EPSC Abstracts
Vol. 6, EPSC-DPS2011-358-1, 2011
EPSC-DPS Joint Meeting 2011

Turning point in differentiation history between Ganymede and Callisto induced by dehydration of primitive hydrous rock

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

Despite Jovian moon Ganymede and Callisto have similar size and bulk density, their interiors are geodetically estimated to be quite different. We propose a new hypothesis to create the interior dichotomy by focusing on a dehydration of primitive hydrous rock and metal mixed core. Numerical simulations for the moons' thermal history are performed with various silicate fractions which are constrained by the factor of moment of inertia and bulk density. In the intermediate silicate fraction (~50 wt %), our results show that Ganymede's interior can form the metallic core while sli-ghtly smaller Callisto would not heat up sufficiently to melt the metal. In addition, the volume expansion due to dehydration and the timing of dehydration event in our results are consistent with the amount of radial increment estimated from previous geological estimate and the cratering age of the grooved terrain.

1. Introduction

From gravity data acquired by the Galileo spacecraft, it has been found that Ganymede has a significantly small value of the moment of inertia (MoI) factor, which suggests a highly differentiated interior with the metallic core at the center [1]. On the other hand, Callisto has size only slightly smaller than Ganymede but shows larger value of the MoI implying incomplete differentiation [2]. Many studies have proposed hypotheses explaining this contrasting interiors between the two moons by the accreting process [3-7], material differences [8], orbital evolution and tidal heating [9, 10], and differences in the impact energy during late heavy bombardment [11]. But none of these theories has been sufficiently convinced.

So far, the possible influence of hydrated silicates to the thermal histories of these satellites has never been explored. 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.

After the end of accretion (and after initial upwelling segregation of excess water by the accretional heating), hydrous rock-metal-mixed core starts to warm due to the decay of long-lived radioactive elements. The thermal convection occurs efficiently in such mixed core because of low viscosity of hydrated minerals. However, once the temperature within the mixed core reaches the dehydration point then the viscosity would significantly increase and the efficiency of heat transport would decrease. As a result, “thermal runaway” would occur, that is, the core temperature would increase higher and the dehydration of rock would further proceed. Consequently, the temperature would exceed the melting point of the metallic component, and thereby metal segregation from rocky material could occur. If the trigger of thermal runaway needs sufficient rocky mass near that of Ganymede, this could explain the dichotomy in differentiation state between the two satellites and the metallic core formation of Ganymede.

2. Numerical Methods

In order to investigate above hypothesis, 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 [12]. Here we take into account the decay energy of long-lived radioactive elements but neglect tidal heating. In structural settings, we put 2-layered structure which consists of the hydrous rock and metal mixed core overlain by the pure water shell within a range of structural parameters adopted by previous interior models [1, 2] (various silicate mass fractions, 20~60 wt %, are assumed). Initial moon has an isothermal profile of 273 K. As for the rheology, we consider that the initial mixed-core has low viscosity (10^{20} Pas independent of temperature as the standard parameter) which corresponds to the hydrous rock [13], and when the temperature exceeds the dehydration point (900 K), the viscosity rapidly increases to that of dry peridotite [14].

4. Results

In case of the same silicate fraction of ~45 wt % in both moons which is an intermediate value, the central temperature would exceeds the dehydration point and then Ganymede's temperature attains the solidus of metallic component, which implies the formation of metallic core. On the other hand, Callisto will not heat up sufficiently to melt the metallic component because the heat loss is more efficient for smaller body. In case that the hydrous core has lower viscosities than the standard (4 times 10^{19} Pa s or lower), both moons cannot be warmed up to the liquidus for the metal. Moreover, in the higher silicate fraction (55 wt % or higher), both moons will be differentiated, while in the lower fraction (40 wt % or lower) both moons will not be differentiated.

These results show that the triggering condition for the thermal runaway and metallic core formation is dependent on the viscosity of hydrated core and the total silicate mass. When the hydrated core has viscosity near 10^{20} Pa s, which is consistent with that of the serpentine within the Earth's upper mantle, the total mass of silicate required for the thermal runaway and metallic core formation is close to that estimated for Ganymede.

5. Implications for the surface tectonics on Ganymede

The grooved terrains on Ganymede have been interpreted as grabens resulting from lithospheric extension (global expansion). To form all the grooves, the satellite radius is estimated to have increased 0.02 to 1 % after the cease of heavy bombardment [15]. On the other hand, dehydration of serpentine is known to have increase in total volume of 10 % [16].

Given the model parameter set consistent with the present structural difference between Ganymede and Callisto, the central region with 800 km radius in the primitive-mixed core has been dehydrated for the model Ganymede. This results in about 1.0 % increase in satellite radius, consistent with the previous geological estimates. In addition, dehydration occurred during 1 to 2 Billion years after the satellite formation, which is also consistent with the cratering age on the grooved terrains [17]. These agreements with observations support that the thermal runaway of initially hydrated core is a favourable process regulating the turning point of thermal history between Ganymede and Callisto.

References

[1] Anderson, J.D. et al., Gravitational constraints on the internal structure of Ganymede, Nature 384, 541-543, 1996.
[2] Anderson, J.D. et al., Shape, mean radius, gravity field and interior structure of Callisto, Icarus 153, 157-161, 2001.
[3] Schubert, G. et al., Internal structures of the Galilean satellites. Icarus 47, 46-59, 1981.
[4] Lunine, J. I. and Stevenson, D. J. Formation of the Galilean satellites in a gaseous nebula. Icarus 52, 14-39, 1982.
[5] Stevenson, D. J. et al., Satellites, pp. 39-88, Univ. Arizona Press, 1986.
[6] Canup, R. M. and Ward, W. R., Formation of the Galilean satellites: Condition of accretion, Astron. J. 124, 3404-3423, 2002.
[7] 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.
[8] 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.
[9] Tittemore, W. C., Chaotic motion of Europa and Ganymede and the Ganymede-Callisto dichotomy, Science 250, 263-267, 1990.
[10] Peale, S. J., Origin and evolution of the natural satellites., Ann. Rev. Astron. Astrophys., 37, 533-602, 1999.
[11] 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.
[12] Kimura, J. et al., Size and compositional constraints of Ganymede's metallic core for driving an active dynamo, Icarus 202, 216-224, 2009
[13] Hilairet N., High-Pressure Creep of Serpentine, interseismic deformation, and initiation of subduction, Science 318, 1910-1913, 2007.
[14] Karato, S. et al., Rheology of synthetic olivine aggregates: Influence of grain size and water. J. Geophys. Res. 91, 8151–8176, 1986.
[15] Golombek, M.P., Constraints on the expansion of Ganymede and the thickness of the lithosphere, J. Geophys. Res. 87, 77-83, 1982.
[16] 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.
[17] Zahnle et al., Cratering rates in the outer Solar System, Icarus, Vol. 163, pp. 263-289, 2003.