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Solids dissolution theory: implications for dry lakebeds composition and lake formation time-scale

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Abstract

The solubility theory, based on solid-liquid equilibrium, allows estimation of the quantities of dissolved solids in the hydrocarbon solutions of Titan's polar lakes. Recently, possible organic deposits have been discovered in lakes drybeds. In this work, thanks to the solubility theory coupled to an evaporation prescription, we have computed abundancies of species that could form these organic layers. Beside this, under simplifying assumptions, the minimum age of lakes can be calculated in the frame of a dissolution scenario.

1 Introduction

Already, during the first RADAR detection of Titan's lakes [7], the presence of features that ressemble to dry lakebeds have been noticed. A strong correlation between RADAR dry lakebeds and surface patches bright at 5-μm has been found [4]. This brightness associated to high reflectivity in the 2.8–μm window relative to the 2.7–μm window, seems to be characteristic of very low water ice abundance relative to the rest of Titan [3, 4]. In summary, all of this suggests the formation of an evaporitic layer of organic matter. The question of the composition of potential lakebeds evaporites is still widely opened; in the present work we show what can be inferred from the solubility models including evaporation of methane and ethane. On another side, a major issue concerning the Titan's lakes is the question of the physical processes involved in their formation. Amongs many hypothesis, including cryovolcanism, thermokarstic, karstic, evaporitic or karto-evaporitic processes; the formation of Titan's lacustrine depressions through karstic or karsto-evaporitic processes can be a possibility. As these latter scenarii are based on the dissolution of the Titan's surface, we will briefly discuss the minimum timescale required to dig a given geological depression.

2 Methods

2.1 General considerations concerning the solubility of solids

The liquid that fills the Titan's lake is likely to be composed by a mixture of which main components are methane and ethane. Coming from photochemical models, the minor non-volatile species which are supposed to dissolved in the methane-ethane mixture are: HCN, C_4H_{10}, C_2H_2, CH_3CN, CO_2, C_6H_6. For each solutes i, the maximum quantity that can be dissolved (the mole fraction at saturation $X_{i,\mathrm{sat}}$) is evaluated assuming an equilibrium between the considered solid phase and the liquid. This mole fraction can be estimated using Eq. 2 of [1].

2.2 Computation of the chemical composition of drybeds evaporites

For each time-step, the quantities of methane and ethane that evaporate are computed and the mole fractions of solutes are updated and called $X_i^{(\mathrm{new})}$. If $X_i^{(\mathrm{new})} > X_{i,\mathrm{sat}}$, then we fix $X_i^{(\mathrm{new})} = X_{i,\mathrm{sat}}$. In our formalism, a precise knowledge of solvents evaporation rates $F_{\mathrm{CH_4}}$ and $F_{\mathrm{C_2H_6}}$ are not required leading to the use of a nonlinear scale for the time. This is very useful as evaporation rates depend on numerous and unknown factors: temperature difference between lake and atmosphere, the speed of wind, etc [5, 8].

2.3 The minimum age of lakes in the case of formation by dissolution

The formation of the largest southern Titan's lake, Ontario Lacus, by the dissolution of a surface layer is supported by its morphology and comparison with a terrestrial analog [2]. The maximum height $h_{\mathrm{max},i}$ of the dissolved material i in one Titan's year can be approximated by

$$h_{\max,i} = X_{i,\mathrm{sat}} \frac{\tau_{\mathrm{CH_4}} V_{\mathrm{m},i}}{V_{\mathrm{m}}(\mathrm{CH_4})} \quad (1)$$

where $\tau_{\mathrm{CH_4}}$ stands for the annual precipitation rate of methane (the only considered solvent here) provided by a Global Circulation Model [6]. The V_{m}'s are the molar volumes.

3 Results

3.1 Composition of evaporites

On one hand, we chose a liquid mixture with dissolved solids mole fractions scaled to precipitation rates; forcing benzene having an initial mole fraction ($X_{\mathrm{liq}}^{\mathrm{ini}}$) equal to half of its saturation value. On the other hand, we took a mixture in which all the species had the same abundance (see Tab. 1). All computations were performed at temperature $T = 90$ K, typical of the lakes regions.

Table 1: Initial liquid mixtures used in this study. The notation $x.y(-n) = x.y \times 10^{-n}$ has been used.

