

The spectral evolution of various Titan geomorphic surface types

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Abstract

We study the various, complex and potentially dynamic mid-latitude geological terrains of Titan. We focus on the geological types identified as possibly active in Lopes et al. (2010, 2015) [1;2] in addition to regions we studied in our recent work [3] where we reported two equatorial regions that present changes in surface albedo with time, such as Tui Regio and Sotra Patera. Here, we study the nature of the various geomorphological unit types (undifferentiated plains, hummocky/mountainous, candidate cryovolcanic sites, labyrinth, dunes, and others) in terms of surface albedo values and their spectral evolution with time (depending on data availability). Hence, we are able to report the differences and similarities among the various regions and provide implications on their chemical composition, which lead us to constrain specific processes of origin.

1. Context/Data

In order to unveil Titan's surface nature, it is important to determine the surface composition of different units, along with their morphological expressions. Matching the surface units with specified mixtures of materials can shed light on the interconnection between the interior, surface, and atmosphere. The Cassini VIMS obtained spectro-imaging data of Titan's surface from flybys performed during the last ten years, in the 0.8-5.2 μm range. The data from the seven narrow methane spectral "windows" centered at 0.93, 1.08, 1.27, 1.59, 2.03, 2.69-2.79 and 5 μm provide some information on the lower atmosphere and the surface parameters. Atmospheric scattering and absorption need to be clearly evaluated before we can extract the surface properties. Here we focus on areas that are close to the equator and are of geological interest. The geomorphological units we analyze are: i. the

Undifferentiated Plains ('Blandlands') [2], ii. Hummocky/mountainous terrains [2;4], iii. Labyrinth terrains [4], iv. Variable Plains, v. Stripe-like plains, vi. Dunes, vii. Candidate evaporates [5], viii. the Huygens Landing site [6], ix. Candidate cryovolcanic sites [7]. For the last four type units we also provide results on the temporal evolution of these surface units for significant period of time between 2004-2013 [6;7].

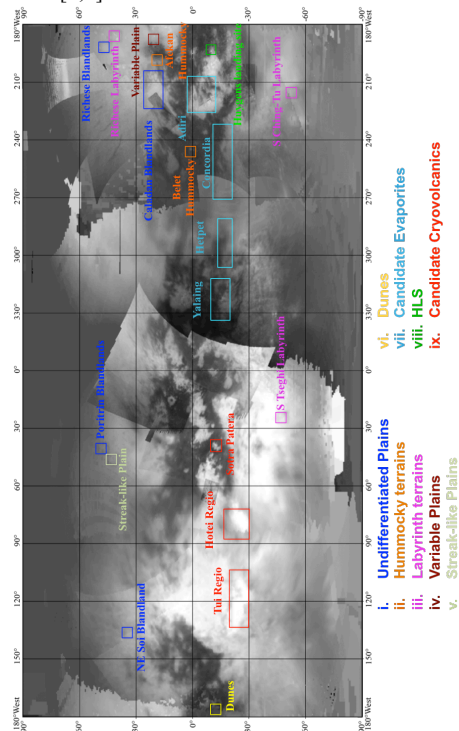


Fig. 1. Studied regions of interest from eleven different geological units on VIMS (2.03 μm).

2. Methods

Our radiative transfer (RT) method is a 1-D multi-stream RT code based on the open-source solver SHDOMPP [8]. As inputs, we used most of the Huygens Atmospheric Structure Instrument (HASI) and the Descent Imager/Spectral Radiometer (DISR) measurements, as well as new methane absorption coefficients. These are important to evaluate the atmospheric contribution and constrain the real surface alterations by comparing the spectra of these regions. Figure 2 shows the difference of the extracted surface albedos from RT of the regions of interest with the ‘ground truth’ albedo derived at the Huygens landing site.

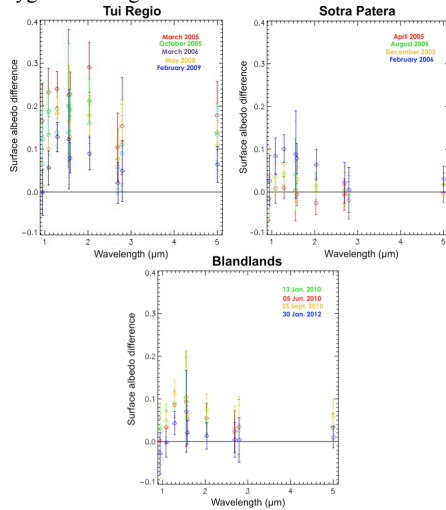


Fig. 2. Surface spectra showing changes in surface albedo shape and values in the near-infrared methane windows as a function of time with respect to the HLS surface albedo. (top left) Tui Regio from 2005-2009, (top right) Sotra Patera from 2005-2006, (bottom) the undifferentiated plains from 2010-2012 (from selective dates). From Solomonidou et al. (2015, Icarus, in press)

3. Results

Tui Regio’s (location shown in Fig. 1 red) surface albedo spectrum remains the same with time, only its overall brightness diminished from 2005 to 2009 (Fig. 2). The Sotra Patera (Fig. 1 red) area became brighter within a year from 2005 by a factor of 2, especially at short wavelengths. The tests, for approximately the same periods of time, of three surface reference points that correspond to dune

fields (Fig. 1 yellow) show that they did not present similar changes in surface albedo. The undifferentiated plains (Fig. 1 blue) and preliminary results from the evaporite candidates ix (Fig. 1 light blue) do not present any surface albedo changes with time. We therefore show that temporal variations of surface albedo (in chemical composition and/or morphology) exist for some areas on Titan’s surface, but that they differ from one region to the other. This could be due to diverse, past and/or ongoing formation processes (endogenic and/or exogenic, possibly cryovolcanic). In addition, in a follow up study we found that the labyrinth terrains (Fig. 1 magenta) and the undifferentiated plains seem to consist of a very similar if not the same material, while the different types of plains show compositional variations (Fig. 1 dark red, light green). The surface albedo variations together with the presence of volcanic-like morphological features suggests that the cryovolcanic candidate features (Fig. 1 red) are possibly connected to the satellite’s deep interior, which could have important implications for the satellite’s astrobiological potential. This idea has been recently augmented by the construction of new interior structure models of Titan and corresponding calculations of the spatial pattern of maximum tidal stresses [9]. However, an explanation attributed to exogenic processes is also possible [10].

Currently, we are working on deriving information on the chemical composition of the aforementioned regions from the extracted surface albedos. This will shed light on the potential formation processes.

Acknowledgements

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Geomorphic Units on Titan: constraints on the origin of Undifferentiated Plains

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Abstract

We present the global distribution of the major classes of units and, where there are direct morphological contacts, describe how these classes of units relate to each other in terms of setting and emplacement history (Fig. 1). In particular, we focus on constraining the origin of the Undifferentiated Plains, which cover large expanses of Titan's surface (Fig. 2). We examined and evaluated different formation mechanisms, including (i) cryovolcanic origin, consisting of overlapping flows of low relief or (ii) sedimentary origins, resulting from fluvial/lacustrine or aeolian deposition, or accumulation of photolysis products created in the atmosphere. The results from our analysis suggest that a sedimentary origin is the most likely, with all the aforementioned processes possibly contributing.

1. Introduction

The Cassini-Huygens mission has revealed the surface of Titan in unprecedented detail. The Synthetic Aperture Radar (SAR) mode on the Cassini Titan Radar Mapper is able to penetrate clouds and haze to provide high resolution (~350 m spatial resolution at best) views of the surface geology. The instrument's other modes (altimetry, scatterometry, radiometry) also provide valuable data for interpreting the geology, as do other instruments on Cassini, in particular, the Imaging Science Subsystem (ISS) and the Visual and Infrared Mapping Spectrometer (VIMS). Continuing the initial work described in Lopes et al. [1] [1], we have established the major geomorphologic unit classes on Titan using data from flybys Ta through T92 (October 2004-July 2013) [2]. The major types of units are Hummocky/mountainous terrains, Undifferentiated Plains, Dunes, Labyrinth terrains and Lakes. The oldest classes of units are the Hummocky/mountainous terrains, which consist of

mountain chains and isolated radar-bright terrains. The Labyrinth terrains consist of highly incised dissected plateaux with medium radar backscatter. The Undifferentiated Plains are younger than both Hummocky/mountainous and Labyrinth. Dunes and Lakes are the youngest major unit types on Titan; no contact is observed between the Dunes and Lakes but it is likely that both processes are still active. We have also identified individual features such as craters, channels, and candidate cryovolcanic features. Characterization and comparison of the properties of the unit classes and the individual features with data from radiometry, ISS, and VIMS provides information on their composition and possible provenance. We can use these correlations to also infer global distribution on regions not covered by SAR. This is particularly important as SAR data will not provide complete coverage of Titan by the end of the Cassini mission.

2. Undifferentiated Plains

We can place constraints on composition of the Undifferentiated Plains using results from VIMS, which senses the top few microns of the surface [e.g. 3;4], and radar radiometry, which has a greater penetration depth [e.g. 5].

The RADAR radiometer data indicate a strong compositional similarity in all high-emissivity terrains on Titan such as those of the Undifferentiated Plains, Labyrinth, and Dunes.

VIMS results show that Undifferentiated Plains and Labyrinth terrain albedo shape and values look very similar to one another, with very high values at all wavelengths. These albedo results show the similarity in composition between the Undifferentiated Plains and the Labyrinth terrains, in addition to the compositional similarity between the Dunes and interdune materials. The composition of the material of the first group (Plains-Labyrinth) appears, at least in the top few microns, to be very

different from the albedo-dark second group (Dunes-interdunes).

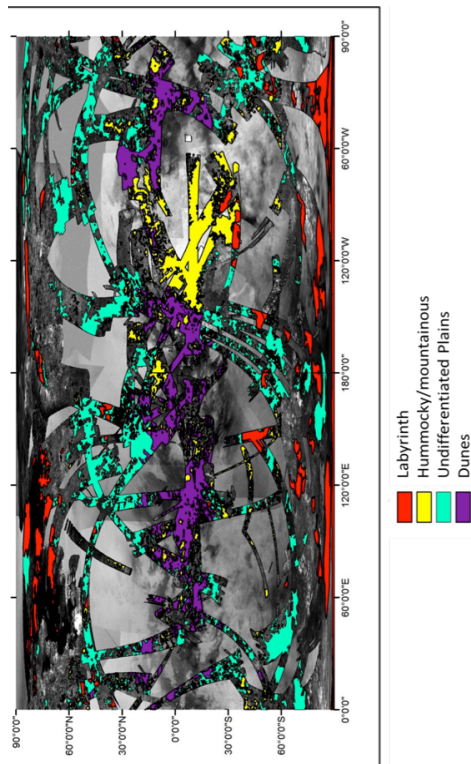


Figure 1: Global distribution of Undifferentiated Plains (green) compared to other major geomorphologic units on Titan (Dunes, Labyrinth, and Hummocky/mountainous). Map is at 1:1,500,000.

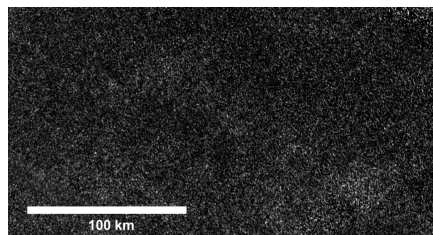


Figure 2: Example of Undifferentiated Plains ("blandlands") in Cassini SAR data. These plains appear relatively homogeneous and dark in the SAR data. This image shows an area of $\sim 36,000 \text{ km}^2$ centered near $(16.3^\circ\text{N}, 217^\circ\text{W})$.

3. Summary and Conclusions

Our analysis, using both VIMS and RADAR SAR and radiometry data, shows that a sedimentary origin for the Undifferentiated Plains is more compatible with the data than a cryovolcanic origin. The Undifferentiated Plains and Labyrinth regions show strong similarities in the radiometry and VIMS data, implying commonalities in surface composition. Analysis of all the data sets shows differences between the composition of the Undifferentiated Plains and Dune/interdune areas, suggesting that the Undifferentiated Plains cannot be composed simply of unmodified wind-blown dune materials. We propose that deposition from fluvial erosion, as well as from aeolian materials [6] and photolysis products, has played a significant part in the origin of the Undifferentiated Plains.

Acknowledgements

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Sun-stirred Kraken Mare: Circulation in Titan's seas induced by solar heating and methane precipitation

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Abstract

Density-driven circulation in Titan's seas forced by solar heating and methane evaporation/precipitation is simulated by an ocean circulation model. If the sea is transparent to sunlight, solar heating can induce anti-clockwise gyres near the sea surface and clockwise gyres near the sea bottom. The gyres are in geostrophic balance between the radially symmetric pressure gradient force and Coriolis force. If instead the sea is turbid and most sunlight is absorbed near the sea surface, the sea gets stratified in warm seasons and the circulation remains weak. Strong summer precipitation at high latitudes causes compositional stratification and increase of the near-surface methane mole fraction towards the north pole. The resultant latitudinal density contrast drives a meridional overturning with equatorward currents near the sea surface and poleward currents near the sea bottom. Weak precipitation induces gyres rather than meridional overturning.

1. Introduction

A large fraction of Titan's northern high latitudes is covered by liquid hydrocarbon seas and lakes. Meanwhile, the global distribution of Titan's seas has been mapped to a large extent [1], so that explicit simulations of the sea/lake circulation on Titan became feasible. Two aspects of ocean circulation in Titan's seas have so far been simulated by ocean circulation models: Tidal currents forced by Saturn [2] and wind-driven circulation [3]. An aspect that was neglected in these studies is the impact of density gradients on the circulation. Total absence of density gradients is an unrealistic assumption for open seas that are not entirely covered by sea ice. In Earth's oceans, differential solar heating and non-uniform freshwater fluxes at the sea surface cause variations in the temperature and salinity, which induce thermohaline or density-driven circulation.

In this study we present numerical simulations of density-driven circulation in Titan's seas associated with solar heating and methane precipitation by an ocean circulation model. The study especially addresses the seasonal and spatial structure of the dynamics of the sea that is difficult to investigate analytically.

2. Model outline

Density-driven circulation in Titan's seas is predicted by a baroclinic ocean circulation model, which was previously used to simulate tides [2] and wind-driven circulation [3]. The driving mechanisms of density-driven circulation considered in this study are solar heating (thermal forcing), which change the density of the liquid by thermal expansion and contraction, and local imbalance between methane evaporation and precipitation (precipitation forcing), which change the density by variable sea composition. Major differences to the model version of [3] concern the treatment of temperature and sea composition, which were previously kept constant. Thermal forcing is given by the surface heat flux along with the vertical profile of light extinction in the sea. Precipitation forcing analogous to freshwater influx or outflux in Earth's oceans is imposed by the surface methane flux, which consists of evaporation and precipitation. The density of the liquid is calculated as a function of temperature and composition.

