CALLISTO'S AMOUNT OF ICE AND WATER DERIVED FROM THE GEOPHYSICAL CONSTRAINTS

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Jovian icy satellite Callisto is comparable in size with Mercury. The average density of Callisto (1.8344 g cm^{-3}) is the lowest one among the Galilean satellites. The density of Callisto suggests that it is composed of a mixture of H_2O ices and rock. The term "rock material" is used here to denote the mixture of the iron-rock (Fe-Si) component composed of dry silicates or hydrous silicates and iron-sulfide core material (Fe-FeS alloy).

An important question is the possible existence of a subsurface water ocean under icy crust. Geophysical data indirectly support the possibility of the presence of a liquid layer (ocean) beneath the solid ice crust. The existence of a water ocean was recently supported by magnetic measurements obtained with *Galileo* mission. The discovery of the induced magnetic field of Callisto has been interpreted as evidence for a subsurface ocean [1].

This work is an attempt to construct a self-consistent model of the internal structure of Callisto using the proposed approach that integrates the geophysical (the mass and moment of inertia [2]) and geochemical (composition of meteorites) constraints [3, 4]. The equations of state of water and high-pressure ices are taken into account [4]. Ordinary L and LL chondrites are taken as representatives of the nebular matter. The paper presents the results for determining the thickness of an ice-liquid shell, the mantle density, and Fe-FeS-core sizes of the satellite on the basis of minimizing the deviations of the calculated and observed geophysical parameters. For this goal, we have used the THERMOSEISM software to estimate phase relations and mantle density of the satellite [3].

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 (Fig. 1).

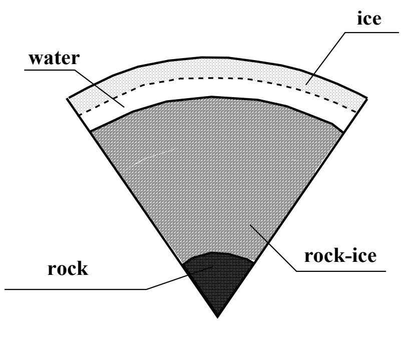

Fig. 1. Internal structure of Callisto

The densities in the mantle shells and core radii are found by the Monte-Carlo method: the entire range of the geophysically and petrologically allowed mantle densities ($\rho_{min,\,i} < \rho_i < \rho_{max,\,i}$) is examined and those values that obey the balance relations for the mass and moment within the uncertainty limit are chosen. The core sizes are evaluated from the conservation equation for the mass.

The concentration of icy component in each (i) rock-ice reservoir was determined as:

$$C_{i,ice} = \left[\frac{\rho_{ice}(\rho_{Fe-Si} - \rho)}{\rho(\rho_{Fe-Si} - \rho_{ice})} \right]_i$$

$$C_{i+1,ice} < C_i$$

In these equations $\rho_{i.Fe\text{-}Si}$, $\rho_{i,ice}$, ρ, and $C_{i,ice}$ - are the densities of the rock-iron component, densities of ice, densities of the rock-ice mixture, and mass fraction of ices.

The weight concentration of ice does not increase with depth, because the denser rock component can move relative to ice only toward the center of the satellite. In the present study we proposed that rheological behavior of the ice-I was non-newtonian. In this case the outer ice shell becomes stable against convection [5]. In agreement with Ruiz [5], the distribution of temperature can be calculated from the conditions of conductive 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.

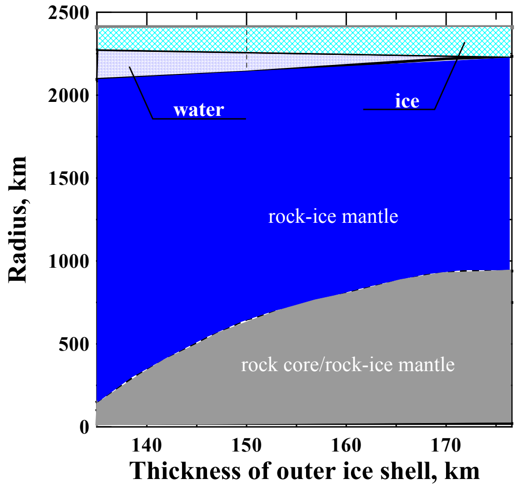

Fig.2. Internal structure of Callisto with an internal ocean. The maximum thickness of the outer water-ice shell is 315 km. The radii of the rock-iron core for a model of Callisto with an internal ocean are in the range of 0-950 km.

