DUST EVOLUTION IN SOLAR NEBULA MODELS WITH GENERIC TURBULENCE; S.J. Weidenschilling, Planetary Science Institute, Tucson AZ 85719

There are several plausible sources of turbulence in the solar nebula: infalling material (1) or solar wind (2) impinging on the disk, and convection (3, 4). The strength of such turbulence is poorly constrained, but it is very unlikely that the nebula was ever perfectly laminar. Small grains and aggregates were coupled to the gas, and their small settling velocities imply that even weak turbulence could have affected their settling to the central plane and incorporation into planetesimals.

I have developed a numerical model for coagulation and settling of particles in a nebular disk with "generic" turbulence having a Kolmogorov spectrum with arbitrary velocity scale V. The largest eddies are assumed to have sizes of order H (scale height) = c/Ω (c = sound speed, Ω = Kepler frequency). Inner scales of the smallest eddies are consistent with the dissipation rate (V^3/H). At a given radius R the disk is divided into levels of varied thickness, with the finest spatial resolution near the central plane. Particle relative velocities and collision rates result from the combination of thermal motion, differential settling, and turbulence. Turbulent diffusion velocity $V_d = V/\sqrt{(1+t_e/t_o)}$ where t_e = response time to drag force and t_o ($=1/\Omega$) is the eddy turnover time. Settling brings particles toward the central plane, but turbulence can cause upward motion as well, if V_d exceeds the settling velocity. The diffusion coefficient $D \sim (\pi/8)\, V_d^2 t_o$, with flux proportional to the gradient in solids/gas ratio (because the gas density varies between layers). If settling forms a dense layer (solids/gas mass ratio $\gtrsim 1$) near the central plane, there is shear between the layer and the pressure-supported gas on either side (5). If the shear flow exceeds a critical Reynolds number $Re^* \sim 100$, the layer becomes turbulent with velocities $\sim \Delta V/Re^*$, in addition to any global turbulence.

Models have been run for a minimum-mass nebula (6) at 1 AU for $0 \leq V \leq 10^3$ cm/s. Initial conditions are uniform dust/gas ratio with mean particle size 1 μm. Particle size distributions, solids/gas mass ratios, and optical thickness (using opacities from (7)) are computed as functions of Z and time. In general, particle sticking yields complex multimodal size distributions with peaks corresponding to sizes where thermal motion and vertical, radial and transverse motions dominate.

For $V=0$, solids/gas mass ratio (δ/ρ) ~ 1 after a few 10^3 y, with mean sizes of a few meters (assuming perfect sticking). Shear-induced turbulence slows further settling; $\delta/\rho \sim 10$ (still 10^{-3} times the density for gravitational instability) when sizes are $\sim$10m. Km-sized bodies may be produced before gravitational instability can occur; their mutual perturbations will thicken the layer and lower its density. For modest turbulence of $V=100$ cm/s, initial growth is slightly faster, as turbulent diffusion transports small aggregates to the central plane more rapidly than settling. For $V=10^3$ cm/s, the time to reach significant concentration in the central plane is significantly longer, $\sim 10^4$ y; bodies must grow larger before they can settle, and the lower concentration decreases the growth rate. For V of this magnitude, δ/ρ may never reach unity at $z=0$. Large ($>$m-sized) bodies begin to decouple from the gas ($t_e >> t_o$) and pursue drag-perturbed Kepler orbits. Inclinations damp at a rate $\propto t_e^{-1}$ (8), while random velocities $V_d \propto t_e^{-1/2}$, thus larger bodies are stirred by turbulence more effectively than they are damped by drag. Gravitational instability of a particle layer is impossible if turbulent velocities are greater than a few cm/s, regardless of particle size.

