ORIGIN OF JUPITER'S AND SATURN'S REGULAR SATELLITES IN CIRCUMPLANETARY DISKS

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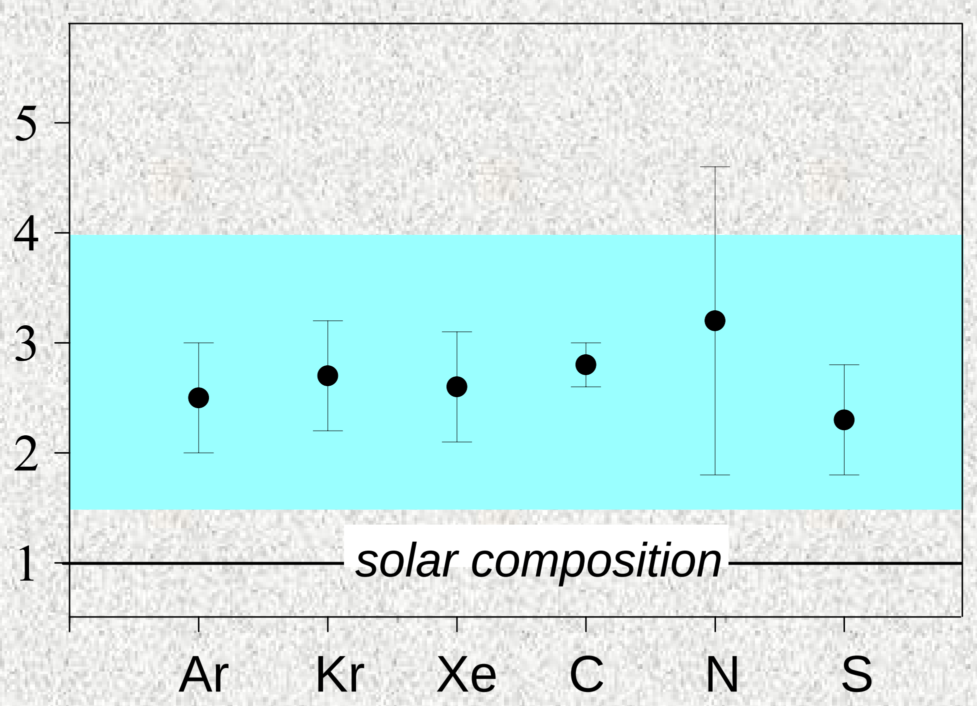
The problem

The models of formation of the Jupiter’s and Saturn’s regular satellites

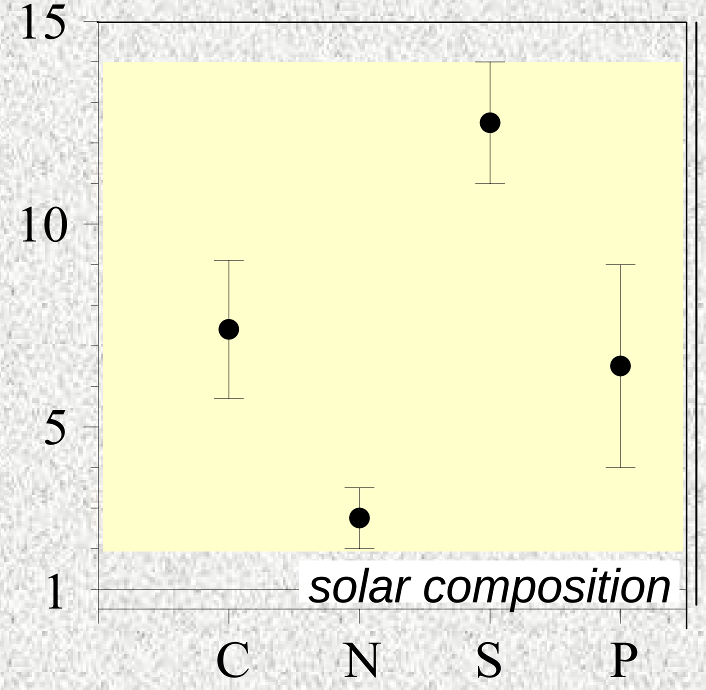
- should reflect the main features of their constitution,
- including the observational data and simulations of water distribution and ice to rock ratio in the Galilean satellites, Titan, and Enceladus;
- should be consistent with the current data on the composition of Titan’s and Enceladus’ atmospheres;
- should not contradict the experimental data on the composition of atmospheres of the giant planets;
- should take into account present astrophysical data on the evolution and dispersal of the protoplanetary disks around the solar-type young stars;
- should be consistent with the modern models of accretion of Jupiter and Saturn.

