論文内容の要旨

Evolution of ice giants in and outside the solar system
（太陽系および太陽系外における巨大氷惑星の進化）

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The aim of this dissertation is to evaluate the impacts of internal compositional distributions on the thermal evolution and the bulk composition's evolution of ice giants. This dissertation is composed of three parts. In chapter 1, general introduction of this dissertation is described. In chapter 2, the evolution of an ice giant in a long-period orbit is described. We deal with the thermal evolution of the ice giants in the solar system Uranus and Neptune and discuss their origins. In chapter 3, the evolution of an ice giant in a short-period orbit, namely water-rich sub/super-Earths, is described. We deal with the thermal and mass evolution of water-rich planets outside the solar system. We reveal the relationships among masses, radii, and semi-major axes of water-rich super-Earths and also sub-Earths that have undergone photo-evaporative mass loss. Through those two parts, we investigate the impact of condensation or evaporation of water on the evolution of ice giants in long-periods, low-temperature or short-periods, high-temperature environments.

Though Uranus and Neptune are similar in the mass and radius, the former is significantly fainter than the latter. As previous theoretical studies of thermal evolution of the ice giants demonstrated, the faintness of Uranus cannot be explained by simple three-layer models that are composed of a

H/He-dominated envelope, an ice mantle and a rocky core. Namely, the observed effective temperature of Uranus is lower than theoretically predicted (e.g., Hubbard & MacFarlane 1980, Fortney et al., 2011; Nettelmann et al., 2013). Since the speed of the thermal evolution is determined by how efficiently the planetary atmosphere radiates energy, the evolution of the atmospheric structure is important. If the atmosphere contains ice materials such as water, ammonia and methane, those materials are condensed and removed from the atmosphere during the cooling. In this study, we quantify the impact of the condensation of ice components in the atmosphere on the thermal evolution to explain the current luminosity of Uranus. To do so, we simulate the thermal cooling of the ice giants, based on three layer models with a relatively ice-component-rich, H/He-dominated envelope on top of a water mantle that surrounds a rocky core. We demonstrate that the effect of the condensation makes the timescale of the thermal cooling of the planet shorter by an order of magnitude than in the case without condensation. Such accelerated cooling is shown to be fast enough to explain the current faintness of Uranus. We also discuss the factors that would have caused the difference in current luminosity between Uranus and Neptune.

Recent progress in transit photometry opened a new window to the interior of ice giants. From measured radii and masses, we can infer constraints on planetary internal compositions. It has been recently revealed that ice giants orbiting close to host stars (i.e., hot super-Earths) are diverse in composition. This diversity is thought to arise from diversity in volatile content. The stability of the volatile components is to be examined, because hot super-Earths, which are exposed to strong irradiation, undergo photo-evaporative mass loss. While several studies investigated the impact of photo-evaporative mass loss on hydrogen-helium envelopes, there are few studies as to the impact on water-vapor envelopes, which we investigate in this study. To obtain theoretical prediction to future observations, we also investigate the relationships among masses, radii, and semi-major axes of water-rich super-Earths and also sub-Earths that have undergone photo-evaporative mass loss. We simulate the interior structure and evolution of highly-irradiated sub/super-Earths that consist of a rocky core surrounded by a water envelope, taking into account mass loss due to the stellar XUV-driven energy-limited hydrodynamic escape. We find that the photo-evaporative mass loss has a significant impact on the evolution of hot sub/super-Earths. With a widely-used empirical formula for XUV flux from typical G-stars and the heating efficiency of 0.1 for example, the planets of less than 3 Earth masses orbiting 0.03~AU have their water envelopes completely stripped off. We then derive the threshold planetary mass and radius below which the planet loses its water envelope completely as a function of the initial water content and find that there are minimums of the threshold mass and radius. We constrain the domain in the parameter space of planetary mass, radius, and the semi-major axis in which sub/super-Earths never retain water envelopes in 1-10~Gyr. This would provide an essential piece of information for understanding the origin of close-in, low-mass planets. The current uncertainties in stellar XUV flux and its heating efficiency, however, prevent us from deriving robust conclusions. Nevertheless, it seems to be a robust conclusion that Kepler planet candidates contain a significant number of rocky sub/super-Earths.

This dissertation investigates the impact of the distribution of condensable constituents on the thermal evolution and the bulk composition's evolution of the ice giants. Long-period ice giants experienced the thermal evolution and the condensation of water, ammonia, and methane in the atmosphere simultaneously. Short-period ice giants experienced the thermal evolution and mass loss simultaneously. Though the effects of condensation and mass loss remove the water or other volatiles from the atmosphere, those effects leave the trails on the evolution and observations of the ice giants. Those results will give essential insights to understand the relationship between origins and observations of planetary systems.