SURFACE DENSITY AND TEMPERATURE PROFILES IN THE EARLY SOLAR NEBULA. Alan P. Boss, DTM, Carnegie Institution of Washington, 5241 Broad Branch Road N.W., Washington DC 20015.

Models of the formation of the solar nebula through the collapse of very dense, rotating, spherical clouds onto protosuns of variable mass have been calculated through numerical solution of the three dimensional (3D) equations of hydrodynamics, gravitation, and radiative transfer in the diffusion approximation. Previous work has shown the probable importance of nonaxisymmetry (i.e., spiral arms) for angular momentum transport in the nebula [1], and the possibility of relatively high ($\sim$ 1500 K) midplane temperatures [2] in the inner solar nebula.

Calculation of these models with an explicit time differences computer code is made possible only by the *ansatz* of starting the collapse from initial densities ($\rho_i \sim 10^{-13}$ g cm^{-3}) that are considerably higher than those of observed dense molecular clouds. Recently, several axisymmetric (2D) solar nebula models have been computed starting from similarly high initial densities [3,4]. While it can be argued that starting from these densities need not have a major effect on the dynamics and thermodynamics [2], it must be noted that this assumption will *overestimate* nebula temperatures. However, the neglect of heating from the central protosun in the 3D models so far *underestimates* nebula temperatures (cf. [3], where inclusion of this heating produced $T > 1600$ K inside 5 AU). Evidently, further work will be necessary before the thermal structure of these models can be considered definitive.

SURFACE DENSITY PROFILES AND PLANET FORMATION:

The original 16 models [1] all started from uniform density ($\rho_i = c$) and uniform rotation ($\Omega_i = c$) initial spheres. In order to learn what effect other initial density and rotation profiles would have on the structure of the nebula, 8 new 3D models have been calculated. Six of these models started with either $\rho_i = c$ and $\Omega_i \propto R$ (R = cylindrical radius) or with $\rho_i \propto r^{-1}$ (r = spherical radius) and $\Omega_i = c$. Two new models were started from $\rho_i = c$ and $\Omega_i = c$, but with large amounts of rotation. The results are shown in Fig. 1.

Surface densities in the inner solar nebula are typically high enough to account for terrestrial planet formation [5]. However, in the outer solar nebula, densities are insufficient for rapid formation of Jupiter through runaway accretion [6], unless the nebula is quite massive ($\approx 1 M_\odot$), in which case a Jupiter which has cleared a gap will likely be lost during subsequent evolution of the bulk of the nebula gas onto the sun. Surface densities in these 3D models are in basic agreement with those produced from the isothermal collapse of axisymmetric clouds [7].

The models imply that if outer solar nebula surface densities are ever to reach the required values in a minimum mass nebula, these densities must be increased through subsequent nebula evolution, e.g., through the action of viscous [6] or gravitational torques [1].

TEMPERATURE PROFILES AND CHEMICAL COMPOSITION:

A simple time scale argument [2] suggests that compressional energy produced by the collapse of the presolar cloud was trapped within the nebula for $\sim 10^5$ years. If so, this means that certain minimum mass solar nebula models can have midplane temperatures in the inner few AU of $\sim$ 1500 K or more (see Fig. 2a). This result also holds for models starting from alternative initial density profiles (see Fig. 2b). Temperatures this high are interesting in light of meteoritical evidence for the condensation of refractory inclusions [9] in a nebula cooling from high temperatures, though such a globally hot nebula would only cool over rather long ($\sim 10^5$ years) time scales. A hot inner solar nebula also may be able to account for the gross depletion (relative to solar) of volatile species in the terrestrial planets [10], because the gaseous C, N, and H_2O may have been removed along with the H and He by the early solar wind.

Midplane temperatures may have been regulated to $\sim$ 1500 K by the thermostatic effect of the opacity (Fig. 2). Because the nebula opacity at high temperatures is dominated by iron grains, which vaporize around 1420 K [11], at higher temperatures the opacity drops by a factor of $\sim$ 100, and hence radiative cooling is more efficient. However, should temperatures drop below 1420K, iron grains reform, the opacity rises, radiative losses decrease, and further decrease of the temperature is slowed. This thermostatic effect may ensure the survival of the most refractory interstellar grains, and prevent condensation from establishing a strong compositional gradient by minimizing the radial thermal gradient in the inner solar nebula.

Finally, one may also speculate that Type II Ca-Al-rich inclusions, which are depleted in both the most volatile and the most refractory rare earth elements (REE) [12], owe their peculiar composition to the thermostatic effect. That is, if midplane temperatures in the asteroid zone never exceeded $\sim$ 1500K, the most refractory components of the pre-existing interstellar grains will survive and rapidly sediment to the dust midplane, producing a population of volatile-poor grains (Type III inclusions [13]). After the nebula cools somewhat, newly-condensed grains will be depleted in the most refractory REE as well as the most volatile REE, as in Type II inclusions. If the nebula is removed prior to further cooling (and naked T Tauri star ages are similar to nebula cooling times), then the most volatile species would be removed altogether.