Composition of atmospheres

Jupiter



Saturn



Experimental data on the Saturn's regular satellites

Titan

P ≈ 1.5 bar, *T* = 90–100 K at the surface

Composition of atmosphere (mol %)

N_2	98–96
CH_4	2–4

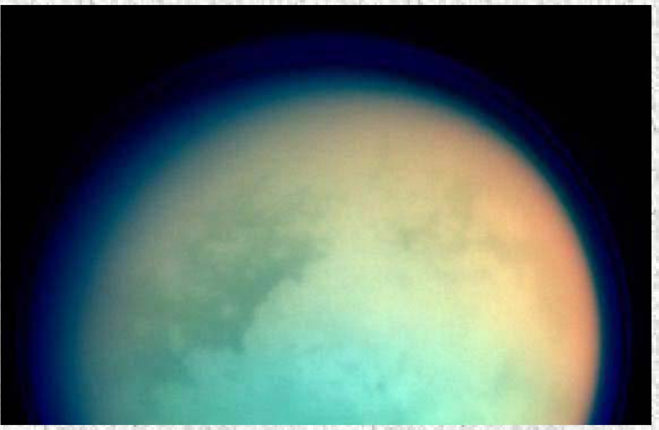
Kr and Xe are not detected

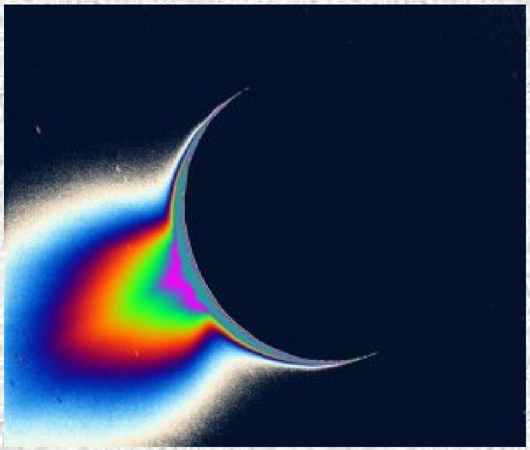
Enceladus

T = 60–70 K at the surface

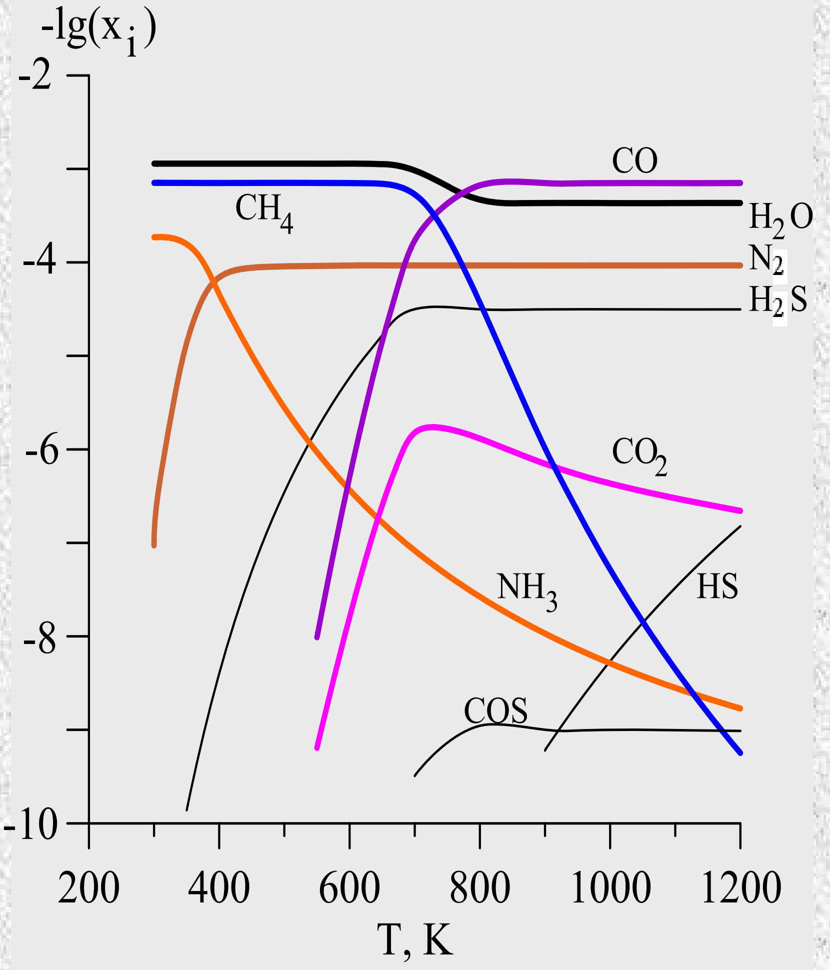
Composition of plumes (mol %):