3. Results

If surface methane fluxes are negligible, density gradients develop only due to differential solar heating of the sea (thermally forced circulation). Negligible surface methane fluxes could occur if there methane precipitation does not reach the sea surface and there is no methane evaporation because of methane paucity in the seas. In such a scenario the stratification and circulation depend on the vertical profile of the absorption of sunlight in the sea. If

most sunlight is deposited near the sea surface, the sea surface temperature depends only on depth, resulting in negligible horizontal density gradients and circulation. If the sunlight penetrates deeper to the sea, the coastal area in summer becomes warmer than the central part of the sea because of topographic heat accumulation. This causes the density in the entire liquid column to decrease towards the shore. The combination of radial pressure gradient force and Coriolis force maintains a stable geostrophic gyre, which is anti-clockwise near the sea surface and clockwise near the sea bottom.

Methane precipitation is another possibility to force a circulation in Titan's seas, but the significance of the precipitation forced circulation is likely to strongly depend on the precipitation distribution and magnitude. As long as the maximum precipitation rate is of the order of 0.1 mm/day or less, the seasonal variation in the sea composition and thus density near the sea surface is too small to generate a density-driven circulation comparable in magnitude with the thermally forced circulation. The model predicts several local gyres, which are less structured than the gyres caused by solar heating. If the precipitation rate in summer exceeds the order of 1 mm/day and the precipitation increases with latitude, the top layer of the sea becomes seasonally methane-enriched and the methane mole fraction in the top layer increases towards the north pole. This creates a compositional stratification and large latitudinal density gradients, especially in warm seasons. The resultant circulation is a meridional overturning with southward (equatorward) currents near the sea surface and northward (poleward) currents near the sea bottom.

Acknowledgements

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Interpretation of the ethane deficiency in Ligeia Mare

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Abstract

Absorption of Cassini's 2.2 cm radar by Ligeia Mare suggests that this north polar sea is dominated by methane. In order to explain this apparent ethane deficiency, we explore the possibility that Ligeia Mare is the visible part of an alkanofor that interacted with an underlying clathrate layer and investigate the influence of this interaction on an assumed initial ethane-methane mixture in the liquid phase.

1. Introduction

On Titan, the temperature and atmospheric pressure conditions prevailing at the ground level permit clathrate formation when liquid hydrocarbons enter in contact with the exposed water ice [1]. Assuming a high porosity for Titan's upper crust, clathrates with hydrocarbon guest species are stable and expected to occur down to several kilometers from the surface [1,2]. These clathrates may contain a significant fraction of the ethane and propane generated in Titan's atmosphere over the solar system's lifetime [1]. On the other hand, hundreds of lakes and a few seas of liquid hydrocarbons have been observed by the Cassini spacecraft to cover the polar regions of Titan [3-5]. If they are isolated from the subsurface, these lakes and seas should display compositions reflecting those of the precipitates, implying that they should contain a significant fraction of ethane. Alternatively, if the basins containing liquids are in contact with the icy crust of Titan, their compositions may be altered by interactions with clathrate reservoirs that progressively form if the liquid mixtures diffuse throughout preexisting porous icy layers [6]. These interactions may explain why the composition of Ligeia Mare appears dominated by methane [5, 7]. The apparent ethane deficiency could have resulted from interaction with an underlying clathrate layer that progressively formed from the entrapment of ethane.

Here we investigate the methane enrichment of a lake or sea due to the progressive entrapment of

liquid in clathrate.

2. Model

Our liquid reservoir consists of a mixture of CH_4 and C_2H_6 , and its equilibration is assumed faster with clathrate than with the atmosphere. We follow the approach proposed by [6] in which a hydrocarbon liquid reservoir is assumed to be in contact with porous ice and clathrate formation is expected to occur at the liquid/ice interface. We consider an isolated system composed of a clathrate reservoir that progressively forms and replaces the crustal material with time and a liquid reservoir that correspondingly empties due to the net transfer of molecules to the clathrate reservoir.

We use the numerical procedure defined in [6] with the intent to determine the mole fractions of each species present in the liquid reservoir and trapped in the forming clathrate reservoir. These mole fractions depend on the fractions of the initial liquid volume (before volatile migration) remaining in the liquid and present in clathrates. Our computation starts from a predefined composition of the liquid reservoir. It uses an iterative process for which the number of moles in the liquid phase being trapped in clathrates between each iteration is equal to 10^{-4} the total number of moles available. The numerical procedure utilized to calculate at each step the relative abundances of guest species incorporated in clathrates is based on a statistical mechanical model that relates their macroscopic thermodynamic properties to the molecular structures and interaction energies [6,8-10]. The computation presented here is based on the assumption that only structure I clathrates form at equilibrium from a mixture of CH_4 and C_2H_6 , supported by experiments [11].

3. Results

Figure 1 represents the evolution of the mole fractions of species present in the liquid reservoir and

its associated clathrate as a function of the progressive liquid entrapping. Our computation has been conducted at a surface temperature of 91 K and the starting mole fractions of CH_4 and C_2H_6 have been set to 0.7 and 0.3 in the liquid reservoir, respectively. The mole fraction of C_2H_6 in the liquid significantly decreases with progressive entrapping of the liquid reservoir, forcing this reservoir to become methane-pure when more than half (in mole fraction) of the initial reservoir has been trapped in clathrates. In this case, the mole fraction of C_2H_6 is below 5% in the liquid phase when more than ~40% of the initial liquid reservoir is trapped in clathrate. C_2H_6 is drawn out of the liquid phase because it is more efficiently trapped in clathrate than is CH_4 . The mole fraction of C_2H_6 decreases progressively in the forming clathrate because of its sharp abundance decline in the liquid reservoir. At the end of the liquid reservoir enclathration, the mole fractions of CH_4 and C_2H_6 trapped in clathrate converge towards their starting values in the liquid, while the latter is methane rich.

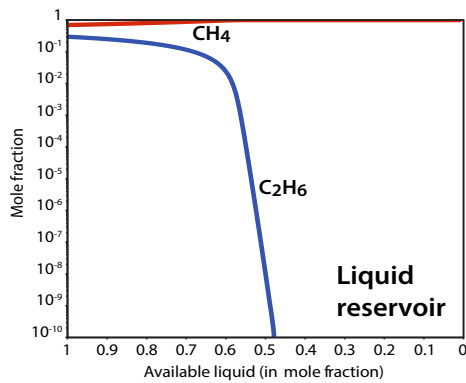


Figure 1: Composition of a liquid reservoir in contact with forming clathrate layers. Mole fractions of CH_4 and C_2H_6 are expressed as a function of the remaining fraction of the initial liquid reservoir.

4. Discussion

Circumstantial evidence from a variety of geologic features and isotopic ratios of carbon, hydrogen, and potassium in the atmosphere suggest that methane resupply from the interior has been extensive, enough to produce vastly more ethane than is seen on the surface [12]. Our model shows that the ethane will

then naturally be incorporated in the clathrate. One issue is how to “renew” the crustal water ice once saturated with ethane clathrate; the subsidence model of Choukroun and Sotin [2] seems promising in this regard.

It is quite likely that Titan’s water ice crust has been largely methane clathrate hydrate over its history [13]. In this case, our model is unchanged, because ethane’s preferential incorporation in clathrate relative to methane means that the latter is driven out of the ice as the former is incorporated. In this way, methane will slowly work its way out of the crust and into the atmosphere—possibly mostly by way of the seas if indeed these are the most active sites of ethane-methane exchange as we suggest above. A signature of such mediation of the exchange of ethane and methane over time might be heterogeneity of the isotopic signature of methane in the seas over fracture zones where the methane is outgassing—or disequilibrium between the isotopic composition of methane in the sea and in the atmosphere. Either way, testing this requires a sea lander.

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About the vertical gradient of composition in Titan's lakes

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Abstract

The hydrocarbons seas of Titan, discovered by Cassini/Huygens mission are among the most interesting features of this object. However, their chemical composition remains not well known. Due to the presence of the methane in the atmosphere, only a few indications favoring the existence of some amount of ethane in Ontario Lacus have been brought by observations reported in [2, 10]. Several numerical models have been proposed: Dubouloz *et al.* (1989), Cordier *et al.* (2009,2013) based on the Regular Solution Theory, Glein *et al.* (2013) [4] and Tan *et al.* (2013) [13] respectively based on a RST family model and on the advanced equation of state PC-SAFT¹ [5, 13, 10, 3]. The atmosphere of Titan is dominated by nitrogen and contains a few percents of methane. The latter, photolyzed by solar radiations in the stratosphere, gives rise to a complex organic chemistry yielding to the production of a plethora of compounds [7]. According to numerical models, the most abundant species, produced by photochemistry, should be ethane. Then, the bulk composition of Titan's lakes can reasonably regarded as a mixture of methane and ethane, with some amount of dissolved N₂. This latter has a melting temperature (63.3 K) much below than that for methane (around 91 K) and ethane (101 K determined by Streng, 1971; 89.2 K measured by Timmermans, 1935); as the ground temperature of Titan in the range 90 – 95 K, the nitrogen may play a role of an antifreezing solute.

In this work, we investigate the possibility of a vertical chemical composition gradient produced by the joint effects of the pressure and temperature gradients. For that purpose, we built an original model based on the hydrostatic equilibrium

$$\frac{\partial P}{\partial z} = -\rho g \quad (1)$$

where P is the pressure, ρ the density and g the gravity. A thermodynamic equilibrium is hypothesized

¹Perturbed-Chain Statistical Associating Fluid Theory

through the liquid

$$\frac{\partial \Phi_i x_i}{\partial z} = 0 \quad (2)$$

where Φ_i is the activity coefficient of the species i and x_i is its molar fraction at the depth z . The coefficient Φ_i and the density ρ are computed in the frame of PC-SAFT.

Beside this, the vertical energy transport is assumed to be governed by the equation (3), adapted from [14, 15] who used the formalism originally introduced in [1]

$$\frac{\partial}{\partial z} \left((\lambda_{L,mix} + \lambda_e) \frac{\partial T}{\partial z} \right) + \frac{\partial Q}{\partial z} = 0 \quad (3)$$

$\lambda_{L,mix}$ is the molecular thermal conductivity of the liquid mixture (W.m⁻¹.K⁻¹) and λ_e represents the contribution to heat transport by the eddy diffusion, which coefficient κ_e scales with the wind speed over the lake and is given by

$$\kappa_e = \frac{0.0325 \exp(-0.01278z) u_r / 10}{1 + \beta \frac{\partial \rho}{\partial z}} \quad (4)$$

u_r is the wind speed, λ_e , and κ_e are simply linked by $\lambda_e = \rho C_P \kappa_e$. The Eq. (4) is also used by [15] who adapted it from [16] and [8]. The former determined the value of β and obtained 5×10^5 m⁴.kg⁻¹. In Eq. (3), the source term $\partial Q / \partial z$ is due to the absorption of sunlight governed by

$$Q(z) = (1 - \alpha) S_g \exp(-\eta(h - z)) \quad (5)$$

in which S_g is the light initial flux, η is the absorption coefficient and h stands for the liquid height. For individual compounds, several empirical estimation techniques are available. We choose the method developed by Latini and his co-workers, published in a series of papers and summarized in [12] (see p. 10.44). In that approach, the thermal conductivity $\lambda_{L,i}$ (W.m⁻¹.K⁻¹) of a compound i is given by

$$\lambda_{L,i} = \frac{A_i (1 - T_{r,i})^{0.38}}{T_{r,i}^{1/6}} \quad (6)$$

where

$$A_i = \frac{A^* T_{b,i}^\alpha}{M_i^\beta T_{c,i}^\gamma} \quad (7)$$

the parameters A^* , α , β , and γ , are shown in Table 10-4 of [12]. The current temperature is noted T while $T_{b,i}$ and $T_{c,i}$ are respectively the temperature at the boiling point and the critical temperature. The molecular weight (expressed in g.mol^{-1}) is represented by M_i , the ratio $T_{r,i} = T/T_{c,i}$ is the reduced temperature. Concerning the thermal conductivity $\lambda_{L,\text{mix}}$ of liquid mixture, we adopted the rule from Vredeveld (1973) [12].

Since $\lambda_{L,\text{mix}}$ depends on the local temperature T , the differential equation (3) is non-linear, then the Crank-Nicholson scheme used by [15] is no longer applicable. Rather, we have employed a finite-differences implicit scheme.

Unfortunately, the methane triple point depression estimation, performed by Mitri *et al.* (2007) [11], relies on a misuse of Landau & Lifshitz (1969) [6]. In addition, this kind of calculation in the context of a triple point, is not relevant for a possible freezing in deep sea liquid, because it assumes the presence of a vapor phase in contact with the liquid.

Alternatively, in order to assess if methane or ethane freezes, we propose a calculation in which we compare the chemical potentials of a species in the liquid phase and in the corresponding solid phase. Then, when the vertical structure is obtained by solving the above mentioned equations, we check if the equation

$$\ln \Phi_i x_i = -\frac{\Delta H_{i,m}}{RT_{i,m}} \left(\frac{T_{i,m}}{T} - 1 \right) \quad (8)$$

is satisfied at some depth z in the sea. In this equation $\Delta H_{i,m}$ and $T_{i,m}$ denote respectively the melting enthalpy and the temperature of melting of the considered compound (*i.e.* methane or ethane), while Φ_i and x_i are provided by the previously computed vertical structure.

Our study is particularly relevant in the context of the possible future space missions. Particularly to ones that consists in *in situ* exploration of Titan's lakes (see for instance Lorenz *et al.* (2015) [9]).

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River deltas on the Earth and Titan - the role of grain size

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Abstract

We performed numerical simulations of formation and development of river deltas under conditions corresponding to surfaces of Earth and Titan for different grain sizes d and discharges Q . The processes leading to formation of fluvial deposits are very similar on both celestial bodies, but there are observable differences in their morphology for the same initial and boundary conditions. These differences must be taken into account for correct interpretation of remote observations. In particular, it is found that due to difference in buoyancy, some depositional landforms on Titan are built from coarser grains than the corresponding landforms on the Earth.

1. Introduction

Observations of the Cassini probe have revealed a complex, Earth-like environment on the surface of Titan, an icy moon of Saturn. The hydrocarbon lakes and river valleys are discovered in polar regions of Titan. A river flowing through the terrain erodes the rocks and carries granular material. Material is deposited along river's course, in particular in the place where river enters a standing body of liquid. This leads to creation of river deltas. The deltas have various areas, slopes and shapes, depending on the terrain type, the discharge (related to the local slope) and the grain size [1].

2. Preliminary results

The simulations presented here were performed with uniform distribution of grains, for constant discharge at the inflow, in conditions corresponding to surfaces of the Earth and Titan. In terrestrial conditions we investigate transport of quartz grains by the fresh water. In Titan's conditions the liquid is methane-nitrogen mixture (Titanian 'rain') and the sediments are water ice grains. We consider also the effects of

different composition of Titanian sediments, namely some admixture of solid hydrocarbons precipitated from the atmosphere.

