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Formation and Evolution of the Protoplanetary Disk

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ABSTRACT

The structure of the solar system, the similarity of isotope compositions of its bodies (in terms of nonvolatile elements), and observational data on the presence of disks (and possibly of planets) around young solar-type stars are evidence of the joint formation of the Sun and the protoplanetary disk. The removal of angular momentum to the periphery (necessary for the formation of the Sun and protoplanetary disk) is possible at the formation stage in the center of the contracting cloud (protosolar nebula) of the stellar-like core (Sun's embryo). The possibility that the core forms before fragmentation begins to impose a constraint on the value of the angular cloud momentum. This value is highly dependent on the distribution of angular momentum within the cloud.

This paper discusses a disk formation model during collapse of the protosolar nebula with $J \sim 10^{52}$g cm^{2}s^{-1}, yielding a low-mass protoplanetary disk. The disk begins to form at the growth stage of the stellar-like core and expands during accretion to the present dimensions of the solar system. Accretion at the edge of the disk significantly affects the nature of matter fluxes in the disk and its thermal evolution.

In addition to the internal heat source (viscous dissipation), there is an external one which affects the temperature distribution in the disk: radiation (diffused in the accretion envelope) of the shock wave front at the core and in the nearest portion of the disk. Absorbed in the disk's surface layers, this radiation heats these layers, and reduces the vertical temperature gradient in the disk to a subadiabatic point. It also renders convection impossible. Convection becomes possible after accretion ceases.

INTRODUCTION

The proximity of planes of planetary orbit in the solar system indicates that planets were formed in the thin, elongated protoplanetary disk surrounding the young Sun.

The coincidence of isotope compositions of the Sun, the Earth, and meteorites for basic nonvolatile elements, and the similarity of the chemical compositions of the Sun and Jupiter are evidence that the Sun and the protoplanetary disk originated from the same concentration of interstellar medium. In view of observed data on the rapid ($\sim 10^6 \div 10^7$ years) removal of gas from the proximity of solar-type stars which had formed (T Tauri stars), it is natural to infer that the convergence of the isotope composition of the Sun and the planets also means that they formed contemporaneously.

According to the theory developed by Jeans early in this century, stars are formed as a result of collapse under the impact of the gravitational effects of compacted regions of the interstellar medium. The collapse occurs when the forces of self-gravity exceed the sum of forces restricting compression. The latter include the thermal pressure gradient, magnetic pull, and centrifugal forces. Data from infrared and radioastronomy tell us that the stars are formed in molecular clouds: low temperature regions ($\simeq 10$ K) with relatively high density $10^{-22} \div 10^{-20}$ g $\cdot$ cm^{-3}, in which hydrogen and other gases (besides the noble gases) are in a molecular state, and condensing matter is included in grains.

Study of the radio lines of molecules has shown that the clouds are highly inhomogeneous. They contain compact areas, cores with densities $\rho \sim 10^{-20} \div 10^{-18}$ g $\cdot$ cm^{-3} and masses $M \sim 0.1 \div 10\ M_\odot$, infrared sources and compact zones of ionized hydrogen with ages $10^4 \div 10^5$ years. Relatively weak, variable T Tauri stars are also seen in certain molecular clouds. They approximate the Sun in terms of mass ($0.5 \div 2M_\odot$), but are much younger, with ages $10^5 \div 10^6$ years (Adams *et al.* 1983). Their formation is related to the compression of cores of molecular clouds under the impact of the forces of self-gravity.

Contemporary theory of evolution holds that the fate of a star is determined by its mass and chemical composition. In view of the similarity of these parameters, we can identify T Tauri stars with the young Sun and use observed data on these stars to construct a theory of the formation of the Sun and the protoplanetary disk.

CIRCUMSTELLAR DISKS

Elongated, disk-shaped, gas-dust envelopes with characteristic masses $0.1M_\odot$ (Sargent and Beckwith 1987; Smith and Terrile 1984) have been discovered around several young stars (HL Tau, DG Tau, β Pic, and a source of infrared radiation L 1551 IRS5). The radii of the gas-dust disks, which were determined by eclipses of the stars, are estimated at $\sim 10 \div 10^2$ AU (see Strom's article in this volume). The radii of the disk-shaped envelopes in CO molecule lines are estimated on the order of 10^3 AU. Data from observations of the IRAS infrared astronomical satellite have shown that 18% of 150 near stars which have been studied exhibit infrared excesses. That is, they emit more in the infrared range than matches their temperatures (Backman 1987). It was proven for a number of closer stars (Aumann *et al.* 1984) that excess infrared radiation is not created by the star itself, but by the envelope of dust grains. The grains absorb the light of the star and reemit it in the infrared range. It is possible that disks exist for all stars which exhibit infrared excesses (Bertrout *et al.* 1988). Thus, there is a greater probability that the formation of a star is accompanied by the formation of a gas-dust disk around it.

IRAS discovered in the envelopes of stars α Lyr, α PsA, and β Pic that the central region with a radius of 30 AU is dust-free (Backman 1987). This empty region could not have been retained after the star's formation stage, since the dust grains from the surrounding envelope shift inside under the Poynting-Robertson effect and fill up the empty space over a time scale of $< 10^5$ years. This is too brief a time scale in comparison with the age of the star. A possible cause of the existence of an empty region around stars is that the large planetesimals and planets may remove those dust grains shifting towards the center.

The first finding of the search for planets around solar-type stars was obtained using an indirect search method: determining with high accuracy (up to 10 to 13 meters per second) the ray velocities of the nearby stars. Seven of 16 stars examined were found to have long-period Doppler Shifts of velocities with amplitudes of 25-45 meters per second. It is probable that these variations in ray velocities are produced by invisible components (planets with masses from one to nine Jovian masses) moving in orbit around the stars (Campbell *et al.* 1988).

These findings, together with observational data on the disks around young stars, are evidence that the formation of the planetary system is a natural process which is related to star formation.