liquid H_2O		91 ± 3
gases:	N_2	4 ± 1
	CO_2	3.2 ± 0.6
	CH_4	1.6 ± 0 4

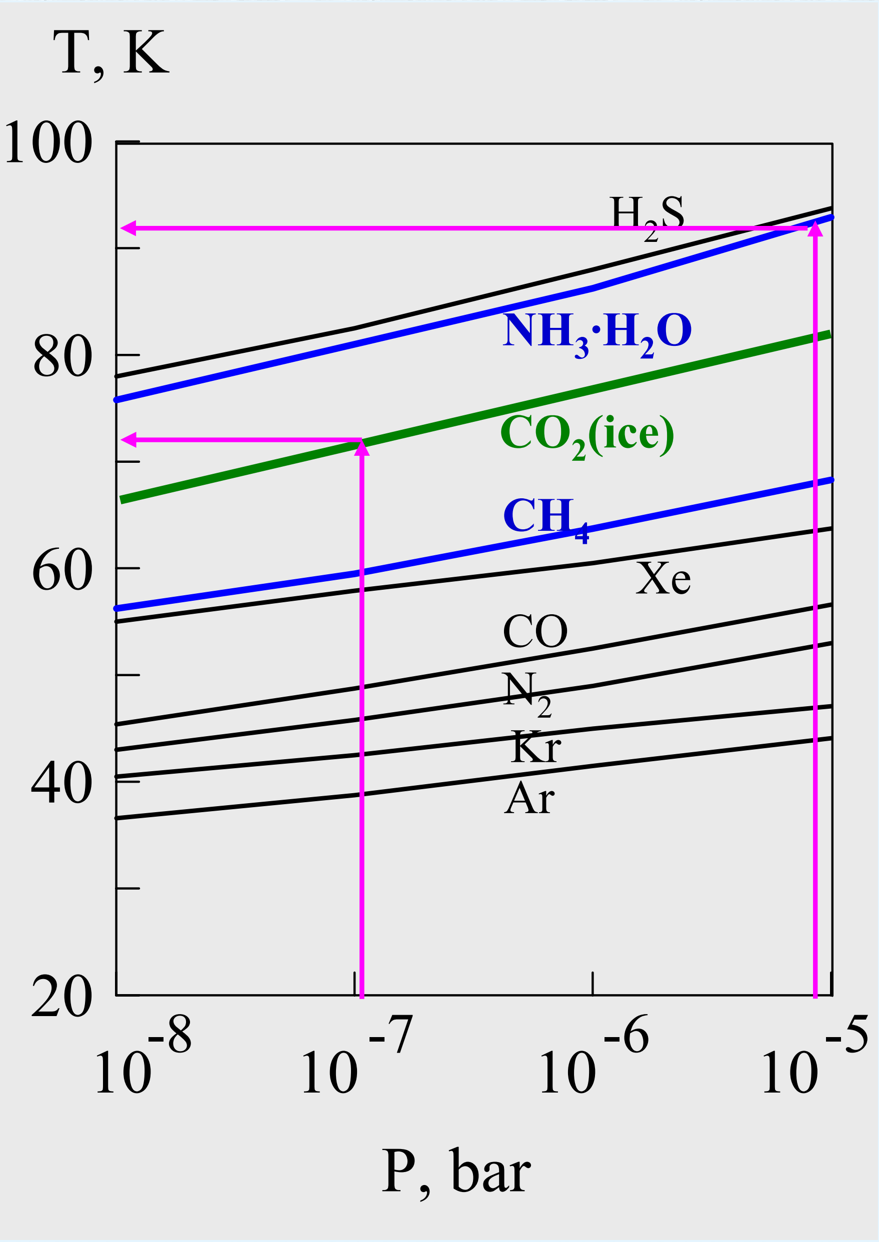




The source of nitrogen and carbon on Titan and Enceladus could be icy bodies, which accumulated these elements in some form in the solar nebula before their accretion onto the circumplanetary protosatellite disk. The compounds of these elements in solids depend on the chemical form of these elements in the gas of the solar nebula and *P-T* conditions of formation of the solids. From the figure it is seen that in the gas phase of the nebula, having solar composition, nitrogen was present as NH_3 and N_2 and carbon was in the form of CH_4, CO and CO_2.



The figure shows that the most high-temperature compound which accumulates nitrogen in the solid phase is the ammonium crystal-hydrate. Formation of N_2 clathrate occurs at the temperature lower than that for formation of clathrate of xenon, the gas which was not observed in the Titan's atmosphere. Therefore we, as many other authors do, suggest, that nitrogen in the regular satellites of Saturn was accumulated in the form of $NH_3{\cdot}H_2O$. The stability curve for this compound yields the upper limit for temperature $T \approx 90 - 80$ K at $P = 10^{-5} - 10^{-7}$ bar. The most high-temperature compound which accumulated carbon in the solid phase, was CO_2 ice. The fact, that CO_2 was observed in the plumes of Enceladus, causes us to suggest that just CO_2 ice was the main form of carbon accumulation on the regular satellites of Saturn. This assumption gives the lower limit for the temperature $T \approx 80$-70 K.



