere. Then, the temperature increased again as the probe neared the surface, rising to a chilly –180 °C at the landing site. Due to the extreme thickness of the atmosphere, the atmospheric pressure at the landing site was about 1.5 times that at the surface of the much more massive Earth.

Atmospheric Dynamics

The term dynamics refers to the movement of the atmospheric particles at different altitudes. During descent, the Huygens probe was attached to parachutes and their relative movement projected down to

Fig. 5: Titan's upper atmosphere consists of a surprising number of different layers of haze, as shown in this ultraviolet image of Titan's night side limb gathered by Cassini's cameras. These layers extend several hundred kilometres above the surface, much higher than the Earth's atmosphere. (Credit: NASA)

the ground allowed for an estimation of the atmospheric dynamics at various heights. In fact, the probe experienced a rough ride: over the duration of the entire descent, the probe glided eastward for a distance of 166 km. The winds were generally prograde, that is in the same direction as the moon's rotation. The wind speed peaked at roughly 120 m/s at an altitude of about 120 km. This is much faster than the rotation speed on the moon's equator. This strange effect is called super-rotation, known to exist on Venus as well. Such super-rotating winds are supposed to be driven by interactions of the atmosphere with the solar wind.

Chemical Composition of the Atmosphere

Of course, the outstanding complexity of Titan's atmosphere was one of the key drivers for launching a mission to Titan and an exceptional challenge for the scientists and engineers who built the instruments. In fact, Huygens had an entire suite of atmospheric chemistry instruments aboard. One of the most important was the *Gas Chromatograph and Mass Spectrometer* (GCMS) for determining the chemical composition of Titan's atmosphere during descent. As only very little was known when the mission was planned, the GCMS had to fulfil extreme requirements. It had to combine an excellent sensitivity (10 parts in 1 billion molecules) with a very wide range of particles (molecular mass range from 2 to 146 amu, where one atomic mass unit amu is equal to $1/12$th of the mass of a ^{12}C atom). The GCMS performed excellently delivering detailed mass spectra during descent (**Fig. 6** on the next page).

Formation and Evolution of the Atmosphere[3]

Planetary atmospheres are supposed to have formed in either one or a combination of two principal ways. During Solar System formation, a body's gravity attracted parts of the surrounding gas and dust constituting the protosolar nebula. The gaseous components of this matter then built the atmosphere, while the solids contributed to the body's mass. Later, planetesimals – the small evolving bodies circling the early Sun – were captured and their material integrated into the emerging planetary body. The impact of gas-rich planetesimals is supposed to have contributed further to building up the atmosphere.

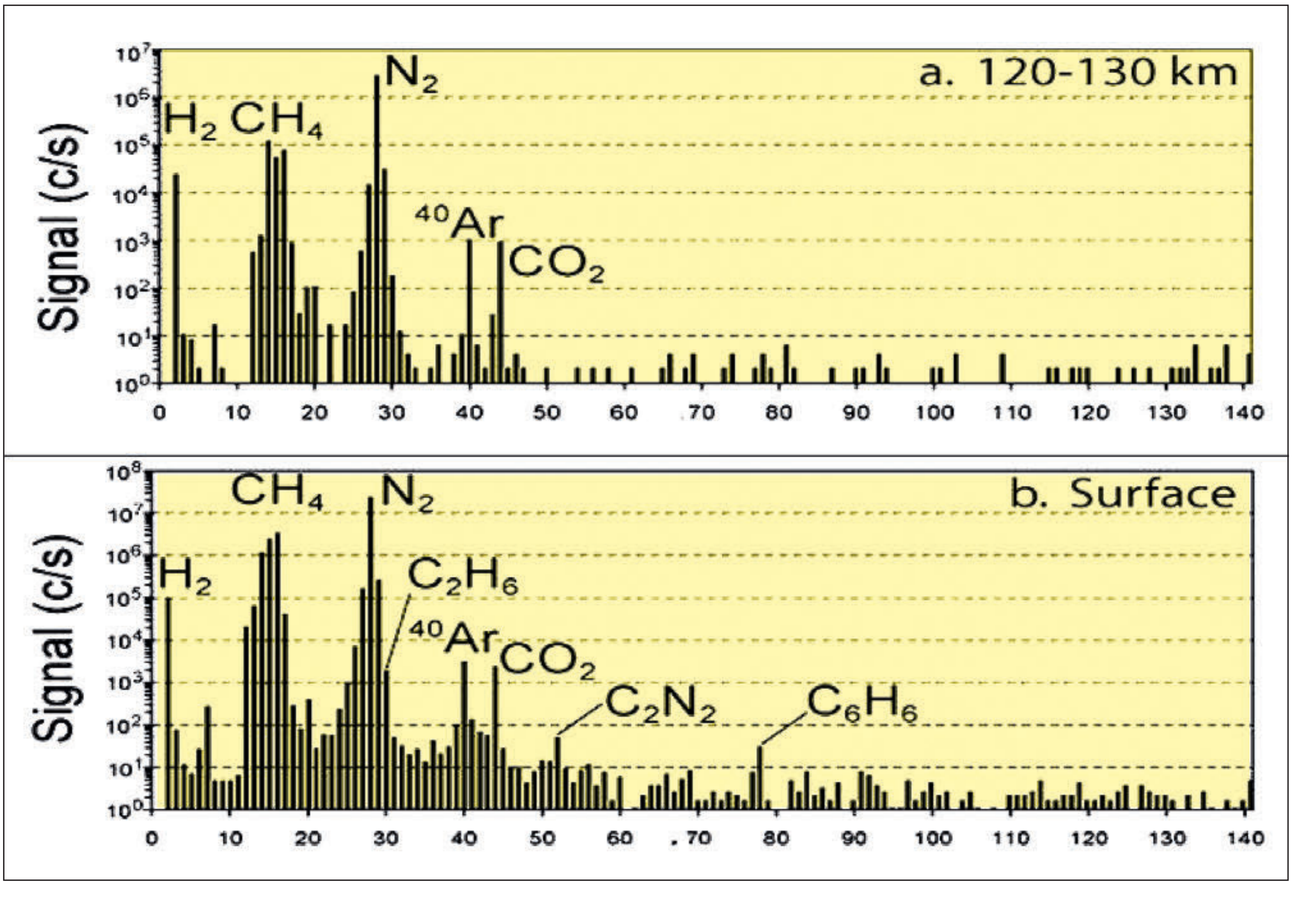
[3] See also *Spatium* no. 36: Formation and Evolution of Planetary Atmospheres by Helmut Lammer, November 2015.