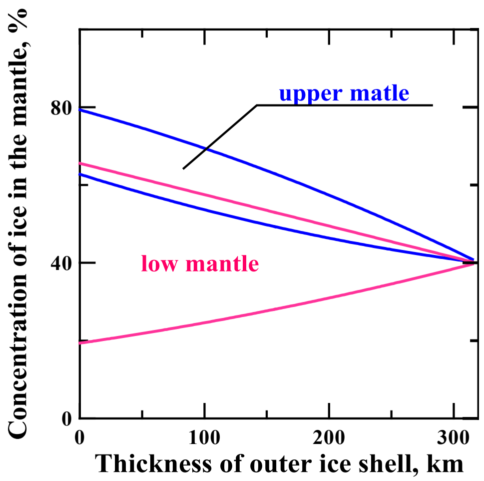

Fig.3. Concentration of ice in the mantle as a function of the thickness of an outer ice shell.

We have constructed models of the constitution of Callisto (Fig.2) with internal ocean. The maximum thickness of the outer water-ice shell is 315 km. The radii of the rock-iron core for a model of Callisto with an internal ocean are in the range 0-950 km. Geophysically permissible concentration of ice in the mantle as a function of the thickness of an outer ice shell is shown in Fig. 3.

Concentration of ice (40 wt%) is constant in the rock-ice mantle if the total thickness of an outer ice shell is maximal and equal to 315 km. The content of water and ice in Callisto is between 47 and 54% (Fig. 4) for a mantle model composed of dry silicates + hydrous silicates and 49-54% for a mantle model composed of dry rock.

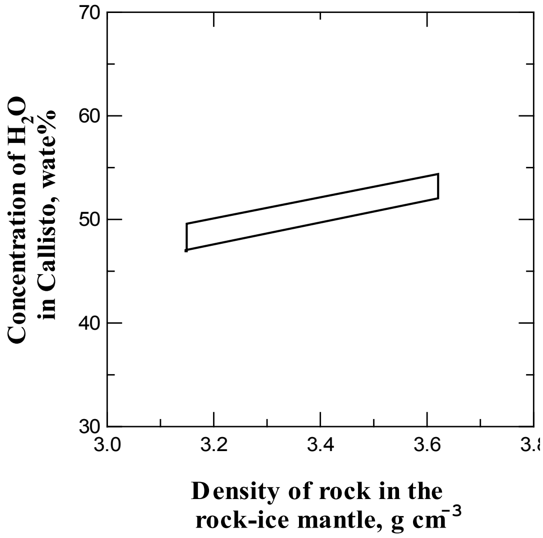

Fig.4. Bulk concentration of H_2O in Callisto - concentration of H_2O includes the total amount of H_2O in the outer shell + ice-rock mantle with dry silicates.

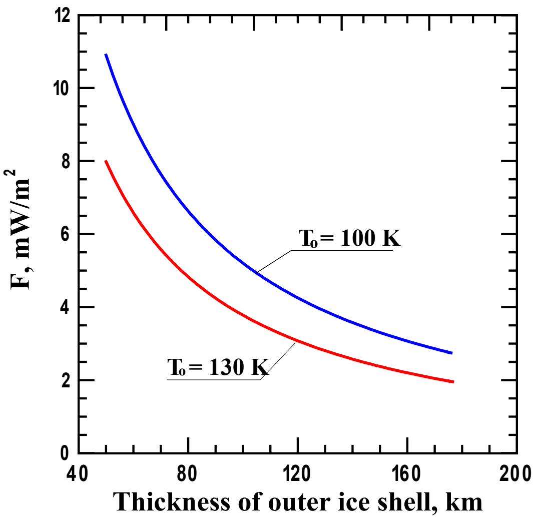

Fig.5. Heat flow F as a function of the thickness of a conductive ice shell of Callisto.

