Titan: an astrobiological laboratory in the solar system

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ABSTRACT

After only three years of close observation from the Cassini-Huygens mission, Titan appears more and more as one of the key planetary bodies in the solar system for astrobiological studies. Titans does not look any more like a frozen primitive Earth, but like an evolving planet, geologically active, with cryovolcanism, eolian erosion, clouds and precipitations, and a methane cycle very similar to the water cycle on Earth. The new data also show a very complex organic chemistry in the highest atmospheric zones of the satellite, with the formation in the ionosphere of high molecular weight organics feeding the lower zones, down to the surface. In spite of the low surface temperature, these organics are probably evolving once in contact with water ice and form organic molecules of biological interest. This may explain the reflectance spectrum of Titan' surface observed by the DIRS instrument on Huygens. Thus, contrary to what was expected, the organic chemistry on Titan seems mainly concentrated in the ionosphere, in the aerosols and on the surface. These astrobiological aspects of Titan are presented and discussed on the basis of the already available Cassini-Huygens data, as well as the needed post Cassini exploration.

Keywords: amino acids, astrobiology, Cassini-Huygens, prebiotic chemistry, primitive Earth, Tholins, Titan

1. INTRODUCTION

Among the various planetary bodies of the solar system, the largest satellite of Saturn, Titan, offers different and complementary aspects of paramount importance for astrobiological researches. Titan presents many analogies with the Earth, in particular with the primitive Earth, and studying Titan today provides information on the conditions and processes which occurred on Earth four billion years ago. In addition, with an environment very rich in organics, it is one of the best planetary environments to study prebiotic-like chemistry at a full planetary scale, and within a time scale which cannot be reproduced experimentally in the laboratory. Moreover, in spite of the low temperature of this outer solar system planetary body, liquid water is likely to be present in its internal structure, as a deep subsurface water-ammonia ocean, opening the possibility that life may have emerged and may be still present in Titan.

What makes Titan very peculiar first is the presence of a dense atmosphere, made of dinitrogen with several percents of methane. Titan is in fact the only satellite of the solar system having a substantial atmosphere. It is also the only one we cannot see the surface, masked by the presence of aerosol layers in the atmosphere. The surface atmospheric pressure is 1.5 bar; this is even the only case of an atmospheric pressure close to that of the Earth. Our knowledge of this mysterious environment has been drastically improved with the Voyager flyby's of Titan in the early 1980's. The vertical atmospheric structure has been determined, and the primary chemical composition, trace compounds, and especially organics constituents described. Additional organics have also been identified later on by ground based observation and by the European Infrared Space Observatory satellite. Other ground based and Hubble observations have also allowed a first mapping of the surface, showing a heterogeneous milieu. However many questions still remained concerning Titan and particularly its astrobiological aspects. How complex is the organic chemistry? What is the processes of formation and the chemical composition of the aerosols particles which are present in the atmosphere? What is the chemical composition of Titan's surface? What is the nature of the various potential couplings between the gas phase the aerosol phase and the surface and their role in the chemical evolution of the satellite and its organic chemistry? How close are

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Instruments, Methods, and Missions for Astrobiology X
edited by Richard B. Hoover, Gilbert V. Levin, Alexei Y. Rozanov, Paul C. W. Davies
Proc. of SPIE Vol. 6694, 66940L, (2007) · 0277-786X/07/$18 · doi: 10.1117/12.732883

the analogies between Titan and the primitive Earth? Are the models of internal structure of Titan predicting the presence of bodies of liquid water below a very thick ice layer correct? What is the habitability of Titan? Is there life on/in Titan?

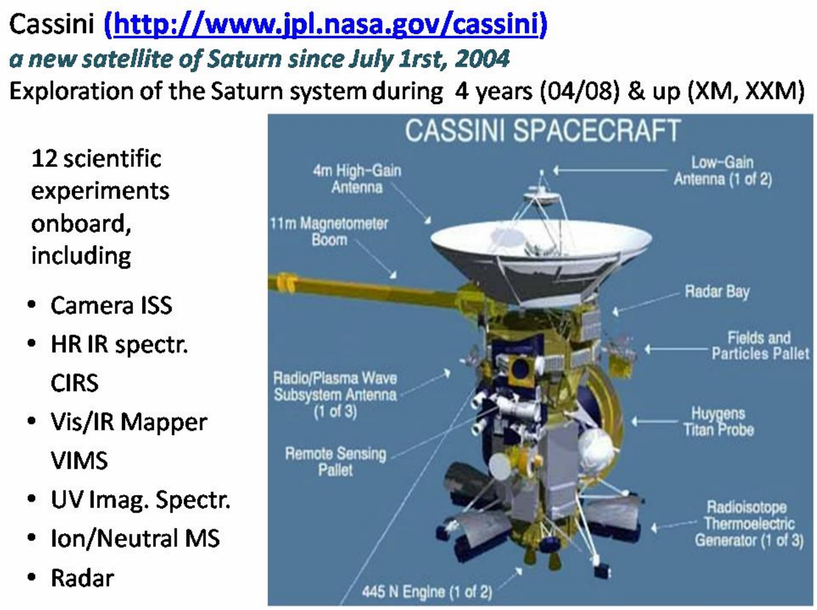

Fig. 1 The Cassini Spacecraft (adapted from NASA/JPL).

Bringing answers to some of these questions were one of the goals of the Cassini-Huygens mission. This very ambitious planetary exploration mission includes a spacecraft, Cassini (Fig. 1), designed by NASA, to become a Saturn orbiter, and a probe, Huygens (Fig. 2), developed by ESA, to descent in Titan's atmosphere. It was designed to explore the Saturn system in great detail, with a particular focus on Titan. After a 7 years journey Cassini reached the Saturn system in 2004 and successfully became an (artificial ...) satellite of the giant planet on July 1st, 2004. Cassini released the Huygens probe on December 25, 2004, and the probe entered Titan's atmosphere on January 14th, 2005 (Lebreton et al, 2005).

