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Three-Dimensional Evolution of Early Solar Nebula

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INITIAL CONDITIONS FOR PROTOSTELLAR COLLAPSE

Mathematically speaking, solar nebula formation is an initial value problem. That is, it is believed that given the proper initial conditions and knowledge of the dominant physical processes at each phase, it should be possible to calculate the evolution of a dense molecular cloud core as it collapses to form a protosun and solar nebula. Also, through calculating the evolution of the dust grains in the nebula, it should be possible to learn how the initial phases of planetary accumulation occurred. While this extraordinarily ambitious goal has not yet been achieved, considerable progress has been made in the last two decades, with the assistance of current computational resources. This paper reviews the progress toward the goal of a complete theory of solar nebula formation, with an emphasis on three spatial dimension (3D) models of solar nebula formation and evolution.

In principle, astronomical observations should provide the initial conditions required for theoretical calculations of solar nebula formation. This assumes that physical conditions in contemporary regions of solar-type star formation in our galaxy are similar to the conditions $\approx 4.56 \times 10^9$ years ago. Whether or not this is a reasonable assumption, considering that the age of the solar system is a fair fraction of the Hubble time, there really is no other means of constraining the initial conditions for solar system formation.

Millimeter wave and infrared telescopes have revealed that low-mass (solar-type) stars are presently forming preferentially in groups distributed throughout large molecular cloud complexes in the disk of our galaxy. These

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molecular clouds have complex, often filamentary structures on the largest scales (~100pc). On the smallest scales (~0.1pc), where finite telescope resolution begins to limit the observations, molecular clouds are composed of centrally condensed cloud cores surrounded by cloud envelopes. The cloud cores are gravitationally bound and, should they begin to collapse upon themselves because of self-gravity, are quite likely to form stars (Myers and Benson 1983). Indeed, when infrared observations of embedded protostellar objects (presumed to be embedded pre-main-sequence T Tauri stars or very young protostars) are combined with millimeter wave maps of molecular cloud cores, it appears that roughly one half of the cloud cores contain embedded protostars (Beichman et al. 1986). The physical conditions in molecular cloud cores, or their predecessors, should then provide the best indication of the initial conditions that are appropriate for solar nebula formation.

Practically speaking, there are several reasons why astronomical observations can only provide us with a range of possible initial conditions for solar nebula formation. First, since even the short time scales associated with low-mass star formation (~10^5 – 10^6 years) are quite long compared to human lifetimes, one can never be sure what a particular collapsing cloud core will produce. Second, although interferometric arrays have the potential to greatly increase our understanding of cloud core properties, the length scales appropriate for the initial phases of collapse are only marginally resolved by current millimeter wave telescopes. Third, because many (if not most) cloud cores have already collapsed to form protostars, their properties may not be appropriate for constraining the earliest phases of collapse. If the immediate predecessors of cloud cores could be identified, then the constraints on the initial conditions for protostellar collapse would be improved considerably.

Given these limitations, observations of cloud cores suggest the following initial conditions for solar nebula formation: 1) Cloud cores have masses in the range of 0.1 to $10M_\odot$, implying that evolution within the molecular cloud complex has already reduced the mass of sub-structures by several orders of magnitude, from masses characteristic of giant molecular clouds (~10^5 – $10^6 M_\odot$), to masses in the stellar range; 2) Dense cloud cores have maximum densities on the order of 10^{-19} – 10^{-18} g cm^{-3}, sizes less than 0.1 pc, and temperatures close to 10K. These are basically the same initial conditions that have long been used to model protosolar collapse (Larson 1969).

One of the remaining great uncertainties is the amount of rotation present in cloud cores, because even the most rapidly rotating clouds have Doppler shifts comparable to other sources of line broadening, such as thermal broadening, translational cloud motions, and turbulence. While there is strong evidence that at least some dense clouds rotate close to

centrifugal equilibrium (specific angular momentum $J/M \sim 10^{21}$ $cm^2 s^{-1}$ for solar mass clouds), it is unknown how common such rapid rotation is, or how slowly clouds can rotate. Three-dimensional calculations (described in the next sub-section) indicate that the initial amount of rotation is critical for determining whether clouds collapse to form single or multiple protostars.

