WHAT DO WE KNOW TODAY ABOUT TITAN?

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Abstract: Ever since the the discovery of the atmosphere surrounding Titan, the real nature of this Saturnian satellite has remained hidden for almost one century. Since two Voyager spacecraft passed the Solar System's sixth planet in 1980 and 1981, Saturn, its rings and the plethora of satellites living in a complex pulsating magnetosphere have greatly called our attention. The joint NASA and European Space Agency (ESA) Cassini-Huygens mission now at the Saturnian System represents the summit of such a curiosity. Launched from Cape Cañaveral on 15 October 1997, since July 1, 2004 it has become a new satellite of Saturn which nowadays explores the planet, the rings and the satellites, and it will continue doing so for at least 4 years. Undoubtedly, from this *in situ* study of the ringed planet, the most awaited exploration was the descent of the Huygens probe through the atmosphere of the largest saturnian moon, Titan, and its subsequent landing on the satellite's surface. Beside the technological success, the Huygens probe has provided us with the view of an astonishing world which appears to have an extraordinarily Earth-like meteorology, geology and fluvial activity (in which methane would play the role of water on Earth).

1 Introduction

Titan, Saturn's largest satellite (the second biggest satellite in our solar system) has attracted the eye of the astronomers more and more since the beginning of the century. It has been long to know to have a substantial atmosphere: in 1908, the Catalan astronomer José Comas Solá [1] claimed to have observed limb-darkening on Titan. At the end of the twentieth century, we knew that its massive atmosphere is the most similar to Earth's among all the other objects in the solar system (see Figure 1 [2]). At the beginning of the twenty first century, although much light has been shed into the understanding of the origin, evolution and nature of this body, the questions raised by the discoveries of the Cassini-Huygens Mission (NASA-ESA) are more fascinating than the discoveries themselves.

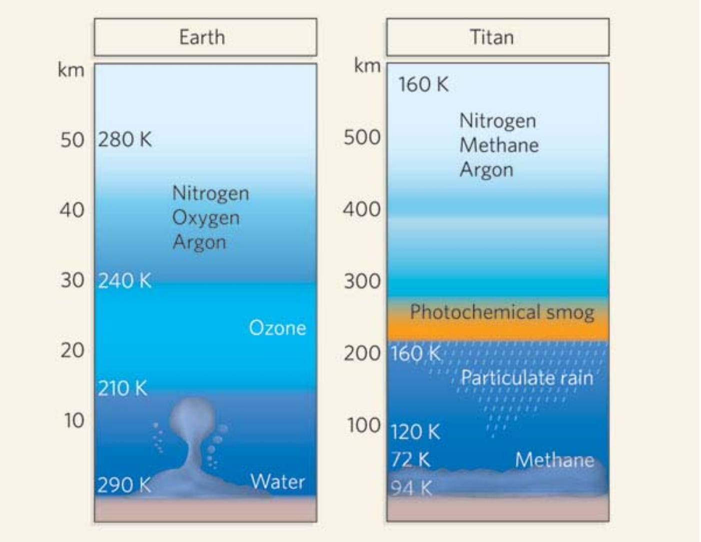

Figure 1: Both atmospheres are nitrogen-dominated, but the low temperature of Titan means that the carbon-carrying gas in its atmosphere is methane (1.6% of the total) rather than carbon dioxide (present at only 345 parts per million). Photochemical reactions involving this methane produce a smog at middle altitudes, and an organic rain of methane and nitrogen-containing aerosols falls steadily onto the satellite's surface, creating an Earth-like terrain of extended river networks. Radiogenic argon (^{40}Ar), which makes up 1% of Earth's atmosphere, is in short supply on Titan (just 43 parts per million).

In this article, we are going to place Titan in its historical context, why Titan deserves such an exploration as the one carried out by the Voyager Missions (NASA) and the Cassini-Huygen Mission (NASA-ESA), the discoveries by the Voyager 1 and 2 spacecrafts, knowledge gained from earth based observatories as preparatory for the Cassini-Huygens Mission and, finally the overall picture we have nowadays of this fascinating body of the solar system.

2 Historical Context

Titan was discovered on the night of March 25, 1655, by a novice Dutch astronomer, Christian Huygens while pointing his telescope to Saturn. This object had been noticed before by Hevelius in Poland and Sir Christopher Wren in England who believed it was a star. Huygens, however, suspected it was a satellite and he confirmed his guess a few days later.

After Solá's claims of having observed an atmosphere around Titan (see Figure 2), Sir James Jeans, by applying his theoretical studies on escape processes in the atmospheres around solar system objects, concludes that this body could have kept an atmosphere if low-temperature conditions (which he estimated between 60 and 100 K) prevailed. In this case, a gas of molecular weight higher or equal to 16 could not have escaped Titan's atmosphere since the satellite's formation. The best "candidates" are CH_4, NH_3, Ar, Ne or N_2 according to what it could be expected to be in nonnegligible quantities in the mix of gas and dust particles that condensed to form the solar system. Among these gases, NH_3 is solid between 60 and 100 K, thus leaving as main candidate CH_4, which fortunately shows strong absorption bands in the infrared (unlike the other mentioned gases).

Figure 2: This is what J. Comas Solá [1] wrote when he observed Titan: *Titan. Le 13 aouût 1907, avec une image très belle et me servant du grossissement de 750 fois, j'ai vu titan avec les bords très foncés, s'estompant dans l'obscurité du ciel (quelque chose de semblable à ce qu'on observe dans le disque de Neptune), tandis que vers la partie centrale, bien plus claire, on voyait deux tasches rondes et blanchâtres qui me faissaient l'effect d'une étoile double diffuse. Nous pouvons suppose, légitimement, que cette grande obscurité des bords démontre l'existence d'une atmosphére très absorbante autour de Titan.*

The first detection of these bands was made in 1944 by Gerald Kuiper at $\lambda \geq 0.6$ μm identifying two methane absorption bands at 6190 and 7250 Å. Kuiper estimated that the methane abundance could be 200 m-amagat (1 km-amagat corresponds to 2×10^{24} molecules per cm^2). Kuiper also concluded that Titan behaved differently in the visible and ultraviolet continuum compared to the other satellites, showing an orange color.