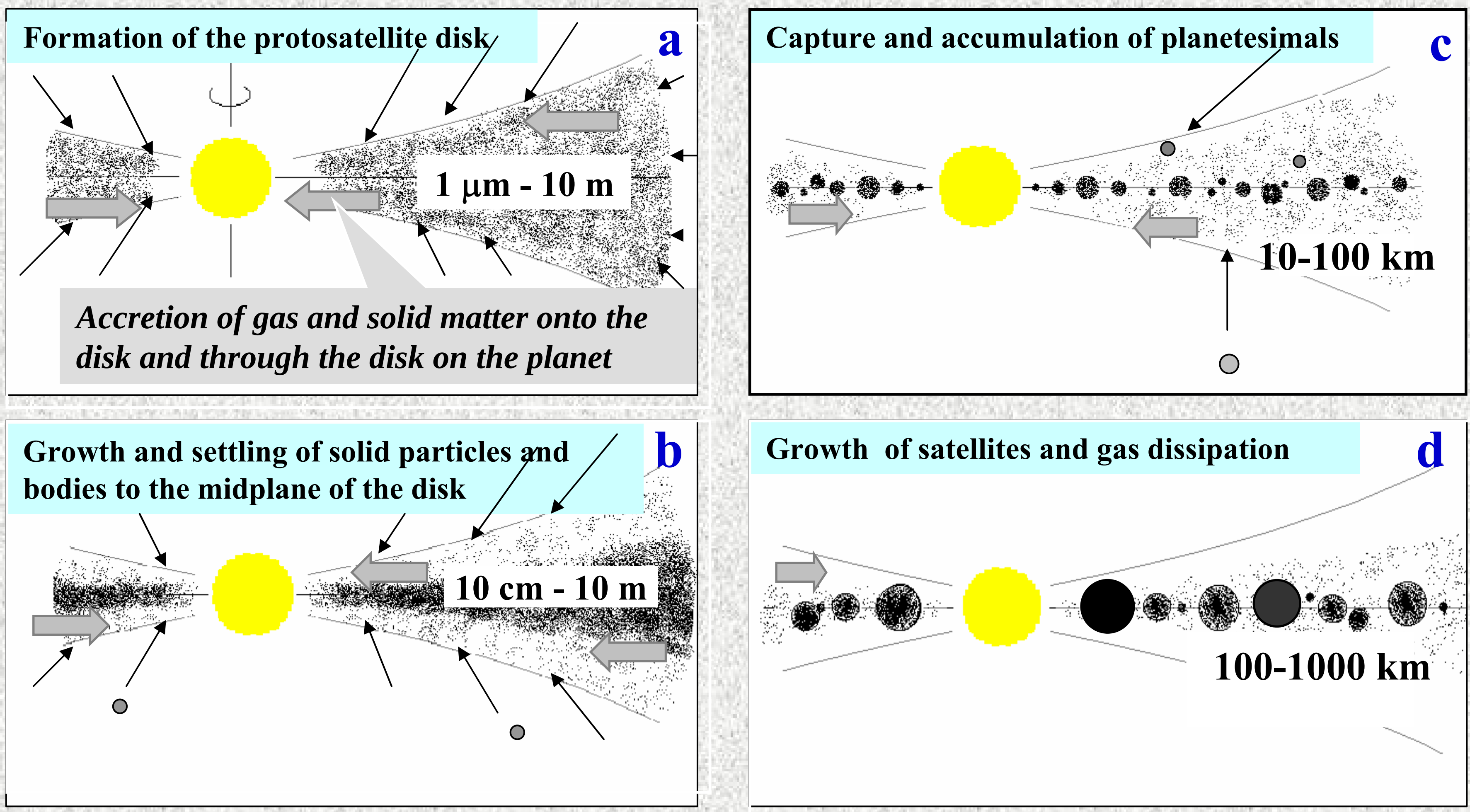
Ice to rock mass ratio for in the Galilean satellites, Titan and Enceladus

Results of modeling internal structure

(Kuskov, Kronrod, 2001, 2005; Kuskov et al., 2009)

		Ice / Rock (mass %)
Jupiter	Io	0 / 100
	Europa	7–9 / 93–91
	Ganymede	46–48 / 54–52
	Callisto	49–55 / 51–45
Saturn	Titan	~ 45 / 55
	Enceladus	~ 50 / 50

Evolution of the solid material in the accretion protosatellite disk
(schematic)



a Formation of the protosatellite disk

1 µm - 10 m

Accretion of gas and solid matter onto the disk and through the disk on the planet

b Growth and settling of solid particles and bodies to the midplane of the disk

10 cm - 10 m

c Capture and accumulation of planetesimals

10-100 km

d Growth of satellites and gas dissipation

100-1000 km

- We construct the numerical two-dimensional models of the protosatellite accretion disks around the young Jupiter and Saturn. The method of modeling is similar to that proposed by us for models of the circumsolar protoplanetary accretion disk (*Makalkin, Dorofeeva,* 1995, 1996) and develops the earlier models of circumplanetary disks around the young Jupiter and Saturn (*Makalkin, Dorofeeva,* 1999, 2006). The models are thoroughly described in the book (*Dorofeeva and Makalkin,* 2004).

Main features of constructed models

- 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.
- The main new feature of present modeling is the combined consideration and comparison of satellite accretion in both Jupiter’s and Saturn’s disks.
- 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 capturing nebula’s solid material.
- The change of the mass accretion rate onto the disk with time is suggested to be small during the period ($\leq 10^6$ yr) of accretion of satellites. Therefore we consider the quasi-steady models.

Main features of constructed models

- Four sources of the disk heating are included: viscous dissipation of turbulence in the disks, radiation of the young central planet, fall of material onto the disks from the surrounding region of the solar nebula, and thermal radiation from this region of the nebula.
- The cosmochemical restrictions on the temperature and composition of solids in the disks of Jupiter and Saturn are allowed for in the computations.
- The dependence of opacity of the disk material on temperature, chemical composition, enrichment and size of dust particles is considered.
- The growth of dust particles is taken into account through the opacity variation.
- The models constructed are two-dimensional: the calculations are made for radial and vertical T-P structure of the disks.

Input parameters of the numerical two-dimensional model of the accretion viscous protosatellite disk:

$\dot{M}$ – the total mass flux (accretion rate) from the solar nebula onto the protosatellite disk, $\dot{M} \sim 10^{-8}$ - 10^{-6} M_{planet}/yr;

α – parameter, which characterizes gas viscosity in the gas-dust disk; according to the model results of Hersant et al. (2004), $2\times10^{-4} < \alpha < 2\times10^{-2}$;

κ – opacity of the disk matter; depends on temperature (for small dust particles) and/or on particle size (for larger grains); κ can vary from 10^{-4} to 10 cm^{2}g^{-1} (*Pollack et al., 1994)*;

X_d – mass fraction of the solid (dust) phase. We assumed $X_d = 0.012$ *(Busarev, Dorofeeva, Makalkin,2003)*;

χ – the enrichment/depeletion factor for the dust phase of material relative to the protosolar proportion;

T_{neb} – the temperatures in the solar nebula (protoplanetary disk) at the distance $r \approx$ 5-10 AU; according to the results of modeling (Makalkin and Dorofeeva, 1996), T_{neb} was higher than 20 K during all period of disk evolution (~ 8 Myr); $P_{neb} \sim 10^{-7}$-10^{-4} bar;

r_d – the disk radius;

r_c – the centrifugal radius for the disk accretion.

