THERMAL HISTORY OF PLANETARY MATERIALS IN THE SOLAR NEBULA

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1. Introduction

The current bulk composition of planets has been cast in some extent during the early history of the solar system, associated with the formation and evolution of the solar nebula. Particularly, this stage regulated the abundance and composition of volatiles absorbed by planetesimals and incorporated into planets, and the composition and texture of the primitive meteorites – chondrites.

The history of the solar nebula is usually conditionally divided into three stages: the infall stage, associated with collapse of the presolar cloud and formation (and viscous evolution) of the primordial solar nebula; the further stage of viscous evolution of the solar nebula and planetesimal accumulation; and, finally, the dissipation of the gaseous part of the solar nebula in the region of terrestrial and outer planets and the gas accretion by the cores of the giant planets.

The infall provided the most intense heating of a significant portion of the matter and, in spite of the "shortness" ($\sim 10^5$ yrs), played an important role in the thermal history of the solar system. The maximal temperature of dispersed solids determined composition of volatiles preserved in them, a possibility of survival of the presolar grains, and influenced the oxidation state of both solids and gas.

One of the parameters of which the evolution of the solar nebula depends the most critically is an angular momentum of the presolar cloud (a fraction of the molecular

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cloud participated in the collapse and joined the Sun or the solar nebula). The larger angular momentum, the larger region over which the gas, falling onto a razor thin solar nebula, is distributed; the radius of this region is called the centrifugal radius. (If the solar nebula has a nonzero thickness and radius larger than the centrifugal radius, then some fraction of the infalling matter will hit the edge of the disk and may join the disk at the distances larger than the centrifugal radius.)

The initial angular momentum of the presolar cloud has an uncertainty of one order or two orders of magnitude, which implies a necessity to investigate the whole range of possible initial angular momenta.

Direct 2D or 3D numerical simulations are restricted at present by angular momenta ($J/M \geq 10^{20}$ cm^2 s^{-1}). (Partially these restrictions are imposed by the spatial resolution of numerical codes; for slowly rotating clouds centrifugal forces in the infalling envelope are important only in a relatively close and not well resolved vicinity of the star). According to Boss (1993), the dynamical compression of the solar nebula in such models can result in the temperature $\geq$ 1500 K in the middle plane of the solar nebula at distances up to 2 – 3 AU. Further work is required to construct the evolutionary models of the solar nebula and investigate the radial transport from the hot region and its mixing with less heated material.

The lower limit for the angular momentum of the presolar cloud was estimated by the reconstruction of the solar nebula from the present-day structure of the solar system. It is equal to a few times 10^{51} g cm^2 s^{-1} to 10^{52} g cm^2 s^{-1}, or the specific angular momentum $J/M \simeq 10^{18}$ to 10^{19} cm^2 s^{-1} (Weidenschilling 1977, Weissman 1991)).

This paper gives a summary of a study of the thermal history of low-mass solar nebula forming in a collapsing cloud with the initial angular momentum $J = 2 \times 10^{52}$ g cm^2 s^{-1} ($J/M \simeq 10^{19}$ cm^2 s^{-1}). (Such a value of the angular momentum might be typical for dense cores of molecular clouds, those rotation was braked before the collapse has started: see, e.g., Safronov and Ruzmaikina 1985). The solar nebula evolution during infall is considered by using a simplified numerical model developed by Ruzmaikina and Maeva 1986, and Ruzmaikina et al 1993, or summarizes the results of these papers. Temperature of presolar silicate dust particles and dust aggregates in the accretional shock (i.e., by the shock produced by the infalling gas at the surface of the solar nebula) were calculated by Ruzmaikina and Ip (1994). The heating of the presolar ices in the shock at the outer solar nebula is a new result, taking into account earlier neglected important effect of the gas cooling in the postshock region.

2. Model of the Solar Nebula Formation

Let us consider the presolar cloud with the mass 1.1 $M_\odot$ and the angular momentum 2×10^{52} g cm^2/s. We investigate the infall stage of the solar nebula formation, i.e., a stage when embryo protosun and solar nebula have been forming already in the center of the collapsing cloud, but they are still surrounded by the infalling envelope of gas and dust. The solar nebula is considered as a viscous disk with the sources of mass and angular momentum associated with the infall; and with effective viscosity $\nu = 1 \cdot 10^{15}\sqrt{\frac{M}{M_\odot}\frac{R}{1\mathrm{AU}}}$ cm^2/s, which corresponds to conversion of a few percent of the kinetic energy of the infalling gas into the turbulence in the solar nebula. The (magnetic) coupling between the solar nebula and protosun is taken into account by imposing nonzero torque at the inner boundary; the shock, produced by the infalling gas, determines the outer edge of the solar nebula. Calculations start at the moment when a low-mass star-like core, containing a few percent of the total mass, and tiny embryo disk have been formed at the center of the presolar nebula, and the bulk of mass remained in the envelope.

