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Titan's degassing history constrained by the isotopic ratio and abundance of Ar in the atmosphere

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The volatile inventory on Titan is a key parameter to reconstruct the evolution of its atmosphere-surface system and climatology. The Cassini spacecraft has revealed the absence of a large liquid CH_4 reservoir on the surface and the presence of radiogenic ^{40}Ar in the atmosphere, suggestive of recent degassing from the interior. However, the timing and magnitude of degassing remain largely unknown. Knowledge on volatile releases from the interior into the atmosphere since its accretion is also essential to understand the thermal history, interior structure, and early evolution of Titan.

Here, we focus on the abundance and isotopic ratio of Ar in the atmosphere to constrain the degassing history of Titan. The abundances and isotopic ratios of Ar in the atmospheres of Earth and Mars have been used to constrain their degassing histories (e.g., Hamano & Ozima, 1978; Tajika & Sasaki, 1996), because of both its inertness and the lack of radiogenic ^{40}Ar in the early solar system. We have developed a degassing model of Titan's atmosphere based on that of Earth's atmosphere (Ozima, 1975). We calculated the time evolution of the amounts of primordial ^{36}Ar and radiogenic ^{40}Ar both in the atmosphere and interior of Titan. In the interior, ^{36}Ar and ^{40}Ar were assumed to be homogeneously distributed. We assumed that the initial abundances of ^{40}K and ^{36}Ar in Titan's rock component were same as those of the average abundances of CI chondrites ([^{40}K] = 0.77 ppm, [^{36}Ar] = 1.25 ppb) (Mazor et al., 1970; Lodders, 2003). We also assumed that the ice component was initially free of primordial ^{36}Ar. We did not consider the escape of atmospheric Ar. The following two extreme cases were considered for the degassing history; (1) continuous degassing through Titan's history and (2) episodic degassing, in which releases of volatiles from the interior occurred episodically in Titan's history (e.g., Tobie et al., 2006).

On the basis of comparison with the observations, we found that the calculated present atmospheric ^{40}Ar/^{36}Ar ratios cannot reproduce the observations (^{40}Ar/^{36}Ar = 106-295, Niemann et al., 2010) for either continuous or episodic degassing. In the case of continuous degassing, the calculated present atmospheric ^{40}Ar/^{36}Ar ratio reaches only 39. Even in the case of episodic degassing, the ^{40}Ar/^{36}Ar ratios become less than 56, which is the calculated present 40Ar/36Ar ratio in the interior 4.55 billion years after the solar system formation.

There are two possibilities to account for the observed atmospheric ^{40}Ar/^{36}Ar ratio and abundance of ^{40}Ar in Titan's atmosphere: (1) More than 60% of primordial ^{36}Ar initially contained in the rock components had escaped in the early history of Titan, or (2) the distribution of ^{40}K in the interior was heterogeneous, and ^{40}K was concentrated in cryomagma $>$ 2.6 times that of CI chondrites in the early stage. Either explanation would require a large-scale interior melting and/or consequent formation and loss of proto-atmosphere (Kuramoto & Matsui, 1994). These conclusions suggest that the accretion time of Titan would be much shorter ($< 10^6$ years) than the prediction by the gas-starved model for the circumplanetary subnebula (Canup & Ward, 2006; Barr et al., 2010) and that Titan's interior would have been differentiated (Fortes, 2012), rather than mixtures of ice and rock components (Iess et al., 2010).

Keywords: Titan, degassing, rare gas, icy satellite, evolution of atmosphere