Basic equations

Balance equations expressed in terms of the column density $\Sigma = \int_{-z_s}^{+z_s} \rho \, dz$, represent the balance of mass (continuity equation) and the balance of specific angular momentum

$$\frac{\partial \Sigma}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}(\Sigma r V_r) = \dot{\Sigma}_a \, ,$$

$$\frac{\partial (j\Sigma)}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}(j\Sigma r V_r) = \frac{1}{r}\frac{\partial}{\partial r}\left(\nu \Sigma r^3 \frac{\partial \Omega}{\partial r} \right) + j_a \dot{\Sigma}_a \, .$$

V_r is the radial velocity of mass transfer in the disk, averaged over the disk thickness,

Ω is the Keplerian angular velocity; index *a* corresponds to the accreting material;

$j_a = j = (GM_\mathrm{Sat} r)^{1/2}$ is the specific angular momentum of the accreting and disk material.

The kinematic viscosity ν in this model is assumed to be proportional to the sound sound velocity *c* multiplied by the half-thickness of the homogeneous disk $h = c/\Omega$ with a constant proportionality factor α:

$$\nu = \alpha c_s h = \alpha c_s^2 / \Omega \, .$$

From the above equations it follows

$$\Sigma\, T_m = \frac{1}{3\pi} \frac{\mu}{\gamma\, R_g} \frac{\Lambda}{l} \frac{\dot{M}}{\alpha} \Omega\,,$$

where T_m is the midplane temperature.
The height of the emitting surface ($z = z_\mathrm{s}$) is determined as

$$\tau = \int_1^\infty \kappa\rho\; dz = \kappa_s \rho_s z_s \int_1^\infty \exp[b_s(1-\xi^2)]d\xi = \frac{2}{3} \quad .$$

The height z_s is found from this condition. The density at the emitting surface (ρ_s) and at any height $\rho\,(z)$, is calculated from the equation of hydrostatic equilibrium

$$\partial P/\partial z = -\rho\Omega^2 z.$$

The opacity depends on temperature as follows: $\kappa = \kappa_0 T^\beta$, where κ_0 and β depend on the chemical composition of solid phase.

Heating of the protosatellite accretion disk

The temperature at the emitting surface of the disk is determined by four heat sources, expressed by four terms on the right:

$$\sigma_{\mathrm{SB}} T_s^4 = D_1 + \frac{\chi_b G M \dot{M}}{4\pi r_c^2 r} e^{-(r/r_c)^2} + k_s F_s + \sigma_{\mathrm{SB}} T_{neb}^4$$

The 1st source D_1 is viscous dissipation of the energy of turbulence:

$$D_1 = \int_0^{z_s} w_{r\varphi}\, dz = \frac{9}{8} \nu\, \Sigma \Omega^2 = \frac{3}{8\pi} \frac{\Lambda}{l} \dot{M}\, \Omega^2$$

The 2nd source is heating of the disk by the fall of material onto the disk;

χ_b is the enrichment of the falling material with the large solid bodies (χ_b = 1–1.5).

The 3rd source $k_s F_s$ is heating of the disk by the radiation of the central planet.

The 4th source $\sigma_{\mathrm{SB}} T_{neb}^4$ is heating of the disk by the radiation of the surrounding region of the solar nebula.

The vertical distribution of temperature

from the emitting surface with $T = T_\mathrm{s}$ to the disk’s midplane:

$$\left(\frac{T}{T_s}\right)^{4-\beta} = 1 + \frac{3}{64}(4-\beta)\frac{D_1}{\sigma_{\mathrm{SB}} T_s^4}\kappa_s \Sigma (q_s^2 - q^2) \quad ; \quad q = \frac{1}{\Sigma}\int_{-z}^{z} \rho \, dz \ ,$$

q is the vertical mass coordinate; $q_s = q(z_s)$.

At the midplane of the disk $T = T_m$;

For small dust particles (< 50 μm)

$$T_m^{5-\beta} - T_s^{4-\beta}\, T_m = \frac{3}{2^9 \pi^2}\frac{\mu}{\sigma_{\mathrm{SB}} R_g \gamma}(4-\beta)\chi \kappa_0 \frac{\dot{M}^2}{\alpha}\Omega^3 \left(\frac{\Lambda}{l}\right)^2 q_s^2 \ ,$$

где $\Lambda = 1 - \frac{1}{5}\left(\frac{r}{r_{\tilde{n}}}\right)^2 - \left(\frac{R_p}{r}\right)^{1/2} - \frac{4}{5}\left(\frac{r_{\tilde{n}}}{r_d}\right)^{1/2} + \frac{4}{5}\left(\frac{R_p\, r_{\tilde{n}}}{r_d\, r}\right)^{1/2} + \frac{1}{5}\left(\frac{R_p\, r}{r_d\, r_{\tilde{n}}}\right)^{1/2}$