CONDITIONS FOR THE FORMATION OF STARS WITH DISKS

The most likely cause of the formation of protoplanetary disks and planetary systems, including the solar system, is the rotation of molecular clouds. The rotation of clouds and separate dense regions in them is a function of the differential rotation of the galaxy and turbulence in the interstellar medium. The rotation velocities of molecular clouds and their nuclei are determined by the value of the gradient of the spectral line's ray velocity along the cloud profile. Angular velocities of rotation Ω, measured in this manner, are included in the interval $10^{-15}-10^{-13}s^{-1}$ (Myers and Benson 1983). For small cores of < 0.1pc, rotation is only measurable for $\Omega > 2.10^{-14}s^{-1}$. Rotation was not discovered with this kind of accuracy for approximately 30% of the cores.

Angular momentum value and internal distribution J(r) are important cloud/core characteristics for star formation. These characteristics depend both on the value Ω on the outer edges of the cloud and its internal distribution. Data on the dependence Ω(r) have been measured for individual, sufficiently elongated molecular clouds. Thus, for cloud B 361, $\Omega \simeq$ const in the inner region and falls on the periphery in the outer region (Arquilla 1984). A concentration of matter towards the center is also observed within the compact cores. The distribution Ω is not known. The maximum laws of rotation which appear to be reasonable are being explored in theoretical studies:

$$\Omega = \text{const with } \rho = \text{const}, \tag{1a}$$

$$\Omega = \text{const with } \rho \propto r^{-2}. \tag{1b}$$

The first describes the angular momentum distribution in a homogeneous and solid-state rotating cloud. It holds for a core which has separated from the homogeneous rotating medium where the specific angular momentum of each cloud element is conserved. The second corresponds to a solid-state rotating, singular isothermal sphere. This is an isothermal cloud with $\rho = C_s^2/(2\pi G r^2)$, in which the forces of self-gravity are balanced out by internal pressure (C_s is the speed of sound). In order for this kind of distribution to be established, the core must exist long enough during the stage preceding collapse for angular momentum redistribution to occur and for solid-state rotation to be established. The characteristic time scale for the existence of cores prior to the onset of contraction is $\tau_{sf} \sim\sim 10^7$ years. This is significantly more than the contraction of an individual core of $\tau_{ff} \sim\sim 10^5$ years (Adams *et al.* 1983).

Random (turbulent) motion with near-sound speeds is present in the cores (Myers 1983). The viscosity created by this motion may be represented as (Schakura and Sunyaev 1973)

$$\nu_T = 1/3 v_T l_T \simeq \propto R c_s, \tag{2}$$

where R denotes the core radius, sc is the speed of sound in it, $\propto$ is the nondimensional value, and v_T and l_T are the characteristic turbulent motion velocity and scale. The time scale for angular momentum redistribution in the core under the effect of viscosity $\tau_\nu \sim R^2/\nu_T$. The condition $\tau_\nu \sim \tau_{sf}$ is fulfilled for

$$\propto \sim R/c_s \tau_{sf}. \tag{3}$$

As a numerical example, let us consider the core TMC-2 . It has a mass $M \simeq M_\odot$, $c_s = 3 \cdot 10^4$cm/s and $v_T \simeq 0.5\ c_s$, $R \simeq 0.1$ pc (Myers 1983). Substitution in (2) and (3) of these numerical values and $\tau_{sf} = 3 \cdot 10^{14}$s give us $\propto \sim 0.03$. This fits with $l_T/R \sim 0.1$. This estimate demonstrates that the efficiency of angular momentum redistribution in various cores may differ depending on the scale of turbulent motion. Therefore, cores with both rotation laws, (see 1a and 1b) and the intermediate ones between them, may exist.

The angular momentum of a solid-state rotating spherical core of mass M is equal to

$$J \simeq 10^{52} K \frac{\Omega}{10^{-15} s^{-1}} \left(\frac{M}{M_\odot}\right)^{5/3} \left(\frac{\overline{\rho}}{10^{-19} gcm^{-3}}\right)^{-2/3} gcm^2 s^{-1}, \tag{4}$$

where k = 2/5 and 2/9 for the rotation laws (1a) and (1b), and $\overline{\rho}$ denotes the mean core density.

The rotation of clouds plays an important role in star formation. Stellar statistics demonstrate that more than one half $\gtrsim$ 60%) of solar-type stars enter into binary or multiple systems which, as a rule, exhibit angular momentums $> 10^{52}$ $g \cdot cm^2 \cdot s^{-1}$ (Kraycheva *et al.* 1978). This means that when a binary (multiple) system is formed, the bulk of a cloud's angular momentum is concentrated in the orbital movement of stars relative to each other. The formation of a single star with a disk is an alternative and additional route by which a forming star expels excess angular momentum.

In a circumsolar Kepler disk, the angular momentum per unit mass is, actually, $j = (GM_\odot R)^{1/2}$. At a Jovian distance (5 AU) $j \sim 10^{20}$cm^2 s^{-1}. This is 100 times more than the maximum possible and 10^5 times more than the present angular momentum related to the Sun's rotation. Therefore, even a low-mass but elongated disk can accumulate a large portion of cloud angular momentum, thereby allowing a single star to form.

Estimates of mass M_D and angular momentum J_D of a circumstellar protoplanetary disk, performed by adding presolar composition dissipated hydrogen and helium to the planet matter, yielded (Weidenschilling 1977),

$$10^{-2} M_\odot \lesssim M_D \lesssim 10^{-1} M_\odot, \text{and } 3 \cdot 10^{51} \lesssim J_D \lesssim 2 \cdot 10^{52} g \cdot cm^2 \cdot s^{-1},$$

that is,

$$J_D/M_D \gg J_\odot/M_\odot.$$

Using a system of two bodies with constant aggregate mass and full angular momentum as an example, Lynden-Bell and Pringle (1974) demonstrated that the system's total energy decreases as mass is transferred from the smaller to the larger body, and the concentrations of angular momentum in orbital motion are less than the massive body. Consequently, dissipation of rotational energy, accompanied by removal of the angular momentum to the periphery and its concentration in a low amount of mass, is necessary to form a single star with a protoplanetary disk as a cloud contracts.

