

CHEMICAL DIFFERENTIATION AND INTERNAL STRUCTURE OF EUROPA AND CALLISTO

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Models of the internal structure of Europa and Callisto based on Galileo gravity measurements and geochemical constraints on the composition of silicate fractions of ordinary and carbonaceous chondrites are constructed. A permissible thickness of Europa's outer water-ice shell lies between 100 and 160 km for these classes of chondritic matter. The total thickness of an outer water-ice shell of Callisto is up to 270-320 km. 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 Europa and Callisto (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 chondrites, 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 and Callisto, accounting for their composition and internal structure.

Approach. The mass and mean moment of inertia [1,2] 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. Two compositional models are considered for a core: an Fe-10 wt%S core for ordinary chondrites and an FeS core for CM chondrites. The phase compositions and mantle densities are modelled within the system $\text{Na}_2\text{O-TiO}_2\text{-CaO-FeO-MgO-Al}_2\text{O}_3\text{-SiO}_2$ 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 THERMOSISM database [3]. The density variations in the mantle and core radii are found by the Monte-Carlo method.

Europa's composition and internal structure. The results show that Europa is differentiated into a water-ice shell, anhydrous mantle and iron-sulfide core [3]. 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, Fig. 1. The

amounts of iron and iron sulfide, and the $(\text{Fe}_{\text{tot}}/\text{Si})$ 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, Fig. 2. 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 ± 10 km ($6.8 \pm 0.6\%$ of total mass) for a differentiated L/LL-type chondritic mantle with a crust to 135 ± 10 km ($7.9 \pm 0.5\%$) for an undifferentiated L/LL chondritic mantle.

Callisto's composition and internal structure. 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 consider a six-layer model of Callisto consisting of an ice layer, a water ocean, a three-layer rock-ice mantle, and a rock-iron core. In this study we proposed that rheological behaviour of the ice-I was non-newtonian. In this case the outer ice shell becomes stable against convection [4]. In agreement with [4], the distribution of temperature can be calculated from the conditions of conductive heat transfer in an ice-I layer, and the temperature profile in the fields of stability of water and high-pressure ices goes along the adiabat. Internal structure of Callisto with an internal ocean is shown in Fig. 3. The maximum thickness of the outer water-ice shell is 315-320 km, Fig. 4. The radii of the rock-iron core for a model of Callisto with an internal ocean are in the range of 0-950 km. Concentration of ice (40 wt%) is constant in the rock-ice mantle if the total thickness of an outer ice shell is maximal (~320 km). The content of water and ice in Callisto is between 47 and 54% for a mantle model composed of dry silicates + hydrous silicates and 49-54% for a mantle model composed of dry rock. The total thickness of an outer water-ice shell of Callisto is up to 270-315 km. The permissible thicknesses of an icy crust and internal ocean are estimated to be 135-150 km and 120-180 km respectively, Fig. 4. The results support the hypothesis that Callisto may have an internal liquid-water ocean.

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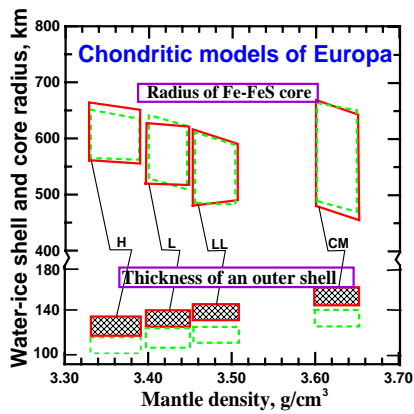


Fig. 1

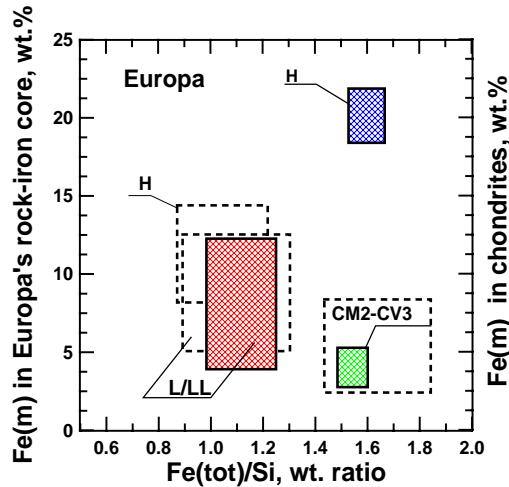


Fig. 2

Fig. 1. The effect of the mantle density on the thickness of an outer water-ice shell and core sizes for chondritic models of Europa's differentiated (dashed lines) and undifferentiated (solid lines) mantle. For the L/LL material, the allowed thickness of H₂O layer ranges from 105 to 145 km; for the CM material, H(H₂O) = 125-160 km.

Fig. 2. Element ratios for Europa (empty boxes) and chondrites (shaded boxes). The empty boxes outline an allowed iron to silicon ratio and content of pure iron, and show that Europa's bulk composition appears to be within the composition of the L/LL chondrites. Geophysical and geochemical constraints show that H and C chondritic materials may be excluded for the bulk compositions of the satellite.

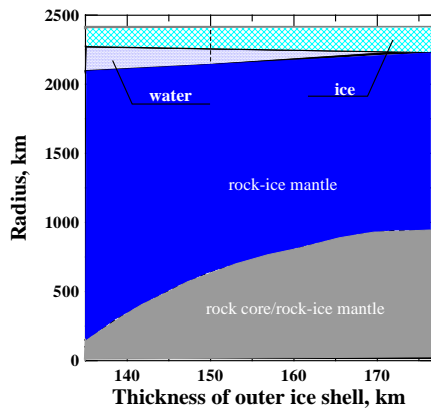


Fig. 3.

Fig.3. Internal structure of Callisto with a subsurface ocean. Because Callisto is only partially differentiated, a layer of a mixture of high-pressure ices and rock-iron material (rock-ice mantle) must exist between the outer ice-water shell and the rock-iron core. The maximum radius of the rock-iron core is 950 km.

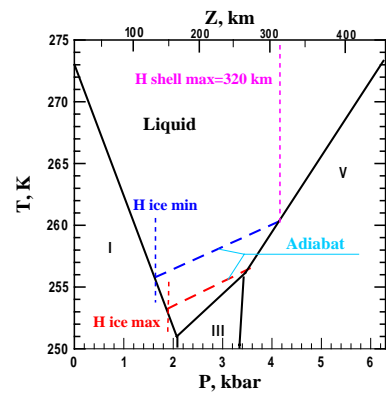


Fig. 4.

Fig. 4. The permissible thickness of Callisto's water-ice shell. If heat flow from Callisto is in the range of 3.3-3.7 mW/m², the permissible thickness of the water-ice shell would be 270-320 km. The thickness of an icy crust is estimated to be 135-150 km. The thickness of an internal ocean is found to be 120-180 km.

References: 1. Anderson J.D. et al., Icarus, 2001, 153: 157. 2. Anderson J.D. et al., Sci., 1998, 281: 2019. 3. Kuskov O.L., Kronrod V.A., Icarus, 2001, 151: 204. 4. Ruiz J., Nature. 2001, 412: 409.