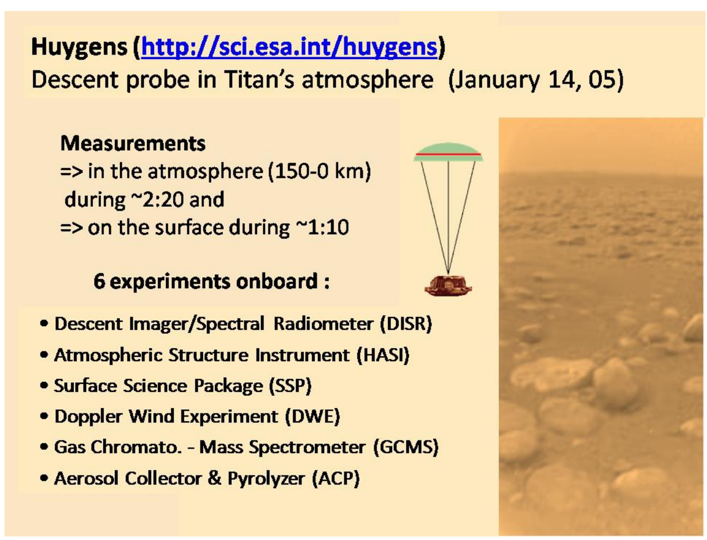

Fig. 2. The Huygens probe and a DISR image of Titan surface (adapted from ESA/NASA/JPL/Univ. Arizona)

A tremendous amount of new information on Titan has already been obtained from the Huygens instruments (2 hours and 20 minutes of descent and more than 1 hour of surface data), together with data obtained from the instruments of the Cassini orbiter during the tens of Titan's fly-by's performed during the past three years. These data have deeply changed our understanding and vision of Titan (Raulin, 2007a; 2007b). In the present paper, we describe the three main astrobiological aspects of Titan, which are already demonstrated by the Cassini-Huygens data together with theoretical modelling and laboratory experimental studies as complementary approaches.

2. SIMILARITIES BETWEEN TITAN AND THE EARTH

Since data on the environment of the primitive Earth, and the conditions in which prebiotic chemistry developed about 4 billion years ago, are very rare, it is essential to find extraterrestrial environments were processes and conditions similar to those on the primitive Earth are occurring now. Titan, in spite of many different conditions, due in particular to the low temperature and smaller size, offers such case. Titan is the largest moon of Saturn and the second largest moon of the solar system, with a diameter of 5150 km. It is the unique satellite of the solar system with a dense atmosphere, clearly evidenced by the presence of haze layers and extending to approximately 1500 km (Fulchignoni et al, 2005). Titan's atmosphere is mainly composed of dinitrogen, N_2. The other main constituents are CH_4, approximately 2.0% in the stratosphere, as measured by CIRS on Cassini (Flasar et al, 2005) and GC-MS on Huygens (Niemann et al, 2005) and dihydrogen (H_2, approximately 0.1%). With surface temperatures of ~94 K, and an average surface pressure of 1.5 bar, Titan's atmosphere is nearly five times denser than the Earth's. Despite the low temperatures of Titan's environment, there are many similarities between the largest satellite of Saturn, and the Earth, particularly the primitive Earth.

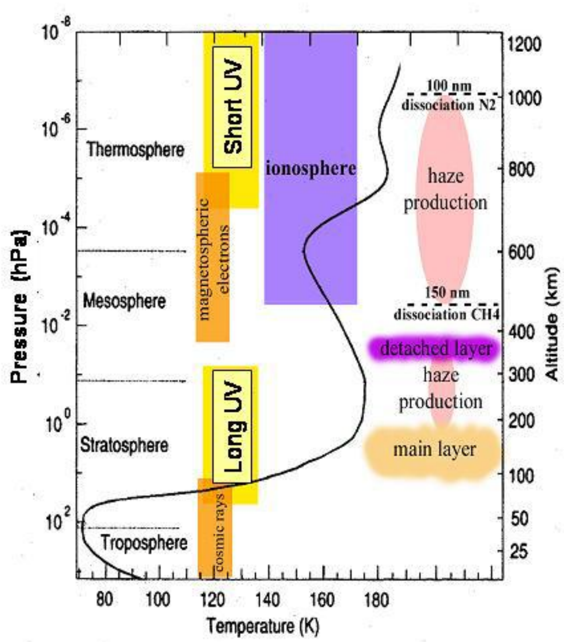

Fig 3. Titan's atmospheric structure with zones of energy deposition

Titan, like the Earth has a dense atmosphere, with N_2 as main constituent, but also with a similar vertical atmospheric structure (see Fig. 3). Although much colder than the Earth's atmosphere, Titan's atmosphere has also a troposphere (with temperatures from ~94 to ~70 K), a tropopause (70.4 K) and a stratosphere (~70-175 K). As recently measured by Cassini-Huygens, it also has a mesosphere, extending to altitudes higher than 400 km (instead of only 100 km for the Earth's atmosphere which has lower density), and a thermosphere. Titan, like the Earth has greenhouse gases and antigreenhouse elements in its atmosphere. CH_4 is a very efficient greenhouse gas in Titan's atmosphere because it has strong absorption bands in the far infrared region corresponding to the maximum of the infrared emission spectrum of Titan and is transparent in the near UV and visible spectral regions. Dihydrogen can also act as a greenhouse gas, because it is absorbing in the far IR (through bimolecular interaction) and is also transparent in the near UV and visible spectral regions. Now, with the conditions of Titan's atmosphere, in term of temperature and pressure, methane can condense but not dihydrogen, thus both behave respectively like water and carbon dioxide, on Earth. Furthermore the haze particles and clouds in Titan's atmosphere play an antigreenhouse effect (McKay et al, 1991) similar to that of the terrestrial atmospheric aerosols and clouds.

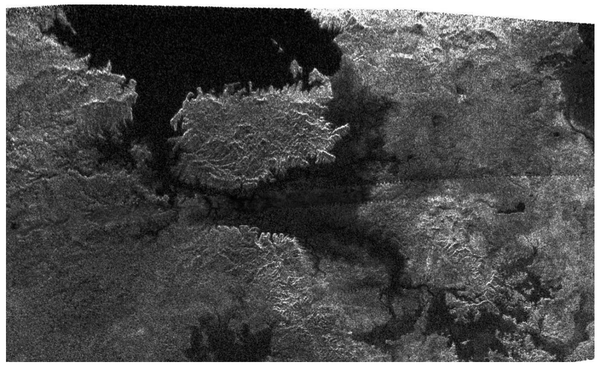

Fig. 4. This Cassini Radar image of Titan's surface shows an island in the middle of one of the large lakes located in the north polar regions. Credit : NASA/JPL.

Thus on Titan methane seems to play the role that water plays on the Earth, with a complex cycle, still to be fully understood, including sources and sinks, clouds, possibly rains, and liquid surface bodies. The possible presence of large oceans of methane (more precisely mixtures of methane and ethane) on Titan' surface, similar to the terrestrial ones was considered (Lunine, 1993), but is now ruled out (West et al, 2005). However, the ISS camera on Cassini has detected dark surface features near the South Pole which could be such liquid bodies. Moreover, very recently, in the near polar regions, a giant lake-like feature has been observed by ISS and several smaller liquid bodies very likely made of these two hydrocarbons, have been identified (Fig. 4) by the radar instrument of Cassini (Stofan et al., 2007; Sotin, 2007).

