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Two evolutionary paths of early terrestrial planets with steam atmospheres

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Recent studies with N-body simulations suggest that Earth-sized planets would experience giant impacts among planetary-sized bodies during formation, implying that the planets would form in a globally molten state. Orbital crossing during the giant impact stage would cause significant radial mixing of material throughout the terrestrial planet formation region. It means that even the planets located close to their host star would still have a chance to acquire some water during formation.

Our goal is to clarify controlling processes of thermal history and water budget of terrestrial planets after the last giant impact until the magma ocean solidifies. Since water vapor is a potent greenhouse gas, the amount of steam atmosphere would strongly affect the thermal history of the planets. On the other hand, high solubility of water into silicate melts suggests that the amount of steam atmosphere would be controlled by water exchange between the atmosphere and the magma ocean. Elkins-Tanton (2008) calculated atmospheric growth and solidification time of the magma ocean, considering such a water exchange. In her model, the effect of condensation of water is neglected on outgoing planetary radiation. Also, it is assumed that the total amount of water of the planets is constant during solidification.

As reported by Nakajima et al. (1992), however, water-saturated atmospheres have radiation limits. The values of the radiation limits are common to the planets with the same mass, while the planet closer to the host star receives the larger incident stellar flux. Therefore, the existence of the radiation limits could make a fundamental difference in the cooling rates of the planets located at different orbital distance from their star. The recent studies with N-body simulations also suggests that planet formation lasts about 10-100 Myr. Strong EUV radiation from a young host stars could drive intense hydrodynamic escape of atomic hydrogen, which would also affect the amount of steam atmosphere and therefore the cooling rate of the planets.

We developed a steam-atmosphere and magma-ocean coupled model, in which a radiative-convective equilibrium model of grey atmosphere was incorporated in order to consider the effect of condensation of water vapor on planetary radiation. Water loss caused by the hydrodynamic escape was also taken into account. Using this model, we investigated solidification time and water budget of Earth-like terrestrial planets orbiting around a Sun-like star with respect to planetary orbital radius and initial water inventory.

Our results suggest that there would be two types of evolutionary paths of terrestrial planets, depending on orbital radius. The condition that separates the two distinctive evolutionary paths is whether the net incident stellar flux that the planet receives exceeds the value of the radiation limit from steam atmosphere or not. In this presentation, we will show the controlling mechanisms and also its implications to exoplanet observations and the early evolution of Earth and Venus.

Keywords: Magma ocean, Giant impact, Thermal history, Water budget, Hydrodynamic escape, Radiation limit