ACCUMULATION OF SOLID BODIES IN THE SOLAR NEBULA

S.J. Weidenschilling and D.R. Davis
Planetary Science Institute, Tucson, AZ 85719

The earliest stage of accumulation of solid bodies in the solar system, i.e., the formation of planetesimals from dust, occurred in the presence of the gaseous component of the solar nebula. The effects of the gas on these particles via aerodynamic drag must be understood in order to produce physically plausible models of this process. There are major uncertainties in nebular properties, e.g., its mass (or the gas density), lifetime, and degree of turbulence. The enigmatic textural and mineralogical properties of primitive meteorites suggest that we still do not understand the formation of their parent bodies. Weidenschilling (1980) modeled the settling of dust to the central plane of the nebula. He argued that coagulation of grains during settling could be expected due to van der Waals surface forces, and was probably necessary for the formation of planetesimals. Coagulation causes settling to be non-homologous; i.e., a small fraction of the total dust content arrives at the central plane as large aggregates, while most of the mass remains suspended. Recently Nakagawa et al. (Icarus 67, 375, 1986) criticized this work because it assumed the dust motions were always controlled by the gas, whereas the reverse would be true (dust controlling gas) at sufficiently high dust density. However, their conclusion was based on an analytic homologous settling model. Weidenschilling has re-examined this problem numerically, using a higher spatial resolution near the central plane than previously employed. He found that the first-formed aggregate layer is thinner than found earlier (~10 km thick at 1 AU for a low-mass nebula), and containing $\lesssim 10^{-3}$ of the total surface density solids. The ~meter-sized aggregates are so widely separated that they behave independently; i.e., there is no stage at which the dust dominates the motion of the gas. Earlier, Weidenschilling (1980) had suggested that planetesimal formation would involve gravitational instability in a layer of >m-sized aggregate bodies. These new results imply that gravitational instability might be avoided entirely, due to the extremely low surface density of the initial layer, with planetesimals forming entirely by collisional coagulation.

An important property of the solar nebula is the non-Keplerian rotation of the gas due to a radial pressure gradient (Weidenschilling, MNRAS 180, 57, 1977). The resulting headwind" on the planetesimals causes their orbits to decay. Weidenschilling and Davis (Icarus 62, 16, 1985) examined the combined effects of gas drag and gravitational perturbations of a planetary embryo on the orbital evolution of planetesimals. They showed that planetesimals could be trapped in stable orbits at commensurability resonances (ratio of periods (j+1)/j, where j is an integer). The resonant perturbations pump up eccentricities to an equilibrium value e(eq) that is independent of planetesimal size. The eccentric orbits cause collisional comminution of the planetesimals. Weidenschilling and Davis suggested a scenario in which this phenomenon allows an early-formed embryo to prevent the growth of rivals, while it grows rapidly by capture of small fragments that are brought through the resonances by drag.

Weidenschilling and Davis have continued their investigation of resonant planetesimal orbits, using analytic and numerical methods. Three dimensional orbit integrations have shown that there is no significant pumping of inclinations; the planetesimal swarm remains highly flattened, with a high collision rate. The rate of eccentricity pumping at a resonance can be expressed as $de/dt \simeq (e(eq)-e)/\tau$, where the time constant τ is independent of the embryo mass or the resonance order, j. τ does depend on the damping coefficient, i.e., τ is proportional to the planetesimal size and inversely proportional to the gas density. A typical value for a low-mass nebula is $\tau \sim 10^3$ yr for a km-sized body at 1 AU. In the outer nebula, with much lower gas density, $\tau \sim 10^7$ yr for a similar body. Thus, large planetesimals at Neptune's distance may not reach e(eq) before the nebular gas is dissipated. The presence of fine dust that is coupled to the gas increases the effective density, and can shorten τ. Collisions with other large planetesimals on Keplerian orbits have no effect on τ, but can decrease the value of e(eq).

Another important consideration for evaluating the effects of resonant trapping is the width of a resonance, i.e., the range of semimajor axis (or mean motion) over which a planetesimal responds to the resonant perturbations. As with any simple damped oscillator, lower damping (a larger planetesimal or lower gas density) produces a narrower resonance peak near exact commensurability; higher damping yields a broader range of response with a lower peak. Using analytic resonance theory (cf. Greenberg, Icarus 33, 62, 1978), it can be shown that the width of a resonance varies slowly with order j, and is proportional to the square root of the product of the gas density, the perturbing embryo's mass, and the planetesimal's size. In a lower-mass nebula containing an Earth-mass embryo, the effective resonance width for a km-sized planetesimal is typically $\sim 10^{-4}$–10^{-3} AU. If a planetesimal has a close encounter or collision with another body, so that its semimajor axis is changed by more than the resonance width, it may pass through the resonance without being trapped. Larger bodies have narrower resonances (less damping), and so require smaller perturbations; also, their larger τ values make it more likely that they will experience a collision or encounter before their eccentricities can be pumped up. Thus, resonances are "transparent" to large bodies. This effect alters the accretion scenario that was proposed by Weidenschilling and Davis. There is a minimum planetesimal size that allows trapping; below that size drag dominates and forces bodies through any resonances. The matter accreted by a planetary embryo is probably bimodal. Much of the mass, especially in the early stage of accretion, will consist of small (<<1 km) fragments. The late-accreted mass will include bodies that have grown large enough (>>1 km) to be unaffected by resonances. This scenario can yield rapid growth of the cores of the giant planets while providing a population of large impactors that produce their obliquities.

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