MODELS OF SATURN'S SUBNEBULA: CONDITIONS FOR TITAN'S FORMATION. A. B. Makalkin[1] and V. A. Dorofeeva[2], [1]Schmidt Institute of Physics of the Earth, Russian Academy of Sciences, B. Gruzinskaya 10, Moscow, 123995 Russia (makalkin@ifz.ru), [2]Vernadsky Institute of Geochemistry and Analytical Chemistry, Russian Academy of Sciences, ul. Kosygina 19, Moscow, 119991 Russia.

Introduction: New models of protosatellite subnebula of Saturn should satisfy cosmochemical constraints on the volatile abundances in the atmospheres of Saturn and Titan with due regard for the data obtained with the *Cassini* orbiter and the *Huygens* probe. Owing to these data, it became possible to find new constraints on the temperature conditions of the evolution of icy particles and planetesimals, from which Titan was formed. In the present study, we use the renewed constraints on temperature in the Saturn's subnebula to refine some other parameters of the subnebula, which allow to determine the conditions for Titan's formation more accurately.

Subnebula's model: From the cosmochemical constraints we obtained the subnebula's midplane temperature which at the stage of the satellite formation ranged from 60–65 K to 90–100 K at pressures from 10^{-7}–10^{-4} bar in the zone of Titan's formation (at r = 20–35 R_{Sat}) [1]. Following the earlier papers on subnebulae of Saturn and Jupiter we suggest that the accretion flux of matter through the protosatellite disk onto the planet is determined by the rate of accretion from the surrounding region of the solar nebula to the planet's Hill sphere, that is, by the interaction between the protoplanetary and protosatellite disks. In the alternative approach it is assumed that the accretion of the material from the solar nebula onto the subnebula has been already finished at the stage of satellite formation (because of the complete loss of gas from the nebula owing to its precipitation onto the Sun and/or scattering due to photoevaporation), and the subnebula evolves as an independent isolated viscous disk, similar to viscous disks around T Tauri. In this case, as follows from [2, 3], the Saturn's subnebula cools by 100 K in 10^4 years at a distance of 20–30 planetary radii. This cooling rate is consistent with the small timescales for cooling (Kelvin–Helmholtz) and viscous evolution [4], which are about 10^3 years at the distance of Titan [1]. Even the largest of the above timescales, 10^4 years, is 10 to 100 times shorter than the timescale of evolution of the solar nebula τ_{sn} and satellite accretion in the subnebula [4, 1]. We suggest that there was a mass flux at the stage of satellites' formation, which slowly decreased with time. It is important in this case that the cooling and viscous timescales are small as compared to the evolution time of the solar nebula τ_{sn} $=10^5$–10^6 years. The radial mass accretion rate $\dot{M}$ from the nebula onto the subnebula varies with timescale τ_{sn} . That is why the protosatellite disk quickly adjusts to the slowly varying accretion rate is in the thermal equilibrium and close to the dynamic equilibrium, slowly evolving as a viscous disk. This conclusion makes it possible to use the quasi-stationary approximation in the models we construct. All basic sources of heating the subnebula and protosatellite bodies are taken into account in the models; namely, dissipation of turbulence in the subnebula, accretion of gaseous and solid material onto the subnebula from the Saturn's feeding zone in the solar nebula, and heating by radiation of young Saturn and thermal radiation of the surrounding region of the solar nebula.

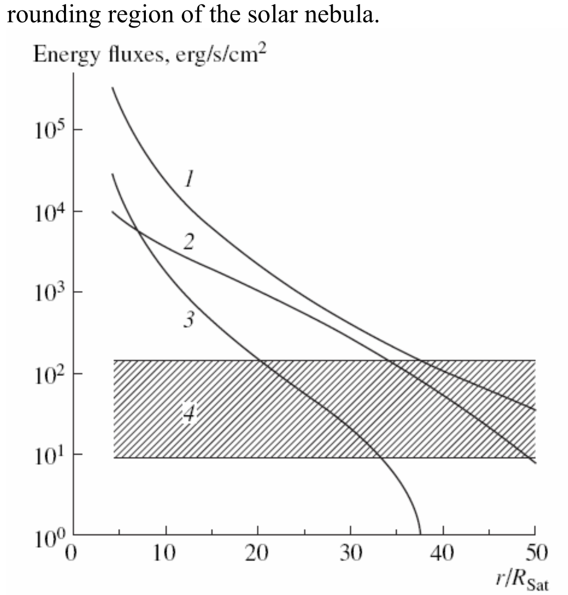

Fig. 1. The contribution of different mechanisms responsible for the energy fluxes to the disk heating for the model with the accretion rate $\dot{M} = 10^{-7}$ M_{Sat}/yr, the opacity $\kappa = 0.1$, and the parameter $\alpha=10^{-3}$. Curve *1* shows the contribution of viscous dissipation (of turbulence); *2*, of the accretion of the material onto the disk; *3*, of radiation of young Saturn. Wide band *4* covers the interval of radiation fluxes from the surrounding region of the solar nebula at the heliocentric distance r = 10 AU and corresponds to the range of possible temperatures in this nebula's region T_{neb} = 20—40 K.