By 1965, there was no consensus on a coherent value of the ground temperature from contradictory radio and infrared measurements, which ranged from 165 to 200 K. In the 70's, much efforts [3, 4, 5, 6] were concentrated on an estimate of the methane abundance and of the pressure conditions in the atmosphere and at the surface from observations made in the 1- to 2- μm spectral region. [3] found an unexpected high intensity in the $3\nu_3$ methane band at 1.1 μm, indicate of either a methane abundance at least 10 times higher than that inferred by Kuiper or a broadening of the methane bands induced by collision with molecules of another gas yet undetected. Further observations were carried out in the following years. The result of these investigations was to set a methane abundance of 320 m-amagat and a surface pressure of 200 mbar [5]. The most immediate consequence of these results was that methane suddenly became a minor atmospheric component. [4] announced a tentative identification of H_2, whereas NH_3 could not be found in the Titan's spectra. Thus, ammonia could be either photodissociated with the subsequent production of H_2, or be restricted to the surface as ice.

Gillet *et al.*[7] and [8] found evidence in Titan's thermal spectrum of not only methane, but also ethane, monodeuterated methane, ethylene and acetylene. A close inspection of the spectra showed that the continuum of Titan's spectrum might allow to probe the satellite's surface which had remained hidden in the visible range due to an aerosol layer uniformly mixed at high altitudes and at every longitude and latitude.

By the end of the 70's, Titan's atmosphere could be described by two competing models. One of them [9, 10] favored methane as the main component (about 90%) and a surface T of 86 K for 20 mbar atmospheric pressure, as well as a temperature inversion in the higher levels. The second model, proposed by [11] and [12], considered N_2 as the major component in an atmosphere of 200 K at the surface and a pressure as high as 20 bars. Let us note that the molecular nitrogen, supposed to be produced by the ammonia photodissociation, is transparent in the IR.

Shortly before the Voyager encounter, [13, 14] obtained brightness and radius measurements of the surface of Titan at 6, 2, and 1.3 cm wavelengths with the Very Large Array radio interferometer. Combined results for the three wavelengths indicated that the radius is 2400 ± 250 km, implying a density of 2.4 ± 0.7 g/cm^3, and that the brightness temperature is 87 ± 9 K. The surface temperature could be somewhat higher if the emissivity were less than unity. In these works, an ocean of methane was even suggested. The new data did not permit a choice between an inversion model for the atmosphere of Titan that predicted a surface temperature of 78 K and a model with both a stratospheric temperature inversion and a modest greenhouse effect that would increase the surface temperature by 10-40 K.

3 Voyager 1 and 2 at Titan

Voyager 1 (launched in 1977) flew through the Saturnian system in November 1980, providing much of the information available up to the age of large ground based telescopes and space observatories (as the Hubble Space Telescope HST, and the Infrared Space Observatory ISO).

Voyager 1 closest approach took place on November 12, 1980 at a distance of 6969 km (4394 km from the surface), whereas Voyager 2 visited Titan at a distance hundred times larger nine months later. Titan's orbital and body parameters, as determined by Voyager, are listed in Table 1.

Surface Radius	2575 km
Mass	1.35×10^{23} kg (= 0.022×Earth)
Mean Density	1880 kg/m^3
Distance from Saturn	1.23×10^{9} m (= 20 Saturn radii)
Distance from Sun	9.546 AU
Orbital Period	15.95 days
Orbital Period around the Sun	29.5 years
Obliquity	26.7°

Table 1: Titan's Orbital and Body Parameters derived from the Voyager 1 and 2 discoveries.

The satellite appears as a reddish brown ball in the visible (see Figure 3), it is completely covered by a thick haze that does not allow to image the surface of the satellite. The most obvious feature seen by Voyager was a difference in the brightness of the two hemispheres beside a dark ring above the north (winter) pole which is more prominent at blue and violet wavelengths. This north-to-south asymmetry is probably related to circulation in the atmosphere pushing haze from one hemisphere to the other [15].

Rages and Pollack [16] and [17] studied the properties of the aerosols and found particle radius to be between 0.2 and 0.5 μm. These smog particles come from a layer that covers the entire satellite and reaches atmospheric levels up to 200 km above the surface, whereas some detached haze layers can be seen at 340-360 km (see Figure 4). These higher altitude layers seem to be composed of larger, more compact and more irregular dark particles than at lower altitudes. The observations may be consistent

Figure 3: Titan's disk seen by Voyager 2 at 2.3 million of km.

with an upwelling circulation carrying particles upward from the summer/autumn hemisphere and allowing them to grow larger.

From the two prevailing pre-Voyager models of Titan's atmosphere, the real one emerged as a combination of both. Molecular nitrogen was detected by the UV spectrometer [18, 19] and it represents the most abundant molecule ($\sim 90\%$), followed by methane ($2-8\%$), molecular hydrogen and a plethora of organic compounds as well as oxygen compounds [20, 21, 22]. The radio occultation experiment provided a precise value of Titan's surface radius: 2575 ± 2 km with a surface temperature of 94 ± 2 K and a pressure of about 1.44 bar [23]. The mean molecular weight of the atmosphere was 28 amu, confirming N_2 as the most abundant constituent, but it may be as high as 29.4 amu, implying the presence of gases heavier than nitrogen (as noble gases) [27]. A reanalysis of the data [24] provided a better constraint on the methane mixing ratio between 0.5 and 3.4% in the stratosphere and as high as 21% at the surface, T could be between 92.5 and 101 K at the ground level and between 70.5 and 74.5 K at the tropopause. The implications of this reanalysis is the likely presence of a global [25] pure methane ocean on Titan acting as a reservoir of this gas in the atmosphere [26]. Under the surface pressure and temperature conditions, beside methane, ethane could exist on liquid phase, while in the stratosphere, methane clouds might cause rains (see Figure 5).

The Voyager 1 radio signal passed through Titan's atmosphere at two near-equatorial locations. The refraction of the signal measured at the ground gave two refractivity profiles, which were converted to density and temperature assuming a pure

Figure 4: Voyager 1 recorded this view looking across the edge of Titan, from a distance of about 22000 kilometers. The detached layers of haze hundreds of kilometers above the surface are clearly seen.

