論文の内容の要旨

論文題目：
Coupled Evolution of Planetary Atmospheres and Magma Oceans after Giant Impacts

(ジャイアントインパクト後の惑星大気とマグマオーシャンの進化)

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Recent advances in planet formation theory have provided several great consequences for formation environment of terrestrial planet and their initial states. First, terrestrial planet formation would involve very huge impacts among planetary embryos. The final configuration of planets would be determined among this giant impact stage. Second, the orbital crossing during the giant impact stage allows the planet located close to its star acquire some amount of water statistically in forms of water (ice) rich embryos and planetesimals. Third, terrestrial planets would be molten at their births because of energetic giant impacts. Fourth, giant impacts would start to occur by triggered by the dissipation of nebula gas (its clearing timescale: ~ 10^7 years) and the planet formation lasts ~ 10^8 years. This implies that terrestrial planets could evolve with hydrodynamic escape of atmospheres driven by strong EUV radiation from young active star.

Based on these outcomes from the recent planet formation theory, I examine early evolution of Earth-like terrestrial planets orbiting around a Sun-like star after the last giant impacts until the planets completely solidify. In this thesis, I focus on a role of water for the early evolution of the planets. It is not only because water vapor would strongly affect outgoing planetary radiation due to its strong greenhouse effect, but also because the evolution of the steam atmosphere would couple with that of magma ocean due to its high solubility in silicate melts. Also, since water vapor is H-bearing gas, it is susceptible to hydrodynamic loss of atomic hydrogen. Furthermore, water vapor is con- densable so that its condensation can affect the atmospheric structure and therefore the planetary radiation. I develop an atmosphere and magma-ocean coupled model, in which radiative-convective equilibrium calculations are performed to provide the planetary ra- diation. Using this model, solidification

timescale and water budget are systematically investigated with respect to planetary orbital radius and initial water endowment for both the cases with and without water loss induced by hydrodynamic escape of atomic hydrogen.

My results suggest that the early evolution of terrestrial planets strongly depends on whether or not the planets are located closer to their host star than a certain orbital distance. I refer to this orbital radius as the critical orbital radius in this thesis. This critical orbital radius is defined as one where the stellar flux that the planet receives equals the value of tropospheric radiation limit from steam atmosphere. In the orbit region outer the critical radius, as the atmosphere grows by degassing, it starts to be saturated from the top of troposphere. This saturation of the atmosphere approaches the planetary radiation to the tropospheric radiation limit. The magma ocean cools surely at least at a rate determined by the difference between the tropospheric radiation limit and the stellar flux. The typical solidification time is several million years in this orbit region. This solidification timescale is less dependent on its initial water endowment, as well as on whether hydrodynamic escape occurs or not. The short solidification time results in less effect of the hydrodynamic escape on the water budget on the early planet.

In contrast, the water loss by the hydrodynamic escape has a significant role for the early evolution and water budget of the planet located beyond the critical orbital radius. Degassing of water vapor makes the atmosphere optically thick so that the planetary radiation finally equals the stellar flux. This means that the heat flux from the magma ocean becomes 0, unless the continuous loss of water thins the atmosphere. Therefore, the water loss rate is a controlling factor for the cooling rate of the magma ocean. The planetary water should be greatly reduced at the time of the complete solidification of the magma ocean. The solidification time is well approximated by the time required for the initial amount of water to be lost from the planet. In this orbit region, the timescale for clearing the nebula gas is also important as well as the timing of the last giant impact because it determines the timing for the onset of the hydrodynamic escape.

Such a long duration of the magma ocean enhances the probability for the observation of terrestrial planets on magma ocean stage in extrasolar planetary systems. The most favorable orbit for discovering the planets with the deep magma ocean is slightly inner the critical orbit radius.

The typical parameters provide the critical radius of about 0.7 to 0.8 AU. This ensures that the Earth is located outer the critical orbital radius. Therefore, its deep part would have solidified within five million years even if accumulating with massive amount of water. Some fraction of primordial water would remain and form the earliest ocean. In contrast to the Earth, two evolutionary scenarios are possible for Venus. If the critical orbital radius is sufficiently small, the early Venus would have evolved in a similar way to the early Earth. If the critical orbital radius is larger than the Venus's orbital radius (about 0.72 AU), the amount of water would be greatly reduced by the time when the Venus completely solidified. This alternative evolutionary path can have an advantage in the disposal of the oxygen left behind the planet. The early thermal history of Venus's interior could be totally different from that of the Earth, depending on its initial water endowment.