Finally, most three-dimensional calculations of protostellar collapse have ignored the possible importance of magnetic fields, in no small part because of the computational difficulties associated with their inclusion in an already formidable problem. OH Zeeman measurements of magnetic field strengths in molecular clouds yield values ($\sim 30\mu G$) in cool clouds implying that magnetic fields dominate the dynamics on the largest scales ($\sim 10 - 100$pc). However, there is evidence from the lack of correlations between magnetic field directions and dense cloud minor and rotational axes that, on the smaller scales (and higher densities) of dense cloud cores, magnetic fields no longer dominate the dynamics (Heyer 1988). Loss of magnetic field support is probably caused by ambipolar diffusion of the ions and magnetic field lines during contraction of the neutral bulk of the cloud. The evidence for decreased importance of magnetic fields at densities greater than $\sim 10^{-20}$ g cm^{-3} suggests that nonmagnetic models may be adequate for representing the gross dynamics of solar nebula formation.

SINGLE VERSUS BINARY STAR FORMATION

The first numerical models of the collapse of interstellar clouds to form solar-type stars disregarded the effects of rotation, thereby reducing the problem to spherical symmetry and the mathematics to one-dimensional (1D) equations (Bodenheimer 1968). The assumption of spherical symmetry ensures that a single star will result, but unfortunately such calculations can say nothing about binary star or planet formation. The first major dynamical problem in solar nebula formation is avoiding fragmentation into a binary protostar.

Larson (1969) found that 1D clouds collapse non-homologously, forming a protostellar core onto which the remainder of the cloud envelope accretes. Once the envelope is accreted, the protostar becomes visible as a low-mass, pre-main-sequence star (T Tauri star). Models based on these assumptions have done remarkably well at predicting the luminosities of T Tauri stars (Stahler 1983). However, there is a recent suggestion (Tscharnuter 1987a) that the protostellar core may not become well established until much later in the overall collapse than was previously thought. The 1D models also showed that the first six or so orders of magnitude increase

in density during protostellar collapse occur isothermally, a thermodynamical simplification employed in many of the two-dimensional (2D) and three-dimensional (3D) calculations that followed.

The first models to include the fact that interstellar clouds must have finite rotation were restricted to two dimensions, with an assumed symmetry about the rotation axis (axisymmetry) being assumed (Larson 1972; Black and Bodenheimer 1976). These models showed that a very rapidly rotating, isothermal cloud collapses and undergoes a centrifugal rebound in its central regions, leading to the formation of a self-gravitating ring. While a similar calculation yielded a runaway disk that initially cast doubt on the physical reality of ring formation (Norman et al. 1980), it now appears that most of the ring versus disk controversy can be attributed to differences in the initial conditions studied and to the possibly singular nature of the standard test problem. With a single numerical code, Boss and Haber (1982) found three possible outcomes for the collapse of rotating, isothermal, axisymmetric clouds: quasi-equilibrium Bonnor-Ebert spheroids, rings, and runaway disks, with the outcome being a simple function of the initial conditions. Two-dimensional clouds with initially high thermal and rotational energies do not undergo significant collapse, but relax into rotationally flattened, isothermal equilibrium configurations that are the 2D analogues of the 1D Bonnor-Ebert sphere. High specific angular momentum 2D clouds that undergo significant collapse form rings, while slowly rotating 2D clouds ($J/M < 10^{20}$ cm^2 s^{-1}) can collapse to form isothermal disks (Terebey et al. 1984).