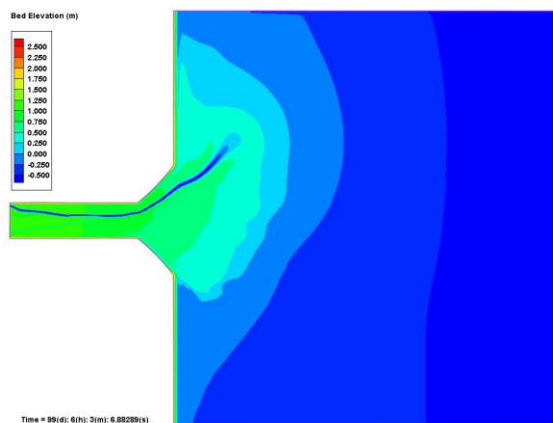


Figure 2: Bed elevation after 100 days: Earth, $d=0.10$ mm, $Q=10$ m³/s.

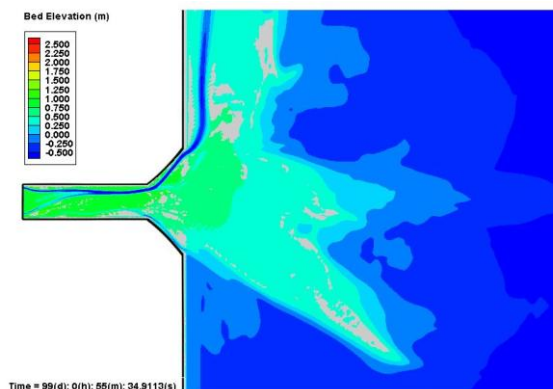


Figure 2: Bed elevation after 100 days: Titan, $d=0.10$ mm, $Q=10$ m³/s.

3. Summary and Conclusions

The research presented here is an extension of our previous work [2].

The processes on the Earth and Titan are very similar, however the differences in development of sedimentary landforms should lead to observable differences in morphology and development of river deltas and alluvial fans. On Titan the sediments could be carried by the flow deep into the lake; sediments may become dispersed over large area and they may not form easily recognizable deposits. The relation between parameters controlling the shape and evolution of river delta is slightly different on both bodies and Titanian deposits may be built from coarser grains compared to the similarly shaped landforms known from Earth.

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Titan's surface properties inferred from the seasonal brightness variation at 2-cm wavelength

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Abstract

A comprehensive calibration and mapping of the thermal microwave emission from Titan's surface at 2.2-cm wavelength has been completed by the passive radiometer included in the Cassini RADAR instrument. A seasonal brightness temperature variation has been determined that is comparable to but slightly smaller than that obtained by Cassini's Composite Infrared Spectrometer (CIRS). This difference has implications for the composition and structure of Titan's surface; namely, that most of Titan's surface is covered by the deposition and possible redistribution of tholin-like atmospheric photochemical products to a depth of at least a meter.

1. Introduction

Brightness temperature data including polarization were accumulated by the RADAR radiometer over the period from Saturn Orbit Insertion in 2005 to the present, and were used to construct global mosaics of effective dielectric constant and emissivity. The mapping approach is described in [1]. Because the observations now span a time interval of nearly one-half a Saturn season, the seasonal brightness temperature variation had to be accounted for. The difference between this variation, originating at some depth to be determined, and that obtained by CIRS at the surface, can be expected to place constraints on the thermophysical properties of Titan's surface layer.

2. The 2.2-cm seasonal variation

Using a massive least-squares approach [1], the accumulated brightness data were used to solve for Titan's surface intrinsic microwave properties of emissivity and effective dielectric constant along with time-dependent Titan and instrumental properties such as the seasonal brightness variation, antenna sidelobes and gain drift. The inter-

dependence of the data allowed a robust solution for all important parameters along with excellent determinations of systematic errors and statistical uncertainties. For the seasonal variation with time and latitude compared with the average, we used a model for that variation obtained by CIRS as a basis [2,3] for comparison with our results. Specifically we determined the amplitude of our observed 2.2-cm variation as a fraction F_{2cm} of that of the CIRS model. Using 2-cm data from all latitudes, we obtained a global result $F_{2cm} = 0.87 \pm 0.05$, where the uncertainty was determined by a Monte-Carlo technique in conjunction with the least-squares approach. In order to test dependence on latitude and terrain, we used subsets of points specific to these parameters and repeated the determination of F_{2cm} and its uncertainty for those subsets, where we found that essentially every subset gave the same result within statistical uncertainty.

3. The 2-cm penetration depth

We used the one-dimensional thermal diffusion equation

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2} \quad (1)$$

to compute the seasonal variation of temperature as a function of depth for likely values of the thermal diffusion coefficient α [4]. We assumed the variation of the thermal diffusivity to be driven by the range of thermal conductivity values for wet and dry organic sands, finding that the seasonal amplitude of the temperature variation is reduced by a factor of 0.87 at depths ranging from 40 to 100 cm.

4. Interpretation

Most organic materials that may be considered candidates for Titan's surface that have been measured in the laboratory under Titan conditions have penetration depths greater than 1 m [5]. The

laboratory data are limited; nevertheless, laboratory-produced tholins have been reported as having penetration depths as small as 22 cm when the material is compacted. While the relationship between tholins produced in the laboratory and that produced by photochemistry in Titan's atmosphere may be debated [6], this is at least an existence proof that the complex organics made by such processes can have constituents with sufficient microwave absorption to accommodate the present results, and provides another connection between atmospheric and surface processes.

5. Summary and Conclusions

The amplitude of the seasonal microwave thermal wave was found to be barely smaller than that at the surface as determined from the CIRS observations. Analysis showed that this relationship holds for the majority of Titan's surface, including most likely all of the radar-dark (high emissivity) terrains, which consist primarily of dunefields and plains. Using Titan-relevant thermophysical properties for the thermal conductivity of the subsurface based on their organic composition, we estimated a mean depth $< 1\text{m}$ for the emission in these terrains. Laboratory-produced tholins demonstrate microwave absorption sufficient to explain this opacity. We infer that photochemical products from Titan's atmosphere with similar properties are a plausible source of the opacity and a potential tracer in understanding the evolution of Titan's surface.

Acknowledgements

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On the origin of Titan's nitrogen

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Abstract

The enigma of the dense nitrogen atmosphere persists even after over ten years of scrutiny through the eyes of the Cassini-Huygens mission. However, recent measurements of the nitrogen composition of the comet 67P Churyumov-Gerasimenko (67P) by the ROSINA instrument onboard the Rosetta spacecraft provide new information that may be of importance in determining the volatile building blocks of Titan's atmosphere. We use these constraints to demonstrate that more than adequate amounts of nitrogen (in the form of both ammonia and molecular nitrogen) can be delivered by cometary-like icy planetesimals (CLIPs) and we discuss potential scenarios for the subsequent evolution that lead to the present day atmosphere as characterized by Cassini-Huygens.

1. Introduction

The Gas Chromatograph Mass Spectrometer (GCMS) onboard Huygens and the Cassini Orbiter Ion Neutral Mass Spectrometer both measured the bulk composition [1,2] including the noble gas ^{36}Ar , which was found to be surprisingly low in concentration as compared to solar abundances – 2.1×10^{-7} molar mixing ratio. The ^{36}Ar deficiency led [1,3] to conclude that the source of Titan's nitrogen was not primordial N_2 , but instead was created by photochemical conversion of NH_3 [4]. It also presented a dilemma as to nature of the inventory of the original volatile complement delivered to Titan during the accretionary process and how extensively these accreting volatiles may have been processed in the early Saturnian sub-nebula. Here we review the results from the ROSINA observations of N_2 in 67P [6] to derive the amount of N_2 that can be supplied to Titan by Comet-Like Icy Planetesimals (CLIPs). Furthermore, we scale this relative to previously measured values of NH_3 and CO from comet Hale Bopp to quantitatively derive the amount of NH_3 and N_2 delivered by CLIPs to Titan. We show that the N_2

and delivered is more than sufficient to explain the present day reservoir.

2. 67P implications for Titan's nitrogen

By assuming that water makes up 50% of present day Titan we can infer the probable volatile content of early Titan from CLIPs. Titan's atmospheric nitrogen has two possible sources. Nitrogen could have simply been delivered to Titan in N_2 form during its formation and then outgassed from the satellite's interior after the core overturn epoch. This assumption is justified by the potentially large N_2/CO ratio measured in 67P (0.16-1.7% [5]), which, based on the $\text{CO}/\text{H}_2\text{O}$ ratio (12-23% [6]) measured in comet Hale Bopp give a $\text{N}_2/\text{H}_2\text{O}$ ratio in the $2\text{-}39 \times 10^{-4}$ range. Hale Bopp is chosen for this scaling due to its presumed pristine composition, since this was its first pass through the heating that occurs when comets pass through the inner solar system. Scaled to the mass of water ice trapped in Titan, the $\text{N}_2/\text{H}_2\text{O}$ ratio implies that the amount of nitrogen present in this form can be substantially larger than the present atmospheric mass of N_2 .

Titan's nitrogen could also originate from the conversion of primordial NH_3 into N_2 via photochemistry and/or shock chemistry. Based on the $\text{NH}_3/\text{H}_2\text{O}$ ratio measured in comet Hale-Bopp (0.7%, [6]), we find that if NH_3 was the source of the nitrogen in the present day Titan's atmosphere then there is 35 times more nitrogen than is presently observed in Titan's atmosphere and if cometary N_2 (at the levels measured in 67P) was the primary source of present day nitrogen the scale factor from the amount of N_2 delivered to present day abundances ranges from 2 to 47.

3. Two possible sources for Titan's atmospheric nitrogen

The origin of the atmospheric nitrogen must be explained in the context of how the formation strategy unfolds. Two end members can be defined based on the energetics of the accretion processes. With minimal differentiation we can imagine that one end member is a slushy ice layer that has outgassed its CO , CH_4 , and N_2 . In the case of this end member a scenario is realized with at least two problems: How to get rid of the CO and how to explain the present day isotopic ratio of nitrogen? The latter concern is based on present day observations where N_2 at Titan has at $^{14}\text{N}/^{15}\text{N}$ ratio of 165 [1] whereas in the Saturn atmosphere a value of ~ 500 [7], which is more compatible with Jupiter and the solar wind [8]. Resolving the isotopic dichotomy has been previously explained through a scenario where the N_2 in Titan's atmosphere is formed from cometary NH_3 with a $^{14}\text{N}/^{15}\text{N}$ ratio near 130 [9,10].

The counter end member for the primordial atmosphere originates from a warm accretion process that leaves Titan with a global water ocean where the volatiles are partitioned between the atmosphere and the ocean according to their solubility and vapor pressure. In this case the CO_2 , CH_3OH , CH_2O , H_2S and NH_3 are highly soluble and largely confined to the ocean. The starting atmosphere volatile content is then primarily CO , CH_4 , and N_2 with small amounts of H_2O and NH_3 . Photochemistry acts on this atmosphere to provide a means of isotopically equilibrating N_2 and NH_3 . This isotopic-exchange photochemistry occurs in a manner similar to the chemical reactions between atomic and molecular nitrogen in molecular clouds when CO is present to produce OH which reforms molecular nitrogen from odd nitrogen [11,12]. In this case the optimum mixing model to obtain a nitrogen isotopic ratio near today's levels suggests that 90% of the original nitrogen is in the form of NH_3 and 10% as N_2 and that the NH_3 is largely in solution in the ocean and the N_2 is in the atmosphere, but that photochemistry mediated by NH_3 vapor and OH produced from CO and H_2O has fully equilibrated the isotopic ratio between the two nitrogen species. Such values for N_2 leave us with a factor of three excess in atmospheric nitrogen that must be lost from impacts during the formation phase or from atmospheric escape over geological time.

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Laboratory simulation of Titan's lakes: developing a new experimental facility to constrain the chemical composition of Titan's liquid surfaces

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Abstract

Since the discovery of Titan lakes by Cassini in 2006, interest in predicting their composition has grown substantially. In order to simulate Titan's liquid surface, we have developed a new experimental setup named Titan's Lakes Simulation System (TiLSS) that is designed to study the composition of these lakes in equilibrium with the atmosphere. In this system, we can prepare a variety of hydrocarbon mixtures (primarily methane, ethane, and propane) in the gas phase, and condense them under Titan-simulated conditions (1.5 bar nitrogen pressure, 92 K). This experimental setup will also provide a 10 Litre volume of liquid hydrocarbons to test the operation of hardware under Titan's lakes conditions.

1. Introduction

One of the most remarkable discoveries of the Cassini-Huygens mission is the presence of hydrocarbon seas and lakes at Titan's poles [1]. While the existence of liquid methane oceans in the surface of Titan was presumed long time before Cassini-Huygens mission, the chemical composition of Titan's lakes is still not well known. The Visual and Infrared Mapping Spectrometer (VIMS) onboard the Cassini spacecraft detected ethane signatures in Ontario Lacus [2]. The detection of methane in Titan's liquid surfaces is very difficult due to the strong absorption bands of gaseous CH_4 existing in the atmosphere of Titan and the similarity between infrared spectra of liquid and gaseous Methane. Most studies aiming to determine the composition of Titan's lakes used theoretical modelling to determine this composition. Different theoretical approaches lead to important discrepancies in the predicted CH_4 - C_2H_6 proportions in the equilibrium between Titan's atmosphere and surface [3] [4]. Moreover, Titan's lakes are recipients of organic products of the atmospheric photochemistry. Here also, models predicted different dissolution percentages. The need for more constraining studies of the chemical composition of Titan's lakes led to the development

of TiLSS experimental platform allowing the measurement of this composition in an environment simulating the equilibrium between Titan's atmosphere and liquid surfaces.

2. Experimental setup

Figure 1 presents a schematic drawing of the Titan chamber facility. It consists of a large bell-jar high-vacuum chamber that contains a stainless steel pressure vessel. This Pressure vessel plays the role of the condenser for hydrocarbons. A Varian turbomolecular pumps out the bell jar to a pressure as low as 10^{-6} torr. Temperatures relevant to Titan's surface are reproduced using a closed-cycle helium cryostat (Cryomech AF63) and a liquid nitrogen flow through a custom cooling plate affixed to the bottom flange of the vessel. Feedthroughs in the top flange of the pressure vessel allow the injection of gaseous N_2 to pressurize the chamber to 1.5 bar pressure relevant to Titan's surface and to introduce hydrocarbons into the condenser. To analyze the chemical composition of liquid hydrocarbons, a liquid sampling valve allows taking a sample of the liquid and sending it to a SRI Gas Chromatograph (GC). Figure 2 shows a photograph of the TiLSS platform.

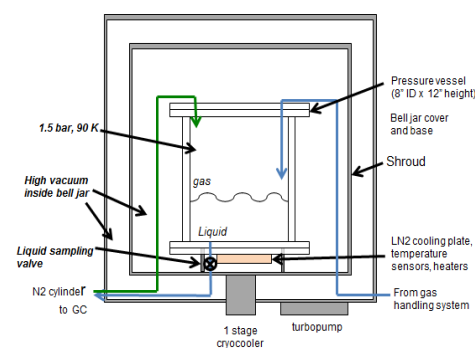


Figure 1: Schematic diagram of Titan's lakes simulation system.