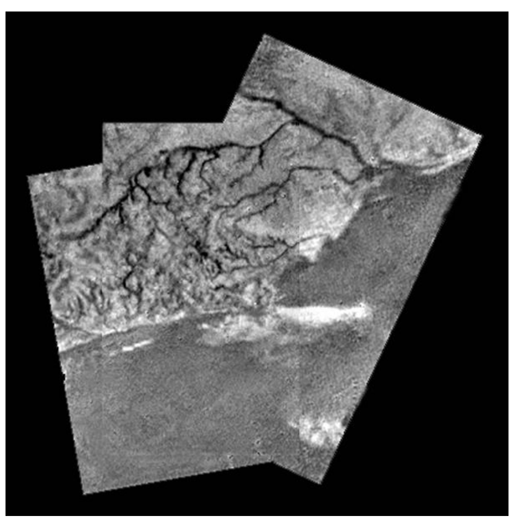

Fig. 5. Dendritic chanel networks, highlands and dark-bright interface seen by the DISR instrument on Huygens at 6.5 km altitude. Credit: ESA/NASA/JPL/University of Arizona.

Pictures of Titan's provided by DISR on Huygens clearly show dentritic structures (Fig. 5) looking like fluvial net, in a relatively young terrain, fresh of crater impacts, strongly suggesting recent liquid flow on the surface of Titan (Tomasko et al, 2005). Moreover, GC-MS data show that methane mole fraction increases in the low troposphere (up to 5%) and reaches the saturation level at approximately 8 km altitude, allowing the possible formation of clouds and rain (Niemann et al, 2005). Furthermore, GC-MS analyses preformed on Titan's surface recorded a ~50% increase in the methane mole fraction once Huygens landed on Titan, suggesting the presence of condensed methane on the surface near the landed probe. Many observations from the Cassini instruments clearly show a very diversified surface with the presence of various features of different origins indicative of volcanic, tectonic, sedimentological and meteorological processes as we find on Earth. On Titan, there are mountains, there are dunes (Lorenz et al, 2006) where water ice probably plays the role of terrestrial sand, there are cryovolcanoes where again water ice replace melted silicates. Cryovolcanism has been clearly evidenced from the first images of Titan's surface provided by the VIMS, ISS and Radar instrument on Cassini (Sotin et al, 2005). There are terrains ressembling terrestrial dry lakebed, with peddles made of water ice, as seen by the DISR camera after Huygens landed (Fig. 2).

Argon has been detected in Titan's atmosphere by INMS on Cassini and GC-MS on Huygens. Similarly to the Earth atmosphere, the most abundant noble gas in Titan's atmosphere is Argon (the only detected so far on Titan) and more precisely ^{40}Ar, with a stratospheric mole fraction of about $4x10^{-5}$, as measured by GC-MS (Niemann et al 2005). This provides important information on the origin and evolution of the atmosphere, since this isotope of Argon comes from the radioactive decay of ^{40}K. Its presence strongly suggests that Titan's atmosphere is of secondary origin, produced by the degassing of trapped gases. Since N_2 cannot be efficiently trapped in the icy planetesimals which accreted and formed Titan, contrary to NH_3, this also indicates that its primordial atmosphere was initially made of NH_3. Ammonia was then transformed into N_2 by photolysis and/or impact driven chemical processes (Owen, 2000; Gautier and Owen, 2002). The $^{14}N/^{15}N$ ratio measured in the atmosphere by INMS and GC-MS (183 in the stratosphere) is 1.5 times less than the primordial N and indicates that the present mass of the atmosphere was probably lost several times during the history of the satellite (Niemann et al, 2005). Since such evolution may also imply methane transformation into organics, this may be also the indication of large deposits of organics on Titan's surface.

Indeed, organic chemistry is very active on Titan and, in spite of the absence of permanent bodies of liquid water on Titan's surface, it shows many similarities with the prebiotic chemistry which was active on the primitive Earth. Several of the organic processes which are occurring today on Titan imply some of the organics considered as key molecules in the terrestrial prebiotic chemistry, such as hydrogen cyanide (HCN), cyanoacetylene (HC_3N) and cyanogen (C_2N_2). By its main molecular composition, the atmosphere of Titan is one of the most favourable for atmospheric prebiotic syntheses, as shown by Miller's type of experiments. The evolution of a gas mixtures made of several % of methane in dinitrogen, under energy flux, yields a wide variety of organics, including the key molecules of prebiotic chemistry mentioned above. Until recently, it was assumed that the primitive atmosphere of the Earth was not chemically reduced and contained C mainly on the form of CO_2 and not CH_4, far from the current composition of Titan's atmosphere.

Re-estimate of H_2 escape recently done by Tian et al (Science 2005) indicates that the early Earth atmosphere could have included more than 30% of H_2. Thus it may have been much more chemically reduced than we thought. This suggests the possible presence of an active atmospheric organic chemistry, including in the solid phase with haze formation, like on Titan.

3. A COMPLEX PREBIOTIC-LIKE CHEMISTRY

In Titan's atmosphere, CH_4 chemistry is coupled with N_2 chemistry producing the formation of many organics in the gas and particulate phase. The products should include hydrocarbons and N-containing organic compounds - mainly nitriles- and complex refractory organics. Several photochemical models describing the chemical and physical pathways involved in the chemical evolution of the atmosphere of Titan and estimating the resulting vertical concentration profiles of the different involved molecules have been published for the last 20 years. For a review, see the most recent publications and the included references (Lebonnois et al, 2001; Wilson & Atreya, 2004; Hébrard et al, 2007a; 2007b). The whole chemistry starts with the dissociation of N_2 and CH_4 through electron and photon impacts. The primary processes allow the formation of C_2H_2 and HCN in the high atmosphere. These molecules play a key role in the general chemical scheme: once they are formed, they diffuse down to the lower levels where they allow the formation of higher hydrocarbons and nitriles. Additional CH_4 dissociation probably also occurs in the low stratosphere through photocatalytic processes involving C_2H_2 and polyynes.

