PLANETESIMAL FORMATION IN TWO DIMENSIONS: PUTTING AN EDGE ON THE SOLAR SYSTEM.

S. J. Weidenschilling, Planetary Science Institute, 620 N. 6th Avenue, Tucson, AZ 85705; sjw@psi.edu

It has been known for decades that the gaseous component of the solar nebula has non-keplerian rotation due to a radial pressure gradient, and that solid bodies in the nebula have radial motion due to drag [1,2]. In general, this motion is inward, toward the Sun, and could in principle cause mixing, migration, and/or loss of solid matter prior to planetary formation. Peak radial velocities developed by m-sized bodies are ~ 50 m/s, or ~ 1 AU/century, so there is the possibility of significant redistribution of solids during the ~10^6 - 10^7 year lifetime of the solar nebula. However, the consequences of this phenomenon for planetesimal formation and global evolution of the solar nebula are not fully understood. This lack of understanding is due in part to the complexity of particle motions: individual bodies have radial velocities that vary non-monotonically with size [3], while particles that settle into a dense layer have collective motions that depend on the density of the layer as well as the size distribution of its components [4]. These motions determine the collision rates and impact velocities of bodies of various sizes, so there is a complex feedback between growth and migration, which will vary with heliocentric distance (R), distance from the central plane (Z), and time (t).

Previous attempts to model the global evolution of solids in the nebula have involved simplifying approximations that make their conclusions suspect. Weidenschilling [5] showed that orbital decay could fractionate large (> m-sized) bodies by size and/or density while depleting solids in the inner part of the nebula, but neglected earlier evolution during growth of such bodies. Stepinski and Valageas [6] and Kornet et al. [7] modeled global redistribution of solids in a turbulent accretion disk, but assumed a single particle size at any (R,t), which did not allow collisions due to size-dependent differential motions; their model is not valid for disks with low turbulence (alpha ≲ 10^{-2}). Youdin and Shu [8] suggested chondrules could be concentrated by radial migration, but neglected collective effects, which should dominate over individual motions in a layer of small particles.

I have produced a numerical model for the evolution of particles in the solar nebula without these simplifying assumptions. It computes the vertical and radial distribution of particles and the evolution of their size distribution as functions of (Z, R, t), considering individual and collective motions and detailed collisional physics. This code is an extension of the 1-D model described in [9], which computed the vertical distribution of particles undergoing coagulation and settling at a single value of R. The 2-D code performs similar calculations in a series of radial zones, transferring particles between them at rates proportional to their radial drift rates. It includes collective effects on a particle layer due to shear-induced turbulence where appropriate, effects of the layer's self-gravity on its vertical structure, and gravitational stirring of large (> km-sized) bodies. The starting condition is a population of um-sized grains, uniformly distributed in the gas, which is assumed to have a power-law radial surface density gradient. The size distribution is modeled by a series of logarithmic diameter bins, extending over 12 orders of magnitude up to sizes ~ 10^3 km.

Results: Simulations have been performed for the outer solar nebula (30 - 90 AU) for a variety of nebular masses, with surface density profiles proportional to R^{-1} to R^{-2}, for model times up to 10^6 y. Disabling radial migration yields results in each zone generally consistent with the 1-D model [9]: coagulation and settling produces a thin layer of particles in the central plane, with thickness determined by shear-induced turbulence. Collisional growth by differential radial drift rates produces a multimodal size distribution with a dearth of m-sized bodies, as their high radial velocities cause short collisional lifetimes, and a mass peak in bodies of size ~ 0.1 - 1 km. Without migration, similar evolution occurs in all zones, on longer timescales at greater heliocentric distances.

Outcomes are qualitatively different with radial migration. In all cases there is significant redistribution of the solids. The size distribution has less prominent peaks and valleys, due to radial mixing of bodies growing at different rates at different distances. If the surface density is too low, or the radial gradient as steep as R^{-2}, coagulation does not produce any planetesimals within the modeled range (R > 30 AU) large enough (km-sized) to decouple from the gas and escape orbital decay, and virtually all of the solid matter is lost (into the inner nebula). A shallower surface density gradient provides more mass in the outer zones while decreasing the orbital decay rate. For a surface density proportional to R^{-1}, large planetesimals can form in the inner zones (30 - 40 AU), and mass accumulates there; with the depletion of the outer zones this produces a much steeper surface density profile with a distinct "edge." There is also a steep change in the mean size of bodies at this distance. There are two reasons for these effects: (a) The peak radial velocity due to drag, and the size at which this peak occurs, do not vary significantly with heliocentric distance. Most of the migration occurs at sizes ~ 0.1 - 10 m, and the distance a body travels is proportional to the time it takes to grow through this range. The lower densities at larger distances produce slower growth, so a body starting farther out experiences greater radial migration. This steepens the gradient in surface density. (b) The growing bodies settle into a very thin layer; those m-sized or larger are effectively decoupled from any turbulence, while gravitational stirring is ineffective at sub-km sizes. Lacking effective stirring, they form a near-monolayer in the central plane during the greater part of their migration. Thus, they have a high probability of colliding with any bodies that have grown large enough (> km) to halt their orbital decay. Drag-driven accretion can form bodies hundreds of km in size on timescales of a few times 10^5 y, faster than gravitational accretion. The incoming mass tends to pile up at the distance where such bodies form, producing a sharp transition in both surface density and mean size. The position of this edge is more sensitive to the gradient of surface density than to the nebular mass. A low-mass solar nebula with radius 90 AU and R^{-1} gradient yields a planetesimal swarm with an outer edge at ~ 40 - 50 AU. A gradient as steep as R^{-2}, even for a much more massive nebula, gives an edge inside 30 AU.

Discovery statistics imply that the Kuiper Belt is truncated at about 50 AU, with a sharp decrease in sizes and/or numbers of bodies at that distance [10]. Models of gas-free accretion predict only gradual change of growth rates and planetesimal sizes with distance, and cannot explain the observations. While various ad hoc dynamical truncation mechanisms have been proposed [11, 12], drag-induced migration provides a natural explanation for the observed edge of the solar system.

Implications: Radial migration of solids yields a planetesimal swarm significantly smaller than the original extent of a circumstellar gas-dust disk. The original extent of the solar nebula may have been ~ 100 AU, with correspondingly larger mass and angular momentum than implied by the size of the planetary system. While observations do not rule out an undiscovered outer Kuiper Belt beyond ~ 70 AU, the difficulty of planetesimal formation at large heliocentric distances renders its existence unlikely.

References: [1] Whipple, F. J. (1972) In *From Plasma to Planet* (A. Evius, Ed.), p.211. [2] Goldreich P. and Ward W. R. [1973] *Astrophys. J.* **183,** 1051. [3] Weidenschilling S. J. (1977) *Mon. Not. Astron. Soc.* **180,** 57. [4] Nakagawa Y. et al. (1986) *Icarus* **67,** 375. [5] Weidenschilling, S. J. (1978) *Icarus* **35,** 99. [6] Stepinski T. and Valageas P. (1966) *Astron. Astrophys.* **309,** 301and *Astron. Astrophys.* **319,** 1007. [7] Kornet K. et al. (2001) *Astron. Astrophys.* **378,** 180. [8] Youdin A. and Shu F. (2002) *Astrophys. J.* **580,** 494. [9] Weidenschilling S. J. (1997) *Icarus* **127,** 290. [10] Trujillo C. et al. (2001) *Astron. J.* **122,** 457. [11] Ida S. et al. (2000) *Astrophys. J.* **528,** 351. [12] Brunini A. and Melita M. (2002) *Icarus* **160,** 32.