Modeling of the thermal evolution of the cores of icy giant satellites

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Abstract. Questions on the composition, aggregate state, size and physical properties of the giant planets satellites cores, their thermal evolution, as well as the mechanisms of their formation, are still the subject of numerous discussions. Models of the internal structure of large icy satellites impose restrictions on the composition of satellite cores in accordance with the matter of L/LL or CI chondrites or their mixture. The temperature distributions in the cores of satellites largely determine the measure of hydration of their silicate component, the presence or absence of internal metal cores. In this paper, we present the results of numerical modeling of nonstationary temperature regimes in cores with allowance for convective transfer processes. According to the results of calculations, it can be concluded that in the presence of convection, the composition of the core largely determines the thermal evolution of the core. For example, the temperature difference between silicate and hydrosilicate composition, can reach ≈ 600 K.

1. Introduction

As a result of research missions to Jupiter and Saturn implemented in recent decades (“Galileo”, “Cassini–Huygens”), a fundamentally new information about the ice giant satellites Ganymede, Callisto and Titan was obtained, which made it possible to construct models of the internal structure of the satellites. The main existing models of satellites include a water-ice shell (± undifferentiated rock-ice mantle), an iron silicate core (± Fe–FeS inner core) [1, 2]. Questions on the composition, state of aggregation, size and physical properties of satellite cores, their thermal evolution, as well as the mechanisms of its formation are still the subject of numerous discussions. Models of the internal structure of large ice satellites [1, 2, 3] impose restrictions on the composition of satellite cores in accordance with the matter of ordinary (L / LL) or carbonaceous (CI) chondrites or their mixture. Temperature distribution in cores largely determine the degree of hydration of their silicate component, the presence or absence of internal metal core. In this paper, we present the results on estimates of non-stationary temperature regimes in cores taking into account the processes of convective heat transfer and the composition of the core.

2. Model Description

At the final stage of accretion from rocky-ice planetesimals, the temperature in the near-surface region of the satellite increases and reaches the melting point of ice. As a result, the separation of the stony-iron component, its migration to the center of the satellite and the formation of the silicate-iron core occurs. The process of heating of the proto-core by the energy of radioactive decay to a temperature...
exceeding the melting point of ice (~500 K), redistribution of ice, water and rock material with the formation of a homogeneous core occurs over a time of about 500 million years [4]. Subsequently, radioactive sources of energy become the cause of the thermal evolution of the core.

It is assumed that satellite core consists of a mixture of L / LL and CI - chondritic substance, further with indices Si (silicate), HS (hydrosilicate), respectively. The mass concentrations of CI chondrites ($C_{\text{CI}}$) and L / LL chondrites ($C_{\text{LL}}$) are specified. The cores of icy satellites, after formation, are heated as a consequence of the radioactive decay of radioactive isotopes. The approximation of the radiogenic heat release of chondrite matter by the radioactive decay equation in the interval of 500–4.500 Ma from CAI leads to the initial value of the power of radiogenic sources $H_{0_{\text{Si}}} = 3.1334 \times 10^{-11}$ W/kg and $H_{0_{\text{HS}}} = 2.1336 \times 10^{-11}$ W/kg, and also allows determine the constants of radioactive decay of L/LL-chondrite and CI-chondrite matter: $\lambda_{\text{SI}} = -1.4457 \times 10^{-17}$, $\lambda_{\text{HS}} = -1.4553 \times 10^{-17}$.

The temperature distributions in the cores are found as a result of the numerical solution of a one-dimensional nonstationary heat equation with initial (500 K) and boundary (360 K) conditions.

Two mechanisms of heat transfer are considered: conductive (diffuse mechanism) and convective (transfer of liquid volumes with different temperatures). The transition from conductive to convective regime is estimated by Rayleigh number ($Ra$) for the case of internal uniformly distributed in the volume energy sources [5, 6]:

$$Ra(t) = \rho^2 m \alpha m g_m R^2 / (k m K_m \eta_m)$$

where the subscript $m$ denotes the average parameters in the inner convective zone with the radius $R_0$. $g$ is gravitational acceleration; $R_0 = R_C - \delta$, $R_C$ – the radius of the core, $\delta$ – the thickness of the thermal boundary layer (the layer without convection). The thickness of the thermal boundary layer $\delta$ is determined from the condition on the critical Rayleigh number $Ra_{\text{cr}} \approx 100$ [5].

Heat transfer in the convective zone is modeled by the effective thermal conductivity coefficient: $K_{\text{ef}} = Nu K_{\text{cond}}$, [6]. Here $Nu$ is the dimensionless Nusselt number; $Nu = 1.04 (Ra / Ra_{\text{crit}})^{1/3}$, $Ra_{\text{crit}} \approx 1000$ [7]. In the case when $Ra < Ra_{\text{crit}}$, $K_{\text{ef}} = K_{\text{cond}}$.

The temperature distributions in the core are found as a result of the numerical solution of a one-dimensional nonstationary equation that takes into account both conductive and convective transfers using the effective transfer coefficient $K_{\text{ef}}$, as well as the processes of heating of the core material due to the radiation energy:

$$\rho C_p \frac{\partial r}{\partial t} = \frac{1}{r^2} \frac{\partial}{\partial r} \left[ r^2 K_{\text{ef}} \frac{\partial r}{\partial r} \right] + A \exp(-\lambda t)$$

where $r$ is the current radius, $\rho$ – the density, $C$ – the heat capacity, $t$ – the time, $A$ – the heat release per unit mass of the core at the initial moment of time, $\lambda$ – decay constant.

