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Formation of a conductive core, grooved terrains, and strongly differentiated interior of Ganymede due to dehydration of primordial hydrous rock with implication for the dichotomy from Callisto

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Abstract

We propose a new hypothesis for the formation of the conductive core and the surface grooved terrains on Ganymede. Numerical simulations for the interior thermal history are performed assuming that the primordial rocky core was initially hydrated. The primordial core is heated by long-lived radiogenic isotopes and becomes dehydrated if the temperature exceeds about 900 K. The volume expansion accompanying the dehydration is possibly enough large for the formation of the observed grooved terrains on Ganymede. Dehydration also results in the sharp viscosity increase, and the central temperature possibly exceeds the eutectic point of troilite and iron oxide, allowing the formation of a conductive core. Given the reasonable silicate fraction (~45-52 wt %), Ganymede's interior can form a conductive core while slightly smaller Callisto can escape from sufficient heating for melting the conductive material. This may explain the observed dichotomy in the surface geology and internal structure between the both giant icy satellites.

1. Introduction

The small value of the moment of inertia factor and the strong intrinsic magnetic field observed for Ganymede are consistent with a strongly differentiated interior with a conductive core [1]. The widespread existence of the grooved terrains, interpreted as grabens, suggests global lithospheric extension at 2.0+/-2.0 Gyr [2]. According to geological estimates, 0.02-4% increase in the satellite radius may be required for their formation [3,4]. Hence, Ganymede has likely undergone significant temperature rise inside allowing the separation of a conductive core and global expansion during its history. On the other hand, Callisto has similar size and mean density to Ganymede, but has remarkably different aspects, the older surface poor in tectonic deformation and the incompletely differentiated interior [5]. Many studies have proposed hypotheses explaining this contrasting characters by the accreting process [6-10], material differences [11], orbital evolution and tidal heating [12, 13], and differences in the impact energy during late heavy bombardment [14]. However, the release of accretional energy is insufficient for the melting of metallic materials. Either the short-lived radio nuclides or the late stage heavy bombardment should heat the interior too early to explain the global expansion at about 2 Ga. Thus, none of those theories has been sufficiently convinced.
The influence of hydrated silicates to the thermal histories of these satellites may solve this problem. During the stage of accretion, rocky component is possibly hydrated because of the chemical reaction with liquid water generated by accretional heating. The similarity in reflectance spectra among hydrated carbonaceous chondrites and asteroids near Jovian orbit also implies that the constituent material of the icy moons has already been hydrated prior than their incorporation into circum-Jovian nebula in which the regular satellites accreted.

2. Numerical Methods

In order to investigate above influence, we performed numerical simulations for the internal thermal evolution using a spherically symmetric model for the convective and conductive heat transfer with radial dependence of viscosity and heat source distribution [15]. Here we take into account the decay energy of long-lived radioactive elements but neglect tidal heating. A model satellite has the total mass of Ganymede or Callisto. In structural settings, we put 2-layered structure which consists of a primordial core, mixture of hydrous rock and dense, conductive material, and an overlain pure water shell within a range of structural parameters adopted by previous interior models [1, 5]. Initial temperature profile is given by the water ice solidus. As for the rheology, the primordial core has low viscosity ($4x10^{19}$ Pa s independent of temperature) which is presumably controlled by the hydrous rock [16], and once the temperature exceeds the dehydration point (900 K), the viscosity increases to that of dry peridotite [17]. In addition, reaction (endothermic) heat $\sim 4x10^5$ J/kg [18] and total volume increase of 10% due to dehydration of serpentine [19] are considered.

3. Results

The primordial core starts to warm owing to the radiogenic heat. The thermal convection is driven efficiently in such a core because of its low viscosity. However, once the temperature within the mixed core reaches the dehydration point, then the viscosity significantly increases to inhibit effective heat transport. As a result, "thermal runaway" possibly occurs, that is, the core temperature increases higher along with the further progress of dehydration. Given 45 wt % or more of the silicate fraction for Ganymede model, the central temperature exceeds the dehydration point and also the solidus of dense, conductive component (here we suppose $FeS-Fe_3O_4$ eutectic melt as conductive material because metallic iron is unstable in the hydrated system), which implies the formation of a conductive core. On the other hand, Callisto model needs more than ~52 wt% of silicate fraction to create the conductive core.