N_2 atmosphere (see Figure 6 [28, 29]). The infrared spectra taken by the Voyager InfraRed Interferometer Spectrometer (IRIS) showed a vast set of emission bands of hydrocarbons, nitrogen compounds and oxygen species [30, 31, 32, 22, 33, 34, 35, 36].

The stratospheric abundances of Titan's minor constituents at the equator are listed in Table 2 [34].

The production of the compounds in Table 2 has been studied by [38, 40, 41, 42, 43, 44, 45, 46] and by [47]. Species as N_2, H_2, CCO and Ar are uniformly mixed in the lower atmosphere. Methane should be also well mixed (it has a very long chemical lifetime) up to the homopause where diffusive separation of the species according to their molecular weight takes place. The mole fraction of hydrocarbons and nitriles produced by photochemistry show altitude variations as expected from a balance of chemical production and loss, dynamical transport and condensation at the tropopause or tens of kilometers above it. Latitudinal variations were observed from some of the least abundant molecules, with an obvious enhancement of HC_3N and C_2N_2, as well as some hydrocarbons, at high northern latitudes. The observed latitudinal variations in hydrocarbons and nitriles [37] may be related to seasonal and spatial variations of the solar flux [39]. Similarly, a maximal temperature decrease of 17 K at the 0.4-mbar level (225 km of altitude) is observed between 5° S (the warmest region) and 70° N, whereas the temperature drops only by approximately 3 K from 5° S to 53° S at the time of the Voyager 1 encounter [37].

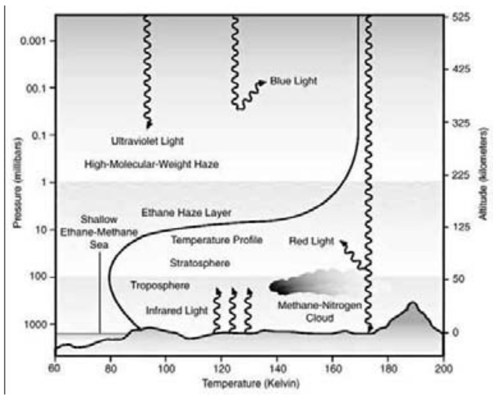

Figure 5: Sketch on the physical and chemical processing of Titan's atmosphere, and its interaction with the surface.

Carbon monoxide (detected from ground-based observations) and carbon dioxide (*in situ* by Voyager 1) were the only two oxygen compounds found in Titan. The formation of CO_2 from CO needs the presence of OH, whose origin is the H_2O photolysis [33, 48, 41]. However, water was not detected until 1998 by the Infrared Space Observatory (ISO) [49]. ISO also provided the first tentative detection of benzene with a constant mean mole fraction of 4×10^{-10}. Mixing ratio upper limits of a few 10^{-10} for molecules as allene, acetonitrile, propionitrile, and other more complex gases were proposed as likely candidates on Titan.

4 Titan's Surface

The chemical composition of the atmosphere and the (T,p) conditions prevailing in it give rise to several haze layers which hide Titan's surface. Much of the outer part of the solid body of the satellite must consist of a thick layer of ice. Whether this is exposed at the surface, or completely or partially covered over with material precipitated out of the atmosphere is one of the key questions that the Cassini-Huygens Mission has recently answered.

Before the Cassini spacecraft reached the Saturnian System, [50], by means of radar reflectivity measurements using a 70-m transmitting antenna in conjunction with the Very Large Array as a receiving instrument, it was found out that the statistically significant echoes obtained indicated that Titan is not covered with a deep global ocean of ethane. Furthermore, one region of Titan's surface seemed brighter at radar wavelengths than the rest, and showed polarization and spectral

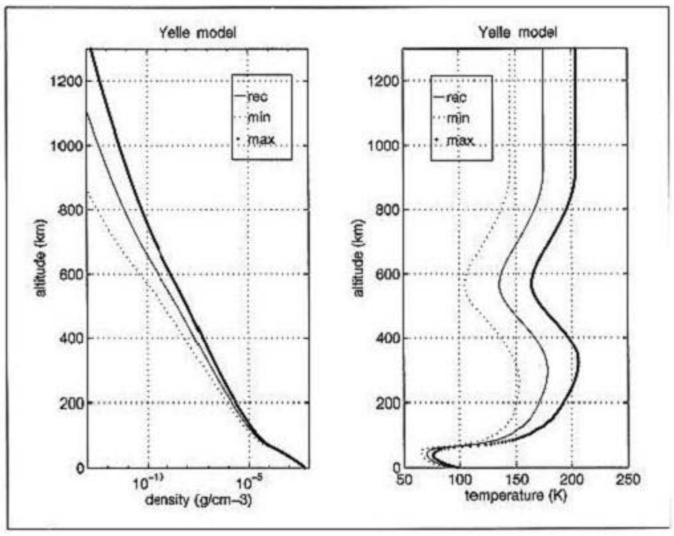

Figure 6: Minimum, maximum and recommended engineering models for mass density (left) and temperature profiles with altitude in Titan's atmosphere.

behavior characteristic of icy surfaces.

The near-IR spectrum of Titan (0.7-5 μm) is dominated by the methane absorption bands. However, there are some clear regions, or windows (near 4.8, 2.9, 2.0, 1.6, 1.28, 1.07, 0.94 and 0.83 μm) where the absorption is weak permitting the sounding of the deep atmosphere and perhaps of the surface. It is at 1.042 μm where the Hubble Space Telescope (HST) imaged Titan's surface in 1994 [51]. Figure 7 shows the intriguing and heterogenous surface of this satellite.

A high contrast 1.575 μm surface map of Titan was also obtained by [52] from the Very Large Telescope by using adaptive optics (NAOS-CONICA) and the Simultaneous Differential Imager mode (SDI). From data spanning seven consecutive nights, Titan's surface is covered in a phase of 275° in longitude. The combination of adaptive optics and simultaneous imaging through three filters sampling the methane absorption at 1.6 μm reveals extraordinary details of Titan's surface as seen in Figure 8.