Whereas the Sun is a single star, a cloud that forms a ring is likely to fragment into a multiple protostellar system (Larson 1972). Because of this, subsequent axisymmetric presolar nebula models have concentrated on slowly rotating clouds (Tscharnuter 1978, 1987b; Boss 1984a). These models, which included the effects of radiative transfer and detailed equations of state, showed that even for a very slowly rotating cloud, formation of a central protosun is impossible without some means of transporting angular momentum outward and mass inward. Consequently, Tscharnuter (1978, 1987b) has relied on turbulent viscosity to produce the needed angular momentum transport, even during the collapse phase, when there are reasons to doubt the efficacy of turbulence (Safronov 1969).

Because isothermal protostellar clouds, and even slowly rotating non-isothermal clouds (Boss 1986), may fragment prior to ring formation (Bodenheimer et al. 1980), a 3D (i.e., fully asymmetric) calculation is necessary in order to ensure that a given collapsing cloud produces a presolar nebula rather than a binary system. Forming the presolar nebula through formation of a triple system followed by orbital decay of that triple system to yield a runaway single nebula and a close binary does not appear to be feasible (Boss 1983), because the runaway single nebula is likely to undergo binary

fragmentation during its own collapse. Hence 3D models of solar nebula formation have also concentrated on low J/M clouds, in a search for clouds that do not undergo rotational fragmentation during their isothermal or nonisothermal collapse phases. Three-dimensional calculations, including radiative transfer in the Eddington approximation, have shown that solar mass clouds with $J/M < 10^{20}$ cm^2 s^{-1} are indeed required in order to avoid binary formation (Boss 1985; Boss 1986).

There are two other ways of suppressing binary fragmentation other than starting with insufficient J/M to form and maintain a binary protostellar system. First, when the initial mass of a collapsing cloud is lowered sufficiently, fragmentation is halted, yielding a lower limit on the mass of protostars formed by the fragmentation of molecular clouds of around 0.01 $M_\odot$ (Boss 1986). The minimum mass arises from the increased importance of thermal pressure as the cloud mass is decreased; thermal pressure resists fragmentation. This limit implies that there may be a gap between the smallest mass protostars ("brown dwarfs") and the most massive planets (the mass of Jupiter is ≈ 0.001 $M_\odot$). Second, clouds that are initially strongly centrally condensed can resist binary fragmentation simply because of their initial geometric prejudice toward forming a single object (Boss 1987). While initially uniform density and initially moderately condensed clouds readily fragment, given large J/M and/or low thermal pressure, it appears to be impossible to fragment a cloud starting from an initial power law density profile (see Figure 1). Considering that the majority of stars are found in binary or multiple systems, it does not appear likely that power law initial density profiles are widespread in regions of star formation, but such a profile could have led to solar nebula formation. Thus, the 3D calculations have shown that formation of the Sun requires the collapse of either a very slowly rotating, high-thermal energy cloud, or else the collapse of a cloud starting from a power law initial density profile. In contrast to 1D calculations, however, no 3D calculation has been able to collapse a cloud core all the way to the pre-main-sequence. In part, this is because of the greatly increased computational effort necessary to evolve a multidimensional cloud through the intermediate phases. Equally important though, is the problem that when rotation is included, accumulation of the central protosun requires an efficient mechanism for outward angular momentum transport. Identifying this mechanism and its effects is one of the major remaining uncertainties in solar nebula models.