There is another approach to study Titan's organic chemistry, very complementary of photochemical modelling: the use of simulation experiments in the laboratory. These experiments seem to well mimic the real processes since those experiments produce all the gas phase organic species already detected in Titan's atmosphere, within the right orders of magnitude of relative concentration for most of them. The experiments also produce many other organics which can be assumed to be also present in Titan's atmosphere, they thus appear as a very useful guide for further searches (both by remote sensing & in situ observations). The gas phase but also the aerosol phases are concerned by such an extrapolation. Indeed, simulation experiments also produce solid organics usually named tholins (Sagan and Khare, 1979). These "Titan tholins" are supposed to be laboratory analogues of Titan's aerosols. They have been extensively studied since the first work by Sagan & Khare more than 20 years ago (Khare & Sagan, 1984; 1986 & refs. included). These laboratory analogues show very different properties depending on the experimental conditions (Cruikshank et al, 2005). The molecular composition of the Titan tholins is still poorly known. Several possibilities have been considered such as HCN polymers or oligomers, HCN-C_2H_2 co-oligomers, HC_3N polymers, HC_3N-HCN co-oligomers (Tran et al, 2003 & refs. included). Information on the chemical groups included in their structure has been obtained from their IR and UV spectra and from analysis by pyrolysis-GC-MS techniques (Ehrenfreund et al., 1995; Coll et al, 1998; Imanaka et al,, 2004; and refs; included). The data show the presence of aliphatic & benzenic hydrocarbon groups, of CN, NH_2 and C=NH groups. Direct analysis by chemical derivatization techniques before and after hydrolysis allowed the identification of amino-acids or their precursors (Khare et al,, 1986). Their optical properties have been determined (Khare et al, 1984; McKay, 1996; Ramirez et al, 2002; Tran et al, 2003; Imanaka et al., 2004), and used to retrieve observational data related to Titan. Finally, it is obviously of astrobiological interest to mention that Stoker et al. (1990) demonstrated the nutritious properties of Titan tholins for microorganisms. Recently, the possible isotopic fractionation of carbon in tholins, compared to the starting methane has been studied (MJN et al, 2007). The results show no important enrichment of light or heavy carbon (Nguyen et al, 2007). This suggests that the chemical scheme to the building of tholins does not involve a large number of reactions. This laboratory data can also been used to retrieve the results from in situ analysis of Titan's aerosols.

Before the exploration of Titan by Cassini-Huygens, several organic compounds were already been detected in Titan's stratosphere: C_1-C_4 hydrocarbons and nitriles (both with saturated and unsaturated chains) and benzene as expected from laboratory simulation experiments. Since the Cassini arrival in the Saturn system, the presence of water and benzene (and of water vapour) in the stratosphere has been unambiguously confirmed by the CIRS instrument. CIRS has also been able to provide the latitudinal variation of many species (Falsar, 2005). But so far, at the exception of isotopomere species (deuterated acetylene), no new molecule has been identified. On board the Huygens probe, surprisingly, GC-MS did not detect a large variety of organic compounds in the low atmosphere. The mass spectra show that the mid- and low stratosphere and the troposphere are poor in volatile organic species, at the exception of methane. This is probably due to the condensation of these species on the aerosol particles (Niemann et al, 2005).

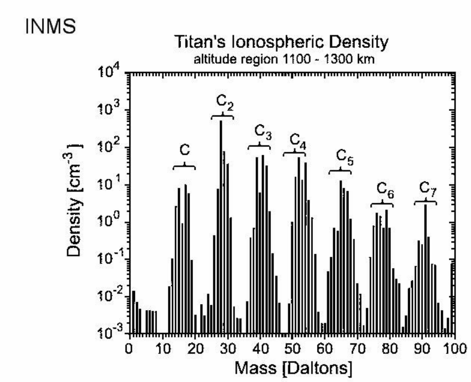

Fig. 6. Mass spectrum of Titan's ionosphere near 1,200 km altitude. The spectrum shows signature of organic compounds including up to 7 carbon atoms. Image Credit: NASA/JPL/University of Michigan.

An essential astrobiological discovery from Cassini observation is the detection of many organic species at detectable levels (Figure 6), in spite of the very high altitude (1100-1300 km) by the direct analysis of the ionosphere by the INMS instrument during the low altitude Cassini fly-by's of Titan. The mass range of INMS is limited to 100 Daltons, however, teh extrapolation of its data and of the CAPS (Cassini Plasma Spectrometer) strongly suggests that much higher molecular weight species, up to several 1000 Dalton, may be present in the ionosphere (Waite et al, 2007). This discovery, if confirmed, could fully change our understanding of the organic processes involved in Titan's atmosphere, and could demonstrate that ionospheric chemistry plays a key role in the formation of the complex organic compounds and aerosols nucleus, which was not considered before.

Another essential astrobiological discovery from Cassini-Huygens is the first direct data on the chemical composition of the aerosol particles in the low atmosphere. They have been analyzed by the ACP instrument. ACP was designed to collect the aerosols during the descent of the Huygens probe on a filter in two different regions of the atmosphere. Then the filter was heated in a closed oven at different temperatures and the produced gases were analysed by the GC-MS instrument. The ACP data show that the aerosol particles include refractory organics which release HCN and NH_3 during pyrolysis (Israel et al, 2005). This strongly supports the tholin hypothesis: from these new and first *in situ* measurement data it seems very likely that the aerosol particles are made of a refractory organic nucleus, covered with condensed volatile compounds (figure 7). The potential presence of nitrile groups (-CN), amino groups (-NH_2, -NH- and -N<) and /or imino groups (-C=N-) in the refractory complex organics of the aerosol nucleus is derived from the chemical nature of the compounds produced by pyrolysis. Moreover, comparison of the data obtained for the first (mainly stratospheric particles) and second (mid troposphere) samplings indicate that the aerosol composition is homogeneous (Israel et al, 2005). This also fits with some of the data obtained by DISR relative to the aerosol particle which indicates a relatively constant size distribution of the particles with altitude (with a mean dimension of the order of one micron).

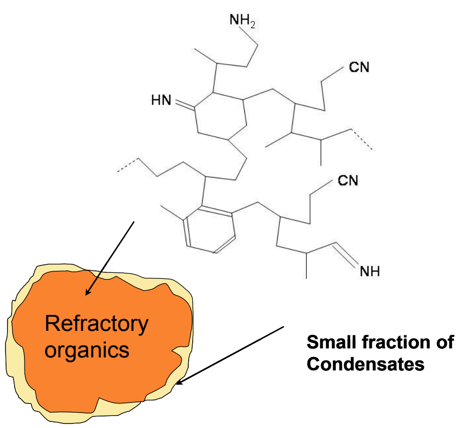

Fig 7. Model of the chemical composition of Titan's aerosols, derived from the Huygens ACP data.

After sedimentation down to the surface, the atmospheric aerosols should form a deposit of complex refractory organics and frozen volatiles. But this is probably not the end of their chemical evolution. They may interact with the water ice of the surface, or even with melting or liquid water which may be present episodically, produced by cryovolcanism activity or by the energy released by large impacts. Modeling of cometary impact on Titan's surface shows that it may melt surface water ice, offering possible episodes of liquid water as long as ~1000 years (-Artemieva and Lunine, 2003). This could provide, although for short time periods, conditions allowing terrestrial-like prebiotic syntheses, in spite of low temperatures of the environment.

