FORMATION OF SATELLITES IN THE ACCRETION DISKS OF JUPITER AND SATURN: COMPARATIVE MODELING. A. B. Makalkin[1] and V. A. Dorofeeva[2], [1]Schmidt Institute of Physics of the Earth, Russian Academy of Sciences (RAS), Bol'shaya Gruzinskaya ul. 10, Moscow, 123995 Russia (makalkin@ifz.ru), [2]Vernadsky Institute of Geochemistry and Analytical Chemistry, RAS, Kosygina St., 19, Moscow, 119991 Russia (dorofeeva@geokhi.ru)

Introduction: The main features of the constitution of the Jupiter's and Saturn's regular satellites should be reflected in the models of their formation. The models should not contradict the experimental data on the composition of atmospheres of these giant planets. We have constructed such models consistent with the internal structure and composition of the Galilean satellites [1,2] and with the data on the Titan's atmosphere composition [3]. All existing models of formation of regular satellites suggest their formation in the circumplanetary disks (planetary subnebulae). Most of authors, including us, prefer to consider satellite formation in the gas-dust accretion disks [4,5] just as planets are formed in the circumstellar protoplanetary disks [6] The protosatellite disks contained solid material not only in dust particles, but also in larger bodies. Formation of planetesimals in the disks through the disk's gravitational instability is highly improbable due to the disk's disturbance by large protoplanetary bodies approaching Jupiter and Saturn. At the same time some of these bodies in the vicinity of the planet could be captured by the disk after the pairwise collisions. Evaluation [7] showed that during the time of satellite formation ~10^5 yr several large (10–100 km) planetesimals could be captured into the subnebula from heliocentric orbits. Small bodies were held by gravity of these planetesimals at their surfaces. Hence the captured planetesimals played the role of seeds (embryos) in the satellite formation. The main income of solid material into the subnebulae and forming satellites from the feeding zones of the planets presumably resulted from the capture of dust particles and small bodies ($R < 10$ m) owing to the gas drag [5,7,8]. Moreover, as the bodies of 1 to 10 m in size could hardly lose their volatiles, we suggest that the satellites obtained most of their mass from smaller bodies and particles. Our model assumes that Titan formed in the relatively warm subnebula ($T \sim 60$–90 K at $r \approx 15$–30 $R_{\rm Sat}$) from the solid material which came from the colder solar nebula and then lost most volatile components in the subnebula's environment. In particular, clathrates of CH_4, CO, N_2 and the noble gases were destroyed in accordance with Cassini–Huygens data which indicate that the Titan's atmosphere does not contain any nonradiogenic noble gases including xenon [3]. In the case of Jupiter's disk the particles during their drift to the planet had lost even H_2O in the inner region of disk. For both planets we consider the models of low-mass gas-starved protosatellite accretion disks, which accumulate the mass of solid material contained in the regular satellites, during the whole period of their formation [4]. Arguments for the gas-starved disk models were clearly demonstrated in [8,9].

Main Features of Constructed Models of Jupiter's and Saturn's Protosatellite Disks: (1) The Jupiter's and Saturn's subnebulae are considered as gas-dust accretion disks with accumulation of solid material on the surfaces of the growing satellite embryos. (2) The disks are considered as open systems with parameters depending on the rate of mass accretion onto the disks from the surrounding regions of the solar nebula and the composition of the solid material captured from the nebula. (3) Four sources of the disk heating are included: viscous dissipation of turbulence in the disk, radiation of the young central planet, the infall of material onto the disk and disk's thermal irradiation by the surrounding region of the solar nebula. (4) The cosmochemical restrictions on the temperature and composition of solids in the disks of Jupiter and Saturn are accounted for. (5) The dependence of the disk's opacity on temperature, chemical composition, enrichment and size of dust particles is allowed for. (6) The growth of dust particles is taken into account through the opacity variation. (7) The models constructed are two-dimensional: the calculations are made for radial and vertical *T*-*P* structure of the disks.

The equations and methods of computer simulations we have presented earlier for the protosatellite disk of Saturn [5]. Here we present the results of comparative modeling of Jupiter's and Saturn's disks. It is important that input parameters for models of both disks are considered in concordance with the modern data on the evolution of disks around the young solar-type stars and the solar nebula.

Results and Discussion: We have constructed the models of protosatellite disks of Jupiter and Saturn, which satisfy the complex of cosmochemical and physical constraints. The cosmochemical data impose restrictions on the temperature distribution in the midplane of the disks. For the disk of Jupiter these data concern the abundance of water in each of the Galilean satellites; for the disk of Saturn we use the data on the Titan's atmosphere obtained by means of the Huygens probe and Earth-based observations, and the assumption, that the basic source of carbon on the satellite was CO_2. One more cosmochemical constraint originates from the data on the enrichment of atmospheres of Jupiter and Saturn in volatile substances heavier than hydrogen and helium relative to the cosmic abundance.