A variation on this theme is accretion from a characteristic sub-nebula in the region surrounding an emerging giant planet. The composition of such an atmosphere seems to reflect a special blend of solar nebula accretion and degassing from planetesimals: Jupiter for instance has an endowment of heavy noble gases and other heavy elements relative to hydrogen that is greater than existed in the solar nebula at those times. In contrast, the rarity of noble gases in the Earth's atmosphere is interpreted as being a consequence of planetesimal influx, and the near absence of noble gases on Titan provides further support for this hypothesis.

Atmospheric Nitrogen

The most abundant constituent is nitrogen, and its origin remains one of Titan's great mysteries. In the stratosphere, some 300 km above ground, nitrogen reaches concentrations of 98.4%. As the Earth's atmosphere also contains some 80% nitrogen, one could infer that the atmospheres of planets and moons would contain nitro-

Fig. 6: The chemical composition of Titan's atmosphere. The two panels present the overall mass spectrum gathered at an altitude of around 120 km and on the surface. A first glance provides an impression of the incredible complexity of the chemical composition of Titan's atmosphere testifying that a wealth of chemical reactions is taking place there. Further, the similarity of the two diagrams suggests that the surface is soaked with products from the chemistry taking place in the upper atmosphere and raining down onto the surface. As expected, the main components are N_2 (nitrogen) and CH_4 (methane). Further notable constituents are the noble gas Argon ^{40}Ar, a series of increasingly complex organic molecules beginning with ethane (C_2H_6), carbon dioxide CO_2, cyanide (C_2N_2), benzene (C_6H_6) up to 140 atomic mass units. (Credit: ESA)



gen in major amounts. Yet, this is not the case; rather, Earth and Titan are notable exceptions. This led scientists to speculate that the actual atmosphere of Titan might resemble that of our planet in its early pre-biotic time that is before living organisms began enriching it with oxygen via photosynthesis.

In order to allow study of the possible origins of nitrogen, the GCMS tracked the ratio of a variety of isotopes and trace species during descent. More specifically, it focussed on heavy noble gases such as argon ^{36}Ar, ^{38}Ar, krypton (Kr), and xenon (Xe). These gases had been identified earlier in meteorites, in the atmospheres of Earth, Mars, Venus (to some extent), and Jupiter. They were possibly present throughout the solar nebula before the planets and moons formed, and should therefore have been incorporated into both Saturn and Titan during the early stages of planetary system formation. Condensation of gases on the young Titan would have resulted in the capture of ^{36}Ar, as well as nitrogen, in proportions present in the protoplanetary disk at those times, for which the composition of today's Sun is a good proxy. However, the depleted nitrogen ratio detected by Huygens implies that it was captured as ammonia (NH_3) or in other nitrogen-bearing compounds. Subsequent photolysis in a hot proto-atmosphere generated and heated up by the accreting Titan or possibly impact-driven chemistry of NH_3 is supposed to have led to the nitrogen atmosphere we have on Titan today.

Atmospheric Methane

An even greater mystery is the presence of methane in Titan's atmosphere because the Sun's ultraviolet radiation destroys methane, which would disappear completely after some 50 million years. Therefore, there must be a mechanism at work that continuously replenishes the losses incurred.