Effectiveness of angular momentum redistribution is the key issue of protoplanetary disk formation. The high abundance of binary or multiple stars of comparable masses and the analysis of the contraction dynamics of rotating clouds indicate that angular momentum redistribution is not always effective enough for a single star with a disk to be formed. The entire process, from the beginning contraction all the way to the formation of a star, has thus far only been examined for a nonrotating cloud (Larson 1969; Stahler *et al.* 1980). Calculations have shown that the initial stage of contraction occurs at free-fall velocities and is accompanied by an increase in the concentration of matter towards the center. Pressure increase, coupled with a rise in temperature, triggers a temporary deceleration in the contraction of a cloud's central region within a density range of $\rho_c \sim 10^{-13} \div 10^{-8}$ g·cm^{-3}. This is followed by one more stage of dynamic contraction that is initiated by molecular hydrogen dissociation. Dissociation terminates at 10^{-2}g cm^{-3}; the contraction process again comes to a halt; and a quasihydrostatic stellar-like core is formed with an initial mass of $M_c \sim 10^{-2} M_\odot$ and central density $\rho_c \sim 10^{-2}$g·cm^{-3}. This core is surrounded by an envelope which initially contains 99% mass and falls onto the core over a time scale of $10^5 \div 10^6$ years. Naturally, a single nonrotating diskless star is formed from the contraction of this kind of protostellar cloud.

It is clear from these general ideas that contraction of a rotating protostellar cloud occurs in a similar manner, when the centrifugal force in a cloud is low throughout in comparison to the gravitational force and internal pressure gradient.

The role of rotation is enhanced with increased density in the contraction process where angular momentum is conserved. (For example, the ratio of rotational energy to gravitational energy is $\beta \propto \rho^{1/3}$ for a spherically symmetrical collapse). Two-dimensional and three-dimensional calculations for the contraction of rapidly rotating protostellar clouds have shown that as a certain β_{cr} is reached in the cloud central region, a ring (two-dimensional) or nonaxisymmetrical (three-dimensional) instability develops. According to Bodenhemier (1981) and Boss (1987) this instability triggers fragmentation: $\beta_{cr} \simeq 0.08$ for ring instability at the hydrodynamic contraction stage (Boss 1984). Naturally, the smaller the angular momentum of the cloud's central region, the later the instability arises. It has been suggested that a cloud's fate depends significantly on the stage of contraction at which instability arises: the cloud turns into a binary or multiple star system when β_{cr} is attained at the initial hydrodynamic stage of contraction (with $\rho_c \lesssim 10^{-12}$ g·cm^{-3}). It becomes a single star with a disk when nontransparency increases, causing the contraction of the portion to decelerate before instability develops. The condition that a nontransparent core be formed before fragmentation occurs, imposes a constraint on the cloud angular momentum: J $\lesssim 10^{53}$ g cm^2·s^{-1} for rotation law (1a) (Safronov and Ruzmaikina 1978; Boss 1985).

Fragmentation may be halted by a sufficiently efficient removal of angular momentum from the center. Turbulence or the magnetic field (Safronov and Ruzmaikina 1978) have been proposed as removal mechanisms. Another is gravitational friction (Boss 1984) generated from excitation by a central nonaxisymmetrical condensation of the density wave in the envelope surrounding the core. Yet to be determined is whether angular momentum removal at this stage can actually prevent fragmentation. The difficulty is that contraction deceleration due to enhanced nontransparency is temporary. It is followed by the stage of hydrodynamic contraction triggered by molecular hydrogen dissociation. During this stage, density increases by several orders and β may attain β_{cr}. The formation of a single star with a disk (or without it) appears to be highly probable when the cloud (or its central portion, to be more exact) exhibit such a slight angular momentum that instability does not develop until the formation of a low-mass, stellar-like core with $M_c < 10^{-2}M_\odot$ (Ruzmaikina 1980, 1981). When it is born, the core must be magnetized as a result of enhancement of the interstellar magnetic field during contraction (Ruzmaikina 1980, 1985). The poloidal magnetic field strength in the stellar-like core is estimated at 10 $\div$ 10^3 Gauss. This field ensures angular momentum redistribution in the core over a time scale less than its evolution time scale ($\gtrsim 10^2$ years) and initiates an outflow of the core's matter, forming an embryonic disk instead of fragmentation.

With disruption of the core's axial symmetry, angular momentum removal to the periphery may also be carried out by the spiral density wave generated in the envelope (Yuan and Cassen 1985). Consequently, the formation of a single, stellar-like core appears to be sufficient for the formation of a single star.

The possibility of the formation of a stellar-like core with $M_c \sim 10^{-2}M_\odot$ imposes constraints on the maximum value of the protostellar cloud's angular momentum. With an angular momentum distribution within the cloud as described in ratio (1a) (solid-state rotation with homogeneous density), the maximum angular momentum value of the cloud at which a single, stellar-like core can form is within the range (Ruzmaikina 1981)

$$0.3\ 10^{52}(M/M_{\odot})^{5/3} \lesssim J^{a}_{max} < 2\ 10^{52}(M/M_{\odot})^{5/3}. \tag{5}$$

With the law of rotation contained in (1b) (solid-state rotation with $\rho \propto r^{-2}$), J_{max} is approximately $(M_{\odot}/M_c)^{4/3} \simeq 500$ times greater than with (1a), that is, $J^{b}_{max} \gtrsim \gtrsim 10^{54}$g cm$^2 \cdot$s^{-1} with $M = 1M_{\odot}$. This is easy to determine by equating the angular momentums of the central sphere with mass $M_c \sim 10^{-2}M_{\odot}$, for distributions (1a) and (1b), respectively.

