COAGULATION OF GRAINS IN STATIC AND COLLAPSING PROTOSTELLAR CLOUDS

S.J. Weidenschilling (Planetary Science Institute) and T.V. Ruzmaikina (Lunar and Planetary Laboratory, Univ. of Arizona, Tucson, and Schmidt Inst. of Earth Physics, Moscow)

The wavelength dependence of extinction in the diffuse interstellar medium implies that it is produced by particles of dominant size $\sim 10^{-5}$ cm. There is some indication that in the cores of dense molecular clouds, sub-μm grains can coagulate to form larger particles; this process is probably driven by turbulence [1]. The most primitive meteorites (carbonaceous chondrites) are composed of particles with a bimodal size distribution with peaks near 1 μm (matrix) and 1 mm (chondrules). Cameron [2] suggested that grains could coagulate during collapse of the presolar cloud, with the short free-fall time ($\sim 10^5$y) offset by higher densities and turbulent velocities. Models for chondrule formation that involve processing of presolar material by chemical reactions [3] or through an accretion shock during infall [4-6] assume that aggregates of the requisite mass could form before or during collapse. Most evaluations of grain aggregation have been simple comparisons of collision timescales with cloud lifetimes and free-fall times; only Cameron computed actual size distributions of aggregates. The effectiveness of coagulation during collapse has been disputed [7,8]; it appears to depend on specific assumptions [9]. Here we report the first results of detailed numerical modeling of spatial and temporal variations of particle sizes in presolar clouds, both static and collapsing.

Static Clouds: Observations of present-day star-forming regions imply that solar-type stars are formed by collapse of small (radius R $\sim 10^{17}$ cm) dense cores in molecular clouds. A core of mass slightly exceeding $M_\odot$ is sufficient to make the Sun and a low-mass solar nebula. Stable Bonnor-Ebert spheres can be considered as models of the cloud cores; the degree of density concentration to the center depends on external pressure at the cloud surface. We consider spherically symmetric clouds with mass $M = 1.1M_\odot$, R = 1.4×10^4 AU and temperature T = 10°K (isothermal sound speed 1.9×10^4 cm/s). We consider clouds with three density distributions: uniform density, singular isothermal sphere ($\rho \propto r^{-2}$), and uniform central density with $\rho \propto r^{-2}$ in the outer part. We assume a Kolmogorov turbulence spectrum with maximum eddy size $0.1R$. The turbulent velocity V is chosen to be either uniform or $\propto r^{-1/2}$ (constant turbulent pressure). Particle relative velocities are modeled from Völk *et al.* [10] as modified by Mizuno *et al.* [11] for the small scale eddies. We divide the cloud into 20 radial zones and compute the evolution of the size distribution in each. Particles can migrate between zones by turbulent diffusion and radial settling.

Particle Properties: The static cloud has an initially uniform grains/gas mass ratio of 0.014, with all grains initially 0.1 μm diameter. Aggregates are assumed to have uniform density or a fractal structure. The simplest assumption of perfect sticking yields an upper limit on aggregate size. We also use the sticking criterion of Chokshi *et al.* [12] with material properties of H_2O ice; impacts at less than a size-dependent critical velocity result in sticking. Erosion and disruption are allowed at higher velocities, assuming an impact strength of 10^6 erg/g.

Collapsing Clouds: The output size distribution of the static case is used as the initial state in the collapse, which follows Shu's [13] similarity solution for $\rho(r,t)$. We compute the collisional evolution of particles in a parcel of turbulent gas with sonic velocity of the largest eddies, $V=c$, as ρ increases during infall. Two assumptions are used to estimate the strength of turbulence: (a) constant largest eddy length scale $L = 0.1R$, and (b) $L = \min(0.1R, cr/\dot{r})$, which causes the inner size scale of smallest eddies to decrease during collapse. The collapse is followed to $r = 3$ AU; ρ increases by $\sim 10^5$.

