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Structure of the proto-atmosphere on Titan accreted in a gas-starved circumplanetary disk

OKADA, Hidetaka[1], KURAMOTO, Kiyoshi[1]*

[1]Department of Cosmosciences, Hokkaido University

Titan, the largest satellite in the Saturn system, is characterized not only by its size comparable to the rocky planets but also by its thick N2 rich atmosphere with the surface pressure as high as 1.5 bar. Recent Cassini gravity measurements imply that its interior is differentiated into a rock-rich core and ice-rich shell. It is therefore likely that Titan has been gone through melting of ice during its history. To understand the origin of atmosphere and the differentiation of interior, it is important to clarify the thermal evolution and possible atmosphere formation of Titan during accretion.

Supposing gas-free accretion, Kuramoto and Matsui (1994) estimated the thermal evolution of an accreting Titan considering the blanketing effect of a steam atmosphere formed by vaporization of icy component. According to their calculation, the surface temperature exceeds the melting point of H2O ice thereby Titan differentiates if the accretion time is within 10^5 yr. Simultaneously, the surface temperature rises above 500 K, which cause significant outflow of atmosphere from Titan's gravity field. However, according to more plausible scenario for the satellite formation, satellites are accreted in gas-starved circumplanetary disks (Canup and Ward, 2002, 2006). This theory implies that Titan captured H2 and He gas from the gas disk. This study, therefore, estimates the thermal structure of the proto-atmosphere which is in hydrostatic equilibrium with a gas-starved circumplanetary disk and discusses its possible roles in differentiation of Titan and origin of N2 rich atmosphere.

The proto-atmosphere is assumed to consist of mixture of disk gas component (H2, He) and volatilized gas component (H2O) with isothermal stratosphere and troposphere where temperature follows the moist-adiabatic lapse rate under hydrostatic equilibrium with the surrounding disk gas. Hydrostatic structures are solved by changing tropopause. By solving the radiation transfer equation regarding H2 and H2O as continuum absorptions, we calculated the outgoing thermal radiation from the top of atmosphere for each hydrostatic structure. The disk temperature and pressure at the orbit of Titan is estimated by a disk model (Canup and Ward, 2002)

For the atmosphere in hydrostatic equilibrium and continuously connected with the surrounding disk, there exists the upper limit of the surface temperature about 300 K. If the surface temperature is higher than upper limit, the assumption of hydrostatic equilibrium and continuousness breaks up and the outflow of proto-atmosphere is likely induced because the pressure at the Hill radius becomes higher than the disk pressure.

By comparing outgoing thermal radiation from the top of the atmosphere with the accretional energy flux, one can estimate that the surface temperature exceeds the melting point of H2O during accretion if the accretion time is shorter than 10^6 yr. Moreover, there exists the upper limit of thermal radiation for the hydrostatic atmospheres. This is about 400 W/m^2, which is equal to the accretional energy flux when the accretion time is 0.4 Myr. Since Titan likely accreted within 10^4 yr to 10^6 yr, the surface temperature may exceed the critical temperature due to the heating by the difference in accretional energy and thermal radiation during accretion. In this case, the outflow of proto-atmosphere is expected to occur.

When such outflow occurs, it is likely that H2, He, and rare gases insoluble to water escape preferentially. The building blocks of Titan likely contain NH3 as a icy component. Because NH3 is highly soluble into water, NH3 likely remains on the satellite surface even if outflow occurs. Chemical conversion of remaining NH3 to N2 may explain why the present atmosphere of Titan is N2 rich but Ar poor in spite of their similarities in chemical properties and cosmic abundance. Impact induced shock chemistry is a candidate mechanism to produce N2 from NH3 on the proto-Titan (McKay et al., 1988).