ANGULAR MOMENTUM TRANSPORT MECHANISMS

Given the formation of a rotationally flattened, presolar nebula through the collapse of a cloud core that has avoided binary fragmentation, the next major dynamical problem is accumulating the protosun out of the disk
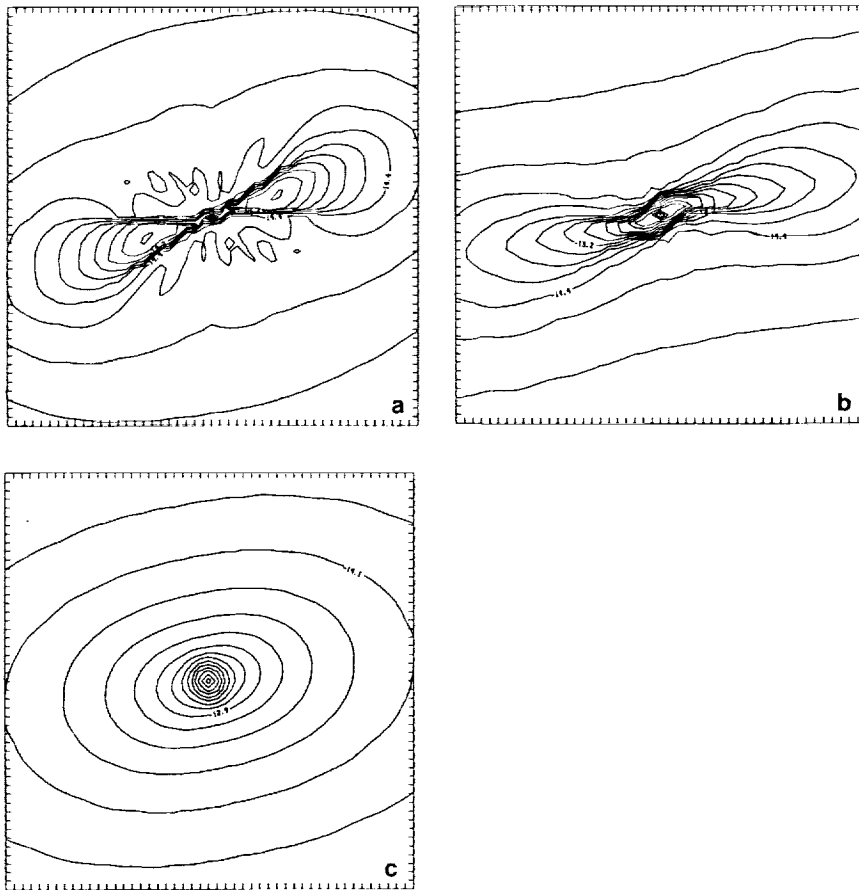
FIGURE 1   Density contours in the midplane of three models of protostellar collapse with
varied initial density profiles (Boss 1987). The rotation axis falls in the center of each plot;
counterclockwise rotation is assumed. Each contour represents a factor of two change in
density; contours are labelled with densities in g cm^{-3}. (a) Initially uniform density profile,
(b) initially Gaussian density profile, and (c) initially power law profile (r^{-1}). As the initial
degree of central concentration increases, the amount of nonaxisymmetry produced during
collapse decreases. Qualititatively similar results hold when the initial cloud mass or initial
angular velocity is decreased; binary formation is stifled. Diameter of region shown: (a)
580 AU, (b) 300 AU, (c) 110 AU.

matter. Angular momentum must flow outward, if mass is to accrete onto the protosun, and also if the angular momentum structure of the solar system is to result from a cloud with more or less uniform J/M. The physical process responsible for this dynamical differentiation is thought to have operated within the solar nebula itself, rather than in the material collapsing to form the nebula.

Three different processes have been proposed for transporting mass and angular momentum in the solar nebula: viscous shear, magnetic stresses, and gravitational torques (see also Bodenheimer, this volume). Molecular viscosity is far too small to be important, so turbulent viscosity must be invoked if viscous stresses are to dominate. The most promising means for driving turbulence in the solar nebula appears to be through convective instability in the vertical direction, perpendicular to the nebula midplane (Lin and Papaloizou 1980). The main uncertainty associated with convectively driven viscous evolution, aside from the effective strength of the turbulent stresses, is the possibility that such a nebula is unstable to a diffusive instability that would break up the nebula into a series of concentric rings (Cabot et al. 1987).

As previously mentioned, magnetic fields need not be dominant during the early phases of presolar collapse, and frozen-in magnetic fluxes scale in such a way that they never become important, if they are not important initially. While some meteorites show evidence for remanent magnetic fields requiring solar nebula field strengths on the order of 30μT (Sugiura and Strangway 1988), the magnetic pressure $(B^2/8\pi)$ corresponding to such field strengths is still considerably less than even thermal pressures in hot solar nebula models (Boss 1988), implying the negligibility of magnetic fields for the gross dynamics of the solar nebula.