For some time the dominant hypothesis for Titan's surface has been that the bright areas are icy highlands and the dark areas are lower lying lakes or tar pits of hydrocarbons deposited from the atmosphere. However, [53] reported spectral evidence that the bright region near 90° W contains exposed water ice. Numerous

Gas		Mole fraction
Acetylene	C_2H_2	2.2×10^{-6}
Ethylene	C_2H_4	9.0×10^{-8}
Ethane	C_2H_6	1.3×10^{-5}
Methyl acetylene	CH_3C_2H	4.4×10^{-9}
Propane	C_3H_8	7.0×10^{-7}
Diacetylene	C_4H_2	1.4×10^{-9}
Hydrogen cyanide	HCN	1.6×10^{-7}
Cyanoacetylene	HC_3N	$\leq 1.5 \times 10^{-9}$
Cyanogen	C_2N_2	$\leq 1.5 \times 10^{-9}$
Carbon dioxide	CO_2	1.4×10^{-8}

Table 2: Abundances of Titan's minor constituents derived Voyager 1 IRIS data at the equatorial stratospheric levels.

surface features down to the limits of the spatial resolution ($\sim 200 - 300$ km) are apparent. No features are easily identifiable in terms of their geologic origin, although several are likely craters [55].

There is not doubt that Titan's surface is heterogeneous, the real nature of this heterogeneity was still to be discovered by the Huygens Probe while descending the atmosphere and landing at the edge of one of the bright areas near the equator.

5 The Cassini-Huygens Mission

The Cassini-Huygens mission to Saturn is the most ambitious effort in planetary space exploration ever mounted. A joint endeavour of ESA, NASA and the Italian space agency, Agenzia Spaziale Italiana (ASI), Cassini-Huygens is a sophisticated spacecraft being sent to the ringed planet to study the Saturnian system in detail over a four-year period. A scientific probe called Huygens (ESA) was released from the main spacecraft to parachute through the atmosphere to the surface of Titan.

Cassini-Huygens, a massive spacecraft of 5600 kg, was launched on a Titan IV-B/Centaur launch vehicle on 15 October 1997. The trip to Saturn is depicted in Figure 9. There were two gravity-assist by Venus on 26 April 1998 and on 24 June 1999, followed by an Earth fly-by 18 August 1999. Given these three gravity assist boosts, Cassini-Huygens finally had enough orbital momentum to reach the outer Solar System. One last gravity assist manoeuvre from Jupiter on 30 December 2000 gave Cassini-Huygens the final thrust of energy it needed to project itself all the way to Saturn. The mission arrived at Saturn in July 2004. The Saturn Orbit Insertion (SOI) was such that the spacecraft had to perform a dangerous and threatening

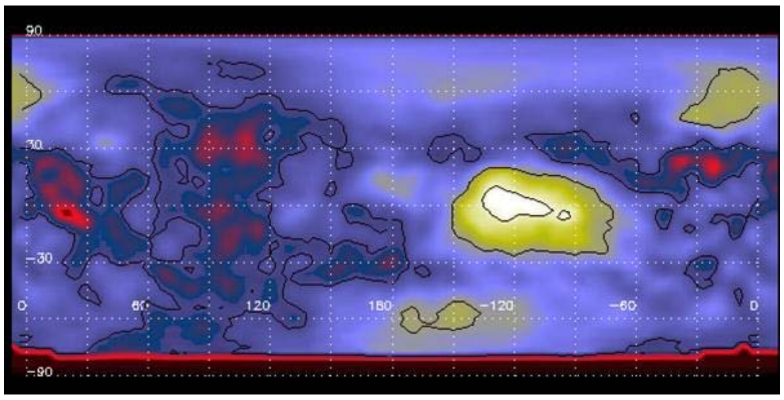

Figure 7: Relative albedo map of Titan's surface made from images taken by the Hubble Space Telescope's planetary camera (295 km per pixel) through atmospheric windows at 940 and 1080 nm. Coverage at all longitudes and between 45° S and 60° N are shown. Many features are clearly visible in multiple images and in both filters, but the surface map is dominated by a large, bright, roughly rectangular feature centered at 110° W, 10° S and elongated in an east-west direction (4000 x 2500 km^2): this feature and others indicate the diversity of Titan's surface. The origin of the bright feature in an otherwise dark landscape suggest that highland washing by methane rainfall is a likely mechanism.

manoeuver, that is, the crossing of the Saturn's ring plane at a relative velocity of 20 km/s and being impacted by the saturnian dust at a rate of 680 impacts per second (i.e. more than 100000 impacts in less than 5 minutes the crossing lasted).

As the mission objectives, questions concerning Titan as the ones listed below are expected to be answered:
Which chemical reactions are occurring in Titans atmosphere?
What is the source of methane, a compound associated to biological activity on Earth, which is so abundant in Titans atmosphere?
Are there any oceans on Titan?
Do more complex organic compounds and pre-biotic molecules exist on Titan?
What is the real nature of Titan's surface?

The Cassini orbiter, with its 12 instruments onboard [56], is orbiting around Saturn, and will do so until end of 2008; it will send back valuable data to Earth that will help us understand the vast Saturnian region. During its stay, Cassini spacecraft will complete 75 orbits of the ringed planet, 44 close fly-bys of the mysterious moon Titan, and numerous fly-bys of Saturn's other icy moons.

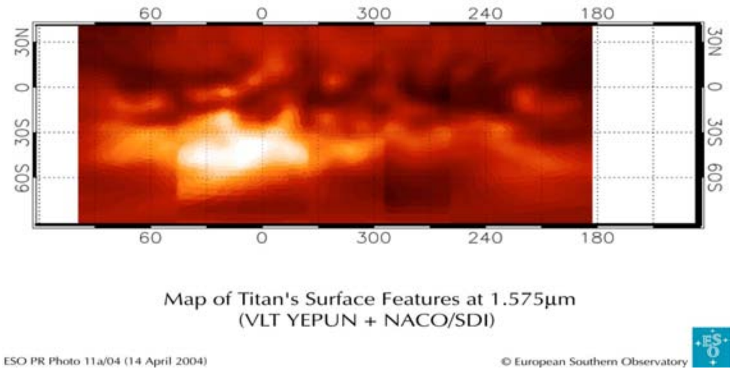

Figure 8: Surface of Titan imaged using adaptive optics (NAOS-CONICA) and the Simultaneous Differential Imager mode (SDI) mounted at VLT Yepun. Note the dark areas at northern latitudes. Their shapes were named, from left to right, as "Lying H", "Ball", "Dog" and "Dragon's Head".