Laboratory study of the behaviour of Titan's tholins in the presence of water is a way to predict the possible chemical evolution of the aerosols on Titan's surface. As mentioned above, the hydrolysis of tholins has already been studied: under very acidic conditions (HCl 6N), it releases many amino acids (Khare etal., 1986). However such conditions of pH are far from that of Titan. Recently systematic studies have been carried out, using tholins produced at LISA by the so called "Plasma" experiment, and different conditions of pH for the hydrolysis, from very acidic (HCl 6N) to neutral (pure water). The results demonstrate that the formation of amino acids is still observed at neutral pH, as well as that of several other organics, specially urea, carboxylic acids and hydroxyl-carboxylic acids (Fig. 8). Those compounds may be also present on Titan's surface.

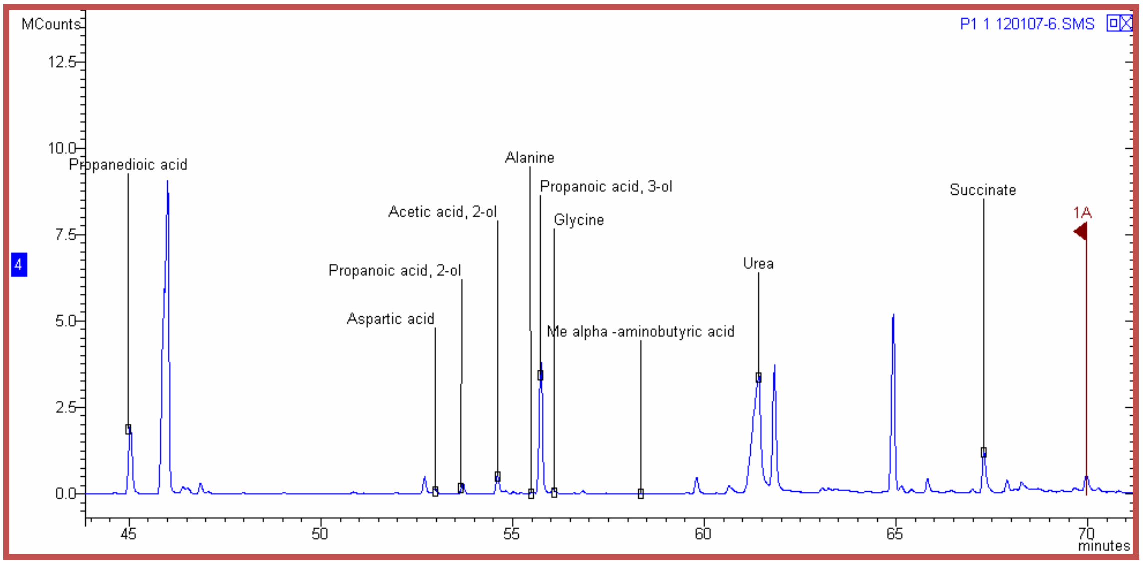

Fig. 8. GC-MS analysis of the products formed after hydrolysis at neutral pH of Titan's tholins: GC conditions: (column Rxt-1 (Restek) L: 30 m; Int. diam.: 0.25 mm, Temperature program: 60°C (20 min) – ramp 2°C/min until 260°C (maintained 10 min); Gas vector: He (flow: 1 mL/min) – sample conditions: (tholins synthesis: 60 mA; 1 mBar, 400 K) - 48 H hydrolysis in water (Millipore) at 70°C, derivatization: 30 µL MTBSTFA; 10 µL DMF.

The observational data related to the chemical composition of Titan's surface are still limited. GC-MS was able to analyse the atmosphere near the surface for more than one hour after the touchdown. The corresponding mass spectra show the signature of several organics, including cyanogen and benzene, indicating that the surface is much richer in volatile organics than the low stratosphere and the troposphere (Niemann et al, 2005). These observations are in agreement with the hypothesis that in the low atmosphere of Titan, most of the organic compounds are in the condensed phase. Data of the SSP instrument on Huygens (Zarnecki et al, 2005) suggest the presence of water ice. Its accelerometer measurements can be interpreted as the presence of small water ice pebbles on the surface where Huygens has landed, in agreement with the DISR surface pictures. On the other hand, DISR collected the infrared reflectance spectra of the surface with the help of a lamp, illuminating the surface before the Huygens probe touched down. The retrieving of these infrared data (Tomasko et al, 2005) shows the presence of water ice, but no clear evidence – so far – of tholins. However, the shape of the reflectance spectrum in the 1100-1500 nm spectral shows the same behaviour than that of the near infrared spectrum of amino-acids, and is thus compatible with the presence of these compounds on Titan's surface.

Thus these new data show the diversity of the locations where organic chemistry is taking place on Titan. Surprisingly the high atmosphere looks very active, with neutral and ion organic processes. In the lower atmosphere this chemistry seems mainly concentrated in the condensed phase. The surface of is probably covered with frozen volatile organics hydrocarbons such benzene and nitriles, such as cyanogen, together with refractory organic materials, including the hydrolysis products of the aerosol organic nucleus, such as amino-acids.

4. LIFE ON TITAN?

Two of the three essential elements for the emergence of life are clearly present in Titan's environment: organic matter and energy sources. The third one –liquid water - is present at least episodically on the surface, as mentioned above. It is also probably present permanently, in Titan. Indeed, models of the internal structure of Titan (Tobie et al, 2005, and refs. included) predict the possible presence of a water-ammonia ocean (with up to 15% ammonia) below a several 10 km thick water ice layer (Fig. 9, right). Such a liquid water body may provide an efficient way to convert simple organics into complex molecules, and to reprocess chondritic organic matter into prebiotic compounds. These processes may have been very efficient at the beginning of Titan's history when this subsurface water-ammonia ocean may have been in direct contact with the internal bedrock, and with the atmosphere (Fig. 9, left), offering another important similarity with the primitive Earth and the potential implication of deep sea hydrothermal vents in terrestrial prebiotic chemistry. The temperature of this water-ammonia ocean may be much colder than the terrestrial ones, but this may not affect too much the rate of the prebiotic reactions. Low temperatures reduce the rate constants of chemical reactions, but may increase the concentration of reacting organics by eutectic effect which increases the rate of the reaction.