The remaining candidate for angular momentum transport is gravitational torques between nonaxisymmetric structures in the solar nebula. Possible sources of nonaxisymmetry include intrinsic spiral density waves (Larson 1984), large-scale bars (Boss 1985), and triaxial central protostars (Yuan and Cassen 1985). Early estimates of the efficiency of gravitational torques (Boss 1984b) implied that a moderately nonaxisymmetric nebula can have a time scale for angular momentum transport just as short as a strongly turbulent accretion disk. Three-dimensional calculations of the aborted fission instability in rapidly rotating polytropes (Durisen et al. 1986) were perhaps the first to demonstrate the remarkable ability of gravitational torques to remove orbital angular momentum from quasi-equilibrium, non-axisymmetric structures similar to the solar nebula.

At later phases of nebula evolution, nonaxisymmetry and spiral density waves can also be driven by massive protoplanets. The possible effects range from gap clearing about the protoplanet, in which case the protoplanet must evolve along with the nebula (Lin and Papaloizou 1986), to rapid orbital

decay of the protoplanet onto the protosun (Ward 1986). While the effects of viscous or magnetic stresses can be studied with 2D (axisymmetric) solar nebula models, in order to model the effects of gravitational torques, a nonaxisymmetric (generally 3D) solar nebula model must be constructed.

THREE-DIMENSIONAL SOLAR NEBULA MODELS

Only a few attempts have been made at studying the nonaxisymmetric structure of the early solar nebula. Cassen *et al.* (1981) used a type of N-body code to study the growth of nonaxisymmetry in an infinitely thin, isothermal model of the solar nebula. Cassen *et al.* (1981) found that when the nebula is relatively cool (~100K) and more massive than the central protosun, nonaxisymmetry grows within a few rotational periods, resulting either in spiral arm formation, or even fragmentation into giant gaseous protoplanets in the particularly extreme case of a nebula 10 times more massive than the protosun. Cassen and Tomley (1988) are presently engaged in using this code to study the onset of gravitational instability in nebula models with simulated thermal gradients.

Boss (1985) used a 3D hydrodynamics code to model the early phases of solar nebula formation through collapse of a dense cloud core, and found that formation of a strong bar-like structure resulted. However, because the explicit nature of the code limited Boss (1985) from evolving the model very far in time, these results are only suggestive of the amount of nonaxisymmetry that could arise in the solar nebula. Recently, Boss (1989) has tried to circumvent this computational problem by calculating a suite of 3D models starting from densities high enough to bypass the intermediate, quasi-equilibrium evolution phases that obstruct explicit codes. While these initial densities for collapse ($\sim 10^{-13} - 10^{-12}$ g cm^{-3}) are clearly not realistic given the present understanding of star formation, it can be argued (Boss 1989) that starting from these high densities should not greatly distort the results.

The 3D models of Boss (1989) show that gravitational torques can be quite efficient at transporting angular momentum in the early solar nebula. The models show that collapsing presolar clouds become appreciably nonaxisymmetric (as a result of a combination of nonlinear coupling with the infall motions, rotational instability, and/or self-gravitation), and that trailing spiral arm patterns often form spontaneously; trailing spiral arms lead to the desired outward transport of angular momentum. The most nonaxisymmetric models tend to be massive nebulae surrounding low mass protosuns in agreement with the results of Cassen *et al.* (1981). Extrapolated time scales for angular momentum transport, and hence nebula evolution, can be as short as $\sim 10^3$ years for strongly nonaxisymmetric models, or about $\sim 10^6 - 10^7$ years for less nonaxisymmetric models. Because

these time scales are comparable to or less than model ages for naked T Tauri stars (Walter 1988), solar-type, pre-main-sequence stars that show no evidence for circumstellar matter, it appears that gravitational torques can indeed be strong enough to account for the transport of the bulk of nebula gas onto the protosun on the desired time scales. While these initial estimates are encouraging, it remains to be learned exactly how a solar nebula evolves due to gravitational torques.