The initial conditions are: $t = 500$ million years, $T = 500$ K, boundary conditions: $R = R_{\text{core}}$, $T = 360$ K; $R = 0$, $\partial T / \partial r = 0$.

Equation (2) is solved by a finite-difference method. The accuracy of the calculations was checked using an analytical solution.

In the calculations, the following values were set for silicates and hydrosilicates, respectively: $\rho = 3620$ and $2800$ kg m$^{-3}$; heat capacity $C_p = 920$ and $1360$ J / kg · K; thermal conductivity $K = 4.2$ W / m K and 2.95 W / m K. The viscosity of silicates–hydrosilicates mixture is calculated using the isostress model [8]:

$$\eta_{\text{HS}} = 4 \times 10^{19} f_S \cdot 4.9 \times 10^{8} f_S \cdot \exp(f_S \cdot 23) \left( T_{\text{molb}} / T \right),$$

(3)
where $f_{HS}, f_S$ are volume fractions of hydrosilicates, silicates; $T, T_{melt}$, is the temperature in the computational domain, the melting point of silicates corresponding to $P$–$T$ conditions. The viscosity of the composite in (3) is calculated from the average physical parameters of the mixture in the calculated volume.

The viscosity of silicates is determined depending on temperature and pressure similarly to [9], the viscosity of hydrosilicates is assumed to be constant $4 \times 10^{19} \text{Pa s}$ in the entire range of temperatures and pressures [10]. Possible phase transitions of hydrosilicates to silicates in the temperature range 900 K are not considered.

3. Results

Calculations of thermal evolution in cores of giant satellites with hydrosilicate concentrations from 0 to 100% and radii $R_{core}$ from 500 to 2000 km were performed.

During the heating of the core by radiogenic sources uniformly distributed over the volume, the temperature in the core gradually increases, and as a consequence, the viscosity of the substance decreases, which leads to the formation of a region of possible convection. Composition has a significant effect on thermal evolution. The higher the content of hydrosilicates in the core, the faster convection occurs. For pure hydrosilicates ($C_{sil} = 0$), convection starts immediately, the convection zone occupies almost the entire core region, and viscosity decreases during cooling, which leads to a decrease in the convective zone radius. The convection intensity depends on the Rayleigh number $Ra$ (Figure 1a) - a dimensionless parameter that determines the behavior of a material under the influence of a temperature gradient. The results are shown for core radius $R_{core} = 1500$ km and various concentrations of silicates. Intense convection is observed at times of 1.5-3.5 Byr from CAI.

![Figure 1](#)
Figure 2 shows the time dependence of $K$ (the coefficient of nonstationarity of heating) (a) and surface heat flux $Q_s$ (b) for core radius $R_{\text{core}} = 1500$ km. With an increase in the content of silicates in the core, the surface heat flux increases (Figure 2a). Coefficient $K$ (Figure 2a) is $\sim 1$ only at times close to the present (4.5 billion years from CAI). This fact should be taken into account for calculating thermal models of satellites when considering stationary models of thermal conductivity.

Figure 2. Time dependence of $K$ (the coefficient of nonstationarity of heating) (a) and surface heat flux $Q_s$ (b). $R_{\text{core}} = 1500$ km.

Figure 3 and Figure 4 show the results of calculations of the temperature distribution $T$ as a function of radius and time for $R_{\text{core}} = 1500$ km. At a low content of silicates (15%, Fig.3b), the temperature in the core increases from the initial moment (500 Ma from CAI, 500 K in the center), reaching the highest value to 2-2.5 Byr ($\sim 900$ K in the center) and then gradually decreases to $\sim 800$ K in the center at the present stage (4.5 Byr). In this case, the temperature of 900 K ($T$ of the phase transition) is not reached at any time. The transition from the central convective zone to the outer conductive zone is clearly visible at a radius of $\sim 1200$-$1300$ km (Figure 3b), which is seen in the graph as a change in the slope of the temperature curves. With a large amount of silicates (85%, fig. 1a), the temperature profile shifts towards higher values, reaching a maximum by 3.5 Byr (1525 K), then the temperature begins to decrease ($\sim 1500$ K at present time). Figure 4 shows the current temperature distribution (4.5 billion years from CAI). For a satellite with a radius of 1500 km, the spread of possible temperatures in the center is from 420 K (at $C_{\text{sil}} = 0$) to temperatures of $\sim 1600$ K, which is close to the melting point of iron (at $C_{\text{sil}} = 100\%$).

Temperature $\sim 900$ K marks the possibility of the beginning of the dehydration process – a phase transition from hydrosilicates to silicates with the release of water. Figure 5 shows the largest radius at which a phase transition can occur at different radii of $R_{\text{core}}$ and the content of silicates (Sil) in the core. At $R_{\text{core}} \leq 1500$ km, phase dehydration is impossible for silicate content $< 30\%$. 
Figure 3. Temperature distributions (T) in the core (Rcore = 1500 km) as a function of radius (R) and time with a silicate content of 85% (a) and 15% (b)

Figure 4. Temperature distribution for a satellite with a core radius of Rcore = 1500 km at present time (t = 4.5 Byr from CAI)
4. Conclusions

Composition has a significant effect on thermal evolution. With a high content of hydrosilicates, the phase transition temperature is not reached. The transition to convection takes place by 2 billion years and can continue until the present time with a high content of hydrosilicates. Stationary models give an error in the temperature estimates. Based on the data obtained, it is possible to build models of the internal structure of satellites.

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