It follows from the above estimates that: (1) single stellar-like cores can be formed during the contraction of clouds whose angular momenta are included in a broad range. This range overlaps to a large degree the angular momentums of cores in molecular clouds. Therefore, there may be a considerably high probability that a single, stellar-like core can be formed in the contracting dense region (core) of a molecular cloud. This depends on the angular momentum distribution established inside the core of molecular clouds at the pre-contraction stage; (2) J^{a}_{max} approximates or exceeds by several times the angular momentum of a "minimal mass" solar nebula (Weidenschilling 1977). J^{b}_{max} is greater than or on the order of the angular momentum of a massive solar nebula (Cameron 1962). Let us note that the idea of a massive solar nebula was recently revived by Marochnik and Mukhin (1988), who reviewed the estimate of the Oort cloud's mass on the hypothesis that the typical mass of cometary bodies in the cloud is equal to the mass of Halley's comet. (Data gathered by the Vega missions have put estimates of its mass at two orders greater than was previously believed.)

For a broad range of J values, scenarios appear possible whereby a single Sun embryo is first formed in the contracting protosolar nebula. A disk then forms around it. Disk parameters and the nature of its evolution are dependent on angular momentum value. However, the presence of a single, stellar-like core in the center has a stabilizing effect on the disk's central portion and may prevent its fragmentation. We will later discuss in more detail a protoplanetary disk formation model with cloud contraction of $J \sim 10^{52}$g cm^2 s^{-1} which appears preferable for a solar nebula (Ruzmaikina 1980, 1982; Ruzmaikina and Maeva 1986; see also review papers Safronov and Ruzmaikina 1985; Ruzmaikina *et al.* 1989).

EARLY EVOLUTION OF THE PROTOPLANETARY DISK

Let us consider the stage of protosolar nebula contraction when a single, stellar-like core and a compact embryonic disk are formed in the center, both surrounded by an accretive shell. The embryonic disk could have been formed from external equatorial core layers under the impact of magnetic pull (Ruzmaikina 1980, 1985) or by direct accretion of the rotating envelope at a distance from the axis greater than the equatorial radius of the core (Tereby *et al.* 1984). The directions of flow of the accretive material intersect the equatorial plane inside the so-called centrifugal radius R_k which exceeds (at least at the final stage of accretion) the radius of the protosun $R_c = 3 \div 5\ R_{\odot}$

$$R_K = \frac{J^2}{K^2 G M^3}. \tag{6}$$

$R_K = 0.15 \div 0.5$ AU where $M = 1\ M_{\odot}$, $J = 10^{52} g{\cdot}cm^2{\cdot}s^{-1}$, and $K = 2/5 \div 2/9$, respectively.

A mechanism for the coformation of the Sun and the protoplanetary disk during protosolar nebula contraction with $J \sim 10^{52} g\ cm^2{\cdot}s^{-1}$ has been proposed in studies by Ruzmaikina (1980) and Cassen and Moosman (1981) and investigated by Ruzmaikina (1982), Cassen and Summers (1983), and Ruzmaikina and Maeva (1986). The disk proposed in these models is a turbulent one. The following points have been offered to justify this: large Reynolds number ($\gtrsim 10^{10}$) for currents between the disk and the accretive envelope and currents generated by differential disk rotation; and the possible development of vertical (Z) direction convection. Investigations have shown that a sufficiently weak turbulence with $\alpha \sim 10^{-2}$ can trigger an increase in the disk radius to the current size of the solar system within the time scale of the Sun's formation (10^5 years). Approximately 1% of the kinetic energy of the accretive material is needed to support this kind of turbulence. Near-sound turbulence produces disk growth to 10^3 AU.

It is noteworthy that the process of disk growth occurs inside the protosolar nebula as it continues to contract. Nebula matter (gas and dust) accrete on the forming Sun and the disk (Figure 1). Matter situated in the envelope and close to the equatorial plane encounters the face of the disk. Turbulence causes accreting matter flowing about the disk to mix with disk matter. Addition of the new matter is especially effective on the face, where this matter falls on the disk almost perpendicular to the surface. It loses its radial velocity in the shock wave and is retarded long enough for effective mixing. Complete mixing on the remaining surface of the disk only occurs in layer Δh. This layer is small at subsonic turbulence in comparison with disk thickness $\Delta h/h \sim \alpha^{1/2}$ (Ruzmaikina and Safronov 1985). Ruzmaikina and Maeva (1986) looked at the process of protoplanetary disk formation for a model with $J = 2 \cdot 10^{52} g\ cm^2{\cdot}\ s^{-1}$ and $M = 1.1 M_{\odot}$, taking into account accretion of material both to the Sun and to the disk. Turbulence viscosity in the disk was alleged to equal $v_T = (1 \div 6){\cdot}\ 10^{15}\ (M/M_{\odot}{\cdot}\ R\ \mathrm{AU})^{1/2}\ cm^2 s^{-1}$. This fits with $\alpha \approx 3 \cdot 10^{-3} \div 4 \cdot 10^{-2}$. As a result, by the completion of the accretion stage (which lasts 10^5 years), the disk radius

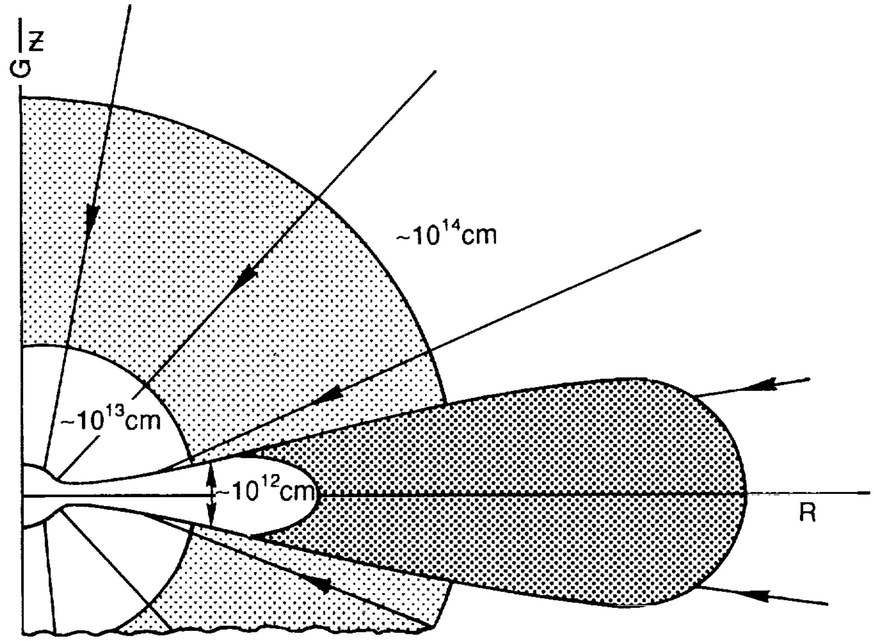

FIGURE 1 Schematic profile of a forming protoplanetary disk immersed in an accretion envelope.

