NUMERICAL MODELS OF TITAN'S INTERIOR WITH SUBSURFACE OCEAN. A. N. Dunaeva, V. A. Kronrod, O. L. Kuskov (Vernadsky Institute of Geochemistry and Analytical Chemistry, Russian Academy of Sciences, Kosygin Str., 19, 119991 Moscow, Russia, dunaeva@kmail.ru).

Introduction: Saturn's moon Titan is one of the most interesting objects for scientific research in the Solar system. Among the most topical areas of its complex study are the works associated with the development of mathematical models of its internal structure, origin and evolution.

The most significant information about Titan necessary for model calculations was obtained during the space research carried out by the *Cassini* spacecraft. One of the most important results of *Cassini*'s work in recent years has been the discovery of the evidences of powerful gravitational tides on Titan indicating the possible existence of a liquid water ocean in the satellite interior [1]. Thereby a liquid water ocean is included into the majority of modern models involving any Titan study.

Computer simulation and results. In this work the possible models of Titan internal structure assuming the inner liquid water ocean were built. The modeling was based on the approach accepted in [2, 3] using geophysical data on mass, average density and moment of inertia of the satellite.

Within the proposed models Titan was assumed to consist of three major structural domains: the outer water-ice shell, rock and ice mantle and rock-iron core. The boundaries between the domains were determined as a result of the calculations performed on the basis of the equations for a hydrostatic equilibrium, moment of inertia and mass of satellite. The density distribution in the water-ice layers was constructed taking into account the features of the water phase diagram, as well as the equations of the state of high-pressure water ice Ih, III, V, VI stable at pressures of Titan's ice crust [4].

In all calculations the density of the inner rocky core of the satellite was assumed to be equal to 3.62 g/cm^3, and the density of the rock-iron (*Fe-Si*) component in the rock-ice area was chosen in the range typical for the chondritic substance taking into account probable hydration of silicates – from 3.15 to 3.62 g/cm^3.

The temperature profile of Titan's inner regions was set with the assumption of conductive (in the region of low temperatures and pressures by the satellite surface) and convective adiabatic medium typical for the deeper layers of Titan (Fig 1). Titan's heat flow was assumed to be 7.0 mW/m^2 [5], which corresponds to its radiogenic and tidal heating, and reliably ensures the presence of a liquid water layer in the satellite depths [6].

The results of performed calculations have shown that Titan may have been formed as partially differentiated satellite consisting, in general, of the following main structural components:

1) External water-ice shell with a maximum thickness of 520 km. The phase composition and structure of the water-ice shell is unambiguously determined by the selected value of the satellite thermal flux. The calculations performed on the basis of the heat transfer equations [6] show that at the heat flow less than 3.3 mW/m^2 Titan's internal ocean is not formed. In this case the satellite's outer water-ice shell is represented only by water ice I*h*, III, V, VI, and the thickness of the external ice I*h*-crust has the maximum possible value for Titan - 160 km.

In case of Titan's heat flux increase the thickness of satellite outer Ih-crust decreases and the depth of the internal water ocean increases respectively from zero to maximum (unlikely) values, when all the water-containing shell is represented only by the liquid phase.

For the heat flux value of 7.0 mW/m^2 accepted in this work the depth of the liquid ocean is about 310 km and the thickness of the upper Ih-crust is equal to 80 km. Water ices V, VI located under the ocean have a total thickness of about 120 km (Fig. 2).

2) The rock-ice mantle, with its average density from 1.4 to 2.6 g/cm^3. The thickness of the mantle depends on the size of the water-ice shell and also on the presence (or absence) of the inner rocky core in the satellite. Maximum mantle size permissible in Titan is about 2000.0 km. The highest density and thickness of the mantle are reached when Titan's inner rocky core is absent. In this case the two-layer model of Titan is realized: it's a particular case of Titan general three-layer model discussed here (Fig. 2).

3) *Fe-Si* core with the density of 3.62 g/cm^3 has a radius which inversely depends on the thickness of Titan's water-ice shell: when the water-ice layer of the satellite increases its inner core (as shown above) decreases up to extinction. Maximum allowed size of Titan's inner core (1500 km) is achieved at the minimum thickness of its water-ice shell, and this corresponds to the particular case of another two-layer model of the satellite (*Fe-Si* core + rock-ice mantle). Such model does not assume the presence of Titan's internal ocean and thus is not considered in this study.