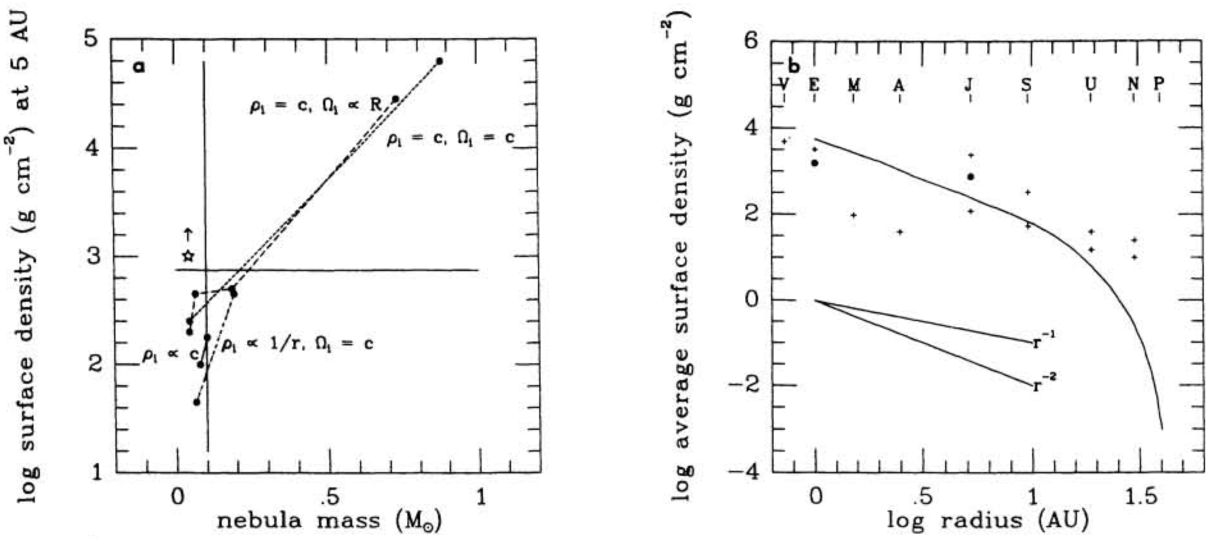

Fig 1. (a) Surface densities (σ) at 5 AU versus nebula masses immediately after formation of nebular disks through collapse starting from varied initial conditions. All models began collapse with protosun mass $M_c = 0.01 M_\odot$ and nebula mass $M_d = 1 M_\odot$, except for the models labelled simply $\rho_i = c$, which began with $M_c = 1 M_\odot$ and $M_d = 0.1 M_\odot$. Variations within a given group are caused by varied initial nebula rotation (Ω_i) rates. The star represents the minimum σ thought necessary for rapid Jupiter formation [6] in a minimum mass nebula; none of the models satisfy this criterion. (b) Surface density profile in a nebula with $M_c = 1 M_\odot$ and $M_d = 0.05 M_\odot$. Solid circles represent σ thought necessary for Earth [5] and Jupiter [6] formation. Plus signs represent σ obtained by enhancing all planets to solar composition [8].

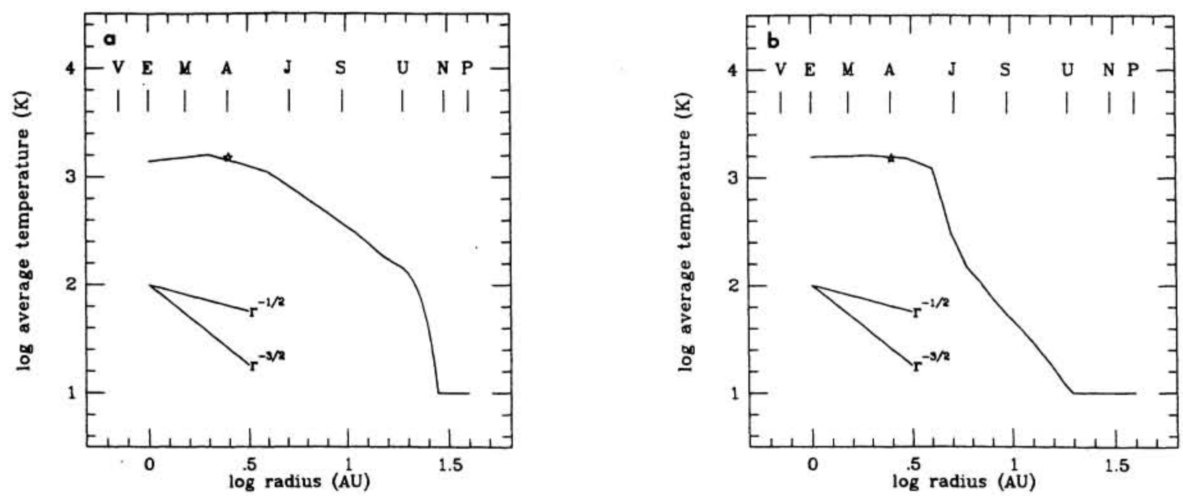

Fig 2. Azimuthally averaged midplane temperature profiles for two roughly axisymmetric nebula models. (a) $\rho_i = c$, $\Omega_i = c$ nebula leading to $M_c = 1 M_\odot$ and $M_d = 0.06 M_\odot$ [2]. (b) $\rho_i \propto r^{-1}$, $\Omega_i = c$ nebula leading to $M_c = 0.84 M_\odot$ and $M_d = 0.19 M_\odot$. The stars denote 1500 K at 2.5 AU. The thermostatic effect of the iron grain opacity [11] is evident in the inner solar system, particularly in (b).

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