On July 2, 2004, at a distance of 339000 km from Titan (fly-by named T0), the imaging science experiment (ISS, Imaging Science Subsystem) onboard the Cassini spacecraft acquired the images shown in Figure 10. The images reveal intricate surface albedo features that suggest aeolian, tectonic and fluvial processes; they also show a few circular features that could be impact structures. These observations imply that substantial surface modification has occurred over Titan's history. There has been not direct detection of liquids on the surface to date. Convective clouds are found to be common near the south pole, and the motion of mid-latitude clouds consistently indicates eastward winds, from which [57] inferred that the troposphere is rotating faster than the surface. A detached haze (see Figure 11) at an altitude of 500 km is 150-200 km higher than that observed by Voyager, and more tenuous haze layers are also resolved.

Before the Huygens probe was released from the Cassini orbiter, two more fly-bys (TA and TB) took place on October 26, 2004 and December 13, 2004 at a closest distance of 1200 km above the surface. Figure 12 shows a sequence of processed images of Titan acquired by Cassini's imaging science subsystem on Oct. 25, 2004, 38 hours before its closest approach to the satellite. The bright area to the top right is named Xanadu. To the west of Xanadu lies an area of dark material that completely surrounds brighter features in some places. Narrow linear features, both dark and bright, can also be seen. It is not clear what geologic processes created these features, although it seems clear that the surface is being shaped by more than

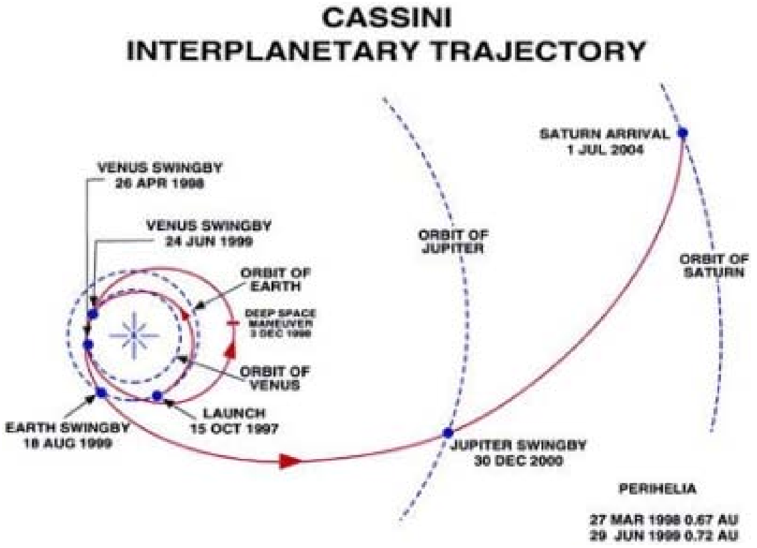

Figure 9: The Cassini-Huygens voyage through the Solar System.

impact craters alone. The very bright features near Titan's south pole are clouds similar to those observed during the distant Cassini flyby on July 2, 2004 (see Figure 10). The region on the left side of these images was also targeted by higher-resolution observations as well as by the radar during TA. The images, shown in Figure 13, reveal a complex surface, with areas of low relief and a variety of geologic features suggestive of dome-like volcanic constructs, flows, and sinuous channels. The surface appears to be young, with few impact craters. Scattering and dielectric properties are consistent with porous ice or organics. Dark patches in the radar images show high brightness temperatures and high emissivity and are consistent with frozen hydrocarbons [58].

The most recent Cassini RADAR images of Titan [59] show regions $\leq 1500 \times 200$ km of near-parallel radar-dark linear features that appear to be seas of longitudinal dunes similar to those seen in the Namib desert or Earth. One of the bands of the radar (2.17 cm wavelength) reveals that the equatorial surface of Titan has ~ 100 m ridges consistent with duneforms and flow interactions with underlying surface winds of ~ 0.5 m/s. These winds are the result of a combination of an eastward flow with a variable tidal wind. To produce dunes it is also necessary to have mechanisms able to give rise to create sand-sized (100- to 300 - μm) particulates and lack of persistent equatorial surface liquids to act as sand traps.

There have been up to 14 targeted fly-bys of Titan by the Cassini spacecraft (to

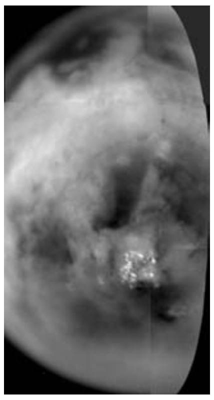

Figure 10: Image of the Titan's south polar region acquired by the Image Science Subsystem, ISS, on board the Cassini spacecraft with filters designed to see through the thick haze and atmosphere [57]. The bright spots near the bottom represent a field of clouds near the south pole. There are many strange dark and bright patterns on Titan's surface – linear, sinuous and circular. The smallest features detected on the surface are about 10 kilometers.

the date of April 30, 2006). Figure 14 shows a mosaic composed with data from Cassini's Visual and Infrared Mapping Spectrometer (VIMS) taken during the T8, T9 and T10 Titan flybys, on Oct. 28, 2005 (left image), Dec. 26, 2005 (middle image), and Jan. 15, 2006 (right image) respectively. The viewing geometry of the December flyby (TB) is roughly on Titan's opposite hemisphere from the flybys in October and January. There are several important features to note in the images. The first is that the south polar cloud system was very bright during the December flyby, while during the October and January flybys, it is barely visible, indicating that the atmosphere over Titan's south pole is very dynamic. In the December (middle) mosaic, a north polar hood that is bright at 5 μm is visible. Its composition is unknown. The north polar hood is barely seen in the October (left image) and January (right image) data. Visible in the October and December images just south of the equator is Tui Reggio, a region nicknamed the "chevron". This region is very bright at 5 μm and is among the brightest features on Titan at that wavelength. Tui Reggio is thought to be a surface deposit, probably of volcanic origin, and may be water and/or carbon dioxide frozen from the vapor. The December flyby data show that the western margins of Tui Reggio have a complex flow-like character consistent with eruptive phenomena. Furthermore, the Cassini VIMS [61] pertaining to the TB flyby indicate that the horizontal structure, height and optical depth of Titan's