In order to shed light on this secret, the GCMS tracked the levels of methane in the atmosphere. Initially, in the highest atmospheric layers, it found only low concentrations of methane. Then, at some 40 km, the concentration started increasing gradually until at approximately 7 km the concentration reached saturation level. Further down, methane concentrations remained relatively constant until the probe touched down on the surface. Immediately after landing, the methane concentration increased by about 40%, while the nitrogen count rate remained constant. This suggests the presence of liquid methane on the surface sputtered by the incoming probe or by the spacecraft heating the surface material.

While on Earth, methane is normally a product of biochemical processes, measurements of the carbon isotopes contained in Titan's methane ruled out the possibility of production by micro-organisms. This leads to the hypothesis that Titan's methane stems from underground (or surface) reservoirs. It is thought that Titan had accreted methane during its formation, and large quantities of liquid methane are assumed to be trapped in ice beneath the surface, possibly reaching the surface through some form of cryo-volcanism. This activity could indeed replace the methane lost by photochemistry in the upper atmosphere.

Beyond its very presence, methane stands out by the role it plays on Titan, which strongly resembles the role of water on Earth. On our planet, water evaporates from the oceans to the atmosphere, from where it rains down to the surface again. River systems collect the water and bring it back to the oceans thereby closing the water cycle. On Titan, the temperature is far too low for liquid water, but it is in the right range for methane to be liquid. In fact, there exists a complex methane cycle embracing the surface lakes, the clouds and the methane rains. A further analogy deserves attention: on Earth, the pressure and temperature values are close to the triple point of water, where water can exist either as solid, liquid or gas. On Titan, the pressure and temperature values are very close to the triple point of methane, allowing it similarly to exist in the solid, liquid or the gaseous state. This makes liquid and solid methane possible at the moon's surface.

Noble Gases in the Atmopshere

Noble gases along with their isotopes play a key role when it comes to hypothesising on the evolution of Titan's atmosphere. Out of the numerous components found, ^{40}Ar-

gon stands out, a noble gas that does not exist naturally, but is always a by-product of radioactive decay of potassium in rocky material. The presence of ^{40}Ar is a very strong support in favour of a rocky core at the centre of Titan as we will see below.

Atmospheric Aerosols

Aerosols are tiny solid or liquid particles suspended in a gaseous environment. To address the role of aerosols in Titan's atmosphere, the Huygens probe carried the Aerosol Collector and Pyrolyser (ACP) experiment aboard. This instrument collected aerosol particles and heated them in a special oven to vaporise all the volatile components in order to analyse their chemical composition.

The ACP acquired two atmospheric samples during the descent, one at an altitude of 130 km and the other at 25 km. The main substances found in the aerosols were ammonia (NH_3) and hydrogen cyanide (HCN) confirming that carbon and nitrogen are major constituents of the aerosols. The two samples did not show substantial differences, which indicates that the aerosols' composition was probably the same at both altitudes. This finding supports the idea that the aerosols have a common source in the upper atmosphere, where, the ultraviolet part of the sunlight splits the atmospheric gases such as methane allowing the emergence of the aerosols **(Fig. 7)**.

