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Magma ocean cooling and hydrodynamic escape under steam atmosphere

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The current planet formation theory suggests that giant impacts would have marked the final stage of terrestrial planet formation. The large amount of energy released in the giant impact event would have melted a significant part of the terrestrial planet, forming a deep magma ocean. The magma ocean would begin to cool and solidify just after the impact and its cooling time affects the differentiation of the mantle and the timing of subsequent water ocean formation.

The magma ocean cooling rate especially in the early stage should have been controlled by the radiation from the top of the atmosphere into space. It is expected that the cooling rate of the magma ocean strongly depends on the amount of the potent greenhouse gases such as water vapor and carbon dioxide. On the other hand, the amount of the gases could be controlled through the exchange between the atmosphere and the magma ocean because of their high solubility in magma. Since the melt fraction in the magma ocean decreases with its cooling, more water and carbon dioxide would be degassed into the atmosphere, which in turn leads to reduce the cooling rate. This means that the evolution of the magma ocean should have been coupled with the atmospheric growth through the volatile exchange between both reservoirs.

Elkins-Tanton (2008) calculated the time scale of the magma ocean on Earth and Mars considering the water and carbon dioxide exchange. The results suggest that the magma ocean cooling time would be at most 5 Myr even in the case of the high-volatile contents. Although the atmospheric blanketing effect was considered in terms of the heat balance on the surface, the atmospheric structure was not calculated for the cooling rate of the magma ocean in her model. Moreover, the effect of condensation of water was not included. Since the water vapor is condensable, the atmosphere would start to be saturated from its top with the cooling. In general, the outgoing radiation decreases with the cooling of the planetary surface. In the optically thick and water-saturated atmosphere, however, the outgoing radiation has a lower limit. This is because the temperature structure at the optical depth of unity is independent on the surface temperature in such an atmosphere. It is expected that whether or not the solar insolation exceeds the radiation limit would make a significant difference in the thermal history of the magma ocean.

If the insolation exceeds the radiation limit, the outgoing radiation could balance with the insolation. In this case, the hot steam atmosphere may persist for a long time so that the significant amount of water could be lost by hydrodynamic escape of hydrogen. The solar UV radiation dissociates water vapor into hydrogen and oxygen atoms in the upper atmosphere. Some previous studies suggest that the strong EUV from the young Sun could drive hydrodynamic loss of hydrogen, while that oxygen could be left behind because of its heavier atomic weight. If the oxygen accumulates into the atmosphere, this would cause the slowdown in the hydrogen escape. During the magma ocean stage, however, such an accumulation would not happen because the oxygen left in the atmosphere behind would be absorbed to oxide the magma at the surface. This significant water loss also would affect the magma ocean cooling.

We developed a simple coupled atmosphere-magma-ocean model to calculate the magma ocean cooling time under steam atmosphere and the amount of water at the end of solidification, taking into account the water loss by hydrodynamic escape. We used a 1D radiative-convective equilibrium model of condensable gray gas atmosphere. The temperature structure was assumed to be adiabatic in the convective magma ocean. Hydrogen loss rate was given by the energy-limited escape rate. We will present the results of a parametric study on the cooling timescale and the amount of the steam atmosphere varying the orbit radius and the initial amount of water on the Earth-sized planet.

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