THE NEBULAR ENVIRONMENT OF CHONDRITE FORMATION

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Two major problems are associated with chondrite formation in the solar nebula: (1) the source of heat that melted chondrules, and (2) the agency that brought dispersed particles of condensate together to form them. Most of the literature of chondrite formation focusses on (1). (2) has been largely neglected, although it is just as important as (1) and perhaps even harder to solve. Papers on chondrule formation tend to assume the existence of precursor dustballs as a starting condition.

Fine grains, whether presolar interstellar dust or secondary condensate, are closely coupled to the gas and difficult to separate from it. A force that acts differentially on grains and gas needs to be applied consistently for long enough to bring the grains together, or at least into close enough proximity for random collisions between them to be frequent. The feeble *z* component of solar gravity is often assumed to be the separating force, acting to concentrate dust near the nebular midplane. A placid nebular setting and long times ($\approx 10^4$ years) are required to concentrate dust in this way [1]. It may be feasible to invoke these in the late, quiescent phase of disk evolution, the setting in which most workers assume the chondrites formed.

However, gravitational settling of dust would have been impossible during the early, mechanically active infall phase of disk evolution, and I have argued that the chondrites are more likely to have formed at that time (because of the high rate of energy dissipation [2]). A different applied force must be sought to separate dust from gas in the early nebula. The turbulence in an active early disk may provide this in the form of centrifugal force. [3] have shown that the rotation of turbulent eddies in such a system tends to spin solid particles out of them and concentrate them for significant periods of time in stagnation zones between the eddies.

The computer simulation of [3] was particularly effective in concentrating chondrule-sized particles. I have written a program that numerically integrates the motion of a solid particle embedded in a whirling cylinder of gas. For a range of physical conditions commonly assumed in the nebula, this reproduces the result of [3] (Fig. 1). Figure 1 shows that, for a given gas pressure (hence density), there is a favored range of particle sizes that is spun out of the eddy faster than other sizes. The particles smaller than this size range experience drag forces too great to make much progress outward in the eddy, while particles larger than the favored sizes have too much inertial mass to be accelerated easily by the gas.

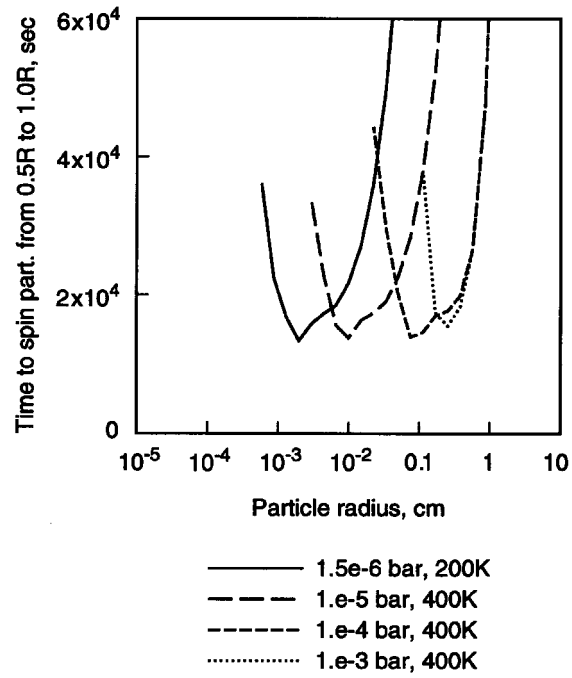

Fig. 1. Times needed for solid particles to spin out of an eddy of 1 km diam., rotation period 3 hr (conditions of [3]).

The work of [3] supplies important insight into how chondrules, once formed, might be concentrated enough to make encounters frequent and aggregation plausible. However, Fig. 1 shows that it provides little help in understanding how fine dust was brought together to form chondrules or chondrule precursors, especially if the nebula was relatively massive ($p = 10^{-4}$ or 10^{-3} bar curves), as it would have been during the infall phase of disk evolution.

