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Can the Alkanofer of Titan show a chemical stratification?

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Abstract

Titan, the enigmatic large moon of Saturn, is the unique satellite of the solar system surrounded by a dense atmosphere. In polar regions, lakes and seas of liquid hydrocarbons have been discovered by *Cassini/Huygens* mission. Thanks to the analysis of radar data, acquired during numerous flybys, it has been recently demonstrated that several liquid bodies have their surfaces at the same equipotential. These altimetric determinations suggest strongly the existence of a kind of subsurface connection between some lakes or maria. In the present work, we investigate the properties of a possible alkanofer, made of a cryogenic liquid mixture, trapped into a porous icy crust. We pay particular attention to the fate of ethane, the main product of atmosphere chemistry, in such a context.

1. Introduction

Titan, the main satellite of Saturn, is the only satellite of the solar system possessing a dense atmosphere. The latter, which composition is dominated by nitrogen and methane, habors a complexe chemistry initiated by the photolysis of these species. Among a plethora of molecules, ethane dominates the products of the atmosphere chemistry. Since the *Voyager* flyby, the existence of liquid bodies at the surface of Titan has been suspected. Thanks to its radar, which had the capability of imaging the surface through the atmosphere opaque to visible light, the *Cassini* orbiter instruments have revealed a collection of dark features dotting the polar regions (Stofan et al., 2007; Turtle et al., 2009). These geomorphological characteristics are interpreted as lakes or seas (depending on their size) of liquid hydrocarbons. These structures were found at both poles and involve diameters up to more than hundreds of kilometers.

Recently, Titan's surface altimetry investigations have shown that several Maria share the same equipotential for their free surface (Corlies et al., 2017; Hayes et al., 2017). These new measurements suggest the existence of some local subsurface connectivity between liquid bodies. The concept of *alkanofer*, analog of terrestrial aquifer, has been already proposed in the literature (Mousis et al., 2014, 2016). Such *alkanofer* consists of a mixture of liquid hydrocarbons trapped in a porous icy crust.

On the Earth, beside already mentioned aquifers, "alkanofers" also exist and are called "hydrocarbon reservoirs", they contain petroleum and gases. For many decades, field measurements have revealed a wide range of compositional variation in these reservoirs. These variations are most of the time vertical (Metcalfe et al., 1988), while horizontal cases are also observed. In general, lighter hydrocarbon are found at the top of the reservoir, while the heaviest molecules are buried at the bottom of the system. The analysis and modeling of such compositional grading is of primary importance for the oil and natural gases industry. In the context of Titan, one may wonder whether such a chemical stratification could appear within an alkanofer mainly composed by a liquid mixture of methane and ethane, under Titan's cryogenic conditions and low gravity.

2. The Diffusion of Species through Titan's Alkanofer

Since the convection is often inhibited in hydrocarbon reservoirs, the transport process at work is based on diffusion processes. In the general case, the total diffusion mass flux $\overrightarrow{j_1}$ (kg m^{-2} s^{-1}) of one of the two components making a binary mixture, may be written (Bird et al., 1960; Ghorayeb & Firoozabadi , 2000)

$$\overrightarrow{j_1} = -\rho D_{12} \frac{M_1 M_2}{\bar{M}^2} \left\{ \left. \frac{\partial \ln f_1}{\partial \ln x_1} \right|_{P,T} \overrightarrow{\nabla} x_1 + \frac{x_1}{RT} \left(\bar{V}_1 - \frac{M_1}{\rho} \right) \overrightarrow{\nabla} P + \frac{k_{T\,1,2}}{T} \overrightarrow{\nabla} T \right\} \quad (1)$$

with ρ the density (kg m^{-3}) of the mixture, D_{12}

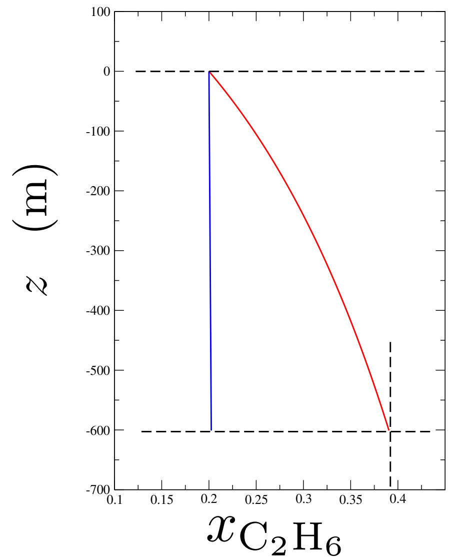

Figure 1: Red line: the ethane mole fraction as a function of depth (z in m) for a semi-ideal model. Blue line: the same thing for a non-ideal model based on the equation of state PC-SAFT.

the Fickean diffusion coefficient (m^2 s^{-1}) of species (1) in a "bath" of species (2), M_1 and M_2 the respective molecular weights (kg mol^{-1}) of involved species (here: (1) C_2H_6 and (2) CH_4), while $\bar{M}$ is the average molecular weight of the system: $\bar{M} = x_1 M_1 + (1 - x_1) M_2$. The fugacity, which measures non-ideal effects for a real gas, is represented by f_1. Adopting an usual notation, x_1 and $\bar{V}_1$ are the mole fraction of species (1) and its molar volume (m^3 mol^{-1}), P and T are respectively the local pressure (Pa) and temperature (K). In the last term, the thermal diffusion ratio $k_{T\,1,2}$ (pure number) is a function of $\alpha_{T\,1,2}$ (pure number) the thermal diffusion coefficient $k_{T\,1,2} = \alpha_{T\,1,2} x_1 (1 - x_1)$.

If in a first approach we neglect the effect of thermal diffusion (third term in the right hand side of Eq. 1), at the equilibrium (*i.e.* when $\overrightarrow{j_1} = \overrightarrow{0}$), the system to be solved becomes

$$\left.\frac{\partial \ln f_1}{\partial \ln x_1}\right|_{P,T} \frac{\partial x_1}{\partial z} = \frac{x_1}{RT}\left(\bar{V}_1 - \frac{M_1}{\rho}\right)\rho\, g_{\text{Titan}} \qquad (2)$$
$$\frac{\partial P}{\partial z} = -\rho\, g_{\text{Titan}}$$

where $\partial x_1/\partial z$ is the vertical gradient of ethane, and g_{Titan} the Titan gravity. The results of this first approach are gathered in Fig. 1, while the semi-ideal model, *i.e.* neglecting almost all intermolecular interactions, shows a massive enrichment in ethane 600 meters below the surface; the non-ideal model, based on the equation of state PC-SAFT produces outputs in which the mixture remains well homogeneous. By adding a certain amount of dissolved nitrogen, we do not change this result at all. The explanation of the uniformity of ethane concentration could be the intermolecular interaction that "force" the molecules to remain mixed, letting the gravity having a purely negligible influence.

3. Summary

In this presentation, we will discuss the influence of factors that could alter the vertical gradient of ethane in the possible Titan's alkanofer. We will particularly focus on the influence of temperature. Other species will be also reviewed.

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