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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($\sim$98%) and CH_4($\sim$2%). The lifetime of CH_4 in the atmosphere is of the order of $\sim$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 $\sim$283 K and trap methane efficiently

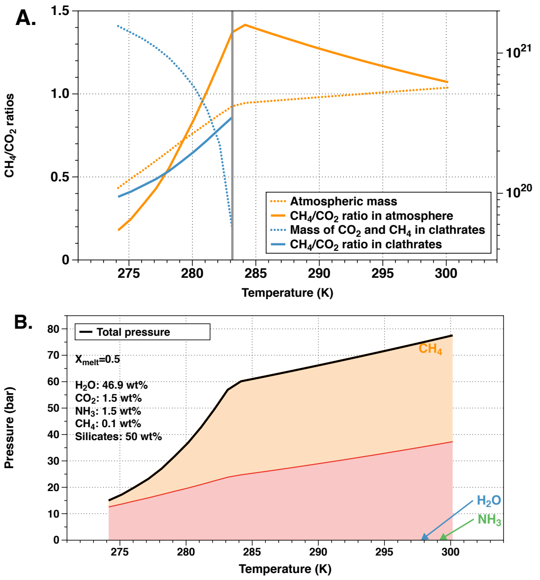

Figure 1: (A) Evolution of the atmospheric mass and mass of volatiles trapped in clathrates as well as the CH_4/CO_2 ratios in these layers. The vertical line marks the maximal temperature of formation of clathrates. (B) shows the corresponding surface total pressure and atmospheric compositions using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

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