Species	$X_{i,\mathrm{sat}}$ (ideal)	Mixture type 1		
		$X_{\mathrm{liq}}^{\mathrm{ini}}$	$X_{\mathrm{sol}}^{\mathrm{ini}}$	$X_{\mathrm{sed}}^{\mathrm{fin}}$
CH_4	–	9.997 %	–	–
C_2H_6	–	89.973 %	–	–
HCN	$6.5\,(-4)$	$1.1\,(-4)$	$3.7\,(-1)$	$1.7\,(-2)$
C_4H_{10}	$1.2\,(-1)$	$1.0\,(-4)$	$3.4\,(-1)$	$5.6\,(-1)$
C_2H_2	$5.4\,(-2)$	$6.2\,(-5)$	$2.1\,(-1)$	$3.4\,(-1)$
CH_3CN	$3.7\,(-3)$	$9.2\,(-6)$	$3.1\,(-2)$	$5.1\,(-2)$
CO_2	$8.7\,(-4)$	$5.8\,(-6)$	$1.9\,(-2)$	$2.3\,(-2)$
C_6H_6	$2.2\,(-4)$	$1.4\,(-5)$	$4.6\,(-2)$	$5.7\,(-3)$
		Mixture type 2		
		$X_{\mathrm{liq}}^{\mathrm{ini}}$	$X_{\mathrm{sol}}^{\mathrm{ini}}$	$X_{\mathrm{sed}}^{\mathrm{fin}}$
CH_4	–	9.993 %	–	–
C_2H_6	–	89.941 %	–	–
HCN	$6.5\,(-4)$	$1.1\,(-4)$	$1.67\,(-1)$	$1.3\,(-2)$
C_4H_{10}	$1.2\,(-1)$	$1.1\,(-4)$	$1.67\,(-1)$	$4.5\,(-1)$
C_2H_2	$5.4\,(-2)$	$1.1\,(-4)$	$1.67\,(-1)$	$4.5\,(-1)$
CH_3CN	$3.7\,(-3)$	$1.1\,(-4)$	$1.67\,(-1)$	$7.2\,(-2)$
CO_2	$8.7\,(-4)$	$1.1\,(-4)$	$1.67\,(-1)$	$1.7\,(-2)$
C_6H_6	$2.2\,(-4)$	$1.1\,(-4)$	$1.67\,(-1)$	$4.3\,(-3)$

Taking as initial values the $X_{\mathrm{liq}}^{\mathrm{ini}}$'s in table 1, we have run the described algorithm. We compare the final composition of the evaporite ($X_{\mathrm{sed}}^{\mathrm{fin}}$) to the composition of solids initially dissolved in the liquid ($X_{\mathrm{sol}}^{\mathrm{ini}}$). In the case of the "type 1" mixture, three species undergo a strong enrichment: C_4H_{10}, C_2H_2 and CH_3CN. Concerning the "type 2" mixture, the final layer of evaporite is depleted in all species excepted in butane and acetylene. In both cases the prominent molecules at the surface are butane and acetylene.
This work suggests, if the evaporation is the dominant physical process causing the formation of Titan's dry lakebeds, that the top layer of evaporite should enriched in butane and acetylene.

3.2 Lakes formation time-scale

The Titan's atmospheric circulation models show methane precipitation rates that range between ~ 1 and ~ 10 m/Titan's year in the polar regions [6]. Assuming a surface composed by the species i, Table 2 gathers the values of $h_{\max,i}$ and the corresponding time-scales $T_{1\mathrm{m}}$ associated to the given compounds.

Table 2: The notation $x.y(-n) = x.y \times 10^{-n}$ has been used.

Species i	$h_{\max,i}$	$T_{1\mathrm{m}}$
	m/Titan year	Earth years
HCN	$6.5\,(-4)(-3)$	$4.5\,(4)(3)$
C_4H_{10}	$2.4\,(-1)(+0)$	$1.2\,(2)(1)$
C_2H_2	$4.8\,(-2)(-1)$	$6.0\,(2)(1)$
CH_3CN	$4.7\,(-3)(-2)$	$6.2\,(3)(2)$
CO_2	$6.4\,(-4)(-3)$	$4.5\,(4)(3)$
C_6H_6	$5.9\,(-3)(-2)$	$5.0\,(3)(2)$

The lakes of Titan are relatively shallow with depths ranging between 1 m and several hundred metres. The time-scales computed here lead to lake formation times shorter than 100 mega-terrestrial years, which is obviously compatible with the age of the satellite itself. However numerous phenomena can conspire to increase this time-scale, for instance: lower solubilities, slow kinetics of the dissolution or smaller precipitation rates.

References

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