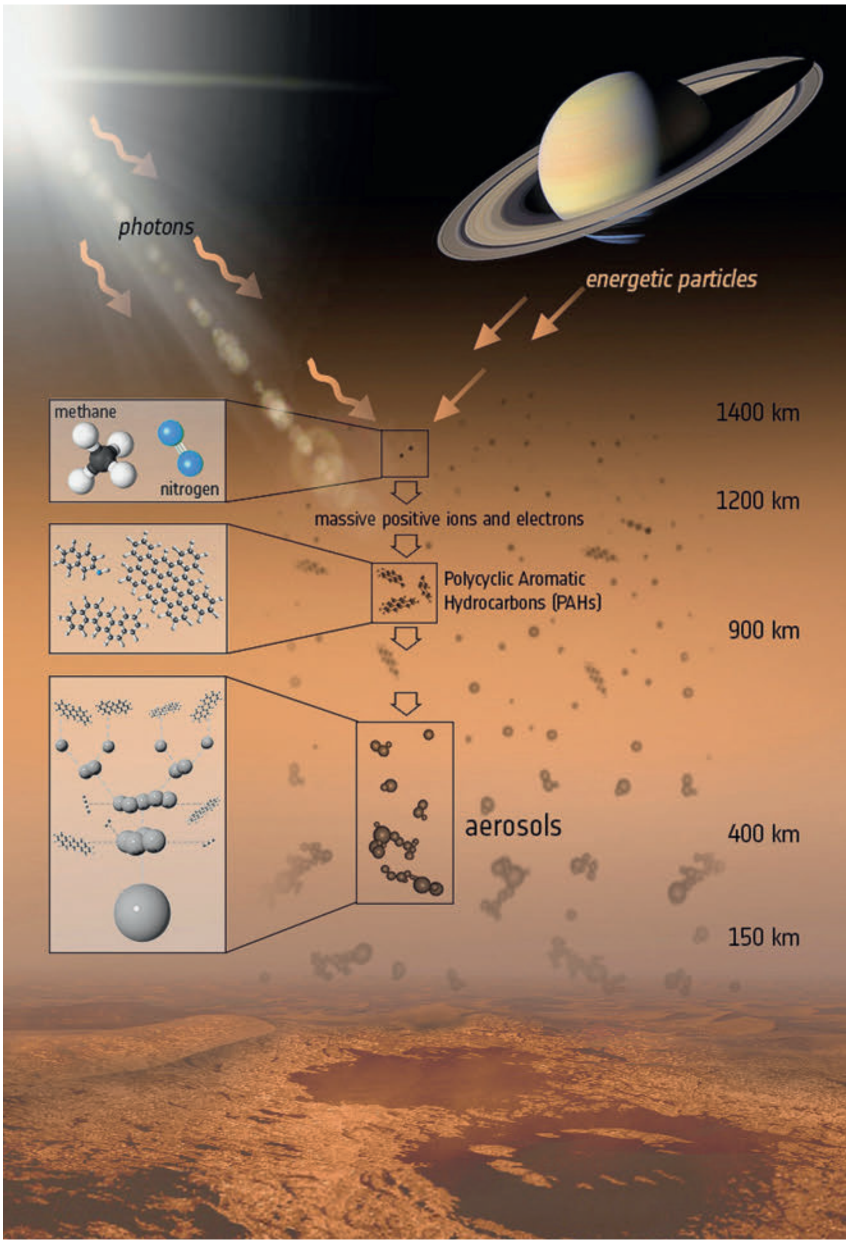


Fig. 7: The emergence of aerosols in the atmosphere of Titan. When sunlight (or highly energetic particles from Saturn's magnetosphere) hits the upper layers of Titan's atmosphere, the nitrogen and methane molecules are broken up. This results in the formation of massive positive ions and electrons, which trigger a chain of chemical reactions, producing a variety of hydrocarbons. These reactions eventually lead to the production of carbon-based aerosols, large aggregates of atoms and molecules that Huygens found in the lower layers of the atmosphere. Large carbon-based molecules form from aggregations of smaller hydrocarbons high up in the atmosphere. Upon reaching a certain size, they drift down much like snowflakes and eventually give rise to aerosols. (Credit: ESA)

In parallel to the chemical analyses of the aerosols, the Descent Imager/Spectral Radiometer (DISR) characterised their optical properties. The results show that they strongly resemble tholins[4], molecules which can be produced in the laboratory by sending electrical discharges into mixtures of nitrogen and methane. This provides an indication regarding their production mechanisms **(Fig. 7)**.

Titan's Surface

Huygens' descent lasted about 150 minutes. Then, the probe made a softish landing on Titan's surface and shortly after sent the first picture to a nervous audience staring at their TV screens on Earth. It was a long awaited, spectacular moment: Huygens had survived the touchdown and started working on the surface. The first image shows a dry river or lakebed with pebbles and sand-like material **(Fig. 8)**. The probe recorded an ambient temperature of about -180°C. Despite the frosty temperature, the probe's thermal control system protected the sensitive onboard electronics and instruments, and during the following 72 minutes, a huge amount of unique data was collected and subsequently downloaded via the Cassini orbiter.

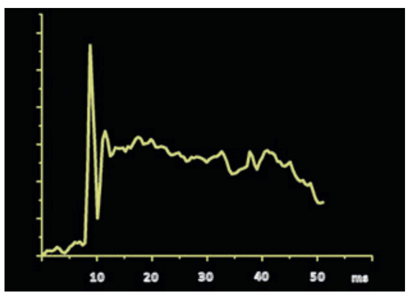
Dry river beds and lakes

Immediately before touch down, Huygens made the first physical contact with the surface by means of a small penetrometer consisting of a rod or stick protruding through the probe's hull. Its purpose was to measure the forces acting on the probe during the very moment of landing. **Fig. 9** shows the penetrator signal produced during landing. The peak force registered at 8 ms is thought to be caused by hitting a smaller pebble, as the big hard pebbles that can be seen in **Fig. 8** would have broken the instrument. The subsequent part of the signal representing medium strength forces is interpreted as pushing down to the underlying softer, granular material, probably Titan's equivalent of sand. Notwithstanding the fact that the penetrometer was quite a simple instrument, its signal provided a great deal of information on the character of Titan's surface at the landing site.

This information is complemented by the imagery gained by the Cassini orbiter during its more than 150 fly-bys made since its entry into the Saturnian system. Surprisingly, the dense haze, that charac-

Fig. 8: A close-up view of Huygens' landing site resembling a dried-up river or lakebed. Rounded cobbles, 10 to 15 cm in diameter and probably made of hydrocarbons and water ice, rest on a darker granular surface. These pebbles are rounded which is indicative of an erosion process by liquids, most probably liquid methane. (Credit: ESA/NASA)

Fig. 9: The Huygens penetrometer signal during landing. The horizontal axis is calibrated in units of milliseconds, while the vertical axis shows the force of Titan's surface acting on the penetrator probe. (Credit: ESA)



[4] The term "tholin" was coined by the American astronomer, Carl Sagan (1934–1996) to describe substances he obtained in experiments simulating the gas mixtures in Titan's atmosphere. Tholins are not one specific compound but rather are descriptive of a spectrum of molecules that give a reddish, organic surface covering on certain planetary surfaces.

terises Titan's atmosphere, offers some narrow spectral windows where Cassini's cameras could peer right down to the surface. In addition, Cassini's radar was able to image the surface undisturbed by the haze. The results of this survey were nothing less than a sensation **(Fig. 10)**: it turned out that Titan and Earth are the only places in the Solar System where stable liquids exist on the surface. While on Earth, the lakes are made of water, on Titan they probably consist of liquid methane. The hypothesis of liquid surfaces was corroborated by an infrared image gained by chance (see **Fig. 11**).