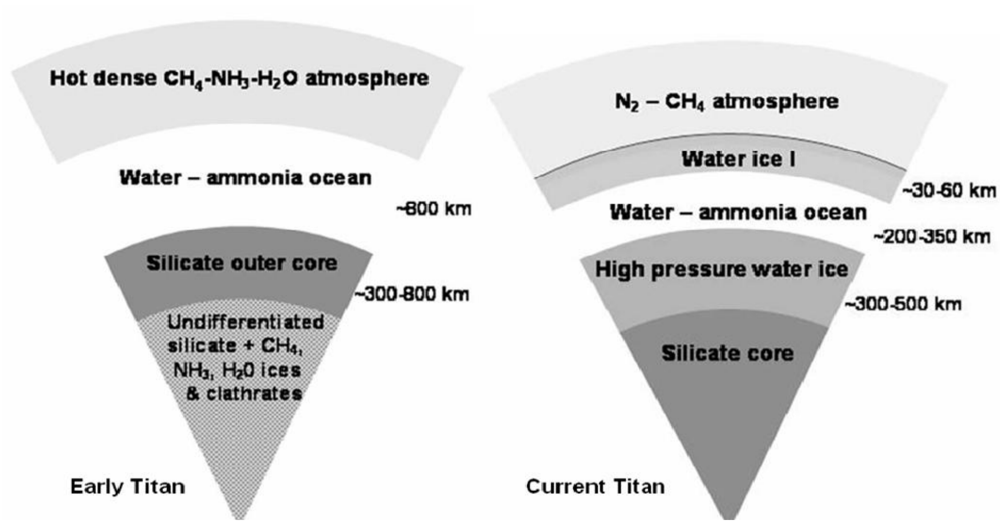

Fig. 9. Internal structure of Titan. Left: during the first 10 million years after its formation. Right: now. Adapted from Fortes (2000).

Thus it cannot be excluded that life emerged on Titan. But if this was the case, are Titan's conditions compatible with the sustaining of life? The surface is too cold and not energetic enough to provide the right conditions. However, the (still hypothetical) subsurface oceans may be suitable for life. Fortes (2000) has shown that there are no insurmountable obstacles. With a possible temperature of this ocean as high as about 260 K and the possible occurrence of cryovolcanic hotspots allowing 300 K, the temperature conditions in Titan's subsurface oceans could allow the development of living systems. Even at depth of 200 km, the expected pressure of about 5 kbar is not incompatible with life as we know it. The pH of a water- ammonia (85%-5%) ocean is about 11.5. Some bacteria can grow on Earth at pH 12. Even the limited energy resources do not exclude the sustaining of life. Fortes (2000) estimated an energy flux available in the subsurface oceans of about 5×10^8 W, taking into account only the potential radiogenic heat flow (~ 5×10^{11} W) and assuming that 1% of that is used for volcanic activity and 10% of the later is available for living system metabolism. Such a flux corresponds to the production of about 4×10^{11} mol of ATP per year and about 2×10^{13} g of biomass per year. With an average turn-over for the living systems in the order of one year, the biomass density would be 1g /m^2. This is very small compared to the lower limit of the value of the biomass for the Earth (about 1000 to 10000 g m^{-2}). Nevertheless, this indicates the possible presence of a non negligible bioactivity on the satellite. The biota on Titan, if any, assuming that the living systems are similar to the ones we know on Earth, and based on the chemistry of carbon and the use of liquid water as solvent, would thus be localised in the subsurface deep ocean. Several possible metabolic processes such as nitrate/nitrite reduction or nitrate/dinitrogen reduction, sulphate reduction and methanogenesis have been postulated (Simakov, 2001) as well as the catalytic hydrogenation of acetylene (Abbas & Schulze-Makuch, 2002; McKay & Smith, 2005). The metabolic activity of the corresponding biota, even if it is localized in the deep subsurface of Titan, may produce chemical species which diffuse through the ice mantle covering the hypothetical internal ocean and feed the atmosphere. Could the methane present in the atmosphere today be the product of biological activity? If this was the case, the atmospheric methane would be notably enriched in light carbon. Indeed, on Earth, biological processes induce an isotopic fragmentation producing enrichment in ^{12}C. Indeed, $^{12}C/^{13}C$ increases from 89 (the reference value, in the Belemnite of the Pee Dee Formation) to about 91-94 depending on the biosynthesis processes. The $^{12}C/^{13}C$ ratio in atmospheric methane on Titan, as determined by the GC-MS instrument on Huygens is 82 (Niemann et al, 2005). This low value suggests that the origin of methane is likely to be abiotic.

4. CONCLUSIONS

Thanks to the rich harvest of the new observational data provided by the Cassini-Huygens mission, Titan looks more than ever as a key object for astrobiology. The many similarities between this exotic and cold planetary body and the Earth and the complex organic chemical processes which are going on now on Titan provide a fantastic means to better understand prebiotic processes which are not reachable anymore on the Earth, within the whole complexity and at the size and time scale of a planetary environment. Study of Titan as a complex system is thus an important approach for astrobiology.

The whole complexity of Titan's system is well illustrated by the question of the origin and cycle of methane, its sinks and sources. The main sink for methane is its photolysis by solar UV, producing mainly ethane and tholins-like organic matter. The resulting life time of methane in Titan's atmosphere is relatively short (about 10 to 30 myr) Thus the presence of methane in Titan's atmosphere implies the presence of sources to continuously replenishing the atmosphere in methane. The large lakes of hydrocarbons seen in the north polar regions do not contain enough liquid methane to be the only source. Several hypotheses are already considered as other methane sources. Methane may have been trapped during the formation of Titan from the Saturnian subnebula where it was formed by Fisher-Tropsch processes (Sekine et al, 2005). If this is the case CH_4 would be stored in large amount in the interior of the satellite, under the form of clathrates (methane hydrates). It may also be produced through high pressure processes, like serpentinization allowing the formation of H_2 by reaction of H_2O with ultramafic rocks, or by cometary impact (Kress and McKay, 2004). Interestingly, those processes have rarely been considered in the case of the primitive Earth, although they may have contributed to a possible reducing character of the primordial atmosphere of our planet. In any case, the methane cycle should result in the accumulation of large amounts of complex organics on the surface and large amounts of ethane, which mixed with the dissolved atmospheric methane should form liquid bodies on the surface or in the near sub-surface of the satellite.

The Cassini-Huygens nominal mission ends in July 2008. But it seems very likely that the mission will be extended up to several years, continuing its systematic exploration of the Saturnian system up to 2011, and beyond if the extended-extended mission is accepted. Many data of crucial importance for astrobiology are still expected from the observation of Titan by the instruments on board Cassini. The presence of the internal ocean may be confirmed by the radio science data. Some surface organic may be identified from the VIMS observation at high spatial resolution mode. However, it is already clear that many questions need a new mission to be solved: what is the molecular, isotopic and chiral composition of the aerosols? Are there amino acids or other molecules of biological interest on Titan's surface ? If yes, do they show an enantiomeric excess ? A proposal for a new mission named TANDEM for exploring in tandem Titan and Enceladus, is already proposed to ESA in response to its Cosmic Vision plan. This very international project includes a Titan-Enceladus orbiter, a Montgolfière and several mini probes to study Titan. The proposed launch is around 2021, which is not that far away, when considering that it took more than 15 years between the emergence of the idea of a mission dedicated to the exploration of the Saturn system and Titan, and the launch of Cassini on October 15, 1997.