Figure 11: Image of Titan's night side limb seen by the Narrow Angle Camera on board the Cassini spacecraft in the UV range [57]. Titan's upper atmosphere shows a surprising number of layers of haze extending several hundred kilometers above the surface. About 12 distinct haze layers can be seen in this image, with a scale of 0.7 kilometers per pixel. The limb shown here is at about 10° south latitude, in the equatorial region.

clouds are highly dynamic. The "meteorological" cycle is as follows: they rise from the middle to the upper troposphere in about 30 minutes and dissipate in the next hour, they evolve convectively, dissipate through rain and over the next several hours, waft downing to achieve their great longitude extents. It is interesting to note that these and other characteristics suggest that temperate clouds originate from circulation-induced convergence, in addition to a forcing at the surface associated with Saturn's tides, geology, and /or surface composition.

This Cassini VIMS result is also supported by the observations of Titan at 350° W longitude, 40° S latitude where a cluster of clouds is placed. [62, 63] conclude that these clouds cannot be explained by a seasonal shift in global circulation (unlike shown in [64]), but they can presumably reflect a geological mechanism such as geysering or cryovolcanism. The methane supplied by these "volcanic" events is enough to balance the CH_4 loss due to photolysis in the upper atmosphere and to trigger the cloud formation.

The information provided so far by the instruments on board the Cassini orbiter is overwhelming. Thirteen fly-bys of Titan have shown the satellite as the most intriguing body in the Solar System. Titan will be still explored by the Cassini spacecraft during 31 more targetted fly-bys until June 2008 (nominal end of the mission) accounting for 45 target fly-bys planned in the mission. Some of these

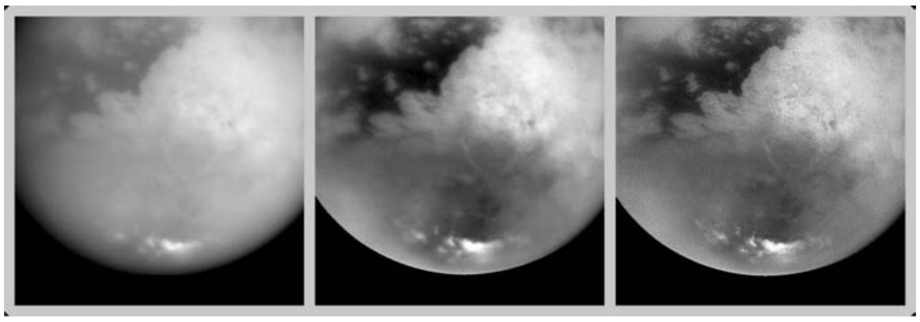

Figure 12: Titan as seen by the ISS [57] at a distance of 702000 km of Titan's surface and a pixel scale of 4.2 kilometers. The original image is the one to the left, whereas the middle and right one are obtained after simple processing to reveal sharp boundaries between dark and light regions on the surface. The Sun was illuminating Titan from nearly behind the spacecraft, thus there are no shadows produced by topography in these images.

fly-bys will have close approach at only 950 km from the surface, well inside the Titan's thermosphere. Every fly-by will have a different orbital geometry as well as from different circumstances of the Saturnian magnetosphere closely interacting with Titan's upper atmosphere and ionosphere. An extension of the mission until 2010 is planned, meaning an unprecedented exploration of a region in the Solar System populated with a vast variety of worlds.

6 Discoveries of the Huygens Probe

Undoubtedly, the landmark of the Cassini-Huygens mission has been the entry, descent and soft landing of the European Huygens Probe. It was equipped with six instrument exclusively designed to *in situ* explore the atmosphere and surface of Titan. These instruments were: 1) Aerosol Collector and Pyrolyser (ACP)[65] to collect aerosols for chemical-composition analysis; 2) Descent Imager/Spectral Radiometer (DISR) [70], to take images and make spectral measurements using sensors covering a wide spectral range; 3) Doppler Wind Experiment (DWE) [67], to deduce atmospheric properties (as winds) using radio signals; 4) Gas Chromatograph and Mass Spectrometer (GCMS) [68], a versatile gas chemical analyser to identify and quantify various atmospheric constituents; 5) Huygens Atmosphere Structure Instrument (HASI) [66], comprised of several sensors for measuring the physical and electrical properties of the atmosphere and an on-board microphone able to send back sounds from Titan; 6)

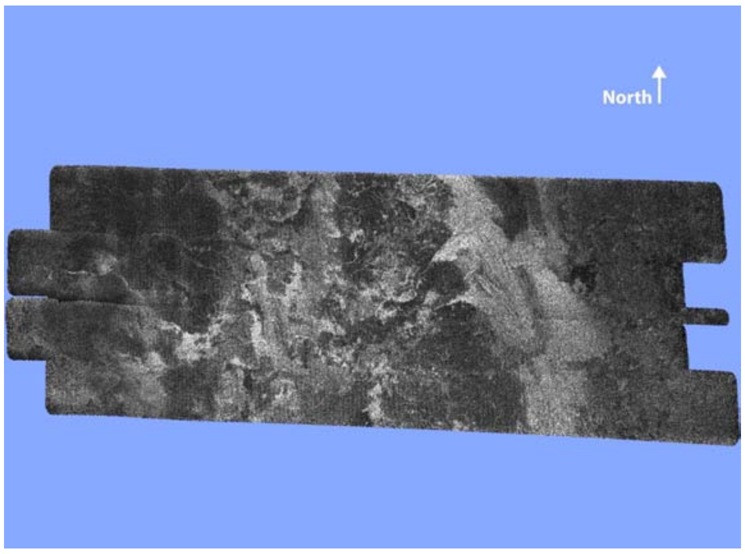

Figure 13: Surface of Titan explored by the Radar Mapper on board the Cassini spacecraft [58]. During TA, it was imaged about 1% of Titan's surface at a resolution of $\sim 0.3-0.5$ km, and larger areas of the globe in lower resolution modes. This area here is $\sim 250 \times 150$ km^2 in the northern hemisphere centered at 50°N, 82°W. This region had not yet been explored in the optical range at the time of the TA encounter. Brighter areas may correspond to rougher terrains and darker areas are thought to be smoother. This image highlights some of the darker terrain. The interconnected dark spots are consistent with a very smooth or highly absorbing solid, or could conceivably be liquid.

