EPSC Abstracts
Vol. 10, EPSC2015-793-1, 2015
European Planetary Science Congress 2015
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A massive primordial-atmosphere on proto-Titan formed in a cold circum-planetary disk

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Abstract

We numerically investigate the property of the primordial atmosphere of Titan that grew in a gas-starved disk, especially in terms of the atmospheric mass and the blanketing effect. In spite of such a disk condition, Titan could capture a thick atmosphere mainly composed of nebula gas components due to the cold formation environment. This would cause a significant blanketing effect inducing differentiation of this satellite.

1. Introduction

Titan, the largest Saturnian moon, has a thick atmosphere mainly composed of N_2. Depletion of primordial Ar strongly suggests that the N_2 was originated from other nitrogen-bearing compounds like NH_3 [1]. Although several hypotheses have been proposed, it remains an open question how and when such a thick atmosphere was generated.

According to the recent satellite formation theory [2], Titan formed along with the other regular satellites within a gas-starved disk characterized low temperature (50-150 K), low pressure (~1 Pa), and long accretion time (~10^6 yr). Previous study on early thermal evolution of Titan indicated that the satellite may accrete avoiding a massive melting ice [3]. This study, however, neglected the blanketing effects of proto atmosphere. When Titan formed within the cold disk, even though the disk pressure was low, it could acquire a significant amount of atmosphere mainly composed of nebula gas strongly bounded by gravity. This may cause an intensive blanketing effect with help of gases evaporated from ice components. In this study, we numerically analyze the structure of proto-atmospheric of Titan formed within a gas-starved disk and estimate the accumulating mass and the blanketing effect of the atmosphere.

2. Model

The atmosphere is assumed to be spherical symmetry and in hydrostatic equilibrium. The atmosphere consists of the mixture of H_2, He (nebula gas components), H_2O and NH_3 (ice-evaporated components), in which the amount of ice-evaporated components obey saturated vapor pressures [4]. The atmosphere continuously connected to the disk at the satellite Hill radius where the disk temperature and pressure are given by the gas-starved disk model [2], T_d = 50 K, P_d = 1-100 Pa. Atmospheric thermal structure follows radiative-convective equilibrium, consisting of the stratosphere and troposphere. The troposphere has moist adiabatic lapse rate [5] the stratosphere is described by the diffusive approximation in the optically-thick region and also by modified solution of plane-parallel radiative-equilibrium problem with taking into account the effect of spherical geometry in the optically-thin region [6]. The Rosseland mean opacity incorporates the collision induced absorptions of nebula gas components [7, 8] and line absorptions and continuum absorptions of evaporating gas components from HITRAN databases.

3. Results and Discussion

Figure 1 represents the atmospheric mass inside the Bondi radius and net outgoing radiative flux at the top of primordial atmosphere of Titan as a function of its surface temperature. Here we compare the results with those for the case of reducing the amount of NH_3 (5% saturated vapor pressure) and Ganymede formation environment (T_d = 150 K, no NH_3 contained). Figure 1a indicates that there is a minimum atmospheric mass for each case in which nebula gas components are dominant at low surface temperatures whereas ice-evaporated components are dominant at high surface temperatures. Titan could acquire a larger amount of primordial atmosphere than Ganymede. This is because the local scale height of the atmosphere is smaller due to the lower disk temperature, which results in the denser atmosphere on Titan. Figure 1b shows that the outgoing radiative flux from Titan is significantly suppressed due to the opacity of nebula gas or ice-evaporated components depending on whether the surface temperature is lower or higher than 250 K.

Figure 1b also indicates that when tiny energy flux was supplied to the surface of Titan, the surface temperature was kept ~230-250 K. Since the radiation from the proto-Sun and/or proto-Saturn is enough large for such energy supply, melting of water/ammonia mixture may occur even after the end of satellite accretion. This suggests that an ammonia-rich proto-ocean could be kept on Titan until the disk and the initial acquisition of proto-atmosphere were largely dissipated. Such relatively warm environment that possibly allows continuous supply of NH_3 in the atmosphere-ocean equilibrated system for a long time, at least the disk dissipation timescale 10^7 yr. A part of the primordial atmosphere, in particular heavier ice-evaporated components may survive after the disk dissipation. UV radiation from proto-Sun would then generate N_2 from NH_3 via photochemistry [9].

Acknowledgements

We thank Ko-ichiro Sugiyama and EPnetFaN members for providing us computation environment and technical support.

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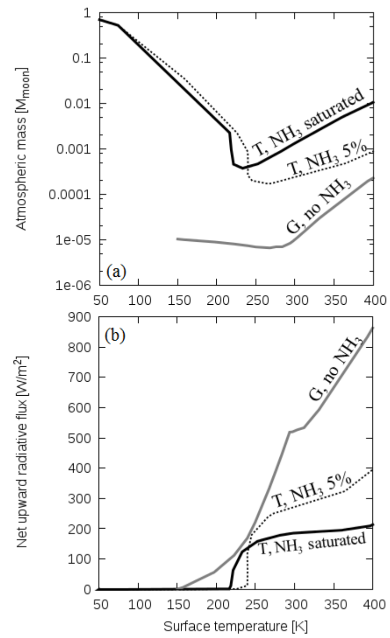

Figure 1: Atmospheric mass inside the Bondi radius (a) and Net upward flux at the top of atmosphere (b) as a function of surface temperature of the satellites. Each line represents the result at the case of Titan (Black solid: T_d = 50 K, P_d = 10 Pa, NH_3 saturated; Dotted: T_d = 50 K, P_d = 10 Pa, NH_3 5%) and Ganymede (Grey: T_d = 150 K, P_d = 10 Pa, no NH_3), respectively.

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