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Internal differentiation and thermal history of giant icy moons: implications for the dichotomy between Ganymede and Callisto

Jun Kimura and Kiyoshi Kuramoto
Center for Planetary Science/Hokkaido University, Sapporo, JAPAN (junkim@ep.sci.hokudai.ac.jp / Fax: +81-11-706-2760)

Abstract

The Ganymede's interior appears to be clearly differentiated and has a metallic core, judging from the gravity and magnetic field measurements. However processes and timing of the internal differentiation including the core formation are highly unclear. Also, origin of different internal state of Callisto which has larger moment of inertia factor compared with Ganymede in spite of the similarity in their sizes has not been well understood. We focus on a process of dehydration of pristine rock-metal-mixed core in both moons, and have numerically investigated the moons' thermal history to explain the difference in differentiation state between both giant icy satellites.

1. Introduction

From gravity data acquired by the Galileo spacecraft, it has been found that Ganymede has a small value of the moment of inertia factor (0.3115), which suggests a highly differentiated interior. Combined with its mean density (1,942 kg m^{-3}), a three-layered structure (that is, an outermost H_2O layer, a rocky mantle, and a metallic core) is most consistent with the gravity data [1]. Also, the intrinsic magnetic field detected by Galileo spacecraft strongly supports the existence of a liquid, iron-rich core [2, 3]. However, process of the internal differentiation including the core formation is highly unclear. The size of Ganymede implies that only accretional heat is insufficient to segregate the water, rock, and metallic materials completely. On the other hand, Callisto, another Jovian moon, has size similar to Ganymede but show larger value of the moment of inertia (0.355) implying incomplete differentiation [4]. Many studies have proposed hypotheses about the accreting process [5-9], material differences [10], orbital evolution and tidal heating [11, 12], and differences in the impact energy during late heavy bombardment [13] to explain this contrasting characteristic between two moons. Here we focus on an internal evolution in early stage and on a dehydration process of pristine rock-metal-mixed core in both moons.

2. Inferred interior structure

Ganymede and Callisto share similar size and mean density at the first glance. However, volume ratio of water and rock (and metal) derived from the mean density of both moons are significantly different. Assumed that both moons consist of two components (water with density of 930 kg m^{-3} and rock with density of 3,300 kg m^{-3}), core radius is ~1,980 km for Ganymede, and ~1,750 km for Callisto. This means that the amount of radiogenic heat source included in the moons is different (Callisto has ~70% amount of Ganymede's radiogenic heat source), assumed the same concentration of radioactive elements. This point has possibly produced the structural difference of both moons' interiors even without contribution of tidal heating.

3. Dehydration of rock

In addition, dehydration of rock might be key process to create the dichotomy between Ganymede and Callisto. During the stage of accretion, rocky component is possibly hydrated because of the chemical reaction with liquid water generated by accretional heating. After the end of accretion (and after initial upwelling segregation of excess water by the accretional heating), metal-rock-mixed core starts to warm due to the decay of long-lived radioactive elements. Once the temperature of the mixed core reaches the dehydration point then the viscosity of metal-rock mixture would significantly increase and the efficiency of heat transport would decrease. As a result, the temperature of the mixed core would increase higher and the dehydration of rock would further proceed. Finally the temperature would exceed the melting point of the metallic component, and thereby metal segregation from rocky material could occur. If Ganymede which has larger amount of radiogenic heat source has experienced this positive feedback process, while Callisto has not, the dichotomy in differentiation state between both satellites is explained.

4. Numerical simulation

To test this idea, we performed numerical simulations for the internal thermal evolution and differentiation. Taking into account the heat transport by convection and conduction, we have solved the one-dimensional heat transfer equations from the moon's center to the surface [14]. We neglect tidal heating or any short-lived radioactive elements. In this work, we assumed that the H_2O layer does not have any contaminants. For an initial setting, we assume that Ganymede and Callisto-sized moons, which were formed by accretion of homogeneous mixture of ice, hydrated rock, and metal. According to the accretional temperature profile, initial moons have an outermost water layer (partly a liquid ocean) underlaid by the mixed core composed of rock, metal, and residual water. Assuming long-lived radioactive elements as the unique heat source, the residual water in the mixed core should has segregate from the rocky and metallic component in relatively early stage. Afterward, the temperature in the rock-metal-mixed core would approach the melting point of the metallic component when the dehydration of rock sufficiently takes place, and it would settle down and the metallic core was formed at the moon's center. We consider the accretional temperature profile and the volume fraction of ice, rock, and metal in moons as a parameter, the variation in timing of the water segregation and subsequent formation of the metallic core will be investigated. And we try to express the formation process of distinct layered structure of Ganymede and the difference from Callisto.

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