For large particles (> 50 μm)

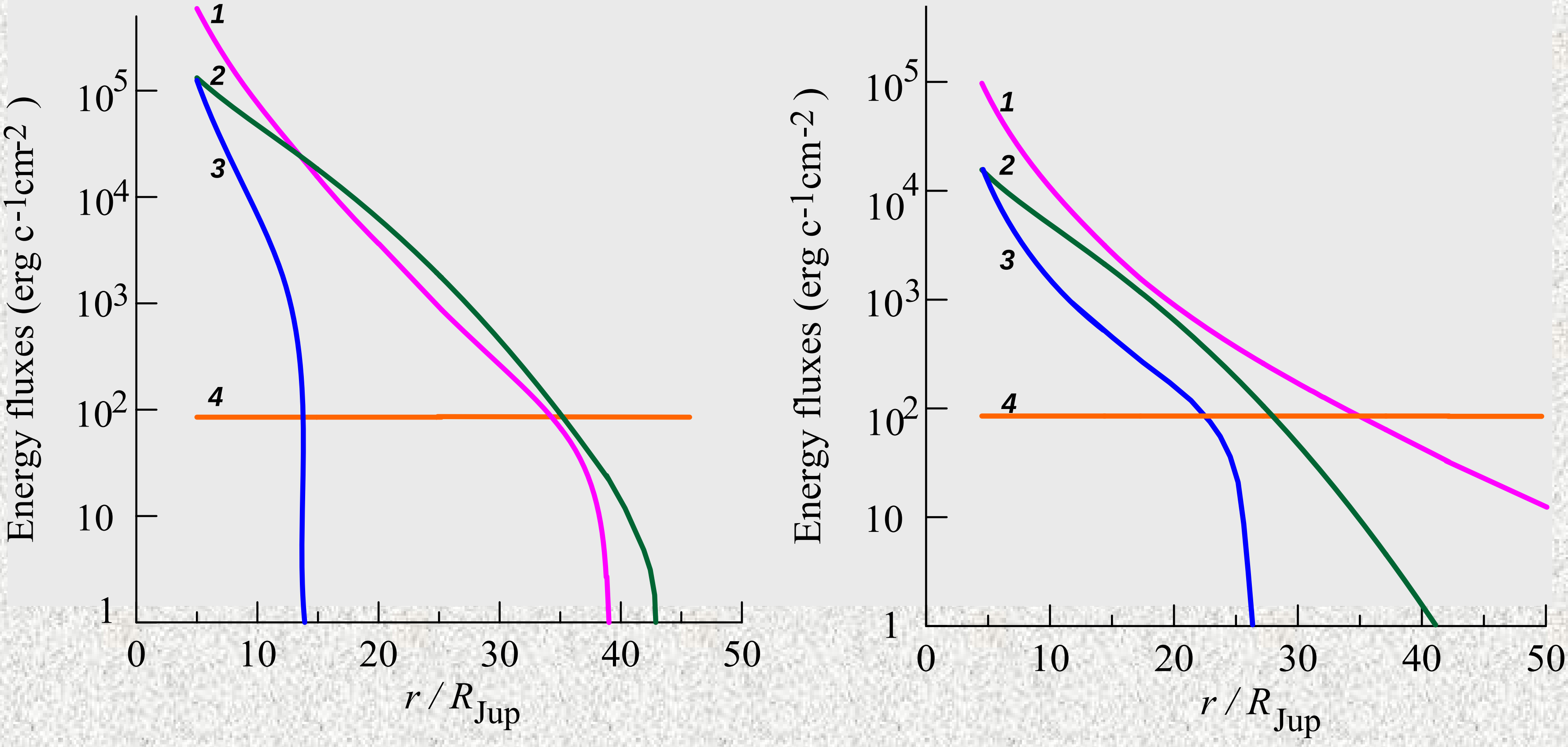
$$T_m^5 - T_s^4 T_m = \frac{3}{2^7 \pi^2}\frac{\mu}{\sigma_{\mathrm{SB}} R_g \gamma}\kappa \frac{\dot{M}^2}{\alpha}\Omega^3\left(\frac{\Lambda}{l}\right)^2 q_s^2 \ .$$

The models of the Jupiter's and Saturn's disks, which satisfy the cosmochemical restrictions on the disk temperatures