Results: Particle growth occurs in the static case for either sticking criterion. For uniform aggregate density, sizes $\sim 100(V/c)$ μm are reached after 10^7y; for perfect sticking aggregate size increases roughly as t^2. Fractal aggregates yield sizes $\sim 10^2$ times larger, but with very low densities ($\sim 10^{-3}$g/cm^3). Still larger particles can form in the inner part of a centrally condensed cloud, but would be lost into the star during collapse. We model the size evolution during collapse only for the outer zone of the cloud; this material would land in the disk. For case (a), particle motions become more correlated and relative velocities decrease during collapse as ρ increases because the response time to drag forces varies as ρ^{-1}, while the turnover time of the smallest eddies decreases as $\rho^{-1/2}$. There are few collisions and very little change in the size distribution. In the more physically plausible case (b), the strength of turbulence and relative velocities increase during collapse, and collisions occur much more often. If perfect sticking is assumed, further growth occurs, as much as several orders of magnitude in mass. However, impact velocities also increase during collapse, and can cause net destruction of aggregates due to high-speed collisions. For impact strength 10^6 erg/g, the aggregates striking the circumstellar disk at 3 AU are ≤ 10 μm in final size.

Thus, we show the possibility of a significant growth of interstellar dust grains in turbulent molecular cloud cores before and during their collapse. Fluffy aggregates grow faster than compact grains. The sticking efficiency and impact strength are important parameters determining the evolution of size and mass of aggregates. Further investigation of these parameters is needed to restrict initial size distribution of aggregates in protostellar clouds and circumstellar disks.

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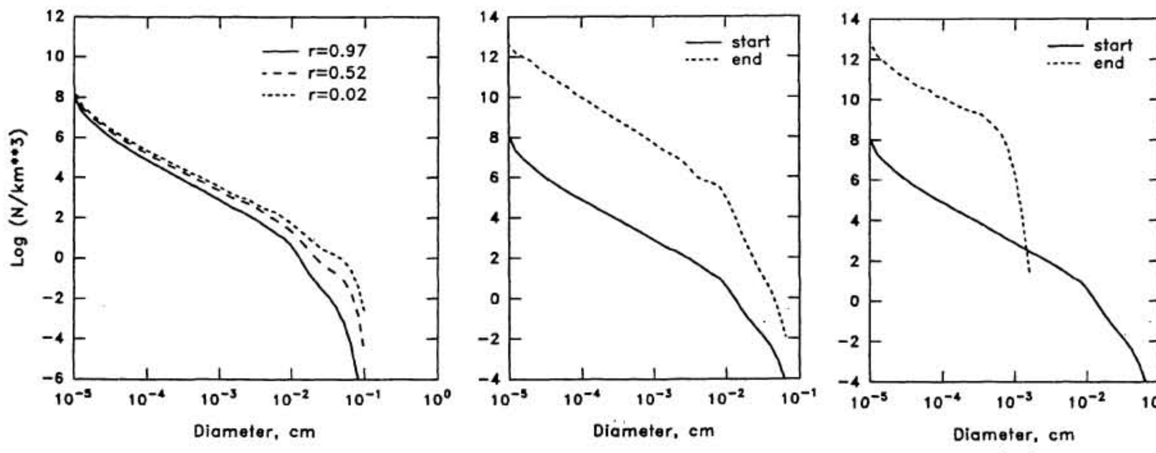

Figure 1. Particle size distribution for a static and collapsing cloud, presented as number density per logarithmic diameter interval $2^{1/3}$. Impact strength 10^6 erg/g. Fractal structure assumed at $d < 30$ μm, where Chokshi *et al.* criterion predicts perfect sticking. Larger aggregates have constant density. (a) Static Bonner-Ebert sphere at $t = 10^7$y. $V = c$ at outer edge, $\propto \rho^{-1/2}$ in interior. Three radial locations shown. (b) Initial and final (r = 3 AU) size distributions for collapse of outer shell of (a), assuming uniform turbulence strength. There is little change in the size distribution, only increased concentration due to compression of gas. (c) Same as (b), but with increasing strength of turbulence during collapse. Collisions destroy most aggregates of size > 10 μm.