The equations, describing the disk evolution could be reduced to the continuity equation with the source term

$$\frac{\partial \sigma}{\partial t} + \frac{1}{R}\frac{\partial(\sigma R u_R)}{\partial R} = f_a, \tag{1}$$

where u_R is the radial velocity of in the disk

$$u_R = -\left[\frac{3}{j\sigma}\frac{\partial}{\partial R}(j\nu\sigma) + 2R\left(1 - \frac{j_a}{j}\right)\frac{f_a}{\sigma} + \frac{\dot{M}}{M}R\right], \tag{2}$$

f_a is the flux of material from the envelope onto the disk, j_a is the angular momentum of infalling matter, $\sigma(R)$ is the surface density of gas in the disks ($\sigma(R) = \int \rho(R,z)\,dz$, where $\rho(R,z)$ is the spatial gas density), M is the current mass of the forming protosun. These equations are solved numerically, with a second-order accurate explicit scheme. The source functions f_a and j_a are taken from analytical solution of distribution of velocities and density in the infalling envelope (Cassen and Moosman 1981, Ziglina and Ruzmaikina 1991).

The equations governing the vertical structure of the individual rings in the disk are the equation of vertical hydrostatic equilibrium

$$\frac{dP}{dz} = -\frac{GM}{R^3}\,z\,\rho, \tag{3}$$

and the equation of the energy balance

$$D_{mech} = D_{rad} + D_{conv}, \tag{4}$$

where P is the gas presure, D_{mech} is the energy released through the shear ($D_{mech} = \frac{9}{4}\frac{G\,M}{R^3}\,\nu\,\rho$ when only the radial shear of the Keplerian motion is taken into account). The radiative transport equation may be written for the frequency-integrated moments, in the approximation of the local thermal equilibrium

$$\frac{dH}{dm} = k_J\,J - k_B\,B = D_{mech}, \tag{5}$$

$$\frac{dK}{dm} = k_H\,H, \tag{6}$$

where J, H, K are the frequency-integrated moments of the specific intensity, and B is the frequency integrated Plank function, k_J, k_B, and k_H are absorption, mean, Plank mean, and flux mean opacity per unit mass, respectively, $m(z) = \int_z^\infty \rho\,dz$. The equations (3 – 6) for the vertical structure of the disk are solved numerically by an iteration procedure, described by Hubeny (1990).

The shape of the disk was identified with the shape of the shock between the disk and accreting envelope determined by the equation (Elmegreen 1978).

$$\frac{dz}{dR} = \frac{\tan\beta - \frac{R}{z}}{1 + \frac{R}{z}\tan\beta}, \tag{7}$$

where the shock exists, and otherwise with the surface at which density of the infalling gas is equal to the density in the disk; β is an angle between radius vector and normal (to the shock front) component of the velocity ($\beta = \arccos\frac{|v_\perp|}{v} + \arcsin\frac{v_\theta}{v}$), and $v_\perp$ is found from the conservation relation for the impulse, which can be reduced to a balance between dynamical pressure of infalling gas and the thermal pressure in the disk, taking into account fast cooling of the shocked gas resulting in a narrowness of the postshock region. This equation, is integrated from the disk edge inside, checking at every grid point if $v_\perp > c_s$. When the shock disappears we continue by solving of equation $\rho_1 = \rho_2$, (where $\rho_1(z, R)$ is the density of infalling gas and $\rho_2(z, R)$ is the density of the solar nebula at the same height), because the shock disappears and arises again at this surface. (In our approximation $v_\perp = c_s$, at the surface $\rho_1 = \rho_2$). Then we find again that $v_\perp \geq c_s$, specify the position where the shock arises, use it as a new boundary condition, and repeat the procedure again.

3. Results

During infall stage of formation (10^5 yrs), the solar nebula, which started from radius < 1 AU and mass $\approx 10^{-5}$ $M_\odot$ has grown to radius $R_{SN} \geq 50$ AU, while the centrifugal radius for the infalling matter did not exceed $R_{ce} \sim 1$ AU (for $J = 2 \times 10^{52}$ g cm^2/s).