IMPLICATIONS FOR PLANETARY FORMATION

The 3D solar nebula models of Boss (1989) show little tendency for breaking up directly into small numbers of giant gaseous protoplanets, contrary to one of the models of Cassen et al. (1981). This difference is probably a result of several features of the Boss (1989) models. The inclusion of 3D radiative transfer means that the compressional heating accompanying nebula formation can be included, leading to considerably higher temperatures than assumed in Cassen et al. (1981), and hence greater stability against break-up. Also, the gradual buildup of the nebula through collapse in the Boss (1989) models means that incipient regions of gravitational instability can be sheared away into trailing spiral arms by the differential rotation of the nebula before the regions become well-defined. These models thus suggest that planet formation must occur through the accumulation of dust grains (Safronov 1969; Wetherill 1980).

Considering that dust grain evolution is not yet included in 3D codes, detailed remarks about the earliest phases of dust grain accumulation are not possible. However, the models of Boss (1989) can be used to predict surface densities of dust grains in the solar nebula, and these surface densities are quite important for theories of planetary accumulation. For example, Goldreich and Ward (1973) suggested that a dust surface density at 1 AU of $\sigma_d \sim 7.5$ g cm^{-2} would be sufficient to result in a gravitational instability of a dust sub-disk (Safronov 1969) that could speed up the intermediate stages of planetary accumulation. More recently, Lissauer (1987) has proposed the rapid formation of Jupiter through runaway accretion of icy-rock planetesimals in a nebula with $\sigma_d > 15$ g cm^{-2} at 5 AU. Rapid formation is required in order to complete giant planet formation prior to dispersal of the solar nebula. Using a gas to dust ratio of 200:1 at 1 AU and 50:1 at 5 AU, these critical surface densities correspond to gas surface densities of 1500 g cm^{-2} at 1 AU and 750 g cm^{-2} at 5 AU. Similar minimum densities are inferred from reconstituting the planets to solar composition (Weidenschilling 1977). The models of Boss (1989) have surface densities in the inner solar nebula that are nearly always sufficient to account for terrestrial planet formation. However, surface densities in the outer solar nebula are less than the critical amount, unless the nebula is quite massive
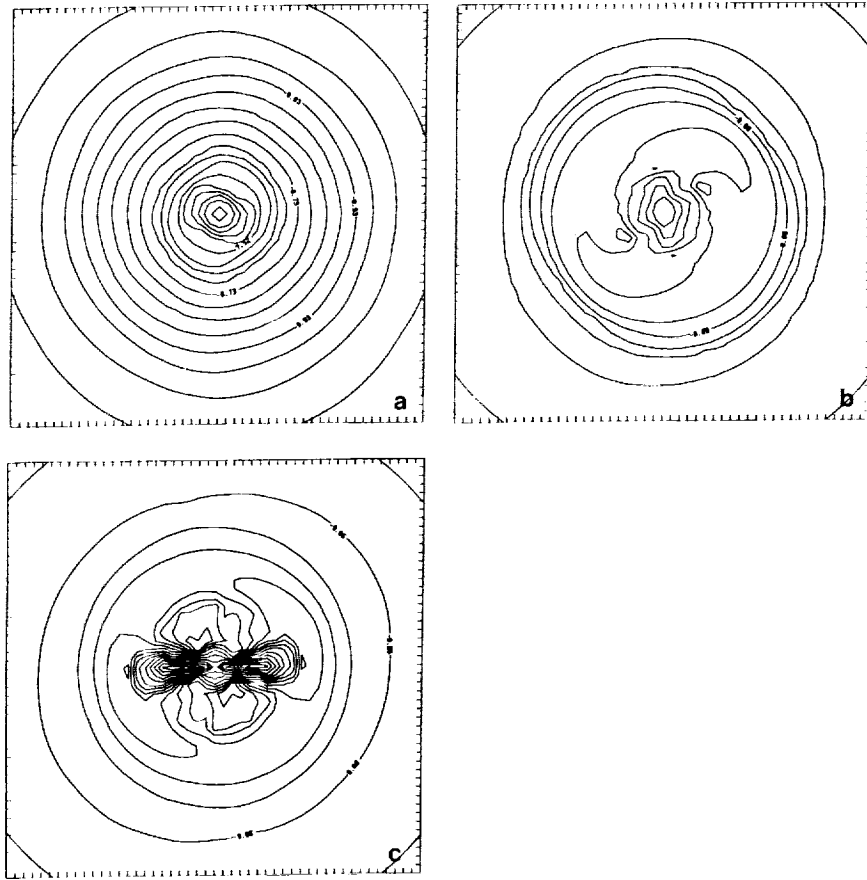
FIGURE 2 Density contours in the midplane of three solar nebula models formed by collapse onto protosuns with varied initial masses M_s (Boss 1989), plotted as in Figure 1. (a) M_s = 1 $M_\odot$, (b) M_s = 0.01 $M_\odot$, (c) M_s = 0$M_\odot$. The initial nebula mass was $1M_\odot$ for each model, and the initial specific angular momentum was J/M = 6.2 × 10^{19} $cm^2 s^{-1}$. The resulting nebulae become increasingly nonaxisymmetric as the initial protosun mass is decreased; (b) forms trailing spiral arms that result in efficient transport of angular momentum, while (c) actually fragments into a transient binary system. These models also illustrate the ability of a massive central object to stabilize a protostellar disk. Region shown is 20 AU across for each model.