Surface Science Package (SSP) [69], made of several sensors to determine the physical properties of the surface at the impact site and to provide unique information about its composition. The package includes an accelerometer to measure the impact deceleration, and other sensors to measure the index of refraction, temperature, thermal conductivity, heat capacity, speed of sound, and dielectric constant of the (liquid) material at the impact site.

After a seven-year journey on board the NASA/ESA/ASI Cassini spacecraft and two orbit around Saturn, ESA's Huygens probe was released on 25 December 2004 (targeted TC fly-by). It reached the upper layer of Titan's atmosphere on 14 January 2005 at a velocity of 6 km/s. It landed softly on the surface after a parachute descent (see Figure 15) of 2 hours and 28 minutes at 11:38:11 UTC (Coordinated Universal

Figure 14: View of Titan constructed with images acquired by the instrument VIMS at 1.6 μm (shown in blue), 2.01 μm (shown in green), and 5 μm (shown in red).

Time). Unfortunately part of the data collected by the DWE and by the PWA (part of HASI) experiments on board Huygens were lost due to what it has been known as Channel A anomaly [60]. Cassini spacecraft received data from the Huygens probe until 12:50 UTC (1 h 12 min after touchdown) when it passed below the probe's horizon. The probe and its scientific payload performed close to and sometimes beyond expectations. An exciting scientific data set was returned by the Huygens probe, offering a new view of Titan, which appears to have an extraordinarily Earth-like meteorology, geology and fluvial activity (in which methane would play the role of water on Earth). The Huygens results summarized in this note reveal the uniqueness of Titan in the Solar System.

The irreversible conversion of methane into higher hydrocarbons in Titan's atmosphere implies a surface or subsurface methane reservoir (the nowadays atmospheric content of CH_4 should have been destroyed in 10-100 million years). Spectra and high-resolution images obtained by the Huygens Probe Descent Imager/Spectral Radiometer do reveal the traces of once flowing liquid. Surprisingly like Earth, the brighter highland regions show complex systems draining into flat, dark lowlands [71]. The IR spectra do also show a unique environment, which has no known equivalent on any other object in the Solar System: there is a red slope in the optical consistent with organic materials as tholins (already suggested by [72]), absorption due to water ice, and a blue slope in the near-IR due an unknown constituent. The number density of haze particles is rather constant from 150 km down to the surface, including at the tropopause (i.e. cold trap). The landing site seen in Figure 16 reveals rocks which -whether made of silicates or, more probably hydrocarbon coated water-ice- appear to be rounded, size selected and size layered as though located in the bed of a stream within the large dark lakebed. No rocks larger than 15 cm are seen in this landscape whose color and the sky above it is rather orange, due to much greater attenuation

Figure 15: Entry, descent and soft landing of the European Huygens Probe. See text for details.

of blue light by Titan's haze relative to red light. These spectra also show a methane abundance near the surface of $5 \pm 1\%$, which is in precise agreement with the 4.9% *in situ* measurements made by the probe's Gas Chromatograph Mass Spectrometer [68]. These new observations make clearer the role of methane in shaping the surface of Titan and how it is recycled into the atmosphere. The substantial relative humidity of methane and the obvious evidence of fluid flow on the surface provide evidence for methane "rain" and subsequent evaporation. Some hints of 'cryovolcanic' flows may also be present in the images.

By assembling the panoramic mosaics acquired during the descent, the trajectory could be used to derive the probe ground track and see how wind speeds changed with altitude. Tomasko *et al.* found that the probe drifted steadily east-northeast due to Titan's "prograde" (in the direction of rotation of the moon) winds. It slowed from near 30 to 10 m/s between altitudes of 50 and 30 km and then slowed more rapidly (from 10 to 4 m/s) between altitudes of 30 and 20 km. The winds dropped to zero and reversed at around 7 km, near the expected top of the planetary boundary layer, producing a west-northwestwardly motion for about 1 km during the last 15 minutes of the descent.

The entire set of DISR observations gives a new view of Titan, and reinforces the view that processes on Titan's surface are more similar to those on the surface of the Earth than anywhere else in the Solar System.

Further information on the nature of the surface was provided by the acoustic sounding over the last 90 m above it revealing a relatively smooth, but not completely flat, surface surrounding the landing site [73]. The signal provided by the sensors

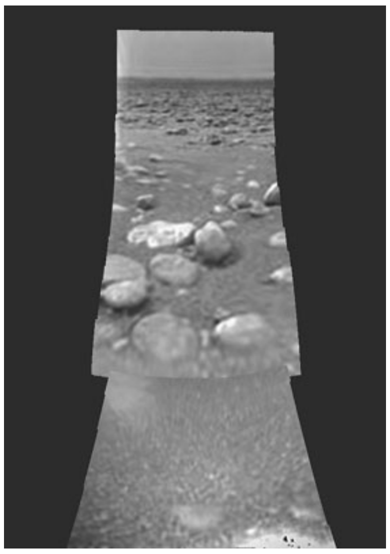

Figure 16: Images from the DISR Side-Looking Imager and from the Medium Resolution Imager, acquired after landing, were merged to produce this image. The horizons position implies a pitch of the DISR, nose-upward, by $1-2°$ with no measurable roll. "Stones" in the foreground are 10-15 cm in size, presumably made of water ice, and these lie on a darker, finer-grained substrate. A region with a relatively low number of rocks lies between clusters of rocks in the foreground and the background and matches the general orientation of channel-like features in the panorama view from 1.2 km (see Figure 17). The scene evokes the possibility of a dry lakebed.

of the SSP indicates that the probe impacted into a moderately firm, perhaps, even granular material overlain by an ice pebble or -perhaps less likely, given the prevalence of pebbles and cobbles in the DISR surface images [71]- a thin crust, and in either case coated with a very soft top layer. Somehow, the landing site had properties analogous to wet (by methane) clay, lightly packed snow and wet or dry sand. A collection of photochemical products and/or fine-grained ice making a plastic or viscoplastic material (i.e. a "tar") cannot be ruled out either.