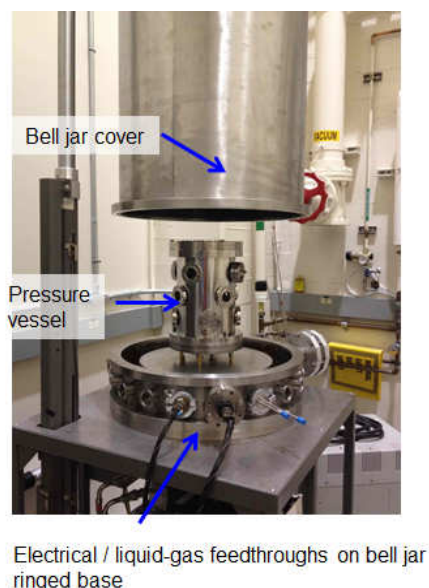


Figure 2: Photograph of Titan's Lakes Simulation System TiLSS.

3. Applications

In addition to the experimental measurement of the chemical composition of the liquid-vapor equilibrium of a hydrocarbon mixture under Titan's lakes conditions, the experimental setup described here allows many other science applications. As example, the system can be used to measure the infrared spectra of mixtures of hydrocarbons and study the influence of the presence of several compounds on the infrared signatures of Methane, Ethane and Propane. These results may prove useful for quantitative interpretation of VIMS spectra of lakes.

Another key application of this chamber is towards instruments and component development, and technology maturation. Indeed, no facility to date is available for reproducing the environment of Titan's lakes with large enough volume to allow testing entire instruments and large components. This chamber is available to the community, and can be used to this end, in preparation of future instruments and missions to Titan.

4. Conclusion

An experimental setup has been designed and developed at JPL to simulate conditions existing at Titan's lakes and seas. The main goal of this experimental platform is to provide experimental control of the theoretical simulations predicting the chemical composition of Titan's lakes.

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Determination of the effect of ammonia on clathrate hydrates at Titan' surface-subsurface conditions

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Abstract

The development and combination of two facilities, a cryogenic calorimeter and a cryostage coupled with a Raman spectrometer, allows for detailed studies of the chemical reactions/phase transformations that may take place in the upper layer of Titan's crust and the subsequent exchange processes with the atmosphere due to phase transitions related to the composition in icy materials and the thermal state of the upper few km.

1. Introduction

Titan is the only icy satellite known so far with a dense atmosphere, in which a hydrocarbon cycle (similar to Earth's hydrological cycle) between the atmosphere, the surface and the subsurface occurs [1]. Several data obtained in Cassini-Huygens mission, such as the high methane concentration and the origin of molecular nitrogen at the atmosphere, can hardly be explained by the current models [2, 3]. In order to resolve these uncertainties, experimental simulation of the surface and the subsurface is required, since the geochemistry in this zone is directly related with the atmospheric composition. In this work we focus in the "methane question". It is known that the surface is likely dominated by water ice I_h and ethane (C_2H_6)-methane (CH_4)-clathrate hydrates, beneath the ice shell is expected an ocean with dissolved ammonia (NH_3) [4]. NH_3 affects deeply the equilibrium regimes of the solid minerals mentioned, causing a depression in the melting temperatures. One plausible explanation for the methane amount observed is that a replenishment mechanism exists from the clathrate dissociation. Previous works have been performed on this regard, observing a temperature decrease in clathrate melting even around 75 K [5,6], but more experiments are necessary to pinpoint the geochemical processes that should be occurring. The study of the system H_2O -THF- NH_3 with the techniques mentioned lead a

better understanding of the NH_3 - H_2O interactions at clathrate conditions. Once established this effect we will be able to analyze with accuracy the system H_2O - CH_4 - NH_3 .

2. Experimental setup

With the Setaram BT 2.15 Calvet calorimeter, coupled with the Residual Gas Analyzer mass spectrometer, it is possible to run tests in a temperature range from 77 to 470 K and a pressure range from 0.1 to 10 MPa. While the Linkam CAP500 cryostage, which operates between 77 and 570 K at a gas pressures up to 20 MPa, allows the monitoring of the runs via Raman spectroscopy, using the Horiba Jobin-Yvon LabRam confocal dispersive spectrometer.

3. Expected results

The combination of calorimetry and spectroscopic analysis allows for a detailed study of the clathrate hydrates system. Inside the pressure-temperature zone of study (i.e. 0.1 – 10 MPa and 77 – 295 K), we are able to determine what chemical reactions take place, the temperature at which they occur, the character (endo/exothermic) and the energy required in these reactions, and the molecular environment changes during the processes.

Phase transitions, energy exchanges and eutectic, peritectic and *liquidus* temperatures have been already determined in perfect agreement with previous works [6, 7, 8] of the systems H_2O - NH_3 , H_2O -THF and H_2O -THF- NH_3 at a NH_3 concentration range from 0 to 25 wt% and 0.1 MPa. Additional observations not observed before are being also assessed. Future runs under pressure of the system H_2O - CH_4 - NH_3 will be conducted early.

Acknowledgements

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Experimental Investigation of the Kinetics of Formation and Substitution in Methane-Ethane Clathrates

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Abstract

The objective of this research is to address a significant gap in the literature: knowledge of the kinetics of formation and clathrate-state reactions upon changes of the environment. This is particularly important to quantify the likelihood that clathrate hydrates may have formed in the solar nebula and thus consisted a significant volatile fractionation medium. Another key application is the understanding of the chemical and geologic processes at play on Titan's surface and sub-surface.

Introduction

Clathrate hydrates are inclusion compounds in which small guest molecules are trapped inside highly symmetric water cages. These ice-like crystalline solids are an abundant source of hydrocarbons on Earth that primarily exist in the permafrost and marine sediments. Icy celestial bodies whose pressure/temperature conditions are favorable to the formation of gas hydrates are also expected to contain substantial amounts of these materials. One such example is Saturn's moon Titan where hydrates of methane are conjectured to be a major crustal component [1]. In addition, methane clathrate dissociation has been suggested to play a significant role in the replenishment of atmospheric methane on this satellite [2].

Release of methane from clathrates on Titan could proceed via a number of pathways: either through interaction of the clathrate layer with subsurface $\text{NH}_3\text{-H}_2\text{O}$ liquid or with ethane percolated from the surface lakes [3]. This research focuses particularly on the latter. Since clathrates of ethane are thermodynamically more stable than those of methane [4], a guest-exchange process is expected to take place upon gas-solid contact. Experiments that specifically measure the exchange kinetics would thus bring forth information on the timescales required for the substitution to occur at Titan's conditions, thereby providing some constraints for geophysical modeling.

Methods

A high-pressure apparatus, which consists of an LN_2 -cooled cryostage (Linkam CAP 500) equipped with a flow-pressure capillary tube, has been developed exclusively for studying the methane clathrate formation and its exchange kinetics. The entire setup is self-contained on a cart (Figure 1) and includes its own gas supplies, handling and distribution lines. Gas pressure is exerted only on the capillary tube and not on the cryostage itself. The maximum allowable working pressure inside the capillary tube is 200 bars. The capillary (Polymicro Technologies) consists of fused quartz with polyimide coating, has a square cross-section, and inner diameters of 50-100 μm . Preliminary data obtained with this system, which provide the first insights into the nature of formation and substitution processes, are presented in the Results section. Raman spectroscopy is used due to its ability to uniquely identify guest environments in various clathrate cages. All spectra are obtained with a Horiba Jobin-Yvon LabRam HR spectrometer using a frequency-doubled Nd:YAG crystal as laser source. The spectral resolution is 0.4 cm^{-1} resolution using a 1800 grooves/mm grating.

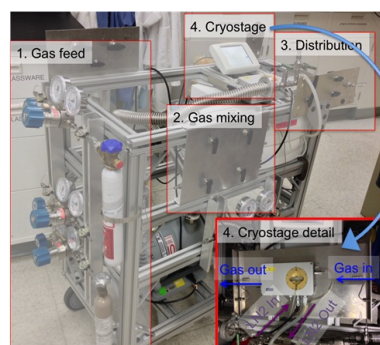


Figure 1. Photograph of the high-pressure system

Results

1. *Clathrate formation:* Pressurization of small ice deposits inside the capillary tube with 30-40 bar of CH₄ at 223-253 K results in clathrate formation within minutes. Conversion of ice into clathrates is confirmed by the presence of the characteristic peak at 2903 cm⁻¹ which represents the symmetric stretch of methane in sI clathrate. The growth of this resonance (area normalized to that of the ice peak at ~3130 cm⁻¹) is monitored as a function of time until it reaches a plateau after ~2 hrs. Standard Arrhenius analyses yield relatively modest activation energies in the range of ~12.3-14 kJ/mol. Subsequent work will examine formation kinetics at other pressures, with an eventual goal elucidating the formation mechanism.

2. *Clathrate substitution:* Following complete conversion of ice into clathrates, excess methane gas is removed from the system. The clathrate is then treated with 30 bar of ethane at 273 K. The substitution is allowed to proceed for ~1 h until a stable product is achieved. Raman signatures point to the presence of a methane-ethane sI mixed hydrate after the exchange. Temperature is then increased incrementally to determine the melting point and composition of the substituted hydrate. A dissociation temperature of 287.8 K is found, which corresponds to a methane fraction of 1.6% [4]. The result suggests that, at least for small clathrate particles with high surface area, the gas replacement process takes place on a rather fast time-scale, contrary to previous work with larger grain size where substitution can for last several days [5]. As such, further experiments are needed to reconcile the discrepancy and pinpoint the exact nature of the exchange kinetics.

Acknowledgements

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Thermal convection in high-pressure ice layers beneath a buried ocean within Titan and Ganymede

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Abstract

Deep interiors of large icy satellites such as Titan and Ganymede probably harbor a buried ocean above high-pressure (HP) ice layers. The nature and location of the lower interface of the ocean involves equilibration of heat and melt transfer in the HP ices. It is ultimately controlled by the amount of heat transferred through the surface ice Ih layer. We describe 3D spherical simulations of thermal convection in these HP ice layers that address for the first time this complex interplay.

1. The ocean/HP ices interface

While observations by the *Galileo* and *Cassini-Huygens* missions have revealed that deep oceans of liquid water could be buried within several of the icy moons in the Jupiter and Saturn systems, two configurations can be considered: for smaller moons or moons with a smaller water content, as Enceladus and Europa, the water ocean is directly in contact with the rocky mantle. For more massive satellites, hydrostatic pressure leads to the formation of high-pressure (HP) ices separating the ocean from the deep rock interior. Whether such environments provide favorable conditions for deep habitats remains largely enigmatic. Such questions will be addressed by the *JUICE* mission prepared by ESA, which goal is to scrutinize Ganymede's interior as an emblematic example of this class of bodies. Modeling efforts focusing on thermal and chemical transport through the HP ice layers are therefore required to accompany the forthcoming observations.

A significant part of the heat transfer could be achieved via the mass flux of warm liquid through the global phase boundary, a process not much different from the *heat-pipe* mechanism first introduced to explain the paradoxical relief of Io observed by the *Voyager* spacecraft, given the huge heat power at the surface [3]. Indeed, as will be shown below in the case of Titan or Ganymede, the Rayleigh number associated to HP ice layers is expected to be much larger than the

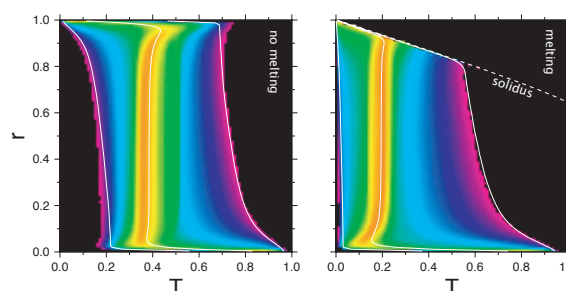


Figure 1: Effect of melting with an instantaneous melt extraction on thermal convection. *left* - no melting. *right* - melting. The three white curves indicate the minimum, average and maximum temperature at a given radius (statistical distributions at a given radius are denoted by colors).

critical value and thermal convection should develop. The presence of a cold boundary layer in the uppermost part of the HP ice layer with a radial temperature gradient much steeper than the expected melting temperature (Fig. 1) however implies that classical subsolidus convection is not a viable mechanism.

2. Numerical experiments

Set-up - Here, we perform numerical simulations of thermal convection dedicated to this configuration. The problem is solved in one block of the spherical shell of lateral angular extent $\pi/6$, using the OEDI-PUS numerical tool [1] with typically 128^3 grid cells. We focus on dimensions typical of Titan or Ganymede with a silicate core of radius 1840 km and a radius corresponding to the ocean/HP ices boundary ranging between 2175 and 2250 km. Considering reasonable viscosities for HP ices leads to Rayleigh numbers between 1.5×10^8 and 2.2×10^9 .

In a first series of calculations, melt production and transport are simply neglected in order to provide reference cases of subsolidus convection. We then consider identical configurations in terms of ge-

ometry and dimensionless parameters and melt production is introduced with the following model: temperatures T exceeding the melting temperature T_m at a given depth are set back to T_m and a fraction $x_m = c_p (T - T_m) / L$ of liquid water is produced per unit time, with L , latent heat of fusion and c_p heat capacity of HP ice. Melt is then instantaneously extracted. The major consequence of the introduction of this simple melting model is the global cooling of the layer. In the example shown in Figure 1, the temperature of the convecting interior is reduced by half.

Scaling for heat and melt for an isoviscous layer-

The cooling effect of melt production/extraction can be described as follows: If volumetric heating (typically tidal dissipation) is neglected, the heat balance implies that the power conducted through the top and bottom boundaries are equal. When melting is introduced, our calculations show that the prescribed melting temperature almost entirely controls the diffusive heat flux (Fig. 1). The remaining transport of heat required to match the power through the basal interface is achieved via melting and melt extraction. We propose scaling relationships to describe this configuration for a large range of Rayleigh numbers and solidus curves (to keep things simple here, we focus on isoviscous convection with a prescribed basal temperature).

Preliminary results for Titan and Ganymede- As a second step, we focus on a more realistic set-up where a basal heat flux (instead of a basal temperature) is prescribed. Thermal history models for Titan [4] indicate that the power out of the rocky core could reach a maximum of 1.5 TW (i.e. a heat flux of 40 mW.m^{-2}) corresponding to the onset of convection after ~ 2 Gyr of evolution. As a lowermost bound, we envision a composition of the rocky core depleted in radiogenic elements and neglect its secular cooling, i.e. $\sim 5 \text{ mW.m}^{-2}$. In addition, we introduce the temperature and pressure dependence of viscosity for HP ices proposed by Durham et al. (1997) [2].