was equal to 24 - 70 AU, its mass is about 0.1 $M_\odot$, and the remaining mass is concentrated in the Sun. The distribution of radial U_R velocity of matter flow in the disk undergoes a complex evolution: at the initial stage, matter in the larger portion of the disk flows towards the center. The velocity is only positive near the disk edge. However, there gradually emerges one more area with a positive radial velocity which is broadening over time. Two regions with $U_R < 0$; $R < R_i \simeq 0.3 \div 0.5$ AU and $0.6\ R_D < R < 0.95\ R_D$ two regions with $U_R > 0$; $R_i < R < 0.6\ R_D$ and $R > 0.95\ R_D$ exist in the disk by the time accretion is completed.

TEMPERATURE CONDITIONS AND CONVECTION IN THE PROTOPLANETARY DISK

The question of temperature distribution and fluctuation in the disk is important for an understanding of the physical and chemical evolution of preplanetary matter. Temperature greatly affects the kinetics of chemical reactions, matter condensation, and vaporization, the efficiency rate at which dust grains combine during collision, and the conditions within planetesimals.

The protoplanetary disk is thin, that is, at any distance R from the center, the inequality $h/R \ll 1$ is true for the thickness of a disk's homogeneous atmosphere of $h = c_s\Omega^{-1}$. Therefore, heat transfer occurs primarily transversely to the disk in the l-c-z direction, between the central plane and the surface. At the same time, a disk of mass 10^{-2}– $10^{-1}M_\odot$ and radius 10 – 100 AU is optically thick (Lin and Papaloizou 1980). Therefore, if there is an internal source heating the disk, the temperature in the central plane is higher than on the surface. Such a source is the internal friction in conditions of differential rotation. Mechanical energy dissipation in the disk is proportional to $\nu_T R^2(d\Omega/dR)^2$. If we propose turbulence as a viscosity mechanism, the viscosity value averaged for disk thickness could be written using Schakura and Sunyaev's $\propto$-parameter as $\nu_T = \propto c_s h$ where the speed of sound is taken from the central plane. As we noted above, the value $\propto$ must equal 10^{-2} for a disk to form over 10^5 years. A number of models were constructed using Lynden-Bell and Pringle's viscous disk evolution theory (1974). These models considered the further evolution of the protoplanetary disk after protosolar nebula matter has stopped precipitating on it. A large portion of disk mass is transported inside and accretes to the Sun at this stage. At the same time the disk radius increases owing to conservation of the angular momentum. According to the estimates, surface density decreases by one order over 10^6 years with $\propto = 10^{-2}$. (Ruden and Lin 1986; Makalkin and Dorofeeva 1989).

Internal disk structure and, in particular, the vertical temperature profile were also considered for this stage (viscous disk diffusion). Lin and Papaloizou's model (1980) proposes Z-direction convection as a turbulence mechanism in the disk. Correspondingly, the temperature gradient in this direction is slightly higher than adiabatic. P-T conditions and matter condensation in the protoplanetary disk's internal portion (Cameron and Fegley 1982) were calculated on the basis of this model. Cabot *et al.* (1987) yielded a more accurate vertical structure which accounts for the dependence of opacity on temperature: beginning with the central plane, the convective layer with a superadiabatic temperature gradient is superseded at a higher elevation by a layer in which the gradient is below adiabatic. One more layer alternation may occur above this if the photosphere temperature is below that of ice condensation. However, on the average, the temperature profile is quite close to adiabatic for the entire thickness of the disk. Temperature distributions in these models are in fairly close agreement with the temperature estimate generated by Lewis (1974) where he used cosmochemical data. His estimate is indicated by the crosses in Figure 2.

Convective models only take into account the internal source of protoplanetary disk heating: turbulence dissipation. However, external sources may provide an appreciable input to disk heating. They are particularly