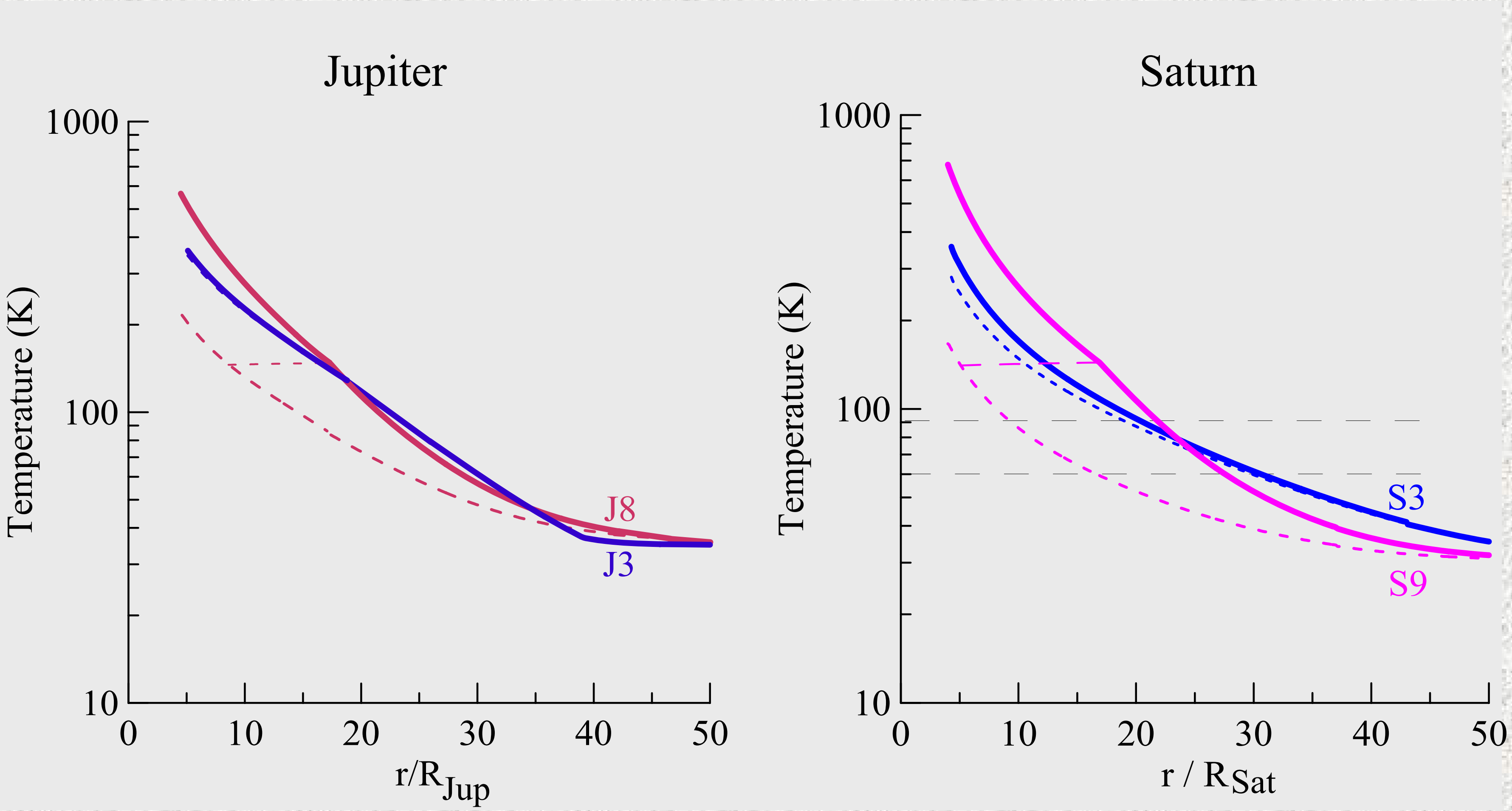
Model	Accretion rate, $\dot{M}$	Opacity, κ	Radial distance of water condensation
J3	$10^{-7}\ M_{\mathrm{Jup}}$/year	10^{-2}	$15\ R_{\mathrm{Jup}}$
J8	$10^{-8}\ M_{\mathrm{Jup}}$/year	~ 10	$18\ R_{\mathrm{Jup}}$
S3	$10^{-7}\ M_{\mathrm{Sat}}$/year	10^{-1}	$11\ R_{\mathrm{Sat}}$
S9	$10^{-8}\ M_{\mathrm{Sat}}$/year	$\sim 10^{2}$	$15\ R_{\mathrm{Sat}}$

Energy fluxes at the surface of the Jupiter's protosatellite disk. Curve ***1*** shows the flux contributed by the dissipation of the energy of turbulence; ***2***, the flux due to the fall of material onto the disk; ***3***, the flux due to radiation of the young Jupiter; ***4***, the energy flux from the surrounding region of the solar nebula.