Our preliminary results (Fig. 2) tend to show that ancient periods with a heat flux of 40 mW.m^{-2} should be characterized by melting in the outer part of the HP ice layer, with noticeable consequences on heat transfer: the bulk temperature is approximately twice smaller when compared with the case without melting and $\sim 85 \%$ of the heat transfer occurs via melt extraction. The bulk temperature lies well below the solidus value at depth so that chemical transport from the rocky core to the surface would only be achieved via solid-state advection. Moreover, the effect of melting is negligible for the case with a very low heat flux

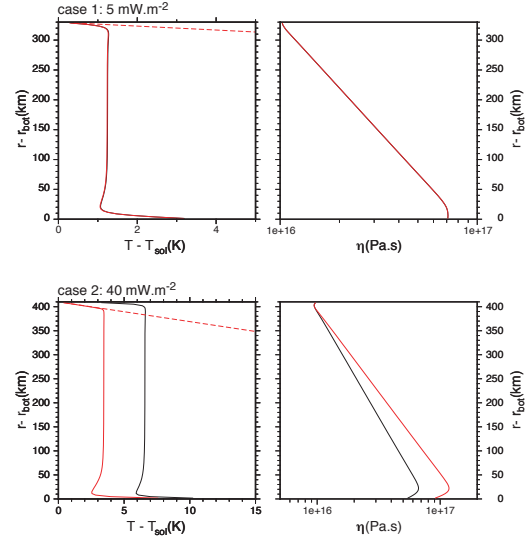


Figure 2: Two endmembers corresponding to the thermal history of Titan. Case 1 (*top*): low basal heat flux. Case 2 (*bottom*): high basal heat flux. For both cases, the left panel displays the average temperature at a given radius with (red curve) or without (black curve) melt extraction. The right panel displays the associated viscosity profiles [2].

value of 5 mW.m^{-2} . More results will be presented with different rheologies and basal heat fluxes. General consequences for the long term evolution will be discussed, noticeably in connexion with heat transfer in the shallow ice Ih layer.

Acknowledgements

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Surface of Titan : model and VIMS observations

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Abstract

In this presentation we will describe how we explain the surface reflectivity observed by DISR and how we retrieved the surface albedo of Titan from VIMS observation, showing where are the main uncertainties. We show that the reflectivity at the Huygens Landing Site may be explained a layer of liquid methane at the surface. We also show that other zones on Titan may have the same type of surface reflectivity than the HLS.

1. Description of the work

The Huygens probe has allowed to describe the atmosphere and the surface of Titan in detail. The surface reflectivity that was measured by DISR shows some characteristic features : a redslope below about $0.75\text{--}0.8\text{ }\mu\text{m}$, a blue slope beyond and the probable water ice signature at $1.5\text{ }\mu\text{m}$. In this work we used a model based of the scattering of an aerosols layer above a ice substrate to explain the observed signal. We find that such a model qualitatively explains the observation but has a peak at $0.92\text{ }\mu\text{m}$, consistently with the properties of the airborne aerosols. To explain a reflectivity peak below $0.8\text{ }\mu\text{m}$, we have to assume a layer wetted by liquid methane. We show under which conditions such a model can reproduce the observations.

In a second step, we seek for indications that terrains have reflectivity peaks at different wavelength depending on the region. Especially, we know that terrain with only water ice and dry aerosols should have a reflectivity peak around $0.9\text{ }\mu\text{m}$ while terrains as at HLS as a reflectivity peak at smaller wavelength. Using a model of radiative transfer, with a description of the atmosphere properties derived from analysis made by Huygens instruments, we are able to reproduce the intensity observed by VIMS, and we can retrieve the surface albedo. We essentially focus on the area around Huygens landing

site, and we characterize the differences between the bright and dark zones. (**Figure 1**).

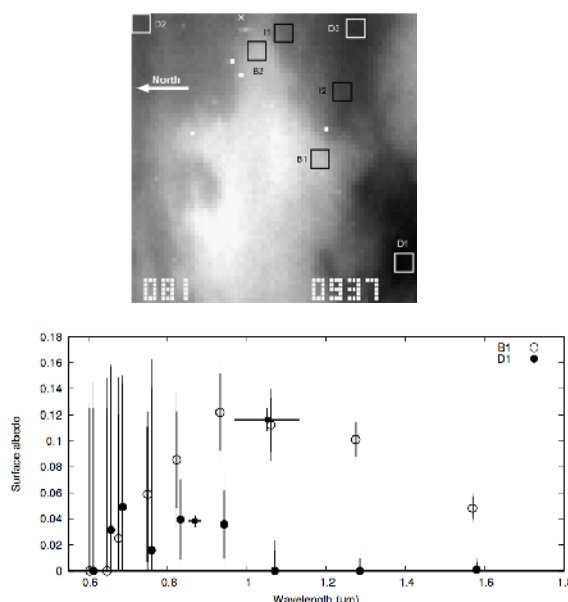


Figure 1: (top) Image acquired by VIMS around the Huygens landing site at 937 nm. We selected 7 zones depending on the apparent reflectivity (Bright, Intermediate, Dark) (bottom) Radiance factor taken in a bright and in a dark zone of Titan, near the Huygens landing site. With the model, we are able to reproduce the outgoing intensity and to retrieve the surface albedo with significant values between 0.8 and $1.6\text{ }\mu\text{m}$.

We finally find that the darkest zone of the image has a reflectivity peak which is at a wavelength significantly smaller than the reflectivity peak of brightest zones. This shows that beyond the difference in reflectivity, Titan terrain also has a clear dichotomy regarding the spectral position of their reflectivity peak.

Composition, seasonal change and bathymetry of Ligeia Mare, Titan, derived from its 2.2-cm thermal emission

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Abstract

Ligeia Mare is the second largest sea of Saturn's moon Titan. It is also the first extraterrestrial sea for which a bathymetry profile was obtained. In this paper, we analyze all data acquired up to July 2013 in the passive mode of the RADAR (i.e., radiometry mode) on board the Cassini probe in order to constrain its composition, seasonal change and bathymetry.

1. Introduction

Titan is the only planetary body besides Earth whose surface presently exhibits significant accumulations of liquids in the forms of lakes and seas. Among these bodies of standing liquid, three are large enough to deserve to be called 'seas': Kraken Mare, Ligeia Mare and Punga Mare. This paper is dedicated to Ligeia Mare.

Though the Titan's polar seas and lakes are thought to be composed of liquid methane and ethane, little is known about the ratio of these hydrocarbons in the lakes. Knowing the composition as well as the volume of liquid they contain would greatly help to improve our understanding of the lake formation and dynamics and therefore provide insights into the carbon cycle on Titan.

Towards that effort, passive microwave radiometry can be a powerful complement to radar backscatter measurements or remote sensing at smaller wavelengths, bringing independent constraints on both the composition and bathymetry of the lakes and searching for signs of evaporative cooling [1]. For the last 10 years, the radiometer incorporated in the Cassini RADAR instrument has been observing the 2.2-cm wavelength thermal microwave emission from Titan's surface. The radiometry global mosaic has been recently updated to include all data accumulated through Feb. 2014

and its calibration has been refined to an unprecedented accuracy of ~1% [2,3]. This paper aims at extracting all scientific information on Ligeia Mare from this dataset.

2. A two-layer model for the seas

The brightness temperatures measured above a Titan's sea consists of two contributions: the thermal emission from the liquid layer and that from the seafloor.

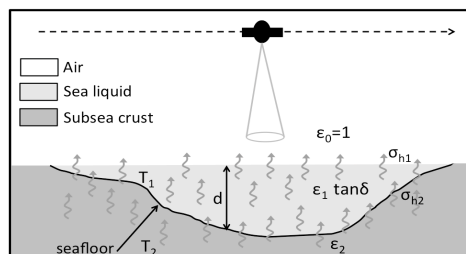
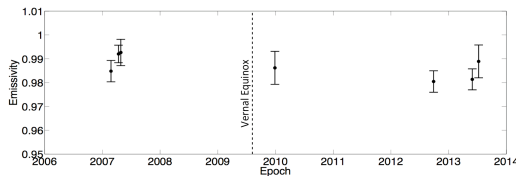


Fig. 1: Two-layer model for modeling the microwave thermal emission from Titan's seas.

Because the seafloor is *a priori* less emissive than the liquid layer, the net emissivity measured over Titan's lacustrine features is expected to increase as the depth of the sea increases i.e., as the contribution from the bottom diminishes. Furthermore, since the expected dielectric contrast between the liquid and the bottom is small (1.6-2 versus 2-3), the emissivity is expected to vary across Titan's seas by less than 1%. Lastly, the smaller the loss tangent of the liquid, the larger the penetration depth of the 2.2-cm emission and therefore the longer (in depth) it takes for the emissivity to reach saturation. Saturation is eventually reached once the sea bottom is deep enough so that its microwave thermal emission does not arise at the surface anymore.

3. Cassini high-spatial resolution radiometry observations of Ligeia Mare, Titan

During the first 9 years of the mission, from October 2004 to July 2013, Ligeia Mare was observed with high-spatial resolution (5-50 km) on 7 occasions (Fig. 2). All these observations were made in the SAR mode of operation of the Cassini RADAR except for one that occurred on 23 May 2013 during the 91th flyby of the moon as the instrument was operating as a nadir-looking altimeter. From that observation a bathymetry profile was obtained [4] that showed a maximum depth of 160 m. As anticipated, the T91 emissivity profile is correlated with the depth profile, with the most emissive areas



being the deepest.

Fig. 2: Mean emissivity (corrected to normal incidence) of Ligeia Mare over the course of the Cassini mission through July 2013.

4. Results

The results briefly given below will be discussed during the paper.

4.1 Seasonal change

The flatness of the curve shown Fig. 2 suggests that Ligeia Mare has not experienced significant evaporative cooling from February 2007 to July 2013. This may change soon or have changed already due to an increasing amount of sunlight heating the northern polar terrains since Titan passed through the vernal equinox in August 2009.

4.2 Composition

Ligeia Mare appears as a radiometrically warm expanse (with an average emissivity of 0.988 ± 0.010) while it is dark on the RADAR mosaic. This is consistent with the low dielectric constant of liquid hydrocarbons and also implies that the surface of the

sea is smooth at the wavelength scale with little or no scattering in the liquid volume. The analysis of the data collected during T91 with the help of a two-layer model (see section 2) allowed us to derive the dielectric constant and loss tangent of the liquid. Overall, these results point to a methane-dominated composition. The dielectric constant of the seafloor was also inferred and is consistent with the presence of a depositional organic sludge layer at the bottom of Ligeia Mare, this layer being more compacted and/or more nitrile-rich than that on the shores.

4.3 Bathymetry

Using the two-layer model with the inferred values the electrical properties of both the liquid layer and seafloor, the emissivity map of Ligeia Mare can be converted into the low-resolution bathymetry map that will be presented in this paper.

Acknowledgements

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Dissolution on Titan and on Earth: Towards the age of Titan's karstic landscapes

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Abstract

The morphology of Titan's lacustrine depressions led to comparisons with terrestrial depressions developed by karstic dissolution. We tested this hypothesis by computing dissolution rates of Titan's solids in liquid methane. We inferred from these rates the timescales needed to create dissolution landforms of a given depth. Dissolution would be a very efficient geological process to shape Titan's surface, on timescales generally shorter than 100 Myrs, consistent with the youth of Titan's surface (<1 Gyr).

1. Introduction

In 2006, the Cassini spacecraft imaged for the first time the lakes and seas of Titan [1]. Some lacustrine depressions are small, rounded, often interconnected, and deprived of apparent connections with fluvial channels [2]. They appear dark or bright to the imaging systems, depending on their surface roughness and composition [3,4,5].

The morphology of these lacustrine depressions led to analogies with terrestrial karstic, evaporitic or karsto-evaporitic terrestrial landforms [2,4]. All these terrestrial landforms share the fact that dissolution triggered their development. Labyrinthic terrains seen on Titan are also similar to terrestrial karst landforms, suggesting a dissolution origin [6]. In the present work, we test the relevance of dissolution as a major landshaping process on Titan by comparison with dissolution on Earth. Our idealized model allows us to determine rough timescales for the development of dissolution landforms at the surface of Titan [7].

2. Methods

We use the formulation of White et al. [9], relating the denudation rate of a solid (DR_S) to its solubility (m_S), molar volume ($V_{m,S}$) and a net precipitation rate (τ , ρ_L being the density of the liquid):

$$DR_S = \rho_L \cdot V_{m,S} \cdot \tau \cdot m_S \quad [\text{m/yr}] \quad (1)$$

All variables are computed by thermodynamics at the relevant conditions for Titan (91.5 K) and the Earth (25°C), with the exception of the precipitation rates, taken from terrestrial databases and from the climate model of Schneider et al. [11] for Titan. We consider the Ideal (IST) and Regular Solutions Theory (RST) for Titan [9] and an Electrolyte Solution Theory (EST) for terrestrial minerals [10] to compute solubilities.

On Titan, we consider either pure compounds or a mixed layer of solid organics in contact with the liquids. The composition of the mixed layer is computed according to a linear mixing scheme where each percent of a given solid at the surface results from its accumulation rate at the surface scaled by its production rate in the atmosphere [12,13].

3. Results

Figure 1 shows examples of denudation rates estimated for pure acetylene in various liquids (methane, ethane and propane) compared to those of common soluble minerals in liquid water. Acetylene has a behaviour between that of terrestrial carbonates and salts according to the RST. We performed the same calculations for various hydrocarbons and nitriles. Most of the simple hydrocarbons seem to be

quite soluble in those liquids, whereas polar molecules such as nitriles would be much less soluble, depending on the liquid considered.

From denudation rates of pure solids in liquid methane and the precipitation pattern given by the GCM of Schneider et al. [11], we evaluate denudation rates of pure solids and of a mixed layer of organic solids (with various compositions) over a Titan year at 6 different latitudes.

Assuming an average depth of 100 m for the lacustrine depressions, Figure 2 shows their estimated timescale of formation by dissolution. The IST and RST give significantly different results, as the IST gives usually higher solubilities than the RST (Figure 1). The asymmetry with latitude is due to the climate difference between the northern and southern hemispheres. Although this asymmetry should be smoothed by periodic climate oscillations [14], it is relatively consistent with the observed repartition of potential dissolution landforms observed on Titan. The maximum timescales needed to dissolve 100 m of solids in methane rains would be lower than ~105 Myr in the polar regions, with the exception of the low southern polar latitudes, which would require longer timescales (~375 Myr).

4. Conclusion

We built a thermodynamic-climatic model to determine the dissolution rates and timescales of Titan's organic solids exposed to methane rains. Solid hydrocarbons would behave like common terrestrial salts in water, while nitriles would be less soluble in Titan's liquids. Titan's surface is unlikely pure. By considering mixtures of hydrocarbons and nitriles at the surface, we evaluated dissolution timescales to develop 100m-deep landforms, such as lacustrine depressions, that indicate that Titan's karstic landscapes could be young (< 100 Myr), which is consistent with the youth of the surface (< 1 Gyr) inferred from crater counting [14].