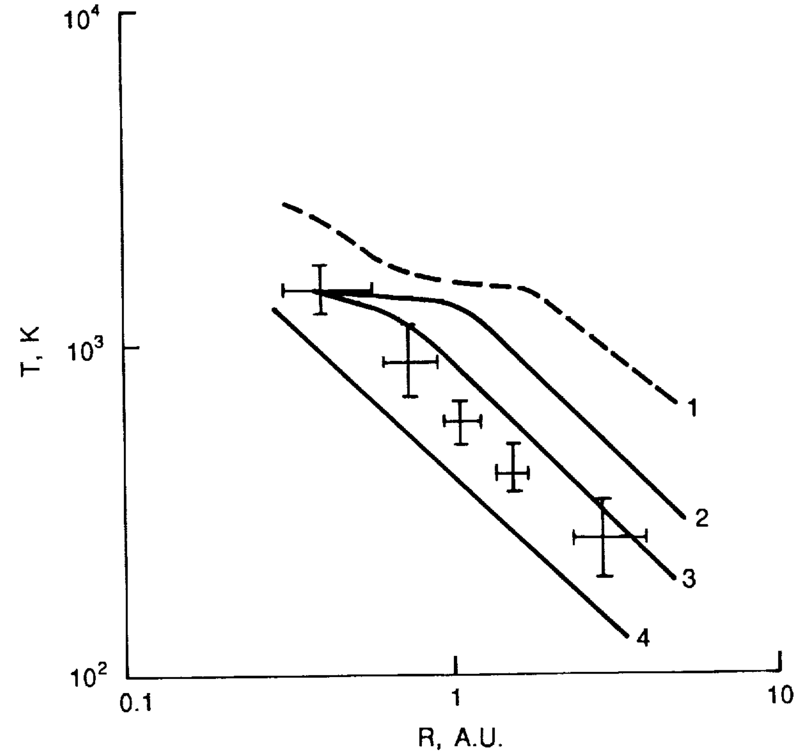

FIGURE 2 Temperature distribution in the central plane of the protoplanetary disk: 1 is the maximum temperatures at the disk formation stage. The figures 2, 3, and 4 are at the subsequent stage of viscous disk evolution (from the study by Makalkina and Dorofeeva 1989): 2 is $1 \cdot 10^5$ years after the stage begins; 3 is $2 \cdot 10^5$ years later; and 4 is after 10^6 years. Ranges of temperature ambiguities as per Lewis' cosmochemical model (1974) are indicated by the overlapping areas.

significant during disk formation. At the accretion stage of contraction of a protosolar nebula with $J \sim 10^{52} g \cdot cm^2 \cdot s^{-1}$, energy is emitted at the shock front of the protosolar core's surface and the portion of the disk with $R_k \sim 10^{12}$ centimeters nearest to it (which is only several times greater than the core radius and two to three orders less than the radius of disk R_D by the end of the accretion stage). This radiation is absorbed and reemitted in the infrared range in the accretion envelope around the core. A significant portion of the disk is immersed in the envelope's optically thick portion and is appreciably heated by its radiation (Makalkin 1987). With a characteristic accretion time scale $\tau_a \sim 10^5$ years, the radius of the optically thick portion of the accretion envelope (the radius of the dust photosphere) is approximately 10^{14} centimeters.

This estimate was made for a spherically symmetric collapse model (Stahler *et al.* 1981). However, it is just in terms of the order of value and for a model with a moderate angular momentum. The estimate of the internal radius of the optically thick portion of the envelope (the radius of the dust vaporization front), which is approximately 10^{13} centimeters (Figure 1), is also true. Where there is a disk around the core, a very rough estimate of luminosity $L = GM_c\dot{M}/R_k$, and a more stringent estimate based on the theory of Adams and Shu (1986), demonstrate that energy ensuring a luminosity value $L \simeq 20 \div 25L_\odot$ is emitted at the shock front near the core ($R \lesssim R_k$) with $\tau_a \approx 10^5$ years and $J \approx 10^{52} g{\cdot}cm^2{\cdot}s^{-1}$. That is, this value is several times less than in Stahler *et al.*'s spherically symmetrical model (1980) where $L = 66L_\odot$. An estimate of the temperature in the envelope using Adams and Shu's method (1985) produces for $L \simeq 20 \div 25L_\odot$ a temperature in the envelope of $T_{env} \simeq 1100$ K at R = 1 AU. We note for comparison that at the same R $T_{env} \simeq 1600$ K with $L = 70\ L_\odot$ and $T_{env} = 800$ K at $L = 15L_\odot$ (for the spherical model of Adams and Shu (1985) with $\tau_a \simeq 10^6$ years). The exact form of the shock front surface and the dependence of the radiation flow on angular coordinates are still unknown. It is considered in a zero approximation that at $R \gg R_k$, isotherms have a near spherical form.

The specific dissipation energy of turbulent motion in the protoplanetary disk can be expressed as $D = 9/4\ \rho\nu_T\Omega^2$. It follows from this that the flow of radiant energy from the disk (per unit of area of each of the two surfaces in its quasistationary mode) is equal to $D_1 = 9/8\Sigma\ \nu_T\ \Omega^2 = \sigma\ T^4{}_{eff}$ where Σ denotes the disk's surface density, and σ is the Stefan-Boltsman constant. It is easy to see that at $\propto \sim 10^{-2}$ the effective disk temperature T_{eff} is significantly lower than the temperature in the accretion envelope T_{env} at the same R. Therefore, the effect of outflow from the disk to heat the envelope at $R \gg R_k$ can be disregarded. Even where a developed convection is present, the flow of radiant energy inside the protoplanetary disk F is approximately three times greater than the convective value (Lin and Papaloizou 1985). This is similar to what occurs in hot accretion disks. The solution to the formula for radiation transport in the disk $dF/dz = D$, where the mean opacity is dependent on temperature according to the power law, $\overline{Ke} \propto T^{\xi}$, is expressed as (Makalkin 1987)

$$(T_o/T_s)^{4-\xi} = 1 + 3/64\ (4-\xi)(D_1/\sigma T_s^4)\overline{Ke}_s\Sigma, \qquad (7)$$

where T_o and T_s denote temperatures in the disk's central plane and on its surface, $\overline{Ke}_s = \overline{Ke}(T_s)$. In the absence of external heating sources, $T_s = T_{eff}$ is fulfilled and, correspondingly, $D_1 = \sigma T_s^4$. In the case of a disk immersed in the accretion envelope, T_s in formula (7) is equal to the temperature in the envelope T_{env} at the same R. T_{env} is several times greater than T_{eff}, and hence, $D_1 \ll \sigma T^4{}_s$. The mean opacity $\overline{Ke}$, examined by Pollack *et al.* (1985) for a protoplanetary disk, taking into account the chemical composition and dimensions of dust grains, can be approximated as a function T^ξ with various values of ξ in different temperature intervals. Below the temperature of dust condensation, the values of ξ range from 0.6 – 1.5. Above this temperature Lin and Papaloizou's approximation (1985) can be used for $\overline{Ke}$(T). The ratio (7) can be applied not only to the entire thickness of the disk, but also to its different layers in order to account for variations in the function $\overline{Ke}$(T). Then Σ and D_1 correspond to the appropriate layer, and T_o and T_s to its lower and upper boundaries. We note that formula (7) differs significantly both in its appearance and its result from the widely accepted, simplified formula $(T_o/T_s)^4 = 3/8\ \overline{Ke}_o\Sigma$, where $\overline{Ke}_o = \overline{Ke}(T_o)$.