Before the onset of convection, heat is transmitted into Callisto's outer ice shell only by conduction. Using the phase diagram of high-pressure ices and temperature distribution in the ice shell, model of the water-ice shell was constructed. The values of heat flow from the satellite interior were estimated. The liquid phase is stable (not frozen in present) if heat flow is greater than 2 mW m^{-2}. Radiogenic heat flow is between 3.3 and 3.9 mW m^{-2}. We have estimated the maximum heat flow up to 3.7 mW m^{-2} and heat flow from Callisto is in the range 3.3-3.7 mW m^{-2}.Fig. 5 shows heat flow F as a function of the thickness of a conductive ice shell of Callisto (H_{ice}) and surface temperature T_o.

The thickness of the outer shell is strongly dependent on the heat flow or on the thickness of ice-I. If heat flow from Callisto is in the range of 3.3-3.7 mW m^{-2}, geophysically permissible thickness of the water-ice shell would be 270-315 km. Fig. 6 shows the thickness of an outer water-ice shell as a function of the thickness of a conductive ice shell. 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; the radii of the rock-iron core are between 0 and 600 km.

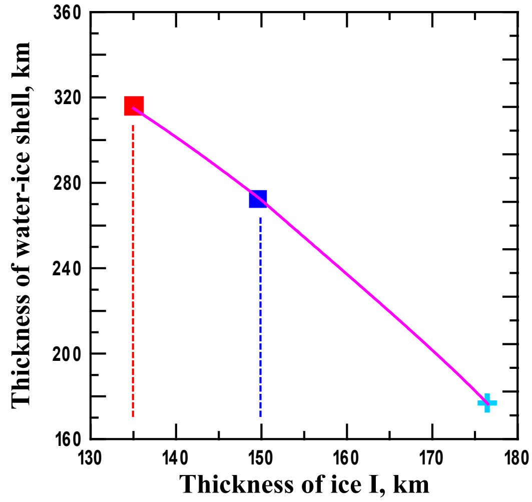

Fig.6. The thickness of an outer water-ice shell as a function of the thickness of a conductive ice shell.

Conclusions

We have constructed models for the internal structure of Callisto. The total thickness of an outer water-ice shell of Callisto is estimated in the range of 270-315 km. The radii of the rock-iron core are in the range of 0-1280 km for a model without internal ocean. The content of water and ice in Callisto is between 49 and 54%. The values of heat flow (3.3-3.7 mW/m^2) from Callisto interior were estimated assuming conductive heat transfer in the solid ice-I crust. The results of modeling support the hypothesis that Callisto may have an internal liquid-water ocean. The permissible thickness of an icy crust is estimated to be 135-150 km and of an internal ocean to be 120-180 km, the radii of the rock-iron core are in the range of 0-600 km. The surface temperature is found to be 100-112 K.

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References

1. *Zimmer C. et al.,* Subsurface oceans on Europe and Callisto // Icarus. 2000. V. 147. PP. 329-347.
2. *Anderson J.D. et al.,* Shape, mean radius, gravity field, and interior structure of Callisto. Icarus, 001. V. 153. PP. 157-157.
3. *Kuskov O.L., Kronrod V.A*. Core sizes and internal structure of the Earth's and Jupiter's satellites // Icarus. 2001. V. 151. PP. 204-227.
4. *Kronrod V.A. and Kuskov O.L.* Chemical differentiation of the Galilean satellites of Jupiter: 1.Internal structure of Callisto's water-ice shell // Geochem. Intern. 2003. V. 41. PP. 968-983.
5. *Ruiz J*. Stability against freezing of an internal liquid-water ocean in Callisto // Nature. 2001. V. 412. PP. 409-411.

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