ACKNOWLEDGMENTS

The authors wish to thanks the European Space Agency, ESA, and the French Space Agency, CNES, for financial support.

REFERENCES

O. Abbas and D. Schulze-Makuch, "Acetylene-based pathways for prebiotic evolution on Titan", *ESA SP* 518, 345-348 (2002).

N. Artemieva and J. Lunine,"Cratering on Titan: impact melt, ejecta, and the fate of surface organics", *Icarus* 164, 471-480 (2003).

P. Coll, D. Coscia, M.-C. Gazeau and F. Raulin, "Review and latest results of laboratory investigation of Titan's aerosols", *Origins of Life and Evol. Biosph*. 28, 195-213 (1998).

D.P. Cruikshank, H. Imanaka and C.M. Dalle Ore, "Tholins as coloring agents on outer Solar System bodies", *Adv. Space Res.* 36, 178-183 (2005).

P. Ehrenfreund, J.P. Boon, J. Commandeur, C. Sagan, W.R. Thompson and B.N. Khare, “Analytical pyrolysis experiments of Titan aerosol analogues in preparation for the Cassini-Huygens mission”, *Adv. Space Res.* 15 (3), 335-342 (1995).
F.M. Flasar et al,, “Titan’s atmospheric temperatures, winds, and composition”, *Science* 308, 975-978 (2005).
A.D. Fortes, “Exobiological implications of a possible ammonia-water ocean inside Titan”. *Icarus* 146, 444-452 (2000).
M. Fulchignoni et al, “Titan’s physical characterisitics measured by the Huygens Atmospheric Structure Instrument (HASI)”, *Nature* 438, 785-791 (2005).
D. Gautier and T. Owen, “Touring the Saturnian system: the atmosphere of Titan and Saturn”, *Space Science Review* 104, 347-376 (2002).
E. Hébrard, M. Dobrijevic, Y. Bénilan and F. Raulin, “Photochemical kinetics uncertainties in modeling Titan’s atmosphere: a review”, *J. Photochem. Photobiol. A: Chemistry*, in press (2007a).
E. Hébrard, M. Dobrijevic, Y. Bénilan and F. Raulin, “Consequences of chemical kinetics uncertainties in modeling Titan's atmosphere”, *Planetary Space Sci*., in press (2007b).
H. Imanaka, B.N. Khare, J.E. Elsila, E.L.O. Bakes, C.P. McKay, D.P. Cruikshank, S. Sugita, T. Matsui and R.N. Zare, “Laboratory experiments of Titan tholin formed in cold plasma at various pressures: implications for nitrogen-containing polycyclic aromatic compounds in Titan haze”, *Icarus* 168, 344–366 (2004).
G. Israël, C. Szopa, F. Raulin, M. Cabane, H.B. Niemann, S.K. Atreya, S.J. Bauer, J.-F. Brun, E. Chassefière, P. Coll, E. Condé, D. Coscia, A. Hauchecorne, P. Millian, M.J. Nguyen, T. Owen, W. Riedler, R.E. Samuelson, J.-M. Siguier, M. Steller, R. Sternberg and C. Vidal-Madjar, “Evidence for the presence of complex organic matter in Titan’s aerosols by in situ analysis”, *Nature* 438, 796-799 (2005).
B.N. Khare, C. Sagan, E.T. Arakawa, F. Suits, T.A. Callicott and M. W. Williams, “Optical constants of organic tholins produced in a simulated Titanian atmosphere: from soft X-rays to microwave frequencies”, *Icarus* 60, 127-137 (1984).
B.N. Khare, C. Sagan, H. Ogino, B. Nagy, C. Er, K.H. Schram and E.T. Arakawa, “Amino acids derived from Titan tholins”, *Icarus* 68, 176-184 (1986).
M.E. Kress and C.P. McKay, “Formation of methane in comet impacts: implications for Earth, Mars, and Titan”, *Icarus* 168, 475-483 (2004).
S. Lebonnois, D. Toublanc, F. Hourdin and P. Rannou, “Seasonal variations of Titan's atmospheric composition”, *Icarus* 152 (2), 384-406 (2001).
J.P. Lebreton, O. Witasse, C. Sollazzo, T. Blancquaert, P. Couzin, A.-M. Schipper, J. Jones, D. Matson, L. Gurvits, D. Atkinson, B. Kazeminejad and M. Perez, “Huygens Descent and Landing on Titan: Mission Overview and Science highlights”, *Nature* 438, 758-764 (2005).
R. D. Lorenz, S. Wall, J. Radebaugh, G. Boubin, E. Reffet, M. Janssen, E. Stofan, R. Lopes, R. Kirk, C. Elachi, J. Lunine, K. Mitchell, F. Paganelli, L. Soderblom, C. Wood, L. Wye, H. Zebker, Y. Anderson, S. Ostro, M. Allison, R. Boehmer, P. Callahan, P. Encrenaz, G. G. Ori, G. Francescetti, Y. Gim, G. Hamilton, S. Hensley, W. Johnson, K. Kelleher, D. Muhleman, G. Picardi, F. Posa, L. Roth, R. Seu, S. Shaffer, B. Stiles, S. Vetrella, E. Flamini, and R. West, “The Sand Seas of Titan: Cassini RADAR Observations of Longitudinal Dunes”, Science 312, 724-727 (2006).
J.I. Lunine, “Does Titan have an ocean? A review of current understanding of Titan’s surface”, *Rev. Geophys.* 31 (2), 133-149 (1993).
C.P. McKay, “Elemental composition, solubility, and optical properties of Titan’s organic haze”, *Planet. Space Sci.* 44, 741-747 (1996).
C.P. McKay, J.B. Pollack and R. Courtin, “The greenhouse and antigreenhouse effects on Titan”, *Science* 253, 1118-1121 (1991).
C.P. McKay and H.D. Smith, “Possibilities for methanogenic life in liquid methane on the surface of Titan”, *Icarus* 178, 274–276 (2005).
M.-J. Nguyen, F. Raulin, P. Coll, S. Derenne, C. Szopa, G. Cernogora, G. Israël, and J.-M. Bernard, “Carbon isotopic enrichment in Titan’s tholins? Implications for Titan’s aerosols”, *Planetary Space Sci*., in press (2007).
H.B. Niemann, S.K. Atreya, S.J. Bauer, G.R. Carignan, J.E. Demick, R.L. Frost, D. Gautier, J.A. Haberman, D.N. Harpold, D.M. Hunten, G. Israel, J.I. Lunine, W.T. Kasprzak, T.C. Owen, M. Paulkovich, F. Raulin, E. Raaen, S.H. Way, “The abundances of constituents of Titan’s atmosphere from the GCMS instrument on the Huygens probe”, *Nature*, 438, 779-784 (2005).
T. Owen, “On the origin of Titan’s atmosphere”, *Planet. Space Sci.* 48, 747-752 (2000).
S.I. Ramirez, P. Coll, A. Da Silva, R. Navarro-Gonzalez, J. Lafait and F. Raulin, “Complex Refractive Index of Titan's Aerosol Analogues in the 200-900 nm domain”, *Icarus* 156, 515-530 (2002).
F. Raulin, “A New Astrobiological Vision of Titan from the Cassini-Huygens”, in *Planetary Systems and the Origins of Life*, R. E. Pudritz, P. Higgs, and J. Stone Eds, Cambridge Astrobiology Series, in press (2007a).
F. Raulin, “Astrobiology and habitability of Titan”, *Space Science Reviews*, in press (2007b).
C. Sagan and B.N. Khare, “Tholins : Organic chemistry of interstellar grains and gas”, *Nature* 277, 102-107 (1979).
D. Schulze-Makuch and L.N. Irwin, *Life in the Universe. Expectations and constraints,* Springer, New York, 2004.
Y. Sekine, S. Sugita, T. Shido, T. Yamamoto, Y. Iwasawa, T. Kadono and T. Matsui, “The role of Fischer–Tropsch catalysis in the origin of methane-rich Titan”, *Icarus* 178, 154-164 (2005).
M.B. Simakov, “The possible sites for exobiological activities on Titan”, *ESA SP* 496**,** 211-214 2001).
C. Sotin, “Titan’s lost seas found”, Nature 445, 29-30 (2007).
C. Sotin, R. Jaumann, B.J. Buratti, R.H. Brown, R. N. Clark, L. A. Soderblom, K.H. Baines, G. Bellucci, J.-P. Bibring, F. Capaccioni, P. Cerroni, M. Combes, A. Coradini, D.P. Cruikshank, P. Drossart, V. Formisano, Y. Langevin, D.L. Matson, T.B. McCord, R.M.

