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AERODYNAMIC AND GASDYNAMIC EFFECTS IN COSMOGONY.

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The solar system is the product of a primordial nebula that was composed mostly of gas, with only a small admixture of solid matter. The early evolution of solid bodies of various sizes in the disk was dominated by a variety of interactions with the gas, e.g., turbulent transport, differential settling, and orbital decay due to drag. These processes controlled relative velocities and hence collision rates and outcomes, over a range of particle sizes roughly from μm to km--some 9 orders of magnitude. Small grains, transported and mixed by turbulence, may have also influenced the gas. Since grains provided most of the opacity, their abundance and properties may have determined whether convection occurred in the disk. Earlier suggestions that turbulent viscosity might have caused major redistribution of mass and angular momentum in the solar nebula now seem unlikely, as recent analyses (Cabot et al., 1987) derive much lower convective velocities. However, even these can inhibit settling to the central plane and prevent formation of planetesimal by the "classical" mechanism of gravitational instability. A general feature of solar nebula models is a radial pressure gradient that causes non-keplerian rotation of the gaseous component. Even in the absence of global turbulence, formation of a relatively dense dust-rich layer would cause shear between it and the surrounding gas, producing localized turbulence sufficient to prevent gravitational instability. Thus planetesimals probably formed by collisional coagulation, with a range of initial sizes.

Weidenschilling has constructed an improved numerical code to model coagulation and settling of particles in a disk nebula containing "generic" turbulence with arbitrary velocities in the gas. The turbulence is assumed to have a Kolmogorov eddy spectrum. Relative velocities of particles, which lead to collisions and possible coagulation, are computed as due all significant causes in their appropriate regimes: thermal motion, shear and inertial effects in turbulent eddies, and systematic motions due to settling and non-keplerian rotation of the gas. Preliminary results have been obtained for a few different values of turbulent velocity (Weidenschilling and Cuzzi, 1991).

Recent work has produced significant improvements to this program. One significant problem was the disparity of timescales for turbulent mixing and coagulation. To accurately compute the former, the timestep must be shorter than the smallest spatial scale (layer thickness) divided by the turbulent velocity. However, the size distribution often varies due to coagulation on much longer timescales. To minimize the computational overhead associated with collisions between particles of all sizes, a dual timestep was introduced. Collisional changes in the size distribution are computed once in every N substeps, where the substep is controlled by the turbulent diffusion velocity, and N is determined by the rate of collisions. This algorithm has allowed simulations to be extended to longer times (up to 10^4y) and later stages (largest bodies ~100 m diameter).

One significant finding that emerged from the later-stage calculations with turbulence was the realization that while growth of large bodies results in their decoupling from the turbulence, this decoupling does not allow them to settle into a thin layer. The particle layer remains thick because while the stirring due to turbulence decreases as the bodies grow larger, the damping of their velocities by gas drag decreases even more rapidly. In numerical simulations, when the mean particle size becomes large (tens of meters), the density of solids in the central plane of the disk begins to decrease. Thus, the suggestion of some theorists that particle growth would eventually allow a Safronov-Goldreich-Ward gravitational instability in a turbulent accretion disk is not correct. In fact, there are stringent limits (a few cm/sec) on turbulent velocities that would allow gravitational instability of a layer of particles, regardless of their size.

Additional improvements to the code include the provision to compute the evolution of the optical thickness of the nebula due to the particles, and variation with time as the size distribution and vertical distribution of the particles change. Opacities are taken from Pollack et al. (1985). Examples of results are shown in Figures 1 and 2.

Later stages of coagulation and settling lead to significant concentrations of particles in a layer near the central plane of the nebula. While the density of this particle layer is still much too low for gravitational instability, it may exceed the density of the gas. Under those conditions, collective effects become important; the particle layer drags the gas with it and produces shear between the dense layer and the surrounding gas (Weidenschilling 1980). The code has been modified to compute the rate of shearing, using the analytic model of Nakagawa et al. (1986). If the Reynolds number of the shear flow exceeds a critical value, then it generates turbulence of magnitude determined by a simple mixing-length model. This shear-generated turbulence can be significant in nebular models with little or no global turbulence. Its inclusion in the model allows simulations to be extended to later stages, with particle sizes approaching 100 m, at which point their mutual gravitational stirring will become important.

REFERENCES: Cabot *et al.* (1987) *Icarus*, **69**, 387. Nakagawa (1986) *et al. Icarus*, **67**, 375. Pollack *et al.* (1985) *Icarus* **64**, 471. Weidenschilling, S. (1980) *Icarus* **44**, 172. Weidenschilling, S. and Cuzzi, J. (1991) *Protostars and Planets III*, in press.