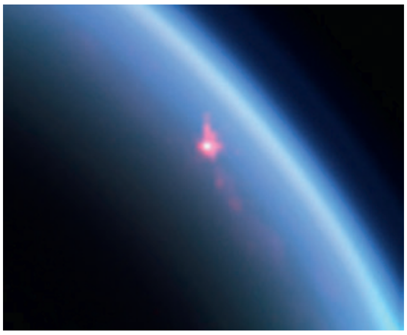
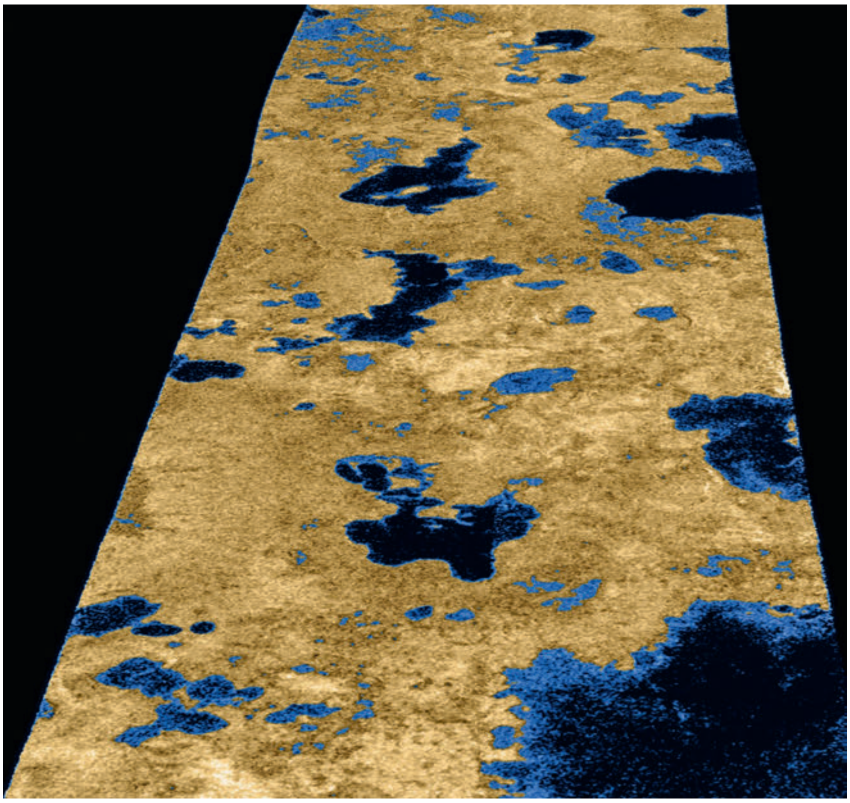


Fig. 11: A telling image of Titan's surface: here, Cassini's infrared camera looks back after a fly-by. A bright red spot appears on the surface almost blinding the instrument. It is the Sun's specular reflection on Cracken Mare, one of the many methane lakes of Titan. The picture is a stunning proof of the existence of liquid surfaces on Titan. (Credit: NASA)

Fig. 10: This false colour radar image from the Cassini orbiter shows a surface strip of Titan's surface. The yellow-hued terrain appears to be peppered with blue-tinted lakes and seas of liquid methane. (Credit: NASA)



Dunes

Besides seas and lakes, there are additional features on Titan that resemble areas on Earth: the dunes. They cover various parts of Titan's surface and are probably composed of sand-sized hydrocarbon and/or nitrile grains mixed with water ice. In contrast, however, to dunes on Earth, the particles constituting the dunes on Titan are supposed to have rained down from the atmosphere. Later, they may have been eroded by liquid methane runoff and moved by eolian processes.

Sizes and patterns of the dunes vary as a function of altitude and latitude. The dunes in areas that are more elevated or in higher latitudes tend to be thinner and more widely separated, with gaps that have a thinner covering of sand. Dunes in lower altitude and latitude regions are wider, with thicker blankets of sand between them. Comparing these features with dunes on Earth shows that the Kalahari dunes in South Africa and Namibia, located in regions with limited sediments available resemble the first type of dunes while on the other hand, Earth's Oman dunes in Yemen and Saudi Arabia, where there is abundant sediment available, resemble the second type more.

