The thermal evolution of Uranus with condensation of ice constituents in the atmosphere: Implications for the N/O and C/O ratios

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The luminosity of Uranus is lower than that of Neptune, though their masses and radii are similar. As previous studies of thermal evolution of the ice giants showed, the faintness of Uranus is unable to be explained by a simple three-layer model that is composed of a H/He-dominated envelope, an ice mantle, and a rocky core from the top to the bottom [1, 2]. Since the timescale of the thermal evolution is determined by the atmospheric structure, the evolution of the atmospheric structure and composition is important. If the atmosphere contains ice constituents such as water, ammonia, and methane, those constituents are condensed and removed from the atmosphere. No studies, however, focused on the thermal evolution of the ice giants with significant amounts of ice constituents in the atmosphere.

In this study, we investigate the effect of the condensation of ice constituents in the atmosphere. We simulate the thermal evolution of Uranus, based on the four-layer model with an ice-rich H/He atmosphere, a water-rich H/He envelope, a water mantle, and a rocky core from the top to the bottom, including the effect of the condensation of water, ammonia, and methane in the atmosphere. We investigate the sensitivity of the evolution timescale to the initial mole fraction of ice constituents and the NH_3/H_2O and CH_4/H_2O ratios.

We demonstrate the effect of the condensation makes the timescale of the thermal evolution shorter than that without the effect of the condensation. Moreover, the values of the NH_3/H_2O and CH_4/H_2O are also important. To explain the present luminosity of Uranus, the NH_3/H_2O value should be larger than the solar N/O value, while the CH_4/H_2O value should be smaller than the solar C/O value. Our conclusions suggest that the disk temperature at the Uranus-forming region would have been higher than the condensation temperature of CO but allows H_2O, NH_3, and CH_4 to condense into the solid phase.

[1] Hubbard & Macfarlane (1980) *J. Geophys. Res.*, **85**, 225-234. [2] Fortney et al., (2011) *ApJ*, **729**, 32.