Nelson, P.D. Nicholson, B. Sicardy, S. LeMouelic, S. Rodriguez, K. Stephan and C.K. Scholz, “Release of volatiles from a possible volcano from near-infrared imaging of Titan”, *Nature* 435, 786-789 (2005).
E. R. Stofan, C. Elachi, J. I. Lunine, R. D. Lorenz, B. Stiles, K. L. Mitchell, S. Ostro, L. Soderblom, C. Wood, H. Zebker, S. Wall, M. Janssen, R. Kirk, R. Lopes, F. Paganelli, J. Radebaugh, L. Wye, Y. Anderson, M. Allison, R. Boehmer, P. Callahan, P. Encrenaz, E. Flamini, G. Francescetti, Y. Gim, G. Hamilton, S. Hensley, W. T. K. Johnson, K. Kelleher, D. Muhleman, P. Paillou, G. Picardi, F. Posa, L. Roth, R. Seu, S. Shaffer, S. Vetrella and R. West, “The lakes of Titan”, Nature 445, 61–64 (2007).
C.R. Stoker, P.J. Boston, R.L. Mancinelli, W. Segal, B.N. Khare and C. Sagan, “Microbial metabolism of tholins”, *Icarus* 85, 241-256 (1990).
F. Tian, O. B. Toon, A.A. Pavlov and H. De Sterck, “A Hydrogen-Rich Early Earth Atmosphere”, *Science* 308, 1014-1017 (2005).
G. Tobie, O. Grasset, J.I. Lunine, A. Mocquet and C. Sotin, “Titan’s internal structure inferred from a coupled thermal-orbital model”, *Icarus* 175, 496-502 (2005).
M.G. Tomasko, B. Archinal, T. Becker, B. Bezard, M. Bushroe, M. Combes, D. Cook, A. Coustenis, C. de Bergh, L. E. Dafoe, L. Doose, S. Doute, A. Eibl, S. Engel, F. Gliem, B. Grieger, K. Holso, E. Howington-Kraus, E. Karkoschka, H.U. Keller, R. Kirk, R. Kramm, M. Küppers, P. Lanagan, E. Lellouch, M. Lemmon, J. Lunine, E. McFarlane, J. Moores, G.M. Prout, B. Rizk, M. Rosiek, P. Rueffer, S.E. Schröder, B. Schmitt, C. See, P. Smith, L. Soderblom, N. Thomas and R. West, “Rain, winds and haze during the Huygens probe’s descent to Titan’s surface”, *Nature* 438, 765-778 (2005).
B.N. Tran, J.C. Joseph, J.P. Ferris, P.D. Persans and J.J. Chera, “Simulation of Titan haze formation using a photochemical flow reactor: The optical constants of the polymer”, *Icarus* 165, 379-390 (2003).
J. H. Waite Jr., D. T. Young, T. E. Cravens, A. J. Coates, F. J. Crary, B. Magee and J. Westlake, “The Process of Tholin Formation in Titan’s Upper Atmosphere”, *Science* 316, 870-875 (2007).
R.A. West, M.E. Brown, S.V. Salinas, A.H. Bouchez and H.G. Roe, “No oceans on Titan from the absence of a near-infrared specular reflection”. *Nature* 436, 670-672 (2005).
E.H. Wilson and S.K. Atreya, “Current state of modeling the photochemistry of Titan's mutually dependent atmosphere and ionosphere”, *J. Geophys. Res. - Planets* 109(E6), E06002 (2004).
J.C. Zarnecki, M.R. Leese, B. Hathi, A.J. Ball, A. Hagermann, M.C. Towner, R.D. Lorenz, J.A.M. McDonnell, S.F. Green, M.R. Patel, T.J. Ringrose, P.D. Rosenberg, K.R. Atkinson, M.D. Paton, M. Banaszkiewicz, B.C. Clark, F. Ferri, M. Fulchignoni, N.A.L. Ghafoor, G. Karg, H. Svedhem, J. Delderfield, M. Grande, D.J. Parker, P. G. Challenor and J.E. Geake, “A soft solid surface on Titan as revealed by the Huygens Surface Science Package”, *Nature* 438, 792-795 (2005).