The physical constraints include modern data on the lifetime and evolution rate of the protoplanetary disks around young solar-type stars and the solar nebula. These data yield the lifetime of the gas-dust solar nebula $\leq 10^7$ yr. The accretion of the giant planets ceased owing to photoevaporation of the gas from the solar nebula by the UV emission of the young sun. As the formation of satellites in the circumplanetary disks should occur at the late stage of planet accretion only, it could not proceed for more than $\sim 10^6$ yr. Any satellite formed in the disk earlier, should drift to the planet and fall on it [8].

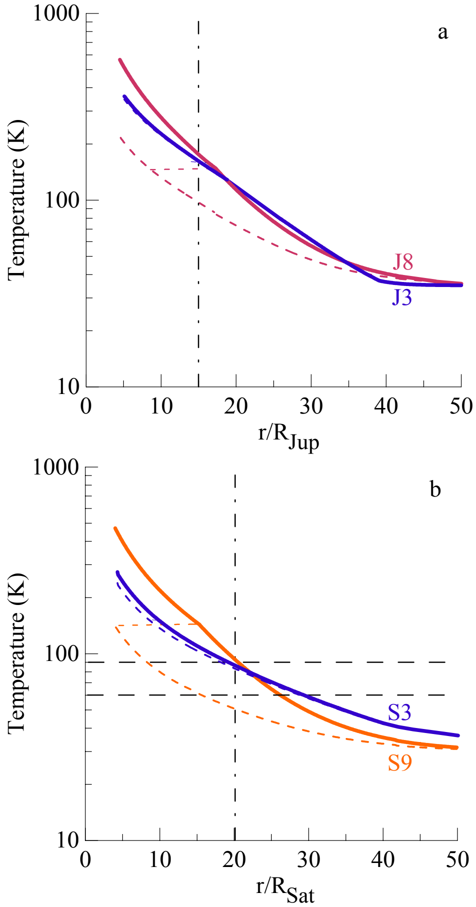

Figure 1. Temperatures at the midplane (solid curves) and the radiating surface (dashed curves) of the disks of Jupiter (a) and Saturn (b) for models fitting cosmochemical restrictions on temperature in the formation regions of Ganymede and Titan. Models J3 and S3 correspond to the accretion rate 10^{-7} M_{Jup} /year and 10^{-7} M_{Sat} /year, $\kappa = 10^{-2}$ cm^2/g and 0.1 cm^2/g. Models J8 and S9 correspond to 10^{-8} M_{Jup} /year and 10^{-8} M_{Sat} /year and temperature-dependent opacity with 10-fold dust enrichment in the case of Saturn. The colored dashed segments indicate the condensation temperarure of H_2O.

We obtained restrictions on the turbulent viscosity and opacity of the disks of Jupiter and Saturn. Too high or too low values of these parameters yield too high or too low temperatures in the disk, which are not consistent with the cosmochemical constraints. Too high opacities do not also fit the rather low enrichment of planetary atmospheres in heavy volatiles. The opacity is strongly dependent on size of the dust particles in the disk. The models that better than others fit cosmochemical restrictions on temperature and astrophysical data on protoplanetary disks around young stars yield opacity of the order of $\kappa \sim 10^{-2}$ cm^2/g and 0.1 cm^2/g and particle size of about $a \sim 1$ cm and $a \sim 0.1$ cm in the disks of Jupiter and Saturn correspondingly.

This size is also consistent with the models of formation of Jupiter [10], which require this rather large size of dust particles in order to obtain sufficiently high accretion rate of the planet. The protosatellite disks with lower opacity due to higher sizes of particles appear to be transparent for the powerful radiation of the young giant planets and hence too hot to satisfy chemical constraints. The duration of satellite accretion $\sim 10^6$ yr shown above would decrease to $\tau_a \sim 2\times10^5$ yr if to consider satellite migration of the first type [8]. The best models we have constructed to fit this timescale show the accretion rate of gas-dust material onto the disk and from the disk onto the planet of about 10^{-7} M_{Jup} /year and 10^{-7} M_{Sat} /year for Jupiter and Saturn. These models better than others also fit the cosmochemical temperature constraints. The accretion rates shown above are consistent with the accretion rate of material in the solar nebula in the region of giant-planet formation of about 10^{-10} M_{Sun}/year, characteristic of the late phase of the solar nebula evolution before its dispersal through photoevaporation [11]. The dispersal timescale would be much shorter than satellite accretion timescale τ_a.

It follows from our estimates that material of large icy satellites Ganymede, Callisto and Titan initially had contained, probably, the whole cosmic abundance of water, but at mutual collisions of pre-satellite bodies the growing satellites had lost up to 60% of this most abundant component. If the primitive material of these satellites also contained refractory organic compounds (CHON), which had (at least partially) entered the composition of these satellites, then the loss of water would be higher.

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