FRACTIONATION OF THE PROTOMATERIAL OF THE GALILEAN SATELLITES IN THE COOLING DENSE CIRCUM-JOVIAN DISK

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Recently we have calculated models of the protosatellite accretion disk around Jupiter in the late phase of its formation that is characterized by a relatively slow accretion onto the planet. In this phase the mass flux onto Jupiter decreased to 10^{-6} -10^{-7} M_J /year, and the Jupiter's luminosity lowered from the maximum values, but still remained high, approximately 1000 times higher than the modern one. We calculated distributions of temperature and pressure as well as positions of evaporation-condensation fronts for the water ice and magnesium silicates. The constraints placed on the disk models are the mass of the Galilean satellites and their chemical composition: the absence of water in Io, the low water content in Europe, and the high water content in Ganymede and Callisto. We found out that it is impossible to construct the model of the accretion circum-Jovian disk, which would simultaneously meet the compositional and mass constraints. Two types of models were constructed: (1) a low-mass, moderately warm, viscous disk, which satisfies the compositional constraint, and (2) three and a half orders more massive and less viscous disk constrained by mass, but substantially more hot that it is necessary for water ice condensation even in the formation zone of Callisto, the outermost of the Galilean satellites [1].

We considered consequences of either of the two disk models for the process of satellite formation. It was found that the low-mass model (1) runs into the problem to accumulate in the disk the mass of solid material, which is sufficient to form the regular satellites. A very high, almost 100%, efficiency of sweeping up the dust particles and small bodies by the satellite embryos over the whole period of their growth is required for the satellite formation, that is highly improbable. For accumulation of satellites from the low-mass disk it is also necessary that the intensive accretion of gas-dust material onto the disk and through it onto Jupiter continued no less than 1×10^7 years, that is, approached the lifetime of the gas in the solar nebula (the protoplanetary disk). However, it is much more probable, that the accretion rate decreased with time. In this case the mass of the solid component of the material arrived at the jovian disk appears to be insufficient to form the satellites.

In the massive disk model (2) such problems do not arise. In this model the matter falling on the disk from the solar nebula, at the early stage of disk evolution is accumulating in it due to its relatively low viscosity and, accordingly, lower radial mass flux through the disk. At this stage the disk temperature is growing. After completing the stage of accumulation of matter the quasi-stationary state is reached in the disk, the temperature of the inner region being higher than necessary to form the satellites of observed density and composition. However, then, as the mass flux on the disk and through it on Jupiter reduces, the temperature in the disk decreases concurrently with decrease of its mass and surface density. It is also possible, that the disk at the late stage of its evolution ceases to be accretion disk, that is, the turbulence is damped out and the viscosity tends to zero. As viscous dissipation decreases, the temperature in the disk is also lowered. In the case that the disk viscosity decreased faster than the mass flux falling on the disk from the surrounding solar nebula, the disk mass could grow till the end of the fall. The loss of the gas from the disk was carried out by the process of thermal dissipation. From our estimates it follows that the rate of this process was lower than the cooling rate of the disk and the growth rate of planetesimals in the inner zone of the disk, at the radial distances of the Galilean satellites (excluding Callisto).

Duration of formation of the satellites is defined not only by their accumulation rate which is proportional to the surface density σ_c of the solid (dust) component of the disk material. For the massive disk, corresponding to the model (2), the value σ_c is three and a half orders of magnitude higher, than for the model (1).

In view of the above considerations we choose the variant of formation of the Galilean satellites, based on the model (2) of the accretion Jovian disk. According to this model, at the steady-state stage of disk evolution (prior to the accumulation of the satellites) the disk was dense and hot. The process of satellite formation occurred at the subsequent stage of disk cooling due to decaying accretion on Jupiter. The temperatures and pressures in the mid-plane of the disk at several successive moments from the beginning till the end of this stage are shown in Fig.1. One can see that the pressures at the radial distances corresponding to the region inside of Ganymede orbit ($r < 15r_j$), were for a long period ($\geq 10^5$ years) higher than 0.01 bar. This suggests that the temperatures inside the disk of solar composition at these radial distances were equal to the condensation temperature of iron-nickel alloy and higher then the condensation temperature of the major magnesium silicates. The difference between these temperatures, according to the calculations of the homogeneous condensation of the solar-composition gas, grows with the increasing total pressure and reaches 100 K at $P = 0.1$ bar and 150 K at $P = 1$ bar [2]. The disk structure just before the cooling stage, obtained from our modeling, is shown in Fig.2. The innermost, rather extended region of the disk ($r < 17r_j$) is a region of partial condensation of the metal, bounded by the front of the total metal condensation (curve z_{Fe}). The condensation front of Mg-silicates is located outside the metal condensation front at the distance ≤ 1 r_j from the latter. The region of partial condensation of Fe-Ni alloy contained also in the solid state Al, Ca and other less abundant refractory elements. The reason why the Fe-Ni in the inner region of the disk was not evaporated totally, is the following. The disk was heated from the interior due to the dissipation of turbulence (viscous dissipation); the energy transfer from the interior to the subsurface layers of the disk was carried out by radiation, and the heat flux depended on the opacity of the disk material. As Mg-silicates in the inner region were evaporated, the opacity there was dictated by the most abundant metal particles. The heating of this region above the condensation temperature of Fe-Ni alloy and its total evaporation would produce a sharp drop of opacity, an increase of the energy flux from the interior layers, and hence a decrease of their temperature and partial condensation of the metal.

