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Internal Structure of Icy Satellites of Jupiter

O.L. Kuskov, V.A. Kronrod and A.P. Zhidikova

(Vernadsky Institute of Geochemistry and Analytical Chemistry RAS, Moscow, Russia, kuskov@geokhi.ru)

Models of the internal structure of completely differentiated Europa and Ganymede, and partially differentiated Callisto have been constructed on the basis of Galileo gravity measurements, geochemical constraints on composition of ordinary and carbonaceous chondrites, and thermodynamic data on the equations of state of water, high-pressure ices, and meteoritic material. Geophysically and geochemically permissible thicknesses of Europa's and Ganymede's outer water-ice shell are determined. We show that Callisto must only be partially differentiated into an outer ice-I layer, a water ocean, a rock-ice mantle, and a rock-iron core. The results of modelling support the hypothesis that Callisto may have an internal liquid-water ocean.

Introduction. The purpose of this study is to reproduce characteristic features of the internal structure of icy satellites of Jupiter (thickness of an outer water-ice shell, mantle composition and density, and core sizes and masses) on the basis of Galileo gravity measurements (the mass and moment-of-inertia factor) and geochemical constraints on the composition of silicate fractions of ordinary and carbonaceous chondritis, which are taken as representatives of nebula matter. The general methodology is to combine the geophysical and geochemical constraints and thermodynamic approach, and to develop, on this joint basis, the self-consistent models of Europa, Ganymede and Callisto, accounting for their composition and internal structure.

Approach. The mass and mean moment of inertia [1-3] are used as input data for determination of (1) the thickness and phase state of an outer water-ice shell, (2) the density distribution with depth, and (3) the core sizes and masses. The higher value of the moment of inertia of Callisto by comparison with the other satellites suggests weaker differentiation of the Callisto interior. Various compositional models are considered for a satellite core: γ-iron core (ρ=8.1 g cm^{-3}), Fe-10 wt%S core (5.7 g cm^{-3}), a eutectic Fe-FeS core (5.15 g cm^{-3}), and troilitic FeS core (4.7 g cm^{-3}). The phase compositions and mantle densities are modelled within the system Na_2O-TiO_2-CaO-FeO-MgO-Al_2O_3-SiO_2-H_2O-Fe-FeS including the solid solutions. The equilibrium phase assemblages were calculated using the technique of free energy minimization and thermodynamic data for minerals summarized in the THERMOSEISM database [4]. The equations of state of minerals were calculated in the Mie-Grüneisen-Debye approximation. The density variations in the mantle and core radii are found by the Monte-Carlo method.

Europa. The results show that Europa is differentiated into a water-ice shell, anhydrous mantle and iron-sulfide core. Both L/LL and CM chondrite compositions match the total mass and moment of inertia value of Europa and can be regarded either as the primary material of Europa (carbonaceous chondrites) or as a reasonable analogue for its anhydrous rock-iron core (ordinary chondrites). Within these models, the permissible thickness of Europa's water-ice shell lies between 105 and 160 km (6.2-9.2% of total mass) for any model of differentiated or undifferentiated chondritic matter. The amounts of iron and iron sulfide, and the (Fe_{tot}/Si) ratio of Europa's anhydrous rock-iron core are not consistent with the bulk compositions of the most oxidized CI chondrites and the most reduced H chondrites. It is likely that Europa inherited a significantly higher proportion of material close to the moderately oxidized L/LL type chondrites rather than to the carbonaceous chondrites. Core radii are estimated to be 470-640 km for the L/LL chondritic models with a central Fe-10 wt%S core (5.3-12.5% of total mass). The allowed thickness of Europa's H_2O layer (whether liquid or ice) ranges from 115$\pm$10 km (6.8$\pm$0.6% of total mass) for a differentiated L/LL-type chondritic mantle with a crust to 135$\pm$10 km (7.9$\pm$0.5%) for an undifferentiated L/LL chondritic mantle.

Ganymede. As for Europa, a competing idea is that Ganymede may or may not possess salty liquid-water ocean. Two alternative density models of an outer shell are considered. Model (A) - an outer shell is completely composed of the high-pressure ice phases (no water is present), resulting in a maximum in the density of an outer shell. Model (B) - in the three-layer model of an outer water-ice shell, we assume that below a shell of ice I (30-120 km thick), a liquid layer of 230-140 km thick may exist, resulting in a minimum density of an outer shell. The ice-V + ice-VI + water triple point lies at 273 K and 0.64 GPa. We adopted a "conductive" model [5] where a mixed layer of water and high-pressure polymorphs of ice may coexist at depths between 260 km and an ice-rock interface. Our calculations show that the ice thickness of the outer shell in model (A) is about 890-920 km and in model (B) is 780-850 km. The content of H_2O in Ganymede's icy envelope is 46-48% of the total mass.

Callisto. The problem of modeling the internal structure of Callisto is described by a system of equations specifying the conditions of thermodynamic and hydrostatic equilibrium, equations of state and heat conduction, and mass and moment conservation. We show that Callisto must only be partially differentiated into an outer ice-I layer, a water ocean, a rock-ice mantle, and a rock-iron core free of ice (mixture of anhydrous silicates and/or hydrous silicates + Fe-FeS alloy, $3150 < \rho < 3620$ kg m^{-3}). Assuming conductive heat transfer through the ice-I crust [6], heat flows were estimated and the possibility of the existence of a water ocean in Callisto was evaluated. The liquid phase is stable (not freezing) beneath the ice crust, if the heat flow is between 3.3 and 3.7 mW m^{-2}, which corresponds to the heat flow form radiogenic sources [7]. The thickness of the ice-I crust is 135-150 km, and that of the underlying water layer, 120-180 km. The allowed total (maximum) thickness of the outer water-ice shell is up to 270-315 km. The results of modelling support the hypothesis that Callisto may have an internal liquid-water ocean. The surface temperature of Callisto is expected to be 100-112 K. Rock-iron core radii, depending on the presence or absence of hydrous silicates, do not exceed 500-700 km, the thickness of an intermediate ice-rock mantle is not less than 1400 km, and its density, ranging from 1960 to 2500 kg m^{-3}, is always less than that of the rock-iron core. The ice content in the ice-rock mantle is between 35 and 42 wt% if the total thickness of an outer shell is maximal and equal to 315 km. The amount of H_2O in Callisto (water + ices) ranges between 46-47 wt% for an ice-rock mantle composed of dry silicates + hydrous silicates and 52-53 wt% for an ice-rock mantle composed of anhydrous rock. Taking into account the H_2O content in hydrous silicates, the total amount of H_2O in Callisto is found to be 48-53 wt%.

The correspondence between the density and moment of inertia values for bulk ice-free Io, rock-iron core of ice-poor Europa, and rock-iron cores of Ganymede and Callisto shows that their bulk compositions may be, in general, similar and may be described by the composition close to a material of the L/LL type chondrites with the (Fe_{tot}/Si) weight ratios ranging from 0.9 to 1.3. Planetesimals composed of these types of ordinary chondrites could be considered as analogues of building material for the rock-iron cores of the Galilean satellites. Similarity of bulk composition of the rock-iron cores of the inner and outer satellites implies the absence of iron-silicon fractionation in the protojovian nebula.

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