I have suggested that the assembly of chondrules from preexisting dust or microdroplets, and the melting of the chondrules, happened simultaneously [2,4], and that shock waves in the nebular gas provided the energy for melting [2,5]. In the context of the present discussion, turbulence and shock heating are assumed to have coexisted. Vaporization and condensation may have occurred concurrently with the centrifugation of particles from turbulent eddies. It is interesting to model the motion of particles in a rotating eddy on the assumption that they increase their sizes by accumulating the involatile elements they encounter as they move through the gas, either in the form of adhering dust or as condensate from the gas. The FORTRAN program of Fig. 1 was modified to test this, and results are shown in Fig. 2. Here the medium of the eddy was taken to have the cosmic composition, 0.8 wt. % of which is collectable or condensible as silicates *etc.*, and particles initially of radius 10^{-5} cm were allowed to grow by collecting the condensibles they encountered as they were spun out of the eddy. It is seen that for relatively dense systems ($p = 10^{-3}$-10^{-4} bar) chondrule-sized objects could "grow" in the order of an hour as they were spinning out of an eddy, which is also the time scale of turnover of the smallest eddies assumed by [3] and this simulation, and the time scale of cooling of chondrules. In less dense systems ($p = 10^{-5}$-10^{-6} bar, characteristic of a minimum-mass quiescent nebula), they would not attain this size.

A system with a fair degree of generality can be pictured, which might be capable of processing the dusty gas received by the protosolar disk into chondritic material. As shock waves move through the mixture, solid particles are heated and vaporized to varying degrees by drag against the shocked gas. Refractory residues are spun out of turbulent eddies, growing by aggregation and/or recondensation in the process. Solids concentrate between eddies for a time, then the turbulence pattern changes and they find themselves within eddies again. Solids-enriched and solids-depleted zones are formed. The solids may go through many cycles of more or less simultaneous heating and centrifugation, and other cycles of cold centrifugation, before they find themselves concentrated densely enough to aggregate into chondritic material, which bears the stamp of this lengthy and complex history.

Several parameters that would have varied with time in the infall disk would affect the character of the chondritic product. One is the level of shock energy in the disk; another is the mass density of disk material (Figs. 1 and 2 show how centrifugation is affected by gas pressure). It may be that the different qualities of the chondrite groups ultimately resulted from differences in these and other parameters at the time and place in the disk where each group formed.

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2. Wood, J. A. (1996) in *Chondrules and the Protoplanetary Disk* (eds. R. H. Hewins, R. H. Jones, and E. R. D. Scott), 55.
3. Cuzzi, J. N., A. R. Dobrovolskis, and R. C. Hogan (1996) *ibid*, 35.
4. Wood, J. A. and B. B. Holmberg (1994), *Icarus* **108**, 309.
5. Wood, J. A. (1996) *Meteoritics and Plan. Sci.* **31**, 641.

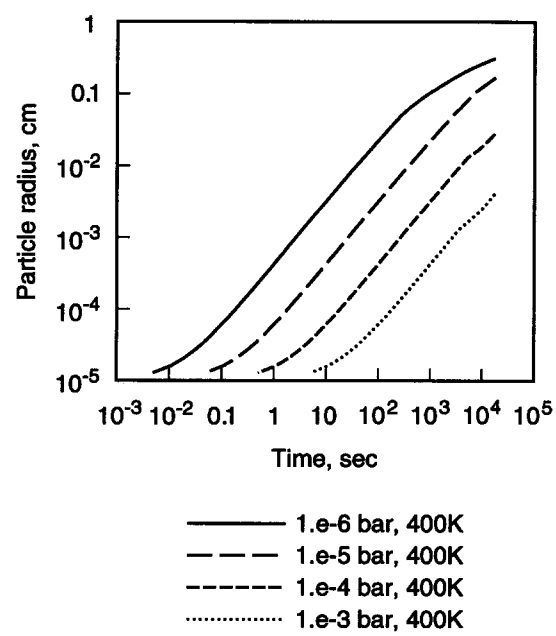

Fig. 2. Growth of particles spinning out of 1-km, 3-hr eddies if they sweep condensate from the gas.