During 4.5 Ga, the central region with 1000-1500 km radius in the primitive core has been dehydrated in the differentiated Ganymede models. This results in the satellite volume expansion yielding about 0.2-0.6 % increase in radius, consistent with the geological estimates for Ganymede. In addition, dehydration occurs around 1 Gyr after the satellite formation, which is also consistent with the cratering age of the grooved terrains.

On the other hand, the Callisto models with mass fraction less than 52 wt% have never heated up sufficiently to melt the conductive component because the heat loss is more efficient for smaller body. This implies that the observed dichotomy between Ganymede and Callisto may be explained by the difference in the thermal evolution of primordial hydrated cores with different size even the both satellites share the same rocky mass fraction around 45-52 wt%. This range of rocky mass fraction is consistent with the bulk properties of both satellites.

References

[1] Anderson, J.D. et al., Gravitational constraints on the internal structure of Ganymede, Nature 384, 541-543, 1996.
[2] Zahnle, K. et al., Cratering rates in the outer Solar System, Icarus, Vol. 163, pp. 263-289, 2003.
[3] Golombek, M. P., Constraints on the expansion of Ganymede and the thickness of the lithosphere, J. Geophys. Res. 87, 77-83, 1982.
[4] Collins, G. C. et al., The role of extensional instability in creating Ganymede grooved terrain: Insights from Galileo high-resolution stereo imaging, Geophys. Res. Lett. 25, 233-236, 1998.
[5] Anderson, J.D. et al., Shape, mean radius, gravity field and interior structure of Callisto, Icarus 153, 157-161, 2001.
[6] Schubert, G. et al., Internal structures of the Galilean satellites. Icarus 47, 46-59, 1981.
[7] Lunine, J. I. and Stevenson, D. J. Formation of the Galilean satellites in a gaseous nebula. Icarus 52, 14-39, 1982.
[8] Stevenson, D. J. et al., Satellites, pp. 39-88, Univ. Arizona Press, 1986.
[9] Canup, R. M. and Ward, W. R., Formation of the Galilean satellites: Condition of accretion, Astron. J. 124, 3404-3423, 2002.
[10] Barr, A. C. and Canup, R. M., Constraints on gas giant satellite formation from the interior states of partially differentiated satellites, Icarus 198, 163-177, 2008.
[11] Friedson, A. J. and Stevenson, D. J. Viscosity of rock-ice mixtures and applications to the evolution of icy satellites. Icarus 56, 1-14, 1983.
[12] Tittemore, W. C., Chaotic motion of Europa and Ganymede and the Ganymede-Callisto dichotomy, Science 250, 263-267, 1990.
[13] Peale, S. J., Origin and evolution of the natural satellites., Ann. Rev. Astron. Astrophys., 37, 533-602, 1999.
[14] Barr, A. C. and Canup, R. M., Origin of the Ganymede–Callisto dichotomy by impacts during the late heavy bombardment, Nature Geoscience 3, 164-167, 2010.
[15] Kimura, J. et al., Size and compositional constraints of Ganymede's metallic core for driving an active dynamo, Icarus 202, 216-224, 2009
[16] Hilairet N., High-Pressure Creep of Serpentine, interseismic deformation, and initiation of subduction, Science 318, 1910-1913, 2007.
[17] Karato, S. et al., Rheology of synthetic olivine aggregates: Influence of grain size and water. J. Geophys. Res. 91, 8151–8176, 1986.
[18] Weber, J. N.et al., Dehydration of serpentine: Heat of reaction and reaction kinetics at P_{H2O}=1atm, American Mineralogist 50, 450-464, 1965.
[19] Kono, Y. et al., Effect of H2O released by dehydration of serpentine and chlorite on compressional wave velocities of peridotites at 1GPa and up to 1000◦C, Phys. Earth Planet. In., Vol. 161, pp. 215-223, 2007.