A notable feature of Titan is probable presence of volatile components (ammonia and hydrocarbons) in its composition. This fact can affect the internal structure of the satellite on the whole.

Experimental studies show that hydrocarbons (primarily ethane, propane, methane) form specific compounds (clathrate hydrates) which are stable in the inner T-P conditions of the satellite. And ammonia is the major salt impurity in Titan's internal ocean [7, 8].

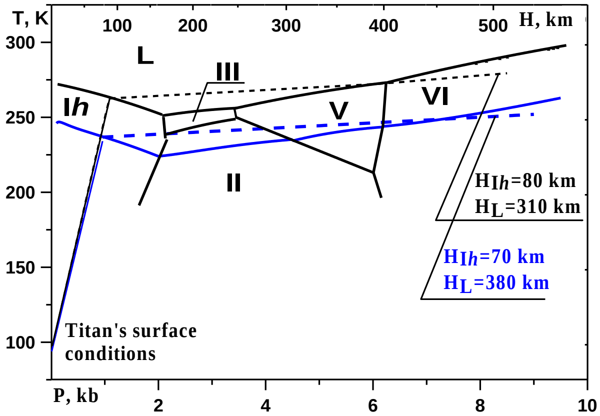

Figure 1. Phase diagram of water and the temperature distribution in the Titan's icy crust.
Straight thin lines - conductive temperature profiles through the external (ice-I*h*) crust. Dashed lines – adiabatic convective heat transfer in the water subcrustal ocean and in high-pressure ices.
H, H_{Ih}, H_L - the distance from the satellite's surface (depth), the thickness of the external ice-I*h* crust and of the inner liquid ocean respectively.
Blue lines - liquidus and temperature profiles in ammonia–water system (15% NH_3).

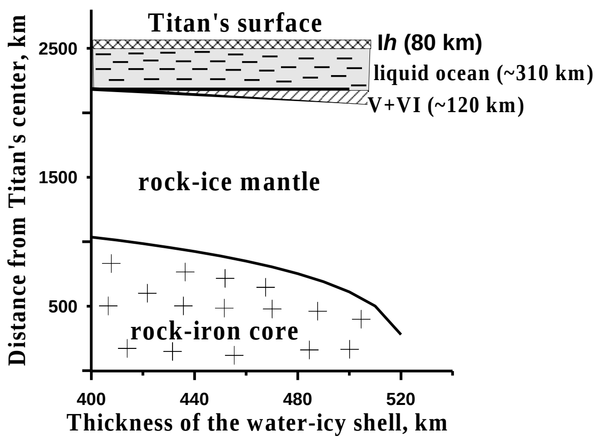

Figure 2. Titan internal structure for the heat flow 7.1 mW/m^2.

Since the amount of hydrocarbon gases trapped in the clathrates of Titan's interior makes up the first per cent against the water content, and the presence of ammonia in the system significantly destabilizes clathrate structures, it can be assumed that hydrocarbon clathrates existence in the satellite will not affect the results of our calculations.

On the contrary, the presence of ammonia in the inner ocean of Titan reduces the density of the ocean and also reduces the crystallization temperature of water ice (blue solid lines in Fig. 1). To estimate the influence of these factors an internal ocean of water-ammonia composition (15% NH_3) was included in Titan models.

The calculations showed that the addition of NH_3 does not change the general three-layer structure of the satellite but has a greater impact on the structure and composition of its water-ice shell:
- the value of the maximum allowed thickness of the water-ice shell was reduced (480 km);
- the thickness of the internal ocean increased significantly with a slight decrease in the outer ice Ih-crust thickness (Fig. 1);
- due to the liquidus reduction the phase composition of Titan ice changed fundamentally: at a given concentration of NH_3 instead of ice III contrary ice II, which is not stable in the pure water system, crystallizes from the solution;
- the phase composition and thickness of the high-pressure ice beneath the internal ocean changed: at the specified heat flux and at the given NH_3 concentration ice V is not formed in the system, and existing ice VI is much thinner (25 km);
- NH_3 adding led to lowering of the temperature of the inner ocean and of the lower regions of the satellite.

It should be noted that these conclusions are evaluative as they are made on the basis of limited experimental data on phase transitions in water-ammonia system with the use of insufficient thermodynamic information on the formed phases' properties. Thus they may be revised in the course of further experimental and theoretical studies.

This research was supported by Russian Academy of Sciences under Programs 22, and by RFBR grant 12-05-00033.

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