Acknowledgements

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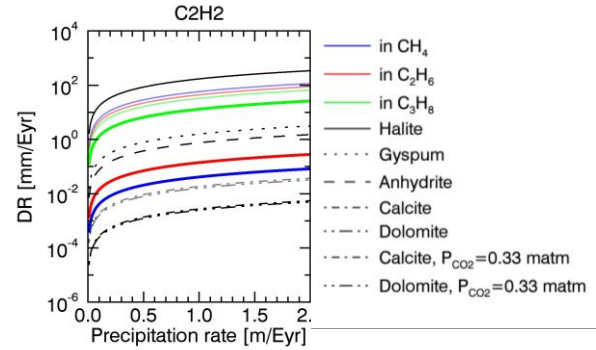


Figure 1: Denudation rates of acetylene in Titan's liquids according to the IST (light color curves) and the RST (bold color curves) compared to those of common soluble terrestrial minerals in water.

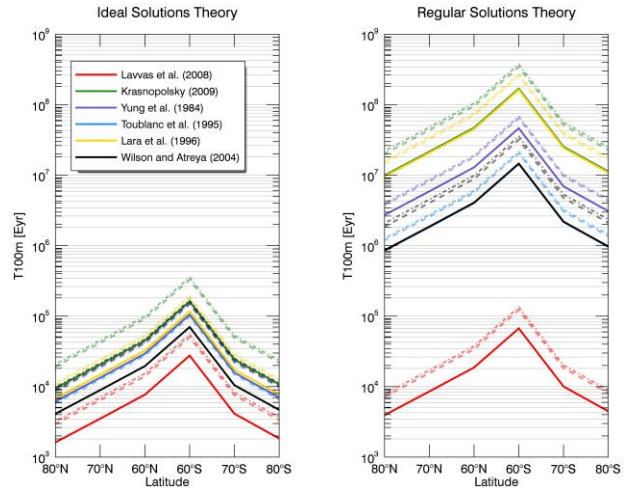


Figure 2: Dissolution timescales to form 100 m-deep depressions on Titan in a surface layer composed of mixed organic solids in contact with methane rains. Methane precipitation rates are those of Schneider et al [11] at 6 different latitudes. The composition of the surface layer is estimated from the accumulation rates at the surface of molecules computed from their production rates in the atmosphere (models listed on the figure).

Modeling the polar motion of Titan

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Abstract

We study the influence of the presence of a global subsurface ocean and of tidal deformations on the polar motion of Titan forced by its atmosphere and lakes.

1. Introduction

Due to the presence of a global subsurface ocean under an ice shell, the rotation of the interior of Titan can differ from the rotation of its surface, leading to torques between the different layers (see for example [6] for the case of the length-of-day variations of Titan). Tidal deformations of the different layers of a satellite also affects its rotation and for example reduce the libration amplitude to values close to that of an entirely solid satellite [2, 3, 7]. We here study the changes in the orientation of the rotation axis with respect to the solid surface, or polar motion of Titan, and include the effects of a subsurface ocean and deformation.

2. Polar motion

2.1 Model

We assume that the internal layers of Titan are flattened due to rotation and tides. For each layer j , we can write the angular momentum equation in the Body Frame of that layer as

$$\frac{d\mathbf{L}_j}{dt} + \boldsymbol{\omega}_j \times \mathbf{L}_j = \boldsymbol{\Gamma}_j \quad (1)$$

where \mathbf{L}_j is the angular momentum of the j th layer (interior i or ice shell s), $\boldsymbol{\omega}_j$ is the rotational vector axis and $\boldsymbol{\Gamma}_j$ the total torque exerted on the j -th layer.

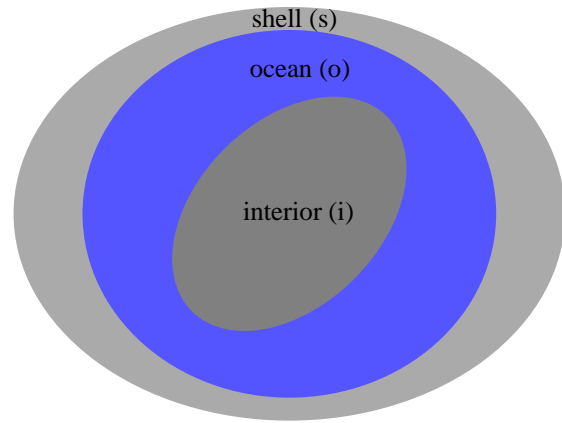


Figure 1: Schematic representation of the different orientations of the interior and the ice shell in the presence of a global subsurface ocean (not to scale).

In the Body Frame of the layer j of the satellite with equatorial axes x and y and polar axis z , the rotation vector $\boldsymbol{\omega}_j$ is written as $(\omega_{j,x}, \omega_{j,y}, \omega_{j,z})$ where $(\omega_{j,x}, \omega_{j,y})$ expresses the polar motion of Titan. Polar motion can then be extracted from the first two components of Eq.1 while the z -component gives the length-of-day variations of Titan.

The total torque $\boldsymbol{\Gamma}_j$ is the sum of the external gravitational torque exerted by Saturn, the gravitational torques acting between the different layers of Titan and the pressure torque exerted by the ocean on its bottom and top surfaces. The atmosphere and lakes of Titan also exert torques on the shell of Titan. These two torques are obtained from Atmospheric Angular Momentum data obtained from a Global Circulation Model of the atmosphere of Titan (from [5]) and the Oceanic Angular Momentum data (from [4]), respectively.

Averaging Eq. 1 over the forcing periods, the first two equations constitute an eigenvalue problem char-

acterized by a free frequency, the Chandler wobble frequency. The Chandler wobble period is about 112 years. With a subsurface ocean, we obtain two free periods: while the first period is close to the free period for an entirely solid Titan, the second period largely decreases with decreasing ice shell thickness and can be as small as 4 years for thin ice shells. As the atmosphere dynamics of Titan presents periods smaller than one Saturnian year (29.42 years), we can expect resonant amplifications of the solution.

2.2 Results

For a solid Titan, the polar motion forced by its atmosphere follows an anticlockwise trajectory with a main period of 29.42 years and an amplitude of about 40 m in the x direction and 60 m in the y direction. Tidal deformations of Titan change the trajectory of the polar motion by no more than 5 m. The polar motion forced by the lakes of Titan is smaller than 1 mm and can therefore be neglected.

With a subsurface ocean and for large ice shell thickness (larger than 70 km), the polar motion forced by its atmosphere follows an anticlockwise trajectory with a main period of 29.42 years and an amplitude that can be several orders of magnitude larger than for a solid Titan (about 400 m in the x direction and 1000 m in the y direction for an ice shell thickness of 100 km). For ice shell thicknesses smaller than 70 km, the main period of the polar motion can differ from the annual period and its amplitude can reach several kilometers due to the resonance with the free period.

3 Conclusion

We have studied the polar motion of Titan forced by its atmosphere and lakes. For a solid Titan, the rotation axis of Titan follows an annual trajectory with an amplitude of 60 m on the surface of Titan. With a subsurface ocean, the polar motion amplitude can be increased by several orders of magnitude depending on the ice shell thickness. Tidal deformations of Titan induce a small modification of the trajectory of the polar motion.

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Chemical exchanges between a global ocean and an atmosphere on early Titan

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Abstract

Saturn's largest satellite Titan is the only satellite in the Solar System possessing a dense atmosphere, which origin is still uncertain. The present-day N_2 -dominated atmosphere is likely the remnant of a more massive atmosphere formed during the accretion from degassing of volatile species brought by Titan's building blocks and released upon impact-induced melting and vaporization [1, 2]. Here, we model chemical exchanges between a global surface ocean produced by accretional melting and a primitive atmosphere are modeled for exploring the mass and composition of Titan's primitive atmosphere and its subsequent evolution during the post-accretional cooling.

1 Context

Titan's atmosphere is predominantly composed of N_2 (~98%) and CH_4 (~2%). The lifetime of CH_4 in the atmosphere is of the order of ~20 Ma, owing to continuous photochemical destruction and atmospheric escape. Therefore, CH_4 has to be regularly resupplied to Titan's atmosphere possibly from a reservoir of clathrate hydrates in the outer ice shell of the satellite [4]. Moreover, nitrogen was not originally captured as N_2 but as easily condensible nitrogen compounds such as NH_3 . Several mechanisms have been proposed to explain the conversion of NH_3 into N_2 for Titan's atmosphere: photolysis [1], atmospheric shock heating [2], impact heating of the NH_3 -enriched icy crust [3], and endogenic production [4]. Except for endogenic production, the conversion mechanism requires the presence of a significant amount of NH_3 in the external envelopes (atmosphere and/or superficial icy layer). The composition and thermal state of the primitive atmosphere was likely very different from today's atmosphere, and exchange with a global water ocean was probably controlling the chemical and thermal state of the primitive

atmosphere. Here, we model the coupled evolution of volatile compounds in the primitive atmosphere and water ocean, taking into account vapor-liquid equilibrium and possible clathration of some atmospheric species during the post-accretional cooling stage. A special focus is dedicated on the fate of nitrogen and carbon bearing species.

2 Model

We consider H_2O , CO_2 , CH_4 , and NH_3 as main volatiles brought to Titan during accretion [4]. The influence of N_2 converted from NH_3 will be tested in a second step. The gas partitioning between the vapor phase (atmosphere) and the aqueous phase (global ocean) is computed for surface temperature ranging between 274 and 300 K, assuming various melt fractions during the accretion. We test different approaches to model the vapor-liquid equilibrium. We also take in account the formation of clathrates of CO_2 and CH_4 at the atmosphere-ocean interface and the formation of the high-pressure ice at the bottom of the ocean during the cooling stage. More details on the model will be presented at the conference.

3 Preliminary results

Figure 1 shows an example of an atmosphere/ocean/clathrate equilibrium for a melt fraction x_{melt} of 0.5, and an initial composition detailed in the figure. For this preliminary calculation an ideal gas equation of state for the vapor phase and the Henry's law for the liquid phase were used.

The figure 1 (A) shows that at 300 K the dominant component of the primitive atmosphere is the CH_4 . As the satellite cools, the solubility of CO_2 increases, then the CH_4/CO_2 ratio increases as well. Clathrates start to form at ~283 K and trap methane efficiently

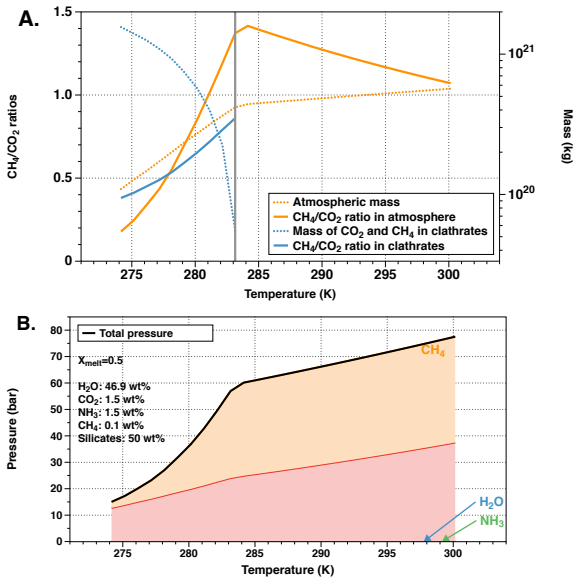


Figure 1: (A) Evolution of the atmospheric mass and mass of volatiles trapped in clathrates as well as the CH_4/CO_2 ratios in these layers. The vertical line marks the maximal temperature of formation of clathrates. (B) shows the corresponding surface total pressure and atmospheric compositions using an ideal gas model.

(see Fig. 1 (B)). When the surface temperature reached the freezing point of water ocean, most of the methane has been removed from the atmosphere and is trapped in the clathrate reservoir. 13 bar of CO_2 are still present in the atmosphere, which will condense when the temperature will drop below the condensation point, forming a CO_2 ice layer of about 790 m. Figure 1 (B) shows that the NH_3 partial pressures in the atmosphere remains extremely low (< 0.03 bar) even for the most elevated temperatures, because ammonia remains preferentially in the aqueous phase. More results will be presented at the conference.

4 Discussion

Assuming no chemical interactions in the aqueous phase, the vapor-liquid equilibrium at these ranges of temperatures and pressures is mainly determined by the behavior of the gas. Basic assumptions used here (ideal gas) allow us to state that the primitive atmosphere was predominantly composed of CO_2 and, at a lesser extent, of CH_4 , at the formation

of the icy crust. As explained above, CO_2 will rapidly condense at Titan's surface and CH_4 will be photochemically dissociated, leading to a Titan with no massive atmosphere shortly after accretion. The NH_3 into N_2 conversion at Titan's surface requires higher temperature and therefore NH_3 partial pressure in the atmosphere. An efficient conversion will lead to a N_2 -dominated atmosphere at time of the formation of the icy crust. We are currently working on implementation of a more sophisticated equation of state for the gas phase to extend the temperature and pressure validity range for our model.

Acknowledgements

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Numerical modelling of rivers on Titan

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Abstract

The differences in evolution of rivers on the Earth and on Titan are investigated. Series of short (from one to several hours) and long (up to 67 days) simulations have been performed. We have found that three different liquid hydrocarbons considered for Titan's rivers give similar velocity field. It is also found that the suspended load is the main way of transport in Titan's rivers while in terrestrial ones, for the same discharge, the bedload could be of the same order as suspended load. Moreover, we suppose that for specific boundary conditions, the evolution of rivers on the Earth promotes developing of braided rivers, while for the same conditions evolution on Titan favours regular meandering rivers.

1. Introduction

Titan is the only celestial body, beside the Earth, where liquid is present on the surface. The liquid is composed mostly of light hydrocarbons. It forms a number of lakes and rivers. However sedimentary processes depend on many parameter, e.g. gravity, fluid viscosity and density, density of solid material etc. Therefore processes on Titan could evolve in different way and rate than similar processes on the Earth. We use numerical model to determine differences in evolution of rivers on the Earth and on Titan. The dynamical analysis of rivers is performed using the numerical package modified for specific conditions on Titan. The model is based on the Navier-Stokes equations for depth-integrated two dimensional, turbulent flow and on three dimensional convection-diffusion equation of sediment transport [1].

2. Results

The results of some of our calculation of sediment transport are seen on Figures 1 and 2. The first conclusion is that on Titan the transport of sediment is more efficient than on the Earth and the main way of transport on Titan is suspended load [2,3]. Another statements is that different combination of initial conditions of suspended and

bedload for the Earth and Titan is able to reconstruct sedimentation of meandering rivers. For the conditions considered in our research evolution of terrestrial river leads to quasi-braided river, while for Titan we still have typical meandering river for the whole simulation time. Also simulations of flow show many interesting conclusions as relationship between initial total discharge and gravity acceleration. Most of the results of our models could be explained theoretically considering different values of gravity, density and viscosity of fluids, density of sediments and different buoyancy forces for Titan and the Earth. This simulation was performed for water (for the Earth) and for liquid corresponding to rain for Titan.