The ratio of the solar nebula mass to the mass of the protosun is < 0.1 during whole stage of infall; the ratio of the maximum height to radius ratio is about 0.1, (see also Ruzmaikina Khatuncev, and Konkina 1993).

Distribution of the radial velocity in the solar nebula depends on efficiency of mixing of newly fallen gas with the solar nebula. In the absence of mixing (when the infalling gas flow around the disk till its centrifugal force balances the gravity, at $R \leq R_{ce}$) the net mass flux in the solar nebula is directed inward in the vicinity of the protosun ($R \leq R_{ce}$), and outward at larger distances. The radial flow in the solar nebula is more complicated if the mixing is efficient (Ruzmaikina and Maeva 1986). It is directed inward in the most part of the solar nebula (except near the edge) at the beginning of the infall, but later an additional region of the outward flow develops at distances between $R_{ce} \leq R \leq 0.5R_{SN}$. In both cases, the outward flow results in spreading of the material from ≤ 1 AU over the asteroid region, and possibly farther. It implies that the radial transport, rather than high temperatures in the solar nebula within several AU, might be a reason for "a hot thermal history" of the matter in the outer part of region of the terrestrial planets. In the most of outer part of the solar nebula the mixing of the falling gas, possessing smaller specific angular momentum than that in the solar nebula, cause inward mass flow. In this region, the strongest heating caused by the shock, produced by the infalling matter at the surface of the solar nebula.

Infalling gas produces strong shocks in two regions - at the vicinity of the star ($R \leq R_{ce}$) and near the edge of the disk. A wide region is situated between them, in which the gas falls under small angles, and the model predicts that the shock should be weak or absent at all. (It could be incorrect if the infalling gas contains inhomogeneities, because denser clumps of the gas penetrate deeper into the solar nebula, and produce strong shock ahead of them at any angle of infall). Note, that the heating of the outer part of the disk by the shock wave makes the IR-spectrum of the disk more flat, and it plausibly could explain an effect observed for some T Tauri stars, a "slow" decrease with the distance from the star of the disk's effective temperature (Beckwith et al 1990).

The shocks can play an important role in the thermal reprocession of dust particles and aggregates, and gas-phase chemical reactions. The peculiarity of the shock in the solar nebula is fast cooling of the gas, (by molecular hydrogen, dipole molecules, and dust emission) resulting in a sharp density gradient in the postshock region, and increase of the gas density up to two orders of magnitude. Subillimeter-size and large dust aggregates, embedded in the infalling gas, have such an inertia that they cross the region of cooling without deceleration, and are heated by the drag through the cooled and compressed postshock gas.

Silicate grains, heated to > 1600 K, were melted and then solidified in $\sim 10^3$ s, plausibly forming chondrules (Ruzmaikina and Ip 1994). The possibility of formation of such aggregates (chondrule precursors) in the collapsing cloud was first discussed by Cameron (1978). A recent detailed numerical simulation by Weidenschilling and Ruzmaikina (1994) reveals a possibility of the formation of fluffy dust aggregates of appropriate masses in turbulent dense molecular cloud cores, and their survival (or further growth) during the following collapse.

In the outer part of the solar nebula, where the temperature of the infalling gas is low enough to preserve presolar organic material and ices, the accretional shock can cause melting, evaporation, and chemical changes of volatile components of dust aggregates. Also, the presence of liquid water or vapor could cause oxidation of less volatile components, such as Fe. The intensity of heating of aggregates and the extent of region of their evaporation in the outer solar system are also dependent on the size and structure of the aggregates. In the shock produced by the gas falling normal to the shock front, millimeter-size dense aggregates could be melted and evaporated at distances up to 30 AU, and possibly farther. If normalized (for the same rate of accretion) the extension of the region of evaporation ice aggregates is larger than was estimated earlier (Mukhin et al 1989, and Lunine et al 1991). This stronger heating is associated with the fast cooling and compression of the postshock gas – the effect which was not taken into account in earlier papers. Smaller (say, $\leq 1\mu$m) grains and very low dense dust aggregates are decelerated faster than the gas cools, and they are heated to lower temperatures. Such particles preserve interstellar water ice beyond 5 to 10 AU, organics beyond 3 to 5 AU, and silicates beyond 1 AU. The outer solar system must contain a mixture of interstellar ices, and ices which were evaporated in the accretional shock and recondensed again.

The general conclusion of this paper is that the presented model can explain the formation of the low-mass solar nebula with a signature of the high temperature reprocessing of the matter within inner several AU and the presence of a relatively unaltered interstellar dust in the outer solar system.

5. References

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