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Volatile partitioning and formation of core, mantle, and atmosphere on early Titan

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Titan is a complex body with a thick atmosphere composed mainly of N2 and CH4, relatively young surface with lakes of liquid hydrocarbons, ice mantle that holds an interior liquid ocean, and low density core. The core may consist of either a mixture of ice and rock or hydrous silicates, suggesting that Titan's interior would have been much colder than previously thought (Iess et al., 2009; Fortes et al., 2012). However, such a view of a cold interior seems to be inconsistent with evidence for extensive geological activities near the surface inferred from the young surface age (Neish and Lorenz, 2012) and presence of radiogenic Ar degassed from the interior (Niemann et al., 2005). In addition, the findings of significant amounts of CO2 in Enceladus plumes (Waite et al., 2009) indicate that the chemical composition of the building blocks of Titan may have also been a comet-like one with a few percents of CO2 content relative to H2O. Nevertheless, the presence of such CO2 in Titan's proto-atmosphere and mantle should have resulted in the formation of large amounts of atmospheric CO in addition to N2 through photolysis (Atreya et al., 1978), shock heating (McKay et al., 1988; Ishimaru et al., 2011), and hypervelocity impacts (Sekine et al., 2011). Although the Cassini spacecraft has provided important clues to understand the origin and evolution of Titan, there is no unified view that accounts for the complex nature of the core, mantle, and atmosphere consistently.

Here we investigate partition and chemical evolution of primordial CO2, NH3 and CH4 in a water magma ocean that is considered to have been formed during Titan's accretion (Kuramoto and Matsui, 1994). On the basis of laboratory experiments, we show that primordial CO2 would have been readily converted to carbonate minerals in the water magma ocean through hydrothermal reactions with primitive minerals, such as olivine. Thus, CO2 would have been partitioned mainly into the core by forming a low density carbonate during accretion. The proto-atmosphere and mantle conversely would have been highly depleted in CO2, preventing the formation of a thick CO atmosphere. On the other hand, our experimental results indicate that NH3 would not have been converted into N2 in the water magma ocean due to the efficient formation of H2 through serpentinization, suggesting that NH3 has been partitioned mainly in the mantle and proto-atmosphere. Given the low solubility of CH4 in the water magma ocean, CH4 is considered to have been partitioned mainly in the proto-atmosphere. Because of the thermodynamical stability of carbonate at high temperatures (e.g., 2000 K) under high pressure conditions corresponding to Titan's core (Isshiki et al., 2004), the carbonate-rich, low density core allows a warm interior of Titan, consistent with the evidence for extensive surface geological activities. Our model provides a new hypothetical starting point for the evolution of interior and atmosphere-surface systems of Titan and other large icy bodies.

Keywords: Titan, partitioning, hydrothermal reactions, icy satellites, core, atmosphere