Curve 1 in Figure 2 illustrates the temperature in the disk's central plane at the end of its formation stage. We calculate this temperature using formula (7) for the disk model, (Ruzmaikina and Maeva 1986) with values = $110^4 gcm^{-2}$ and $\nu_T = 1.210^{15} cm^2 s^{-1}$ at R = 1 AU. This accounts for the fact that $\Sigma\ \nu_T \propto R^{-1/2}$ is everywhere except the disk center and edge. The temperature in the accretion envelope is estimated for L = 25 $L_\odot$. The plateau in curve 1 fits that part of the disk where its vertical structure is two-layered. A dust-free (owing to its high temperature) layer is located around the central plane. The mean opacity here is two orders lower (and the vertical temperature gradient is commensurately low), than in the higher, colder layer. This colder layer contains condensed dust grains. The vertical profile of this portion of the disk is represented in Figure 1. It is clear from Figure 1 that the condensation front has a curved shape. Computations have shown that for all R $\lesssim 10^{14}$ centimeters the inequality $T_o < 2T_s$ is fulfilled. It follows, in particular from this, that the vertical temperature gradient at the disk formation stage is noticeably lower than the adiabatic value calculated in many studies. There is, therefore no convection.

Vityazev and Pechernikova (1985) and Ruzmaikina and Safronov (1985) estimated the maximum for additional heating of matter as it falls onto the disk surface; in the shock wave (where it had been) and via aerodynamic friction of the dust. The effect is relatively insignificant in the area $R \gg R_k$, R $\lesssim 10^{14}$ centimeters. Thus, the dust temperature does not exceed 600 K for 1 AU with $J \sim 10^{52}\ g \cdot cm^2 \cdot s^{-1}$. That is, it is much lower than the temperature inside the disk (Curve 1, Figure 2).

Solar radiation falling at a low inclination on its surface (Safronov 1969) is an external source of disk heating after accretion of the envelope to the protosun and disk is completed. It should be taken into account together with turbulence (an internal source) when calculating temperature in the disk. T_s in (7) is determined at this stage by the formula $\sigma T_s^4 = D_1 + F_s$, where F_s denotes the solar energy flux absorbed by the disk surface. It follows from the computations of Makalkin and Dorofeyeva (1989) that $D_1 \gg F_s$ everywhere for $R \gtrsim 0.1$ AU. The vertical temperature gradient is only higher than the adiabatic where dust grains are not vaporized. Where there is no dust, low opacity $\overline{Ke} \lesssim 10^{-2} cm^2 \cdot g^{-1}$ generates a very low-temperature gradient. The temperature distribution is then close to isothermic. With this in mind, the authors calculated a combined (adiabat - isotherm) thermodynamic model of a protoplanetary disk. Figure 2 (Curves 2, 3, and 4) illustrate the temperature distributions in the central plane generated in this model for different points in time. Temperatures as per Lewis' cosmochemical model (1974) are a good fit with calculated temperatures for the time interval $(2\text{-}5) \cdot 10^5$ years.

This model of protoplanetary disk formation predicts a significantly different solid matter thermal history: vaporization and subsequent condensation of dust grains in the internal region of the solar system as it forms, and the conservation of interstellar dust (including organic compounds and ices) in the peripheral (greater) portion of the planetary system. These predictions are in qualitative agreement with cosmochemical data and, in particular, with the latest data on Halley's comet (Mukhin *et al.* 1989). According to estimates of thermal conditions in the disk, the radius of the zone of vaporization of silicate and iron dust grains ($T \gtrsim 1400$ K) reached 1 - 2 AU. However, matter which passes through a vaporization region as the disk forms is dispersed to a larger region. This is a consequence of both the mean, outwardly-directed flux of matter in the internal portion of the disk (Ruzmaikina and Maeva 1986), and turbulent mixing.

REFERENCES

Adams, F.C., and F.H. Shu. 1985. Infrared emission from protostars. Astrophys. J. 296:655-669.

Adams, F.C., and F.H. Shu. 1986. Infrared spectra of rotating protostars. Astrophys. J. 308:836-853.

Adams, M.T., K.M. Strom., and S.E. Strom. 1983. The star-forming history of the young cluster NGC 2264. Astrophys. J. Suppl. 53:893-936.

Arquilla, R. 1984. The structure and angular momentum content of dark clouds. Dissertation, University of Massachusetts.

Aumann, H.H., F.C. Gillett, C.A. Beichman, T. de Jong, J.R. Houck, F. Low, G. Neugebauer, R.G. Walker, and P. Wesselius. 1984. Discovery of a shell around Alpha Lyrae. Astrophys. J. 278: L23-L27.

Backman, D. 1987. IRAS statistics on IR-excesses and models of circumstellar disks. IAU Coll. No. 99, Hungary, June 22-27.

Bertrout, C., G. Basri, and J. Bouier. 1988. Accretion disks around T Tauri stars. Astrophys. J. 330:350-373.

Bodenheimer, P. 1981. The effect of rotation during star formation. Pages 5-26. In: Sugimoto, D., D.Q. Lamb, and D.N. Schramm (eds). Fundamental Problems in the Theory of Stellar Evolution. D. Reidel, Dordrecht.

Boss, A.P. 1984. Protostellar formation in rotating interstellar clouds. IV. Nonisothermal collapse. Astrophys. J. 277:768-782.

Boss, A.P. 1985. Angular momentum transfer by gravitational torques and the evolution of binary protostars. Icarus 61:3-17.

Boss, A.P. 1987. Protostellar formation in rotating interstellar clouds. VI. Nonuniform initial conditions. Astrophys. J. 319:149-161.

Cabot, W., V.M. Canuto, O. Hubickyj, and J.B. Pollack. 1987. The role of turbulent convection in the primitive solar nebula I. Theory. II. Results. Icarus 69:387-442, 423-457.

Cameron, A.G.W. 1962. The formation of the sun and planets. Icarus 1:13-69.

Cameron, A.G.W., and M.B. Fegley. 1982. Nucleation and condensation in the primitive solar nebula. Icarus 52:1-13.

