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Liquid hydrocarbons at the surface of Titan: bubbling or not bubbling?

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Abstract

In the polar regions of Titan, the main satellite of Saturn, hydrocarbon seas have been discovered by the *Cassini-Huygens* mission. RADAR observations have revealed surprising and transient bright areas over Ligeia Mare surface. As suggested by recent research, bubbles could explain these strange features. However, the nucleation and growth of such bubbles, together with their RADAR reflectivity, have never been investigated. All of these aspects are critical to an actual observation. We have thus applied the classical nucleation theory to our context, and we developed a specific radiative transfer model that is appropriate for bubbles streams in cryogenic liquids. According to our results, the sea bed appears to be the most plausible place for the generation of bubbles, leading to a signal comparable to observations. This conclusion is supported by thermodynamic arguments and by RADAR properties of a bubbly column. The latter are also valid in the case of bubble plumes, due to gas leaking from the sea floor.

1. Introduction

After the arrival of *Cassini/Huygens* in the Saturn system, hundreds of lakes and seas of hydrocarbons were detected in Titan's polar regions (Stofan et al. 2007). One of the northern seas, Ligeia Mare, has shown a strange property: ephemeral RADAR bright areas, nicknamed "Magic Islands," which appear and disappear from one flyby to another (Hofgartner et al. 2014, Hofgartner et al. 2016). Several ideas have been proposed to explain these transient features. Up to now, only scenarios based on streams of bubbles, due the nitrogen exsolution, seem to possess a firm physical basis (Cordier et al. 2017, Malaska et al. 2017). Indeed, Titan's seas are probably composed of methane and some ethane, in which atmospheric nitrogen can easily dissolve. The existence of such bubbly plumes is not extravagant, since bubbles of methane megaplumes are observed in Earth's oceans (Leifer et al. 2015, Leifer et al. 2017). To be efficient RADAR waves reflectors, bubbles must be of a size roughly the same as the RADAR wavelength, *i.e.* 2.2 cm. Here, we focus our purpose on bubbles nucleation and growth, and on bubble plume reflectivity.

2. Lakes and Maria Composition – Possible Mechanisms of Bubbling

Since the Kuiper detection of methane and the flyby of *Voyager* probe, we know that the atmosphere of Titan is meanly composed by nitrogen and methane, with respective mole fractions around 95% and 5%. At ground level, the thermodynamic conditions, *i.e.* 90-94 K and a pressure of 1.5 bar, are close to the methane triple point, letting the latter being liquid. Beside, due to the solar UV irradiation and the bombardment by energetic particles trapped in Saturn magnetosphere, methane and nitrogen molecules are broken, forming highly reactive radicals. These entities react with nearby molecules, iniating a complex organic chemistry (Lavvas et al. 2008a,b). The main products of this active photochemistry is ethane, which is also liquid under the conditions of Titan surface. Thus, the bulk composition of Titan Maria and lakes should be a liquid mixture of methane, ethane, with some amount of dissolved nitrogen (Dubouloz et al., 1989, Cordier et al., 2009, Tan et al., 2013). Many other compounds may dissolve in this organic cryogenic solvent, and may also be retrieved as evaporite deposits over lake banks or in dry lake beds (Barnes et al., 2011, Cordier et al. 2013, 2016).
For decades, it is known that ternary can undergo phase splitting, forming three distincts phases: two liquids, of different compositions, and one vapor phase (Lu et al., 1970, Fig. 1). This process, for some

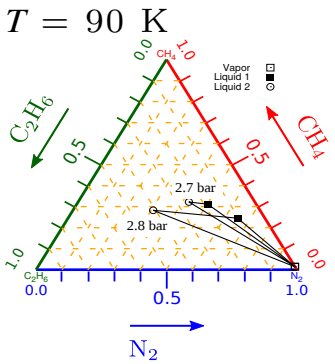

Figure 1: Diagram representing a ternary system N_2-CH_4-$C2H_6$, with co-existence of three phases: two liquids and a vapor.

species, occurs in conditions close to room conditions, whereas others required significantly different conditions. In the case of Titan's Maria or lakes, the phase splitting of the cryogenic solution needs pressure slightly higher than the surface pressure, *i.e.* values around $\sim$ 3 bars. These conditions may be found in the depths of Titan seas, where, due to internal circulation of the fluid, time to time, an ephemeral formation of ternary equilibria may could occur. The expelled nitrogen form bubbles with a maximum radius around 2 cm, consistent with a Cassini radar detection (Cordier et al., 2017).

3. Nucleation, Growth and RADAR Signature of Bubbles in Titan's Seas

Prior to get an equilibrium state, involving two or more phases, embryonic bubbles, or droplets, have to be created. The very first step of phase transition, called nucleation, has been studied in the present work. In the context of Titan's seas, two alternatives exist: an homogeneous nucleation and an heterogeneous nucleation. In the first case, bubbles appears in the volume of the liquid, while in the second case, the presence of some a piece of solid material is required. We show that homogeneous nucleation is practically impossible, but, the seabed offers a favorable place for heterogeneous nucleation.

In a second step, bubbles have to growth in order to get sizes large enough to be radar detectable and explained the phenomenum of "Magic Island". We have demonstrated the unefficiency of growthing by diffusion of nitrogen. Indeed, this process requires a supersaturated liquid layer relatively deep, which poses the problem of its appearance. The presence of centimeter-sized bubbles, due to bubbles coalescence within the stream, has been also studied, and it offers a plausible opportunity of building up such large bubbles.

Finally, we developed a two stream model of radar wave scattering by a population of bubbles distributed in a column of liquid.

4. Summary

Titan presents an unique object where organic matter is massively present in liquid state at the surface. Several efforts have been made by the the community to understand their composition, it appears that the mixtures of methane and ethane may be a good solvent for other heavier species. Beside, the observed liquid bodies have several strange properties, among them the "Magic Island" may be explained by a phase splitting in the depth of the seas. More widely speaking, the polar regions of Titan may harbor system that could be the prototypes for other system, existing at the surface of exoplanets, and open the door to a new kind of oceanography.

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