This altitude effect suggests that the material building the dunes is found mostly in the lowlands of Titan. Saturn's elliptical orbit around the Sun along with Titan being tidally locked to Saturn make the summers on the moon's southern hemisphere shorter and warmer than in the northern hemisphere. This leaves the soil in the south possibly dryer due to increased evaporation during the hotter summer time. In contrast, in the northern hemisphere, the soil hypothetically contains more moisture, making it more difficult to build dunes and to move their particles because they are stickier and heavier.

Titan's Interior

The data provided by Huygens and Cassini allows speculation about the moon's interior. The currently preferred physical models suggest a core of solid silicate rock as is the case with most bodies of the Solar System. Then, above, follows a layer of water ice under high pressure, and possibly a large subsurface ocean covered by the moon's icy surface.

A Subsurface Ocean?

The argument for a water-based ocean below the surface is based on extremely precise observations of Cassini's trajectories during the fly-bys. The orbital parameters of these trajectories allow for the estimation of the pull of gravity and its fluctuations and since gravity is an indication of the distribution of matter within the moon, these data allow for the building of models of Titan's interior. From these observations, one can deduce the existence of a global ocean of water.

Such an adventurous hypothesis needs corroboration by independent findings. Radar images of Titan's surface show that some of its features are in the wrong place at the wrong time! Obviously, the rotation of Titan's surface is not as expected. At a much finer level, one can make similar observations on Earth and Mars, where the atmosphere and the solid body continuously transfer momentum between each other. With the impressive mass contained in Titan's thick atmosphere one might presume a similar process, but it is much bigger than expected. The only way to explain this observation is to say that the surface is decoupled from the bulk of the core by floating on an ocean of liquid water in between.

Further results point in the same direction: Huygens had instruments aboard that allow the detection of lightning in the moon's atmosphere. On Earth, thousands of lightning flashes take place every minute, and each bolt generates a radio crackle. They propagate in the form of extremely low frequency (ELF) pulses around the globe in the cavity formed by Earth's surface and the ionosphere, a region of electrically charged particles in Earth's upper atmosphere. Although Huygens did not detect any lightning or thunderstorms, it registered an ELF signal at around 36 Hz. In order to explain this unique signal, scientists have proposed that Titan's atmosphere might act like a giant electrical circuit where electrical currents are generated in the ionosphere when it interacts with Saturn's magnetosphere. While Huygens found electrically conductive ionospheric layers at about 60 km above the surface, the cavity's lower boundary reflecting the ELF signals could be an electrically conductive ocean of water and ammonia below a non-conducting icy crust.

A Rocky Core?

The indication for a rocky core comes from the Argon isotope ^{40}Ar detected by the Huygens Gas Chromatograph Mass Spectrometer. This noble gas does not exist naturally, rather, it is the exclusive decay product of potassium ^{40}K contained in radioactive rock. This noble gas offers, therefore, a unique window to the interior of Titan as the only possible source of ^{40}Ar is the rock existing deep in Titan's interior.

Cryo-volcanism?

The term cryo-volcano refers to a geologic feature working at very low temperatures, where material from the underground protrudes up to the surface. On Titan, there are possibly about half a dozen of such cryo-volcanoes (see **Fig. 12** overleaf). The presence of ^{40}Ar at the levels seen by Huygens is a strong indication of geological activities on Titan consistent with the assumed periodic replenishment of atmospheric methane. In fact, cryo-volcanism provides one possible process for release of methane and ^{40}Ar from the interior out into the atmosphere.

Besides the circular features interpreted as cryo-volcanoes, there are also a few patterns interpreted as impact craters **(Fig. 13).** On Titan, we see at most ten such features. While most surfaces in the Solar System are peppered with impact craters, Titan's surface is very sparsely cratered. There are probably two reasons for this. One is the thick atmosphere, which acts as a filter, causing the smaller impacting bodies to burn up before reaching the surface. The other factor is the dynamic nature of the surface. Weathering by wind and liquids obliterate the impact craters over long time spans. This is another indication, that the surface is active.