Two-dimensional (axisymmetric) temperature, pressure, and density distributions are calculated for the subnebula, which satisfy the above cosmochemical constraints on the disk temperature. Variations of the basic input parameters (accretion rate onto the protosatellite disk of Saturn from the feeding zone of the planet $\dot{M}$; parameter α characterizing turbulent viscosity of the disk, and mass concentration ratio in the solid/gas system) satisfying the temperature constraints are found.

Conclusion: The spectrum of models, satisfying the cosmochemical constraints, covers a considerable range of consistent parameters. A model with a rather small flux of $\dot{M} = 10^{-8}$ M_{Sat}/yr and a tenfold depletion of the Saturn's disk in gas due to gas scattering from the solar nebula is at one side of this range. A model with a much higher flux of $\dot{M} = 10^{-6}$ M_{Sat}/yr and a hundredfold decrease in opacity of the disk matter owing to decreased concentration of dust particles and/or their agglomeration into large aggregates and sweeping up by planetesimals is at the other side of the range.

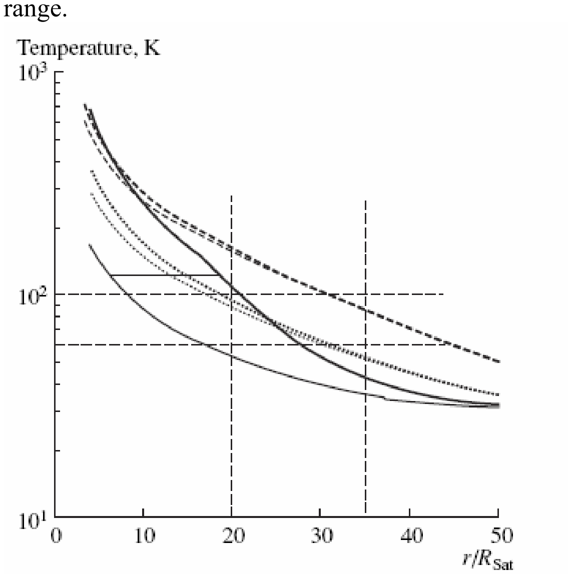

Fig. 2. The midplane temperature of the disk (thick curves) and the temperature at the emitting surface of the disk (thin curves) for three models with different mass fluxes and opacities: $\dot{M} = 10^{-8}$ M_{Sat}/yr and dust enrichment χ]= 10 (solid curves $\dot{M} = 10^{-7}$ M_{Sat}/yr,, κ = 0.1 (dotted curves); and $\dot{M} = 10^{-6}$ M_{Sat}/yr, κ= 10^{-2} (dashed curves). For all models α] = 10^{-3}. The horizontal dashed lines bound the temperature interval obtained by cosmochemical data, while the vertical dashed lines limit the interval of radial distances, at which Titan's accretion probably occurred. The preferable models should give the results in the rectangular limited by the dashed lines.The horizontal thin line shows the evaporation temperature of water ice.

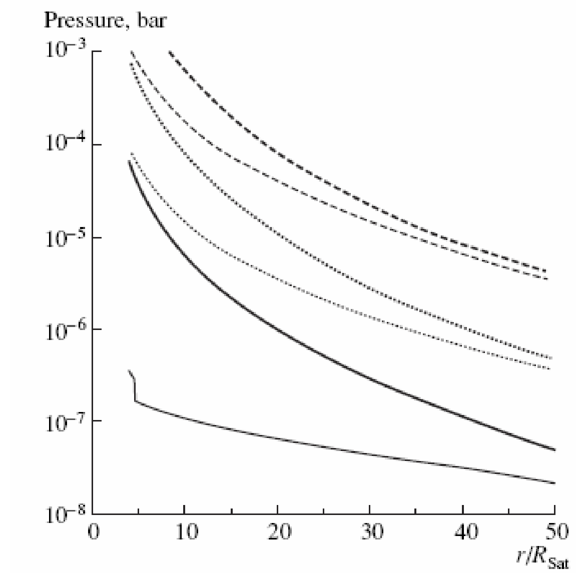

Fig. 3. The midplane pressure of the disk (thick curves) and the pressure at the emitting surface of the disk (thin curves) for the same three models as in Fig. 2. Greater mass fluxes correspond to higher pairs of curves.

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References: [1] Makalkin A. B. and Dorofeeva V. A. (2006) *Solar Syst. Res., 40,* 441–455. [2] Alibert et al. (2005) *A&A., 439,* 1205-1213. [3] Alibert Y. and Mousis O. (2006) *LPS XXXVII,* #1141. [4] Canup R. M. and Ward W.R. (2002) *Astron. J., 124,* 3404-3423.