($\sim$1M$_\odot$). Any protoJupiter that is formed rapidly in a massive nebula is likely to be lost during subsequent evolution, either because gap clearing will force the protoplanet to be transported onto the protosun with the rest of the gas (Lin and Papaloizou 1986), or because motion of the protoplanet relative to the gas will result in orbital decay onto the protosun (Ward 1986). The planetary system is the debris leftover from formation of the voracious Sun, and so prematurely formed protoplanets are at peril.

Variations in the initial density and angular velocity profiles do not appear to be able to produce sufficiently high surface densities at 5 AU in low-mass solar nebula (Boss 1989), so it does not appear that the surface densities required for planet formation can be accounted for simply by collapse onto a nebula. Diffusive redistribution of water vapor could preferentially accumulate ices wherever temperatures drop to 160K (Stevenson and Lunine 1988), but this mechanism can only be invoked to explain the formation of one of the outer planets. The most promising means for enhancing surface densities of the outer solar nebula appears to be through nebula evolution subsequent to formation. Viscous accretion disks can increase the surface density in the outer regions where the angular momentum is being deposited (Lin and Bodenheimer 1982; Lissauer 1987). While the long-term evolution of a 3D nebula subject to gravitational torques is as yet unknown, gravitational torques should produce a similar result (Lin and Pringle 1987). Determining the evolution of a nonaxisymmetric solar nebula thus appears to be a central issue in finding a solution to the problem of rapid Jupiter formation.

Finally, the 3D models of Boss (1988, 1989) have important implications for the thermal structure of the solar nebula. Provided the artifice of starting from high initial densities does not severely overestimate nebula temperatures, it appears that the compressional energy released by infall into the gravitational well of a solar-mass object can heat the midplane of the inner solar nebula to temperatures on the order of 1500 K for times on the order of 10^5 years. Such temperatures are high enough to vaporize all but the most refractory components of dust grains. In particular, because the vaporization of iron grains around 1420 K removes the dominant source of opacity, temperatures may be regulated to values close to $\sim$1500 K by the thermostatic effect of the opacity. A hot inner solar nebula can account for the gross depletion of volatiles on the terrestrial planets (relative to solar) by allowing the volatiles to be removed along with the H and He of the nebula. Hot solar nebula models were introduced by Cameron (1962) in one of the first solar nebula investigations, but have since fallen into disfavor (Wood 1988), so it will be interesting to see whether high temperatures in the inner nebula can be successfully resurrected, and whether they will prove to be useful in explaining planetary and asteroidal formation.

ACKNOWLEDGMENTS

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