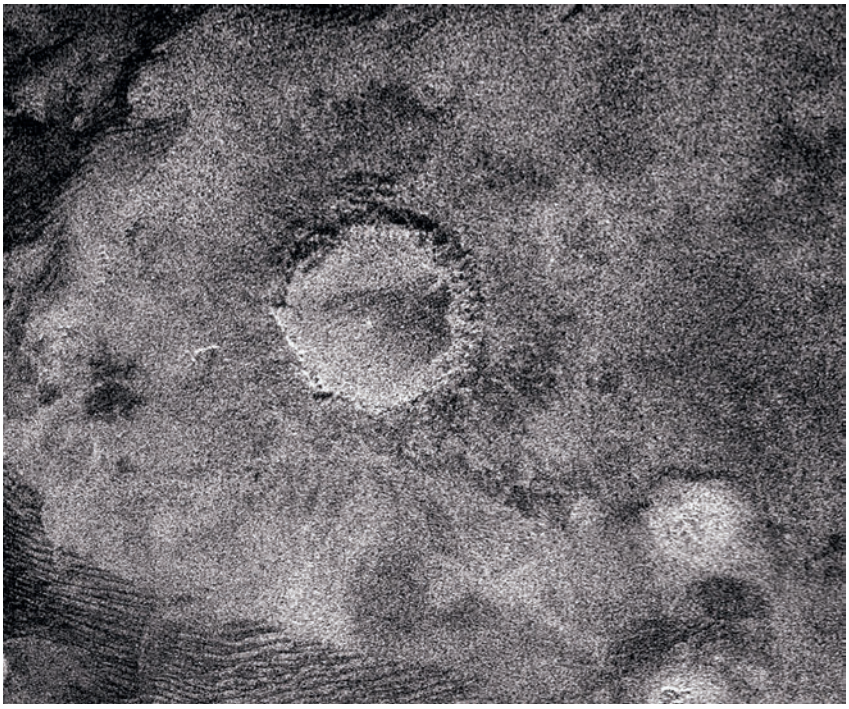
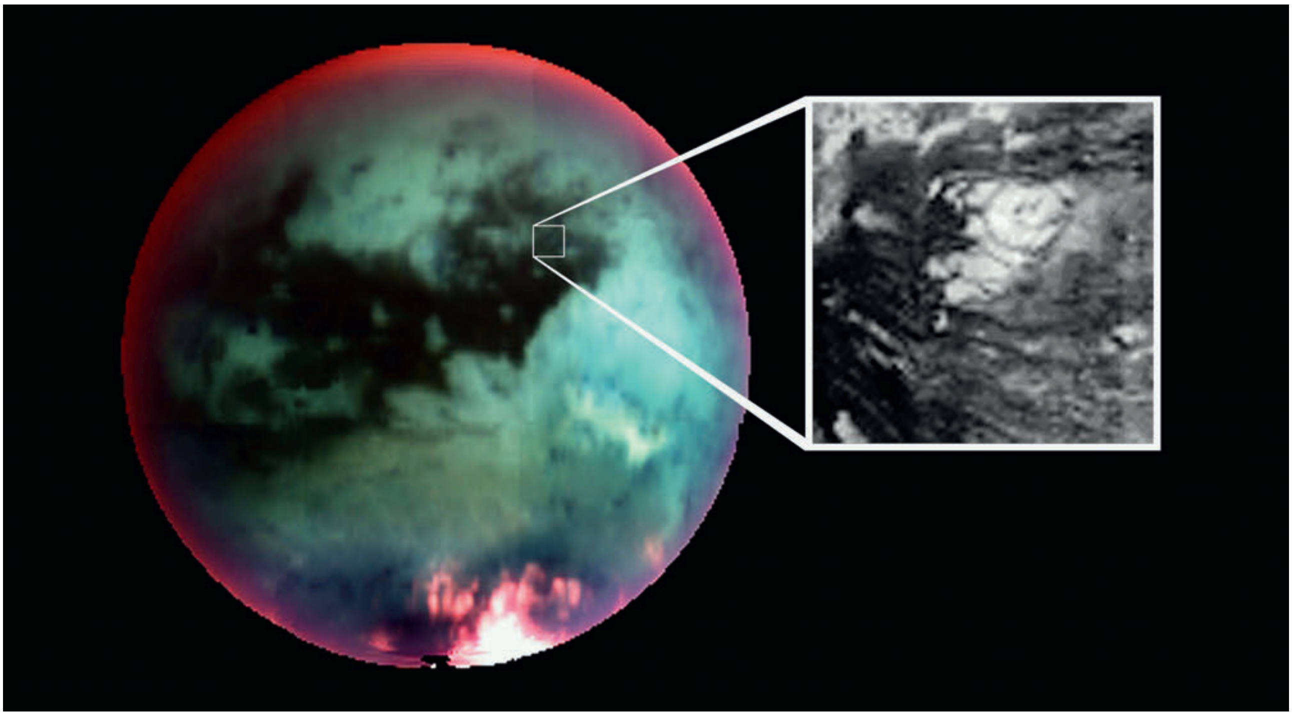


Fig. 13: Sinlap is a relatively fresh impact crater with a diameter of about 80 km. (Credit: NASA)

Fig. 12: A surface feature that is interpreted as a cryo-volcano, a type of volcanism operating at very low temperatures. Lava welling up to form the volcanic mound is a semifluid of methane, ammonia, and water ice combined with other ices and hydrocarbons. The circular feature is roughly 30 kilometres in diameter. (Credit: NASA)



Life on Titan?