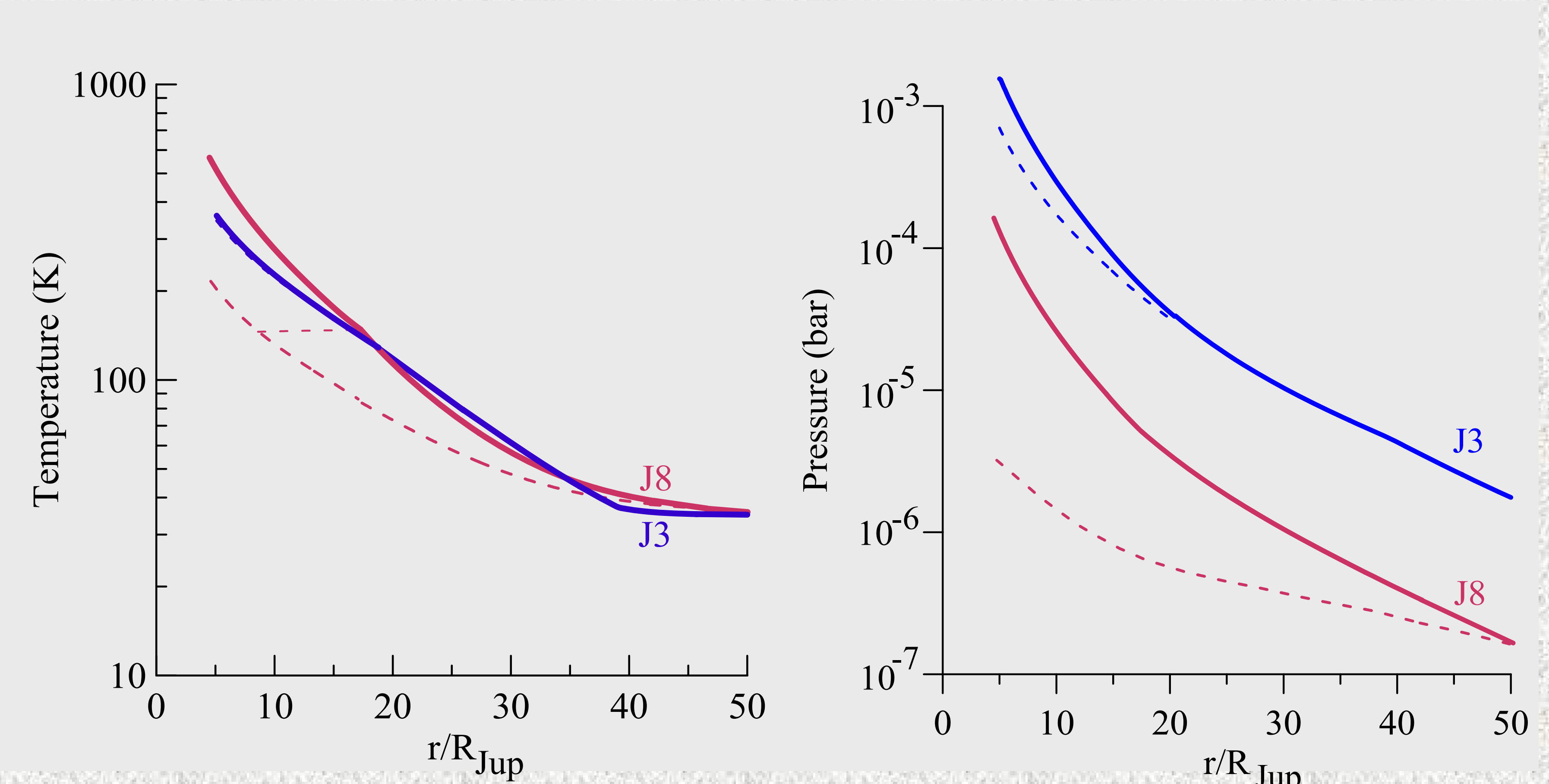
At the left panel the model is presented for the disk with the accretion rate $\dot{M}=10^{-7}$ M_{Jup}/year, at the right panel is the model with the accretion rate $\dot{M}=10^{-8}$ M_{Jup}/year.



Temperatures at the midplane (solid curves) and at the radiating surface (dashed curves) of protosatellite disks of Jupiter and Saturn for the models fitting cosmochemical restrictions on temperature in the formation regions of Europa and Titan.



Temperatures and pressures at the midplane (solid curves) and the radiating surface (dashed curves) of protosatellite disk of Jupiter for the models fitting cosmochemical restrictions on temperature



Conclusions

- Formation of satellites in the circumplanetary disks should occur at the late stage of planet accretion and could not proceed for more than ~10^6 yr. Any satellite formed in the disk earlier, should drift to the planet and fall on it due to the satellite migration of the first type. The models which 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}-10^{-8} M_{Jup} /year for Jupiter and 10^{-7} -10^{-8} M_{Sat} /year for Saturn. These models best of all also fit the cosmochemical temperature constraints.
- The models that better fit cosmochemical restrictions on temperature and astrophysical data on protoplanetary disks around young stars, yield opacity $\kappa \sim 10^{-2}$ $\mathrm{cm^2 g^{-1}}$ for the Jupiter's disk and $\kappa \sim 0.1$ $\mathrm{cm^2 g^{-1}}$ for the Saturn's disk. At a moderate enrichment of the disk in dust particles as related to the protosolar dust /gas ratio, the mean particle size is estimated to be 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 Jupiter formation, which require these rather large sizes of dust particles in order to obtain sufficiently low opacity, leading to the high accretion rate of the planet.
- The protosatellite disks with significantly larger sizes and lower opacity of particles are transparent for the powerful radiation of the young giant planets and hence too hot to satisfy chemical constraints.
- The material of 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 entered (at least partially) the composition of these satellites, then the loss of water would be higher.

For future missions to Europa the retrieval of the following data would be of top priority for cosmochemistry:

- The isotopic composition of the water ice on the surface and in the interiors: This will allow to determine if the ice was primordial or recrystallized after evaporation.
- The chemical composition of ice: This will permit to obtain abundances of volatiles, at the first place, CO_2, NH_3, CH_4, N_2.
- In the future missions to Jupiter the high-priority problem is the measurement of the abundance and distribution of water in the Jupiter's atmosphere as well as the refinement of nitrogen abundance which is defined with a large error now.
- All these parameters are of great importance for the solution of problem of the origin of volatiles (H_2O, C, N, the noble gases) and forms of their accumulation by the giant planets and their regular satellites.
- These data will also set limits on the temperature conditions in the protosatellite disks and make possible an adequate estimation of the effect of thermodynamic parameters of the disks on composition of the regular satellites. This will benefit the widening of our notions about the origin of the solar system as a whole.