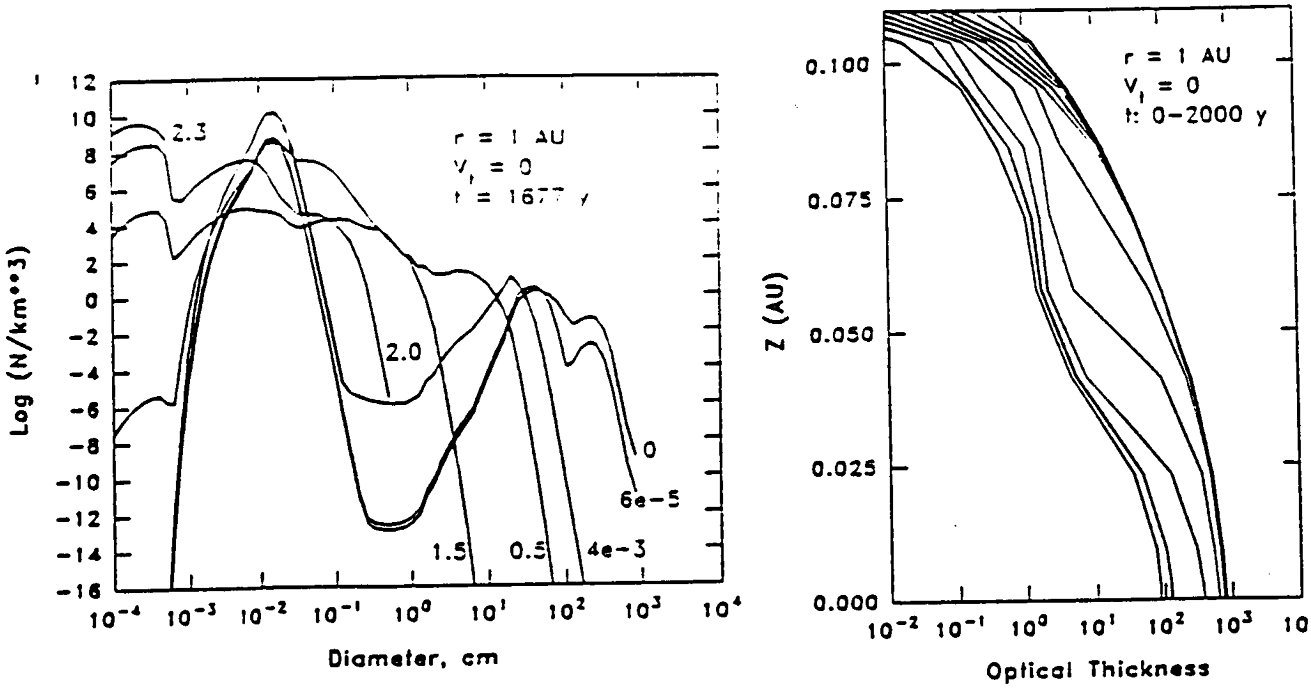

Figure 1. Particle evolution due to coagulation and settling in a nebular disk without turbulence. a) Size distribution at different levels (numbers refer to Z in units of scale height) at the time when solids/gas mass ratio equals unity at Z = 0. b) Cumulative optical thickness above each level (Z) vs. time; contour interval 200y.

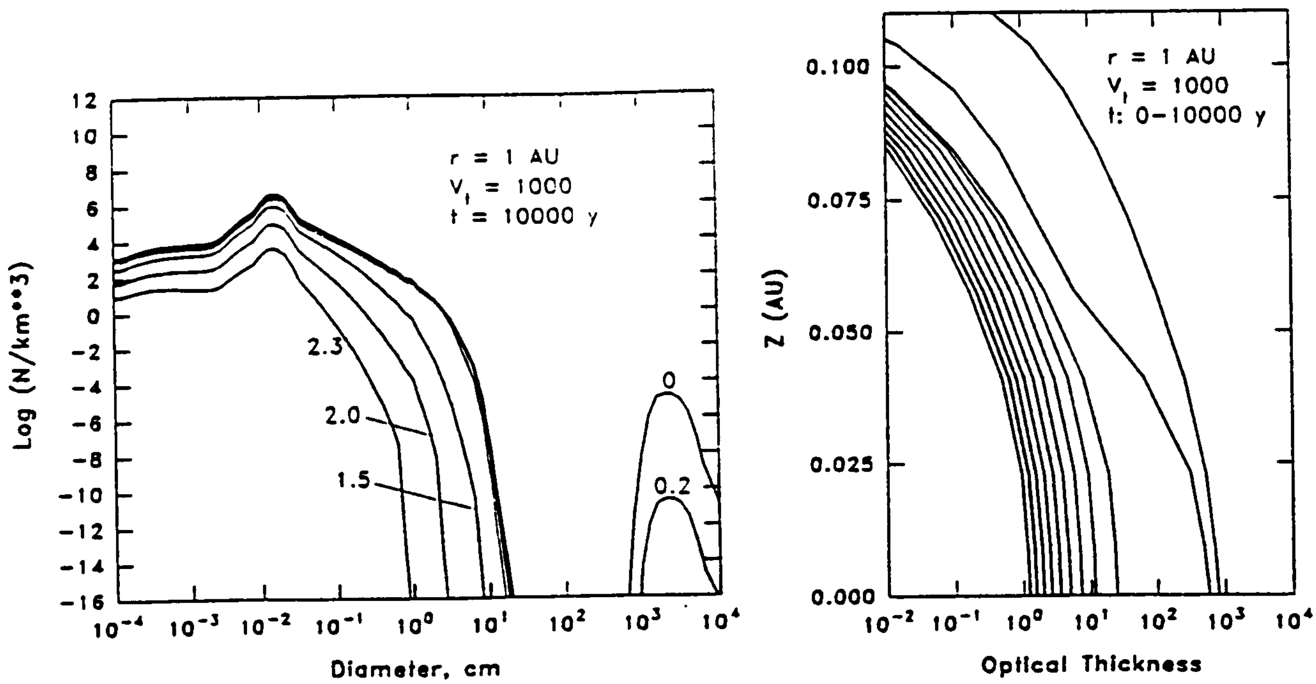

Figure 2. Same as Figure 1, but with turbulent velocity in the gas of 1000 cm/s. After 10000y, solids/gas ratio at Z = 0 has reached ~0.4.