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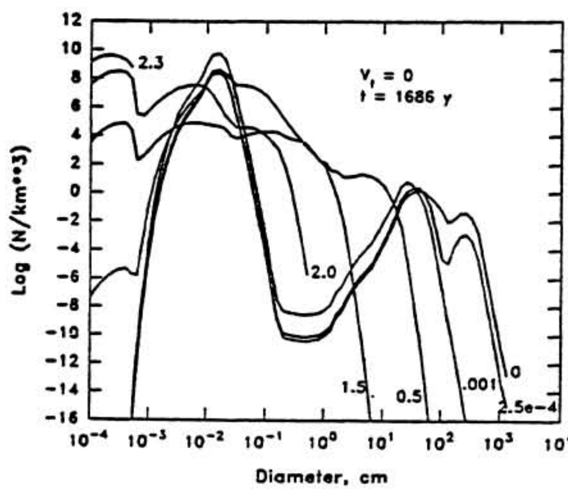

Fig. 1a. Distribution of particle size in a non-turbulent disk (V=0). Numbers refer to distance from central plane in units of H.

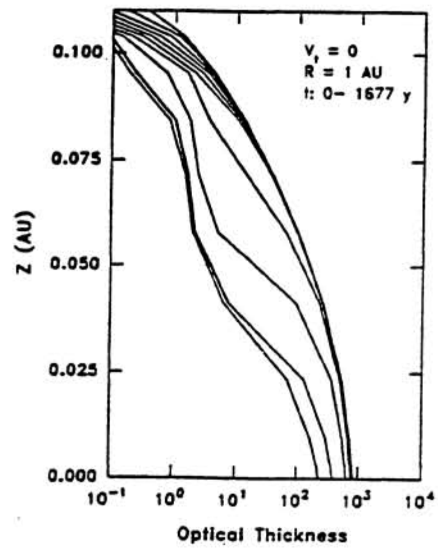

Fig. 1b. Cumulative distribution of optical thickenss vs. Z and time, shown at 200-y intervals.

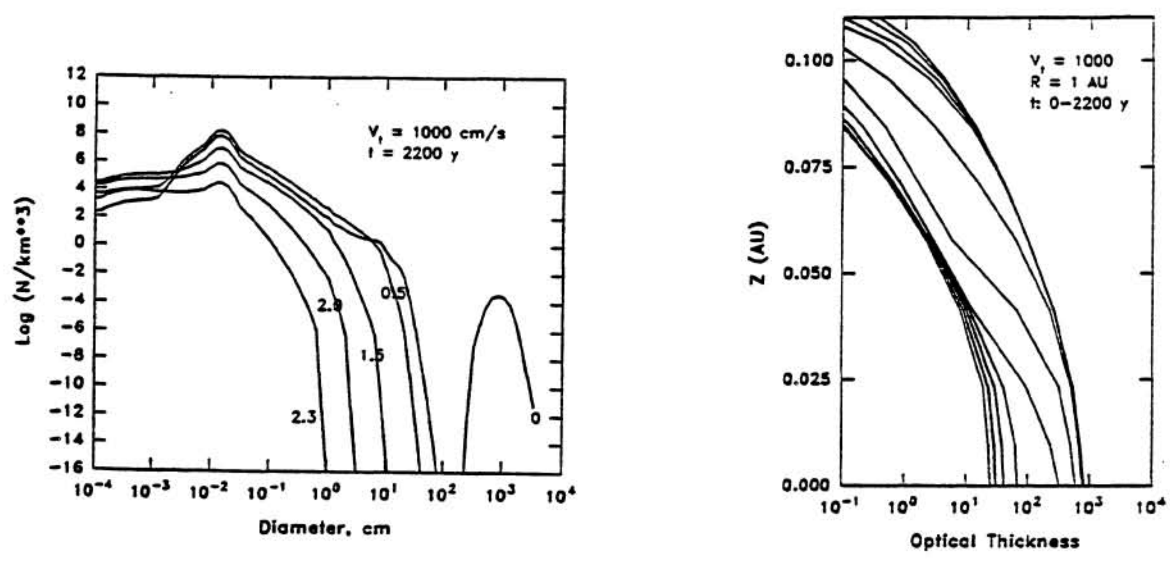

Fig. 2a,b: Same for V=1000 cm/s.