

DEHYDRATION PROCESSES IN THE HYDRATED CORES OF LARGE ICY SATELLITES.

E. V. Kronrod¹, V. A. Kronrod¹, O. L. Kuskov¹, Vernadsky Institute of Geochemistry and Analytical Chemistry, Russian Academy of Sciences (RAS), Kosygina St., 19, Moscow, 119991 Russia, e.kronrod@gmail.com.

Introduction. Space-research missions to Jupiter and Saturn (Galileo, Cassini – Huygens) have provided fundamentally new information about the icy giant satellites - Ganymede, Callisto and Titan. Based on the obtained geophysical and geochemical data, numerical models of the internal structure of the satellites were constructed containing a water-ice shell, an iron-stone core (\pm inner Fe – FeS core) [1], mantle located between them, consisting either of an undifferentiated rock-ice mixture [2, 3, 4], or a layer of hydrated silicates [5, 2]. Depending on the model and composition, the size of the core can vary from ~ 500 to ~ 2000 km. The composition, state of aggregation, size and physical properties of satellites, their thermal evolution, as well as the mechanisms of its formation are still the subject of research in numerous works [5,6,7,8]. This paper presents the results of calculations of unsteady temperature regimes in the cores of ice satellites taking into account the composition, convective heat transfer, and possible processes of dehydration of hydrosilicates in the interior of the cores of the satellites.

Description of the model. During the last stages of accretion of satellites, as a result of impactors action, the temperature of the near-surface regions increased sufficiently to initiate the ice melting. This leads to the separation of the rock-iron component and its migration to the satellite center accompanied by formation of inner rock-iron (silicate-iron) core. The process of heating of the proto-core with the energy of radioactive decay to a temperature above the melting temperature of ice (~ 500 K), the redistribution of ice, water and rock materials with the formation of a homogeneous rocky core takes about 500 million years [5, 8]. Further, the thermal evolution of the cores goes on due to radioactive energy sources.

We have considered two geochemical models, the most different in different in physical properties, and their combinations. In the first (hereinafter silicate) geochemical restrictions on the composition of the iron-stone material of Titan are imposed similarly to the material of the Galilean satellites of Jupiter, for which the isochemistry of the bulk composition to the matter of ordinary (L / LL) chondrites is shown [1,4]. The second type of models (hydrosilicate) is used in models of the internal structure of Titan, assuming complete differentiation of the satellite's material: the iron-stone core can be composed of a hydrated low-density mineral material such as serpentine (antigorite), which is close in composition to the material of carbonaceous CI chondrites [5].

It is assumed that the cores consist of a mixture of L/LL and CI – chondritic matter. At a temperature $T_f = 873$ K [9], the reaction of dehydration of hydrosilicates occurs. Anhydrous olivine and water are formed from serpentine and talc. The dehydration reaction is endothermic with energy consumption: $Q_f = 4.17 \cdot 10^5$ Jkg⁻¹ [9]. As a first approximation, we assume that the water released as a result of dehydration process does not significantly affect the physical properties of the rock and its chemical composition. The change in volume due to a decrease in density during dehydration is also not taken into account. The viscosity of silicates is determined, depending on temperature and pressure, similarly to [10], the viscosity of hydrosilicates is assumed to be constant ($4 \cdot 10^{19}$ Pa·s) in the whole range of temperatures and pressures [11]. The viscosity of the silicate + hydrosilicate mixture (η_{GS}) was calculated using the isostress model for the composite [12]. Two heat transfer mechanisms are considered: conductive (diffuse mechanism) and convective. Heat transfer in the convection zone is modeled by multiplying the thermal conductivity coefficient by a dimensionless coefficient (Nusselt number): $K_{ef} = Nu \cdot k_{cond}$, $Nu = 1.04 (Ra_0 / Ra_{crit})^{1/3}$, $Ra_{crit} \approx 1000$, k_{cond} – coefficient of thermal conductivity, Ra_0 – Rayleigh number in the convection zone, Ra_{crit} – critical Rayleigh number [13, 14].

The temperature distributions in the core are obtained as a result of the solution of a one-dimensional non-stationary equation, taking into account both conductive and convective heat transfers using the effective heat transfer coefficient K_{ef} , as well as the processes of heating of the core material due to the radiation energy and the energy of the hydrosilicates–silicates phase transition. At $t = 500$ Myr, the initial condition for temperature is 500 K and boundary condition is 360 K.

To assess the heat transfer regime (Rayleigh numbers), the entire region is divided into four zones: 1) Temperature T_1 exceeds the phase transition temperature. All hydrosilicates have changed into silicates ($C_{IHS}=1$). 2) The temperature T_2 is equal to the phase transition temperature, dehydration reactions occur. In this region, the density gradient has a sign opposite to the temperature gradient. Therefore, we can assume that there is no convection. 3) Temperature T_3 is less than the phase transition temperature. There is no dehydration. 4) Thermal boundary layer with a thickness of δ with a conductive heat transfer mechanism. The value of δ is found from the constraints

on the Rayleigh number in the boundary layer $Ra_\delta \approx 9.4Ra_0^{0.076}$ [15]. Ra_0 – Rayleigh number in layer 3.

Rayleigh numbers in layers 1, 3 is determined by the known expressions for the case of convection in a layer with internal heat sources [8, 14]. Since the density of silicates significantly exceeds the density of hydrosilicates, it is assumed that there is no mass transfer between the calculated zones. Changes in concentrations due to mass transfer processes within each zone are also not taken into account. Rayleigh numbers in each computational zone are calculated from the volume-averaged parameters. Therefore, the above assumptions have little effect on the calculation results.