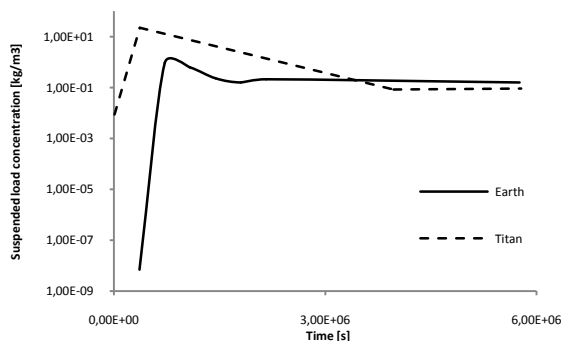


Figure 1: Suspended load concentration versus time for mesh node number 5620 for simulations 1T_6 and 1Z_6

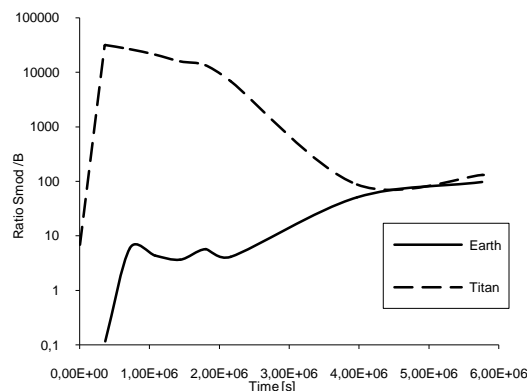


Figure 2: Ratio of modified suspended load concentration S_{mod} to bedload transport rate B versus time for mesh node number 5620 for simulations 1T_6 and 1Z_6

3. Parameters of the model

A few kinds of liquid are found on Titan. The liquid that fall as a rain has different properties than the fluid forming lakes. To our calculation we use only the liquids mentioned in Table 1 and 2 (e.g. [4]).

Table 1: Composition of two considered liquid existing on Titan's surface.

	Rain	Lake liquid
Methane	75%	10%
Ethane		74%
Propane		7%
Butane		8,5%
Nitrogen	25%	0,5%

Table 2: Material properties of liquids.

	Viscosity [Pa s]	Density [kg m ⁻³]	Heat capacity [J kg ⁻¹ K ⁻¹]	Thermal expansivity [K ⁻¹]
Water	$1,52 \times 10^{-3}$	999,8	4187	$2,07 \times 10^{-4}$
Rain	$1,51 \times 10^{-4}$	518	3250	$1,14 \times 10^{-3}$
Methane	$2,08 \times 10^{-4}$	454	3290	$3,54 \times 10^{-3}$
Lake liquid	$1,42 \times 10^{-3}$	658	2400	$1,61 \times 10^{-3}$

4. Laboratory model

We are developing the laboratory facilities for modeling extraterrestrial rivers. Although the size and discharge of the model are negligible comparing to real rivers, the experimental results are of great importance. They could be used for testing methods of scaling as well as the results of numerical models.

5. Conclusions

The results of our simulation show the differences in behaviour of the flow and of sedimentation on Titan and on the Earth. Our preliminary results indicate that transport of material by Titan's rivers is more efficient than by terrestrial rivers for the same geometry parameters and initial conditions. Suspended load is the main way of transport in Titan's simulated rivers. For the Earth the behaviour of the considered ratio is more

complicated. The suspended load S_{mod} could be of the same importance as the bedload, lower, or significantly higher but not higher than $\sim 100 B$. The bedload transport rate is also much bigger on Earth than on Titan, the maximal value is around $0.3 \text{ kg m}^{-1} \text{ s}^{-1}$ on Earth and negligible on Titan. Also for the conditions considered in our research evolution of terrestrial river leads to quasi-braided river, while for Titan we still have typical meandering river for the whole simulation time.

Acknowledgements

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Complex organics in Titan lakes: Spectral detection and Chemical behavior

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Abstract

The chemical composition of Titan's lakes is still poorly determined. Liquid ethane and methane may be abundant with the presence of other organic species from atmospheric precipitation, such as complex organics similar to Titan tholins. Our study aims to examine how Titan tholins may interact with non-polar solvents (liquid methane, liquid ethane and their mixture) and if in such liquid medium their spectral identification is possible, in application to future exploration of Titan's lakes.

1. Introduction

Due to its complexity, heterogeneity and chemical singularity, Titan surface composition is particularly intriguing and still poorly identified and determined. In 2005-2006, Cassini ISS and RADAR (SAR) instruments discovered a large dark lake feature in the Titan south-polar region (Ontario lacus) [1] and of a vast array of lake and sea like features in the north polar region [2]. Observations of the Titan's lakes and seas by Radar radiometry and VIMS have emerged to try to characterize the polar lakes and seas, however, their chemical composition is still undetermined. It is supposed that they should be composed of the Titan atmospheric precipitates, mainly hydrocarbons, such as ethane and methane. Thermodynamic equilibrium models predict liquid ethane and methane to be the most abundant constituents in Titan lakes [3] and other organic species from atmospheric precipitation to be additional constituents such as complex organics including the refractory macromolecular material of Titan's aerosols (Titan tholins). While VIMS is still providing data on Titan surface, it is important to study how the deposits of the atmospheric organic

aerosols may interact optically and chemically with the hydrocarbons lakes. In this work, we present the results of experiments examining the spectroscopic signatures of a liquid ethane, liquid methane and the mixture of both in contact with laboratory analogs of Titan's aerosols.

2. Laboratory simulation of Titan's lakes

Experiments have been performed in the Titan simulation facility of the W.M Keck laboratory at the University of Arkansas [4]. An insulated cylindrical steel cryo-vacuum chamber accommodates out a Titan module that sits inside a main chamber. Titan module contains a temperature control box internally and externally lined with LN₂ cooling pipes allowing approaching temperatures relevant to Titan surface (90-94 K). 128 mg of Titan tholins synthesized at Keck lab were introduced inside a Petri dish into the sample collection pan sit inside the module. The pressure was maintained at 1.5 bar N₂ atmosphere throughout the experiments to simulate Titan atmospheric pressure at the surface. Once the required temperature and pressure were reached, the sample (ethane, methane) was introduced into the chamber and the module, through a condenser, using condenser input coils. The behavior of the sample was monitored via FTIR, in the near-infrared from 2.5 to 1.0 μm (4000-10000 cm^{-1}).

3. Results

Several spectra were acquired during the following experiments: tholins in liquid ethane, liquid methane, in the mixtures of liquid ethane/methane and liquid ethane/acetonitrile.

3.1 Ethane-tholins results

Absorption band of tholins are centered at 1.54, 1.62, 1.74, 1.92, 2.0 (Fig. 1, 2). The results for tholins in liquid ethane show modifications of the ethane bands at 1.7 - 1.75 μm and 2.0 μm as flattening and broadening (Fig. 1).

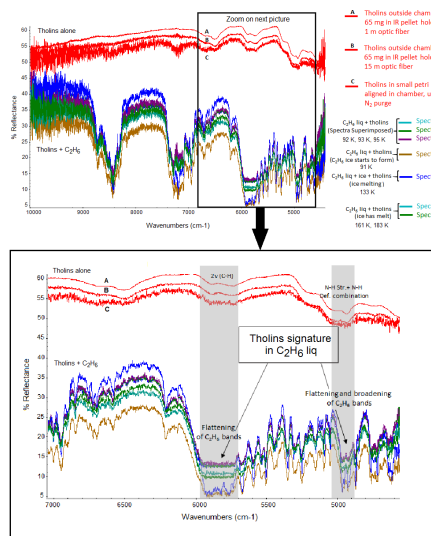


Figure 1: Spectra of tholins and ethane mixtures at 94 K (liquid C_2H_6) and between 88 K (solid C_2H_6) and 183 K.

3.2 Methane-tholins results

In the mixture of tholins and liquid methane, numerous methane absorption bands have been detected (Fig. 2). Identified CH_4 bands are centered at 1.16, 1.33, 1.41, 1.66, 1.72, 1.79 and 1.85 μm .

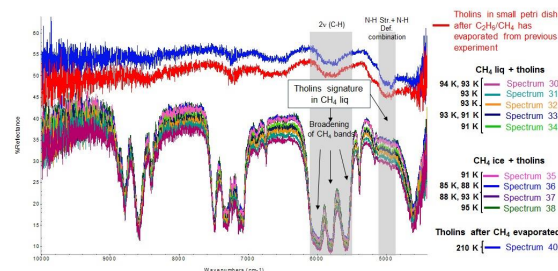


Figure 2: Spectra of tholins and methane mixtures between 95 K (liquid CH_4) and 85 K (solid CH_4).

In liquid methane, the presence of tholins is observed through a broadening of the CH_4 bands between 1.8 and 1.6 μm and a positive slope at 2.0 μm .

Once the solvents are evaporated from the mixtures, all the tholins absorption bands are retrieved and no new feature is noticed, resulting in no detectable reactivity/solubility of tholins with liquid ethane and liquid methane.

4. Conclusions

Our laboratory experiments show that tholins can be detected in liquid ethane, essentially through flattening and broadening of bands at 1.7 - 1.75 μm and 2.0 μm and in liquid methane through the broadening of the bands at 1.8 - 1.6 μm . These features might allow tholins identification in Titan's lakes for future in-situ missions. We have observed that tholins when in contact with these solvents are not remaining in suspension. In this case, the refractory material of Titan's aerosols would not be dissolved in the Titan surface lakes and seas but would rather sink. However, to confirm these first data, additional experiments are needed and are in the prospect of our next work. Results for the mixtures of liquid ethane with liquid methane and liquid ethane with acetonitrile will be presented at the conference. Our experimental approach and its resulting data are relevant in regards to current VIMS observations of Titan's lakes and proposed future missions to Titan like the ESA's Titan Saturn System Mission (TSSM).

Acknowledgements

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Identification of Acetylene on Titan's Surface

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Abstract

Titan's atmosphere is opaque in the near infrared and the composition of surface remains difficult to access from space and is still poorly constrained. Photochemical models suggest that most of the organic compounds formed in the atmosphere are heavy enough to condensate and build up at the surface in liquid and solid states over a geological timescale. Here we report evidence of solid acetylene (C_2H_2) on Titan's surface using Cassini Visual and Infrared Mapping Spectrometer (VIMS) data. C_2H_2 should be one of the most abundant organic molecules in the atmosphere according to chemistry models. By comparing VIMS observations and laboratory measurements of solid C_2H_2 , we identify a specific absorption at $1.55 \mu m$ that is widespread over Titan, but is particularly strong in the brightest terrains.

1. Introduction

Saturn's moon Titan possesses a thick atmosphere that is mainly composed of N_2 (98%), CH_4 (2 % overall, but 4.9% close to the surface) and less than 1% of minor species, mostly hydrocarbons [1]. According to photochemical models, the dissociation of N_2 and CH_4 forms a plethora of complex hydrocarbons and nitriles in the atmosphere. In particular, models predict a net creation of C_2H_2 approximately 125-2000 times larger than for any other hydrocarbon and nitriles produced in the atmosphere. Over the geological time scale, a C_2H_2 solid layer, a few hundred meters thick could have formed on the surface of Titan [2]. But despite its predicted high abundance, so far, C_2H_2 has not been unambiguously detected on Titan's surface. Here we present an analysis of Titan's infrared spectra to search for the presence of solid C_2H_2 on the surface.

2. Methods

In our study, we use a high-resolution laboratory spectrum (4 cm^{-1}) of solid C_2H_2 acquired in the $1.2\text{-}2.2 \mu m$ wavelength range [3] to compare with VIMS' Titan spectra. Convolved to the VIMS spectral resolution (~ 300), the laboratory data show that C_2H_2 exhibits a strong absorption band at $1.55 \mu m$ that should be detectable in the Titan spectrum and in fact is present. We know of no other organic or nitrile candidate that possesses such a localized and strong absorption feature at $1.55 \mu m$.

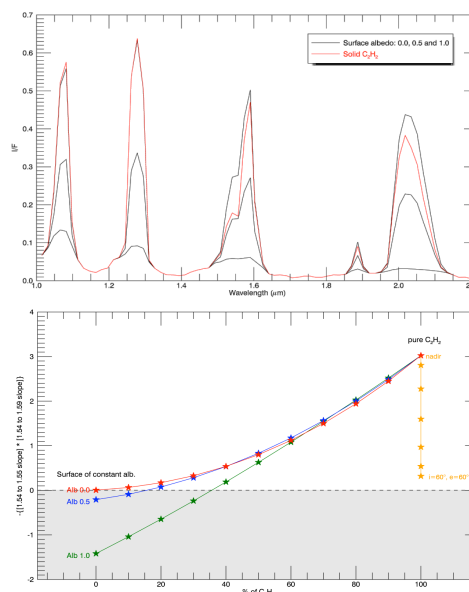


Figure 1: a) Spectra of C_2H_2 (red) mixed with neutral albedo compared to spectra of constant albedo ranging from 0 to 1 (black), at the VIMS resolution and seen through the atmosphere of Titan.

We use our Radiative Transfer (RT) model to simulate Titan's spectra at the VIMS spectral resolution (Fig. 1a) and thus evaluate the “C₂H₂ index” in the cases of uniform surface albedos, linearly mixed with our laboratory spectrum of solid C₂H₂ (from 10% to pure C₂H₂). Those - calculations were performed with the nominal model for the atmospheric gases [4][5] and aerosols with zero incidence and emergence angles. The impact of the geometry has also been tested in the limits of validity of the plane parallel approximation ($\sim 60^\circ$ in incidence and emergence) for the pure C₂H₂ case. These calculations of the “C₂H₂ index” are summarized in Fig. 1b.

4. Results/Discussion

We show three global maps of Titan showing a mosaic of VIMS images at 2.01 μm (Fig. 2a), a map that presents the value of the index (Fig. 2b), and a map with the 1-sigma errors on the index due to intrinsic noise in VIMS data (Fig. 2c). For all these maps, pixels with incidence and emergence angles greater than 60° were excluded to stay in the validity domain of the RT computations of the C₂H₂ index. For the detection map (Fig. 2b), pixels with a negative and slightly positive index (up to 0.014 following the maximum possible index found in the case of uniform albedos) are characteristic of uniform surface albedo and only positive index greater than 0.014, associated with a deep band at 1.55 μm , are plotted. Finally, pixels with index values lower than their 1-sigma error are also excluded.

As a result, we see potential presence of C₂H₂ almost everywhere in our study area (Fig. 2b). Since C₂H₂ likely is produced everywhere in the atmosphere and observations show that its atmospheric abundance is quite uniform within the $\pm 60^\circ$ latitude band, it is not surprising to find evidence of its ubiquitous sedimentation on the surface of these regions. The highest C₂H₂ indices are strongly correlated with bright terrains, fully consistent with the fact that C₂H₂ has a high albedo, especially at 1.59 μm . With a weaker signature, we also found some presence of C₂H₂ in dark areas, but with less obvious correlation with albedo. Thus, even if C₂H₂ is present almost everywhere, the spatial distribution of the intensity of its spectral signature is not homogeneous, indicating that surface processes responsible for its segregation or masking may be at work.