At high temperatures iron particles grow rapidly at collisions due to their high plasticity [3]. In conditions of circum-Jovian disk at the distance $r = 10r_J$ they reached the size 1 cm in 10^3 years. As it follows from our estimates, a decrease of orbital radii of the particles due to gas drag resulted in their fall on Jupiter in a time of the same order. The gas drag is caused by the difference between the orbital velocities of the particles and gas: the gas velocity is lower due to existence of the radial gradient of gas pressure in the disk. The time of settling (precipitation) of the particles to the midplane of the disk with regard to disk's turbulence at $r = 10r_J$ is estimated as $\geq 10^3$ years. This means that iron particles before their fall on Jupiter had no time to form in the midplane the gravitationally unstable dust layer, necessary for formation of large planetesimals, those could not be removed from the disk and carried to Jupiter.

The gas drag continuously supplied new portions of dust particles from the outer to the inner zone of the disk. These particles contained Fe, Mg and Si in the solar proportion. On arrival in the inner zone, Mg and Si evaporated, and the Fe-Ni particles (containing also more refractory elements) drifted to Jupiter due to gas drag. Hence, during a considerable period (10^5-10^6 years) of the high-temperature stage, there happened a depletion of the proto-satellite matelial in Fe. At the later stage the mass of the disk substantially decreased, the temperatures became lower, and the major mass of the rock-forming elements condensed in the zone of formation of the inner Galilean satellites - Io and Europe. However, due to preceding fractionation, the condensate was depleted in iron and more refractory elements. This conclusion agrees with the models of the internal structure of Io and Europe, based on evidence from new measurements of physical parameters of these satellites [4].

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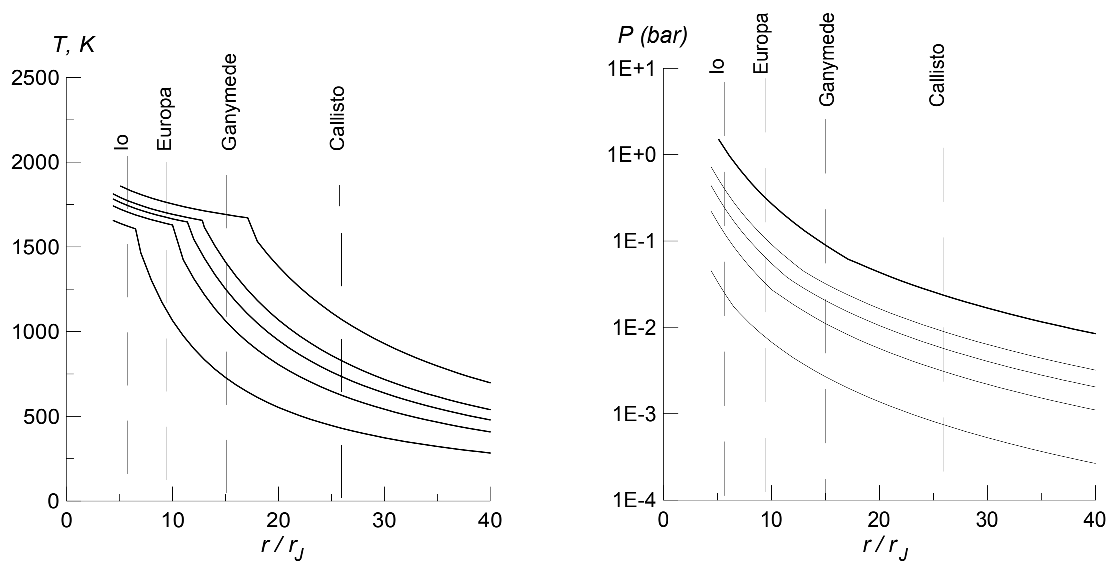

Fig.1. Radial distribution of the temperature and pressure at several successive moments of the stage of disk cooling and formation of the Galilean satellites. The radial coordinate is given in the units of the present mean radius of Jupiter

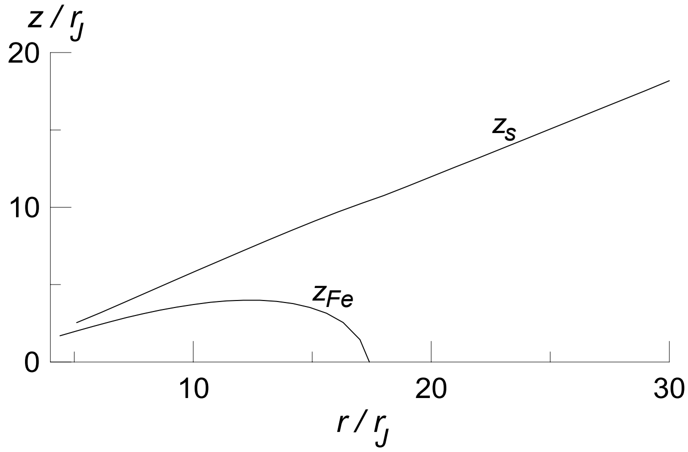

Fig.2. Meridional section of the protosatellite circum-Jovian disk at the stage prior to disk cooling. Curves z_s and z_{Fe} are the optical surface of the disk and the metal condensation front. All heights are measured from the midplane of the disk