A MODEL OF THE PROTOPLANETARY DISK AT THE FORMATION STAGE

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We have constructed a model of the internal structure of the protoplanetary disk around the forming sun at the stage of collapse of the protosolar nebula with the angular momentum J = 1-4 X 10^{52} g cm^2 s^{-1} [1]. In calculations of the external heating of the disk we adopt the duration of this stage 10^5 yr resulting from observations [2]. Distributions of the temperature, pressure and other disk parameters are found. Our calculations for the end of the collapse stage showed that magnesium silicates and iron are totally condensed at the radial distance 2 AU and water ice about 20 AU.

The material of the accretion envelope falls onto the growing sun and the surrounding disk. The disk mass grows through accretion of this material, but the viscous transport of angular momentum in the disk decreases its mass by carrying most of disk material to the sun. At the same time this transport implies the increase of disk radius r_d by the outward motion of the minor part of disk material [3]. The collapse is nearly spherically symmetric at $R > r_c$, where r_c is the centrifugal radius [4,5]. At the end of the collapse stage r_c = 0.1-2 AU for the foregoing angular momentum range. The total luminosity of the growing sun and disk is practically the same as in the case of spherically symmetric collapse [1]. Thus in the range $R > r_c$ one can use the spherically symmetric model of the accretion envelope [6]. The radial dependence of temperature in the envelope $T(R)$, obtained in the paper [6] for accretion rate $\dot{M} = 10^{-5}$ $M_\odot$/yr, can be represented in the form $T = 1460(R/1\ \mathrm{AU})^{-0.75}$ K at R from 0.6 to 4.5 AU (the optically thick part), and $T = 870(R/1\ \mathrm{AU})^{-0.4}$ K at $R >$ 4.5 AU. The disk is immersed in this envelope and is heated by reradiated there solar radiation.

The structure of the disk at radial distance (measured in the midplane) $r > r_c$ and $r < r_d$ satisfies the equation [4,5]

$$\Sigma \nu r^{1/2} = const \qquad (1)$$

where Σ is the surface density of the disk, ν is the kinematic viscosity in its midplane.

When constructing the disk model we used Eq.(1) to find distributions $\Sigma(r)$ and $T_m(r)$ in the range of r from 1 to 10 AU. Here T_m is the temperature in the disk midplane. We have adopted the value of the constant in Eq.(1) so that the mass and the radius of the disk are appropriate to the definite moment at the stage of disk and sun formation. Maximum values of Σ and T_m correspond to the end of the collapse stage, when $r_d \approx 20$ AU [5], the disk mass peaks at about 0.1 $M_\odot$ [2,5], and the mass of the forming sun reachs $\approx 0.9 M_\odot$.

Eq.(1) is alternative to the equation $\dot{M} = 3\pi\Sigma\nu = const$, that we used when studying the structure of the disk at the subsequent stage of evolution - the T Tauri stage [7]. Other equations and a method of model construction remain as in the work [7].It is

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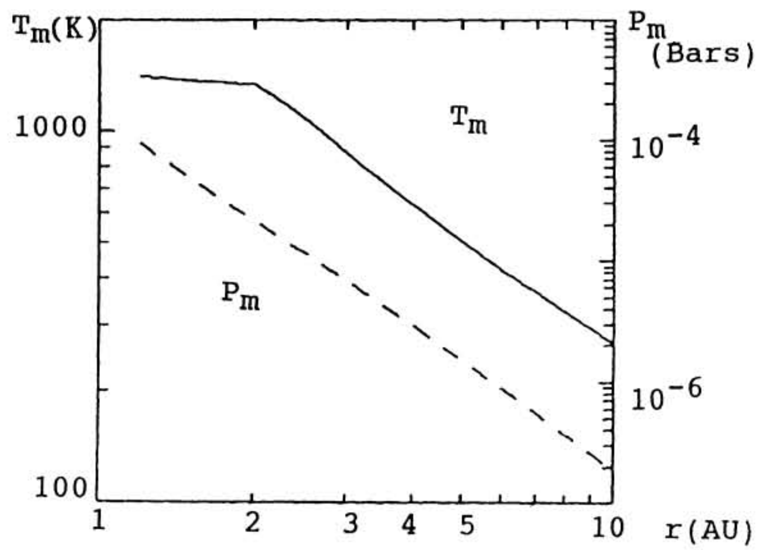
worth noting that for the collapse stage the main heat source in the equation for temperature of the disk emitting surface T_s is thermal radiation of the envelope instead of the viscous dissipation D_1 (as is the case for T Tauri stage): $\sigma T_s^4 = \sigma T_e^4 + D_1$, where $\sigma T_e^4 \gg D_1$. The disk effective temperature T_e results from disk irradiation by the envelope and is equal to envelope temperature T at the same (spherical) radial distance $R < 4.5$ AU, that is in the inner optically thick part of the envelope. In the optically thin region $R > 4.5$ AU T_e would be slightly lower than T.

P-T parameters in the disk midplane (P_m and T_m) at the end of the collapse stage are shown in the figure (1). These are in fact the maximum values in the indicated range of radial distances over the whole time of disk evolution. Magnesium silicates and iron are at this moment condensed at the radial distance $r = 2$ AU. The disk temperature remains higher than condensation temperature of water not only at 10 AU, but at the edge of the disk ($r_d \approx 20$ AU) as well; that is water in the disk is totally evaporated at the moment. This result would be of importance for fractionation of preplanetary material.



Although at $r \approx 10$ AU the vertical temperature distribution through the whole thickness of the disk approaches the isothermal one, a layer containing about $0.3\ \Sigma$ survives near the midplane, where the vertical temperature gradient is superadiabatic and therefore the turbulence, driven by thermal convection, is possible. The turbulence is necessary for transport of material and growth of the disk.

This work was supported in part by the ISF grant ML6000, and by the RFBR grant 94-02-03925.

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