Campbell, B., G.A.H. Walker, S. Yang. 1988. A search for substellar companions to solar-type stars. Astrophys. J. 331: 902-921.

Cassen, P.M., and A. Moosman. 1981. On the formation of protostellar disks. Icarus 48:353-376.

Cassen, P.M., and A.L. Summers. 1983. Models of the formation of the solar nebula. Icarus 53:26-40.

Kraicheva, Z.G., E.I. Popova, A.V. Tutukov, and L.P. Yungelson. 1978. Some properties of spectrally binary stars. Astron. J. 55:1176-1189.

Larson, R.B. 1969. Numerical calculations of the dynamics of a collapsing protostar. Mon. Not. Roy. Astron. Soc. 168:271-295.

Levy, E.H., and C.P. Sonett. 1978. Meteorite magnetism and early solar-system magnetic fields. Pages 516-532. In: Gehrels, T. (ed). Protostars and Planets. University of Arizona Press, Tucson.

Lin, D.N.C., and J. Papaloizou. 1980. On the structure and evolution of the primordial solar nebula. Mon. Not. Roy. Astron. Soc. 191:37-48.

Lin, D.N.C., and J. Papaloizou. 1985. On the dynamical origin of the solar system. Pages 981-1007. In: Black, D.C. and M.S. Matthews. Protostars and Planets. II. University of Arizona Press, Tucson.

Lynden-Bell, D., and J.E. Pringle. 1974. The evolution of viscous disks and the origin of the nebular variables. Mon. Not. Roy. Astron. Soc. 168:603-637.

Lewis, J.S. 1974. The temperature gradient in the solar nebula. Science 186:440-443.

Myers, P.S. 1983. Dense cores in dark clouds. III. Subsonic turbulence. Astrophys. J. 257:620-632.

Myers, P.S., and P.J. Benson. 1983. Dense cores in dark clouds. II. NH_3 observations and star formation. Astrophys. J. 266: 309-320.

Makalkin, A.B. 1987. Protoplanetary disk thermics. Astron. vestnik 21:324-327.

Makalkin, A.B., and V.A. Dorofeeva. 1989. P-T conditions in a preplanetary gas-dust disk and dust component evolution. Pages 46-88. In: Magnitskiy, V.A. Planetary Cosmogony and Earth Science. Nauka, Moscow.

Marochnik, L.S., and L.M. Mukhin. 1988. "Vega" and "Jotto" missions: Does an invisible mass exist in the solar system? Letters to Astron. J. 14:564-568.

Mukhin, L.M., T.V. Ruzmaikina, and A.I. Grechinskiy. 1989. The nature of the dust component of Halley's comet. Kosmicheskye issledovania. 27:280-286.

Pollack, J.B., C.P. Mckay, and B.M. Christofferson. 1985. A calculation of a Rosseland mean opacity of dust grains in primordial solar system nebula. Icarus 64:471-492.

Ruden, S.P., and D.N.C. Lin. 1986. The global evolution of the primordial solar nebula. Astrophys. J. 308:883-901.

Ruzmaikina, T.V. 1981. On the role of magnetic fields and turbulence in the evolution of the presolar nebula. 23rd COSPAR Meeting, Budapest. Adv. Space Res. 1:49-53.

Ruzmaikina, T.V. 1981. The angular momentum of protostars that generate protoplanetary disks. Letters to Astron. J. 7:188-192.

Ruzmaikina, T.V. 1982. In: Volk, H. (ed.). Diskussions forum Ursprung des Sonne-systems. Mitt. Astron. Ges. 57:49-53.

Ruzmaikina, T.V. 1985. The magnetic field of a collapsing solar nebula. Astron. vestnik 18:101-112.

Ruzmaikina, T.V., and S.V. Maeva. 1986. Research on the process of protoplanetary disk formation. Astron. vestnik 20:212-227.

Ruzmaikina, T.V., and V.S. Safronov. 1985. Premature particles in the solar nebula. LPSC XVI (Abstracts):720-721.

Ruzmaikina, T.V., V.S. Safronov, and S.J. Weidenschilling. 1989. Radial mixing of material in the asteroid zone. University of Arizona Press, Tucson, in press.

Safronov, V.S. 1969. Preplanetary cloud evolution and the formation of Earth and the planets. Nauka, Moscow.

Safronov, V.S., and T.V. Ruzmaikina. 1978. On the angular momentum transfer and accumulation of solid bodies in the solar nebula. Pages 545-564. In: Gehrels, T (ed). Protostars and Planets. University of Arizona Press, Tucson.

Safronov, V.S., and T.V. Ruzmaikina. 1985. Formation of the solar nebula and the planets. Pages 959-980. In: Black, D. and M.S. Matthews. Protostars and Planets. II. University of Arizona Press, Tucson.

Sargent, A.I., and S. Beckwith. 1987. Kinematics of the circumstellar gas of HL Tau and R Monocerotis. Astrophys. J. 323:294-.

Smith, B.A., and R.J. Terrile. 1984. A circumstellar disk around β. Pictoris. Science 226:1421-1424.

Tereby, S., F.H. Shu, and P.M. Cassen. 1984. The collapse of cores of slowly rotating isothermal clouds. Astrophys. J. 286: 529-55.

Schakura, N.I., and R.A. Sunyaev. 1973. Black holes in binary systems. Observational appearance. Astron. Astrophys. 24:337-355.

Stahler, S.W., F.H. Shu, and R.E. Taam. 1980. The evolution of protostars. I. Global formulation and results. Astrophys. J. 241:637-654.

Vityazev, A.V., and G.V. Pechernikova. 1985. On the evaporation of dust particles during the preplanetary disk formation. LPSC XVI Abstracts:885-886.

Weidenschilling, S.J. 1977. The distribution of mass in the planetary system and solar nebula. Astrophys. Space Sci. 51: 153-158.

Yuan, C., and P. Cassen. 1985. Protostellar angular momentum transport by spiral density waves. Icarus 64:435-447.