論文の内容の要旨

Role of Mean Motion Resonances in Planetesimal Accretion
onto Proto-Gas Giant Planets
(原始巨大ガス惑星の微惑星集積における平均運動共鳴の役割)

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The formation of gas giant planets is a complicated process composed of many underlying physical sub processes such as circumstellar disk evolution, core formation, gas accretion and planetary migration. Thanks to progresses in respective theoretical studies, we can construct unified planetary formation models from planetesimals to gas giant planets; however, there are still many uncertainties related with each process and initial conditions. The bulk composition of gas giant planets is used for retrieving the information of planetary formation because the composition evolution of gas giant planets is strongly related to the evolution paths of gas giant planets. According to the theoretical estimation (Thorngren+2016, The Astrophysical Journal, 831, 64) based on transit observations, close-in gas giant planets contain large amounts of heavy elements, suggesting need for an additional process for increasing the amount of heavy elements other than the standard formation processes. Planetesimal accretion is regarded as one of the main sources of such massive heavy elements; however, how many planetesimals can be captured by a gas giant planet has not been known because of a lack of understanding about the role of mean motion resonances in planetary migration phase. In this thesis, we focus on the role of mean motion resonances in the planetesimal accretion onto a migrating proto-gas giant planet.

We consider the limiting case where the mean motion resonances with a migrating planet work most strongly with the aim to reveal the fundamental physics of mean motion resonances in planetesimal accretion. Using direct orbital integration of planetesimals, we find that mean motion resonances play important roles in planetesimal accretion. Planetesimal accretion is inhibited by two kinds of shepherdings, aerodynamic shepherding and resonant shepherding. When both shepherdings become ineffective, planetesimal accretion occurs efficiently. The relatively narrow region of a circumstellar disk where planetesimal accretion occurs is named as the sweet spot in this thesis. The total

amount of planetesimals captured by the migrating planet increases with the amount of planetesimals shepherded into the sweet spot during the planetary migration. Deriving the conditions of the sweet spot analytically, we find that the location of the sweet spot barely depends on the structure and evolution of the circumstellar disk.

During the planetary migration phase of proto-gas giant planets, the eccentricities of planetesimals trapped in the resonance are excited more than ~0.1, which brings high-velocity mutual collisions of planetesimals. Such strong collisions have a possibility of breaking the resonant trapping and changing the location of the sweet spot, which affects the planetesimal accretion. Thus, we focus on the effects of high-velocity collisions on the stability of the resonant trapping. We derive the condition for breaking the resonant trapping analytically and find that the collision of planetesimals is strong enough to break the resonant trapping. Including the effect of planetesimal collisions in orbital integration code, we investigate the effect of high-velocity collisions on planetesimal accretion. Using the numerical simulations, we find that high-velocity collisions break the resonant trapping and change the total amount of captured planetesimals by a factor of 2 at most. On the other hand, the location of the sweet spot is barely changed by the high-velocity collisions.

Based on above results, we discuss the effect of planetesimal accretion on the composition evolution of gas giant planets. Using the results obtained above, we construct a simple model for estimating the amount of heavy elements brought by planetesimal accretion. Our model shows that a Jupiter-mass planet can capture the large amount of planetesimals if the core forms in the outer disk. The amounts of heavy elements accreted onto gas giant planets increase with the semi-major axis of core formation location and the planetesimal disk mass. Due to the planetesimal accretion in the planetary migration phase, gas giant planets currently observed in the region interior to the sweet spot have more heavy elements than those exterior to the sweet spot. Comparing the theoretically and observationally estimated amounts of heavy elements in close-in gas giant planets, we conclude that close-in gas giant planets migrated over tens AU in their formation stages and the migration distance was longer for heavier planets. The large scattering in the amount of heavy elements likely comes from the circumstellar disk diversity. Our model also suggests that the extremely enriched close-in gas giant planets with more than ~100 Earth-mass heavy elements formed via gravitational instability.

Our models used in this thesis contain many assumptions and simplifications, on which we need further investigations. However, we showed that the various features found in the heavy element contents in close-in gas giant planets can be explained by the effect of planetesimal accretion. This result suggests that planetesimal accretion is a main source of heavy elements in gas giant planets. The findings in this thesis are expected to make a great contribution in linking the current composition of gas giant planets with their formation history. Along with the future development of observation and characterisation of exoplanets, the formation paths of gas giant planets will be constrained by the model including the effects of planetesimal accretion in planetary migration phase.