Results and discussion. According to the calculation results, the initial concentration of hydrosilicates (C_{HS}) and the radius of the core (R_{core}) significantly affect the thermal evolution and dehydration of the core. The higher the content of hydrosilicates in the core, the faster convection appears. For the concentrations of hydrosilicates $C_{HS} \geq 0.85$, weak convection ($Nu > 1$) arises very quickly, the convective zone spreads almost throughout the entire core region except for the boundary layer. At large core sizes ($R_{core} > 700$ km) and $C_{HS} < 0.85$, the temperature at the center of the core reaches 873 K, and the process of a phase transition of hydrosilicates to silicates begins. The phase transition begins at times from ~1 billion years (with a low initial content of hydrosilicates – 10–15%) to ~1.5 byr (with a high content of hydrosilicates) and continues up to ~2.5 byr. Figures 1, 2 show the change in the bulk concentration of hydrosilicates in the interval of 500 myr to 4.5 byr from CAI. It is seen from Fig. 1 that at $C_{HS} \geq 0.9$, dehydration processes do not occur at any size of the core.

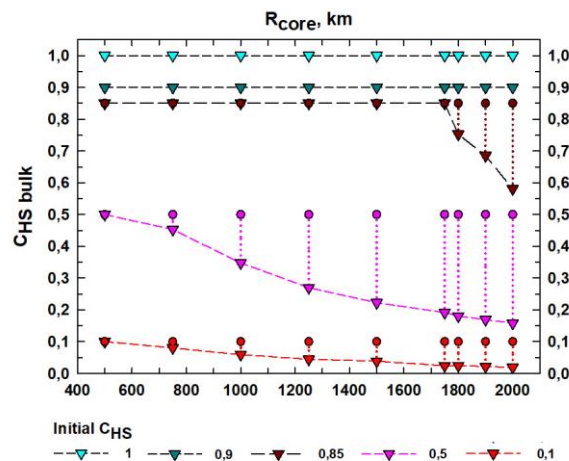


Fig.1 Dependence of the bulk concentration of hydrosilicates in satellite cores ($C_{HS \text{ bulk}}$) on the radii of the cores (R_{core}). Circles – $t = 500$ Myr from CAI, Triangles – $t = 4.5$ Byr. The color indicates the initial concentration of hydrosilicates in the core.

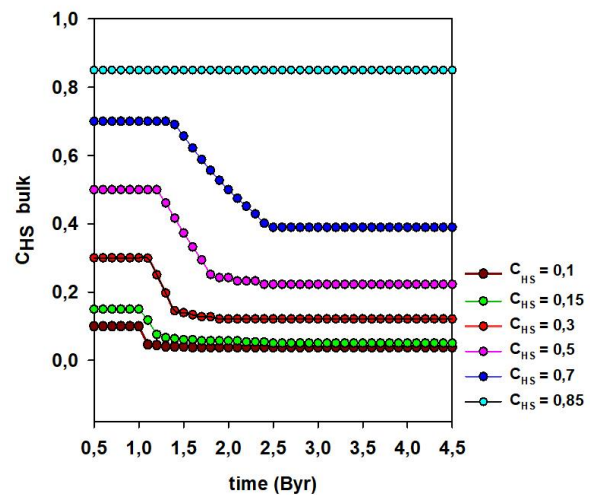


Fig.2 Dependence of the bulk concentration of hydrosilicates ($C_{HS \text{ bulk}}$) in the core for $R_{core} = 1500$ km on time from CAI. The color indicates the initial concentration of hydrosilicates in the core.

Conclusion: According to the calculation results, it can be concluded that in the presence of convection, the initial concentration of hydrosilicates in core rocks mainly determines the thermal evolution of the cores. At $C_{HS} \geq 0.9$, dehydration processes do not occur for all core sizes.

Acknowledgments: The work was performed as part of the state assignment of Vernadsky Institute of Geochemistry and Analytical Chemistry № 0137-2021-0004

References: [1] Kuskov O.L., Kronrod V.A. (2001) *Icarus* 151, 204–227. [2] Dunaeva A.N., Kronrod V.A. and Kuskov O.L. (2016) *Geochem. Int.*, 54, 1, 27–47. [3] Kronrod V. A., Dunaeva A. N., Gudkova T. V., Kuskov O. L. (2020) *Solar System Research*, 54, 5, 405–419. [4] Kuskov O.L., Kronrod V.A. (2005) *Icarus* 177, 550–569. [5] Castillo-Rogez J.C., Lunine J.I. (2010) *Geophys. Res. Lett.*, 37, L20205. [6] Kimura J., Kuramoto K. *EPSC Abstracts*, 7 EPSC2012-560-2 2012. [7] Sotin C. and Reynard B. (2012) *EPSC Abstracts*, 7 EPSC2012-868. [8] Grasset O., Sotin C., Deschamps F. (2000) *Planet. Space Sci.*, 48, 617–636. doi 10.1016/S0032-0633(00)00039-8. [9] Wakita S., Sekiya M. (2011) *Earth Planets Space*, 63, 1193–1206. [10] Kimura J., Nakagawa T., Kurita K. (2009) *Icarus*, 202, 216–224. [11] Hilairat N. et al. (2007) *Science*, 318, 1910–1913. [12] Ji S. and Zhao P (1993) *Earth Planet. Sci. Lett.*, 117, 181–187. [13] Sharpe H. N., Peltie W. R. (1978) *Geophysical Research Letters*, 5, 9, 737–740. [14] Czechowski, L. and Witek, P. (2015) *Acta Geophys.* 63, 3, 900–921. [15] Sotin C., Labrosse S. (1999) *Phys. Earth Planet. Int.* 112 (34), 171–190.