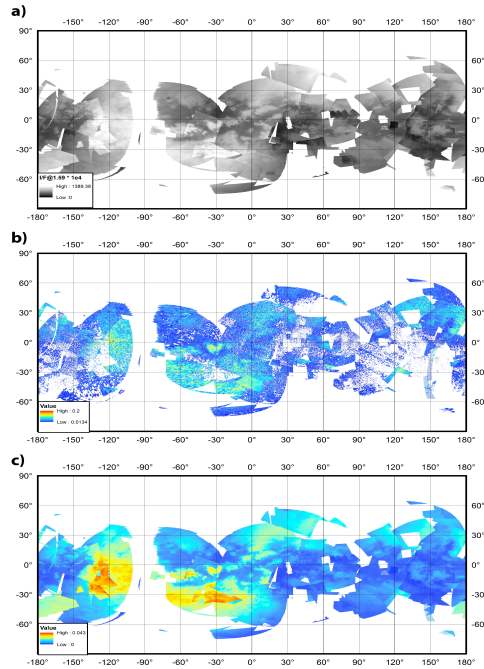


Figure 2: a) 1.59 μm map of Titan of the investigated areas where the surface has been illuminated and viewed at less than 60° angles. b) Acetylene detection map for a criterion value exceeding a 0.0134 threshold determined from Radiative Transfer simulations applied to laboratory spectra. c) A map showing the calculated errors on the slope criterion values due to the intrinsic noise in the VIMS data

Acknowledgements

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A massive primordial-atmosphere on proto-Titan formed in a cold circum-planetary disk

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Abstract

We numerically investigate the property of the primordial atmosphere of Titan that grew in a gas-starved disk, especially in terms of the atmospheric mass and the blanketing effect. In spite of such a disk condition, Titan could capture a thick atmosphere mainly composed of nebula gas components due to the cold formation environment. This would cause a significant blanketing effect inducing differentiation of this satellite.

1. Introduction

Titan, the largest Saturnian moon, has a thick atmosphere mainly composed of N_2 . Depletion of primordial Ar strongly suggests that the N_2 was originated from other nitrogen-bearing compounds like NH_3 [1]. Although several hypotheses have been proposed, it remains an open question how and when such a thick atmosphere was generated.

According to the recent satellite formation theory [2], Titan formed along with the other regular satellites within a gas-starved disk characterized low temperature (50-150 K), low pressure (~ 1 Pa), and long accretion time ($\sim 10^6$ yr). Previous study on early thermal evolution of Titan indicated that the satellite may accrete avoiding a massive melting ice [3]. This study, however, neglected the blanketing effects of proto atmosphere. When Titan formed within the cold disk, even though the disk pressure was low, it could acquire a significant amount of atmosphere mainly composed of nebula gas strongly bounded by gravity. This may cause an intensive blanketing effect with help of gases evaporated from ice components. In this study, we numerically analyze the structure of proto-atmospheric of Titan formed within a gas-starved disk and estimate the accumulating mass and the blanketing effect of the atmosphere.

2. Model

The atmosphere is assumed to be spherical symmetry and in hydrostatic equilibrium. The atmosphere consists of the mixture of H_2 , He (nebula gas components), H_2O and NH_3 (ice-evaporated components), in which the amount of ice-evaporated components obey saturated vapor pressures [4]. The atmosphere continuously connected to the disk at the satellite Hill radius where the disk temperature and pressure are given by the gas-starved disk model [2], $T_d = 50$ K, $P_d = 1$ -100 Pa. Atmospheric thermal structure follows radiative-convective equilibrium, consisting of the stratosphere and troposphere. The troposphere has moist adiabatic lapse rate [5] the stratosphere is described by the diffusive approximation in the optically-thick region and also by modified solution of plane-parallel radiative-equilibrium problem with taking into account the effect of spherical geometry in the optically-thin region [6]. The Rosseland mean opacity incorporates the collision induced absorptions of nebula gas components [7, 8] and line absorptions and continuum absorptions of evaporating gas components from HITRAN databases.

3. Results and Discussion

Figure 1 represents the atmospheric mass inside the Bondi radius and net outgoing radiative flux at the top of primordial atmosphere of Titan as a function of its surface temperature. Here we compare the results with those for the case of reducing the amount of NH_3 (5% saturated vapor pressure) and Ganymede formation environment ($T_d = 150$ K, no NH_3 contained). Figure 1a indicates that there is a minimum atmospheric mass for each case in which nebula gas components are dominant at low surface temperatures whereas ice-evaporated components are dominant at high surface temperatures. Titan could acquire a larger amount of primordial atmosphere than Ganymede. This is because the local scale

height of the atmosphere is smaller due to the lower disk temperature, which results in the denser atmosphere on Titan. Figure 1b shows that the outgoing radiative flux from Titan is significantly suppressed due to the opacity of nebula gas or ice-evaporated components depending on whether the surface temperature is lower or higher than 250 K.

Figure 1b also indicates that when tiny energy flux was supplied to the surface of Titan, the surface temperature was kept ~ 230 -250 K. Since the radiation from the proto-Sun and/or proto-Saturn is enough large for such energy supply, melting of water/ammonia mixture may occur even after the end of satellite accretion. This suggests that an ammonia-rich proto-ocean could be kept on Titan until the disk and the initial acquisition of proto-atmosphere were largely dissipated. Such relatively warm environment that possibly allows continuous supply of NH_3 in the atmosphere-ocean equilibrated system for a long time, at least the disk dissipation timescale 10^7 yr. A part of the primordial atmosphere, in particular heavier ice-evaporated components may survive after the disk dissipation. UV radiation from proto-Sun would then generate N_2 from NH_3 photochemistry [9].

Acknowledgements

We thank Ko-ichiro Sugiyama and EPnetFaN members for providing us computation environment and technical support.

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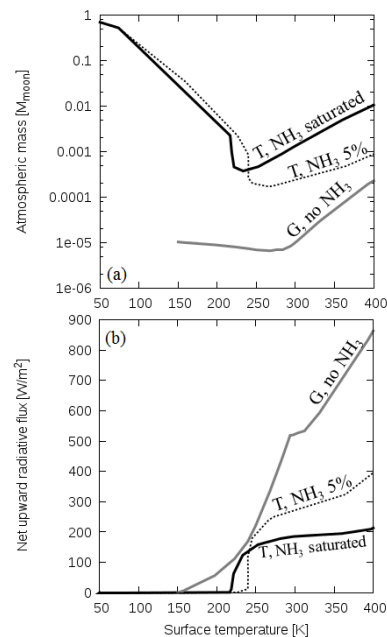


Figure 1: Atmospheric mass inside the Bondi radius (a) and Net upward flux at the top of atmosphere (b) as a function of surface temperature of the satellites. Each line represents the result at the case of Titan (Black solid: $T_d = 50$ K, $P_d = 10$ Pa, NH_3 saturated; Dotted: $T_d = 50$ K, $P_d = 10$ Pa, NH_3 5%) and Ganymede (Grey: $T_d = 150$ K, $P_d = 10$ Pa, no NH_3), respectively.

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Titan's Topside Ionospheric Composition: Cassini Plasma Spectrometer Ion Mass Spectrometer Measurements

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Abstract

We present ion composition measurements of Titan's topside ionosphere using T15 Cassini Plasma Spectrometer (CAPS) Ion Mass Spectrometer (IMS) measurements. The IMS is able to make measurements of Titan's ionosphere due to ionospheric outflows as originally reported by [1] for the T9 flyby. This allows one to take advantage of the unique capabilities of the CAPS IMS which measures both the mass-per-charge (M/Q) of the ions and the fragments of the ions produced inside the sensor such as carbon, nitrogen and oxygen fragments. Specific attention will be given to such ions as NH_4^+ , N^+ , O^+ , CH_4^+ , $CxHy^+$, and $HCNH^+$ ions as examples.

1. Introduction

[1] were the first to quantitatively show ion outflows ($r > 10,000$ km) $\sim 5 \times 10^{24}$ ions/s coming from Titan's ionosphere using the CAPS IMS data for the T9 flyby. Later it was shown by [2] that ionospheric outflows for T63 and T75 were also occurring at similar levels $\sim 5 \times 10^{24}$ ion/s. [3] showed evidence for ionospheric outflows for the T15 wake flyby. [1] were the first to use the T9 outflows to make compositional estimates of Titan's topside ionosphere (i.e., composition freezes in for altitudes greater than exobase altitude ~ 1400 km) and concluded that CH_5^+ and $C_2H_5^+$ were the dominant ions of these outflows.

Normally, the CAPS IMS cannot be used to measure Titan's relatively dense ionosphere because the IMS has high sensitivity to measure the more tenuous plasmas of Saturn's magnetosphere and its detectors will experience count rates beyond their maximum allowed rates, therefore the IMS was configured not to measure the ionospheric ions. But, whenever there

are high altitude Titan wake flybys such as T9, T15, T63, and T75, the ion densities are low enough that CAPS IMS count rates are within operational limits, so the IMS can be configured to measure these ionospheric outflows and measure the composition of these outflows.

2. Compositional Analysis

The CAPS IMS which uses a time-of-flight (TOF) technique which measures both straight through (ST) and linear electric field (LEF) TOF data. The ST data measures the neutral and negative fragments exiting the instrument's carbon foil while for the LEF data positive ions exit the carbon foil. The ST data allows the IMS to measure the M/Q of the atomic and molecular ions, while the LEF gives information about the atomic fragments. In order to perform this analysis we have had to use composition data of both the flight model and the prototype model of the IMS for which the latter resides at GSFC. This analysis requires one to know the relative probabilities of the ST and LEF data, as well as the probabilities between the ion peaks within the ST and LEF spectra, respectively. In order to get the relative probability between C^+ and O^+ fragments we've used CO^+ and CO_2^+ data at a range of energies from 64 V to 30 kV, respectively. We also used the CO_2^+ data to give us the line profiles for C^+ for the $C_3H_m^+$ and $C_4H_m^+$ ions since we only have calibration data for $C_nH_m^+$ for $n = 1$ and 2. We've also had to use published data probabilities for C^+ , N^+ and O^+ data [4], [5] and [6]. In the future we would like to get calibration data for $C_nH_m^+$ for $n = 3$ and 4, HCN^+ for relative probability between C^+ and N^+ and NO^+ data for relative probability between the N^+ and O^+ fragments.

3. Summary and Conclusions

By using IMS compositional measurements of T15 ionospheric outflows, and using the various pieces of compositional data and published probabilities of ions penetrating carbon foils at different energies, we will show evidence for methane group ions, nitrogen ions, ammonium ions, water group ions and $C_nH_m^+$ ions with $n = 2, 3$, and 4 within Titan's topside ionosphere.

Acknowledgements

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Do Titan's tides imply a dense subsurface ocean?

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1. Abstract

Time-dependent tidal effects in Titan's gravity field are strong evidence of a global subsurface ocean. Surprisingly, tides are 30% stronger than what plausible interior models predict. Two solutions are obvious: either the tidal amplitude is close to the 2σ lower bound of the measurements, or the ocean is extremely dense because it is nearly saturated in sulfate salts. I examine here a third possibility, consisting of an ocean mostly unsaturated in salts, except in a thin and dense layer close to the mantle. In this model, tidal amplitudes are within the 1σ bounds of the central measured value.

2. Problem

Cassini radio-science data yield a tidal gravity Love number of $k_2 = 0.589 \pm 0.15 (2\sigma)$ [1]. Earlier interior models assuming a subsurface ocean predicted that k_2 would be about 0.45 [2] or even as low as 0.3-0.4 [3]. A first solution to this problem is to suppose that the actual value k_2 is at the lower end of the 2σ allowed range [4]. This assumption has the advantage of not imposing any radical change on the existing interior models, but could be invalidated by future measurements. If the value of k_2 is indeed as high as 0.6, the most plausible way to raise the predicted k_2 is to increase the ocean density. If the ocean is a brine rich in ammonium sulfate, its density can reach 1300 kg/m^3 in which case the value of k_2 is 30% higher than if the ocean is made of pure water [5]. This effect is easily understood with the toy model of an infinitely rigid mantle surrounded by a surface ocean, for which

$$k_2 = \frac{3\xi}{5 - 3\xi}, \quad (1)$$

where $\xi = \rho_{\text{ocean}}/\rho_{\text{bulk}}$ is the ocean-to-bulk density ratio (a 50 km elastic crust reduces this k_2 value by about eight percents [6]). It is however not obvious how a large quantity of sulfur could leach from the core to the ocean through the icy mantle [1].

3. Another stratification model

Since the ocean density has such a large effect on k_2 , it is worthwhile to go beyond the approximation of an ocean of uniform density. In particular, *Mitri et al.* observed that ocean density gradually increases with depth because of water compressibility [5]. The density difference between top and bottom is about 160 kg/m^3 for a 350 km-deep ocean. As a result, k_2 increases by about 3 to 4%.

In fluid bodies, density stratification typically leads to a decrease of k_2^f , the Radau approximation relating the fluid Love number k_2^f to the moment of inertia. The situation is more complicated if a fluid layer is sandwiched between elastic layers: the nearly rigid core-mantle system acts as a gravitational brake on the deforming ocean layer. If you redistribute mass from the top of the ocean to its bottom, the lower denser layer partially screens the gravitational braking effect of the mantle. As a limiting case, a lower denser layer having the same density as the core-mantle system would have the same effect as a fluid core-mantle, and thus significantly increase the deformation (Fig. 1).

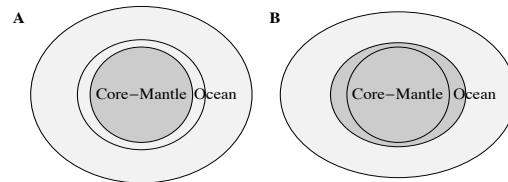


Figure 1: Screening effect due to ocean density stratification: (A) no stratification, (B) thin denser layer at the bottom of the ocean. Darker shades represent higher densities [6].

This *screening effect* [6] suggests another stratification model: the ocean could be globally of low density, except for a thin bottom layer (say 1% of the ocean depth) saturated in sulfate salts. Fig. 2 shows that k_2 could increase by more than 10%, bringing it well inside the 1σ bounds of the measured value.

The possible presence of a thin dense layer at the

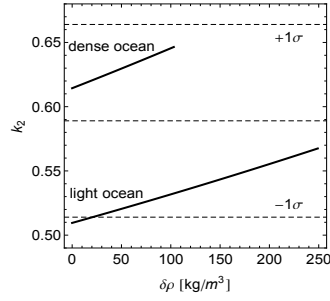


Figure 2: Effect of a thin dense layer at the bottom of the ocean on Titan's k_2 . On the x -axis, $\delta\rho$ represents the density deviation of the bottom ocean layer with respect to the rest of the ocean. The 'light' and 'dense' ocean models are end-member models (50 km crust) taken from [5]. Dashed lines represent the measured values of k_2 and the 1σ error bounds.

bottom of the ocean immediately raises two questions: (1) how can it be formed, and (2) is it stable against convection or crystallization?

Acknowledgements

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