Temperature and density profiles, as determined by the Huygens Atmospheric Structure Instrument (HASI) were retrieved from 1400 km down to the surface [74], which resulted to be higher than expected in the upper atmosphere. The subsystem Permittivity and Wave Altimeter (PWA) recorded the existence of an ionospheric layer between 140 and 40 km due to the interaction of the Galactic Cosmic Rays and

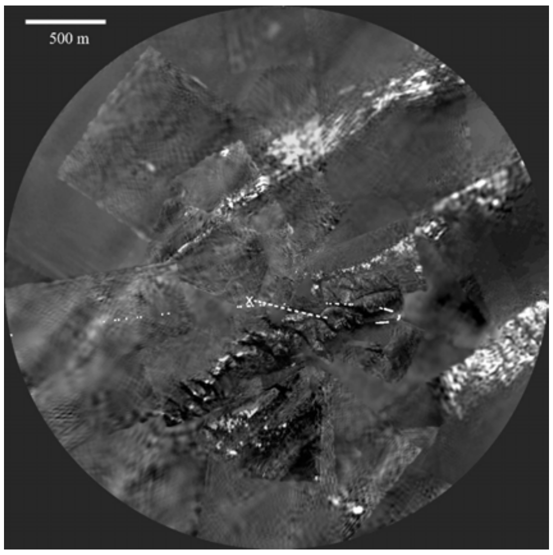

Figure 17: Images recorded by the Huygens DISR between 7 and 0.5 km were assembled to produce this panoramic mosaic. The probe groundtrack is indicated as points; north is up. The ridge near the centre is cut by a dozen darker lanes or channels. The landing site is marked with an X' near the continuation of one of the channels.

the dense atmosphere. The conductivity, and hence the ion density, peaks at 60 km. At the surface, the temperature was 93.65 ± 0.25K and the pressure was 1497 ± 1 mbar. The integration of accelerometer data gives a probe impact velocity of 4.33 m/s on a surface which did not show the presence of liquid phase.

Already Voyager 1 fly-by and occultation in 1980 provided clear evidence for the presence of strong zonal winds [75]. Its dense atmosphere shows not features as the Saturn and Jupiter does. Thus, the the winds regime on Titan has been studied during the Huygens probe descent with the DWE [76] by tracking its motion. As already mentioned, all data on channel A, including the probe telemetry and the planned DWE measurements, were lost [60]. However, the channel A signal was monitored on Earth during the Huygens mission at fifteen telescopes, six of which recorded ground-based DWE measurements of the carrier frequence. Bird *et al.* have analyzed the data from the NRAO Green Bank Telescope in West Virginia, and the CSIRO Parkes Radio Telescope in Australia to report on the winds regime in Titan's atmosphere. At the time of the start of descent, the spatial coordinates were estimated to be at latitude at ($10.33 \pm 0.17°$ S), longitude ($196.08 \pm 0.25°$ S)at (154.8 ± 11.2km). The probe drifted 165.8 ± 2.7 km over the duration of the descent from the entry, allowing for the determination of the wind field in the last 150 km of the descent. The zonal winds are prograde (eastward flow) above 14 km. Between 45 and 70 km altitude and above 85 km, the prograde wind speed is much larger than Titan's equatorial rotation speed, and thus represents the first *in situ* confirmation of the inferred superrotation of the atmosphere at those levels. The most striking departure of the measured profile from the engineering model is the region of strong reversed shear between 65 and 75 km altitude, where the wind speed decreases to a minimum of 4 m/s, which then reverts to strong prograde shear above 75 km. Surface winds are measured to be weak, speed not larger than 1 m/s.

The GCMS composition and isotopic measurements provided important constraints on models on the formation of Titan and its atmosphere in particular. Molecular nitrogen and methane (stratospheric mole fraction of 1.41×10^{-2} and 4.9×10^{-2} near the surface) were confirmed to be the primary constituents [77]. Because photochemistry destroys methane irreversibly on Titan (lifetime is only 10-100 million years), and because the carbon in CH_4 does not show the same kind of isotopic fractionation as the nitrogen and oxygen isotopes do, methane must be continually or periodically replenished on Titan. A geological source for methane, with a possible clathrate reservoir as storage in the interior of Titan is rather likely. Alternatively, methane may have been captured from the sub-nebula in the form of clathrate hydrates that now float on a plausible subcrustal ammonia-water ocean.

Noble gases other than argon were not detected. The argon includes primordial ^{36}Ar (mole fraction $(2.8 \pm 0.3) \times 10^{-7}$, and the radiogenic isotope ^{40}Ar (mole fraction of 4.32×10^{-5}), decay of ^{40}K. The low abundance of primordial noble gases implies that the nitrogen was captured as NH_3 and in other non-N_2-bearing compounds. Subsequent photolysis in a hot protoatmosphere generated by accreting Titan or possible impact driven chemistry of NH_3 lead to the nitrogen atmosphere we have on Titan today. Thus, the question whether the nitrogen arrived in planetesimals as N_2 or as mixture of nitrogen compounds dominated by NH_3 seems to be answered. Once the probe was in surface, trace organic species including carbon dioxide (CO_2), cynogen (C_2N_2), benzene (C_6H_6) and ethane (C_2H_6) were found.

The aerosols in Titan's atmosphere were analyzed by the Aerosol Collector and Pyroloyser (ACP) [78]. This instrument collected two atmospheric samples in the altitude ranges of 130-30 km and 25-20 km which were heated up to 600°C to transfer the gaseous products of the pyrolysis to the GCMS. The pyrolysis products were NH_3 and HCN (major contributor), that is, the aerosol particles include a solid organic refractory core where ammonia and hydrogen cyanide are incorporated to. The complex organic matter produced by Titan's atmospheric chemistry is being irreversibly carried to the surface by aerosols.

After the Huygens probe landing, we have not only a better knowledge and understanding of Titan's surface and atmosphere, but also a complete set of data, together with those provided by the Cassini orbiter, which will allow us in the very near future to answer most of the still unresolved questions, as the mystery of the missing methane [79]. As every scientific milestone, its success is not the answers provided, but the challenging questions it raises for a future exploration.

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