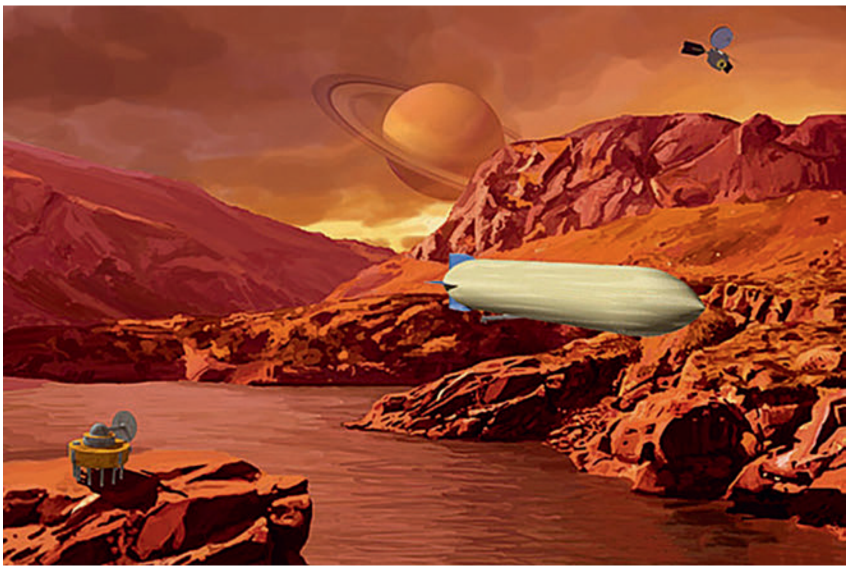
The similarities of Earth's and Titan's atmospheres were one basic motivation for ESA and NASA to send a mission to Titan. Upcoming speculations about the existence of some unknown form of life provided an additional thrust to embark on such an outstandingly daring mission. Now, after its completion, the similarities have become even more compelling, but also the differences between the two.

The similarities refer to the organic chemistry taking place in Titan's atmosphere that resembles the chemical processes on our early planet that possibly paved the way for the emergence of life. In addition, Titan has a greenhouse effect like Earth contributing to stabilising the global climate. Geological similarities are striking as well: liquid bodies, river networks, dunes, mountains and hills, and possibly even some sort of tectonic activity may be at work. The chief difference is temperature: while on Earth, the mean surface temperature is around 17 °C, on Titan it is a mere −180 °C. Therefore, water at the surface exists in the solid state exclusively; yet methane may assume the role of water on Titan as a solvent for living systems. In addition, water-based living systems might evolve in Titan's warm subsurface ocean. The Cassini-Huygens mission did not provide evidence for any form of life on Titan; in fact, it was not equipped to do so.

Outlook

The Cassini-Huygens mission is a seminal success not only from a scientific point of view but also with regard to the effective transatlantic cooperation between the two space agencies ESA and NASA. Yet, unsurprisingly, many questions remain open. This gives ample motivation to plan a further mission to that miraculous, distant world which in many respects is so astonishingly similar to ours. Such a new mission could exploit the detailed information delivered by Cassini-Huygens and the special conditions prevailing on Titan: its thick atmosphere and low gravity (about ⅐ of Earth's) may be an ideal place for an approach based on aerial vehicles: from a balloon or a Montgolfier, cameras could observe the moon's surface conveniently at close quarters. From what we know about the winds, it would take something like two weeks to execute an entire circuit at the equator to find the most interesting places where a lander could then address specific issues. An alternative could be a probe floating on one of Titan's many lakes. In any case, Titan remains an outstandingly compelling destination for future science missions.

Fig. 14: Constituents of a hypothetical follow-on mission to explore Titan include an aerial platform, an orbiter and a lander.



SPATIUM

The Author

John Zarnecki grew up in London, England. In his early years, space and space exploration attracted his attention and it is no wonder that the youngster was amongst the public when Yuri Gagarin, the first human astronaut visited London in 1961. John started his studies at Queens' College, Cambridge, where he graduated with a physics degree before obtaining a doctorate at the Mullard Space Science Laboratory (University College London) in Surrey.

Prepared with a sound scientific education, John Zarnecki started his professional career at British Aerospace working in a team developing the Hubble Space Telescope's Faint Object Camera. Then, in 1981, he moved to the University of Kent in Canterbury to become the project manager for the Dust Impact Detection System on board ESA's Giotto probe that visited Halley's Comet. Yet the most exciting programme was still ahead: the Huygens probe scheduled to land on Saturn's moon Titan, some 1.5 billion kilometres away. John Zarnecki was appointed Principal Investigator for Huygens' Surface Science Package in 1990. The instrument collected over three and a half hours of data, which, thanks to its efficient encoding, could be stored on board the lander before being relayed by the Cassini orbiter down to Earth.

In 2000, John Zarnecki, along with the other members of the Surface Science Package team, moved to the Open University in Milton Keynes, in central England, where he became Director of the Centre for Earth, Planetary, Space & Astronomical Research, some years later. In 2013, Professor Zarnecki was invited to take up a Directorship at the International Space Science Institute in Berne, Switzerland.

Prof. Zarnecki has given long and distinguished service to the global space community, working in numerous international teams and committees such as for instance for ESA's Senior Review Committee, charged with selecting the scientific themes that would form the basis for ESA's L2 and L3 missions in 2028 and 2034, respectively.

An outstanding, charismatic personality, Prof. John Zarnecki has been granted numerous honours of which the Gold Medal of the Royal Astronomical Society in 2014 stands out.