Particle concentration in an evolving disk: Implications for early accretion and planetesimal formation

Anna L.H. Hughes and P.J. Armitage, University of Colorado, Boulder, CO

Introduction:

One of the greatest puzzles today in the study of planet formation and of the processes operating within the early Solar nebula is the formation mechanism for planetesimals. These bodies must be large enough to overcome gas drag in the early disk that can cause rapid inward migration. They make up the building blocks of our planets, asteroids, and comets. Traditional approaches to planetesimal formation are of two kinds, (1) the steady agglomeration of ever-larger particles from sub-micron particles up to tens of kilometer planetesimals, and (2) the direct formation of planetesimals from dust grains by dust settling toward the disk midplane and collapse by gravitational instability. Recent work, however, has advocated a combination approach combining turbulent and gravitational effects [1]–[3]. These new models are most efficient for particles that have already experienced some growth (up to a few–tens of cm in size) and tend to require enhancements in the local dust-to-gas ratio on the order of ~2–10 times over cosmic.

Meanwhile, clues to the history and processes of planetesimal formation in our solar system exist in the form of meteorites, comets, and asteroids. Recent models of the size distribution of objects in the main asteroid belt suggest that the initial population was very large with first objects of order ~100 km in size [4]. On the other hand, Cuzzi et al. [1] make the case that properties of primitive meteorites point to parent bodies that formed from cm and smaller particles of a mixture of ages and compositions over a period of a ~1–3 Myr. Furthermore, results from the Stardust mission and the return of samples from the Jupiter family comet 81P/Wild 2 suggest very early formation — perhaps before the primary accretion of primitive meteorite parent bodies [5] — following large scale radial mixing within the disk of grains formed at less than an AU from the Sun out to the Uranus–Neptune region [5]–[6].

Here we follow an approach similar to Youdin and Shu [2] to examine the particle-to-gas concentration in the disk evolving under the influence of gas drag and accretion. The early Solar nebula is a dynamically evolving environment and we include the effects of disk accretion and viscous spreading. We use the one-dimensional (1D) disk evolution and particle transport model originally developed to study the radial mixing of high-temperature solids within the disk [7]–[8], and follow the distribution of an ensemble of particles randomly seeded at $t = 0$ to match the $t = 0$ distribution of the disk-gas mass. We consider variations in particle size and in the initial-disk radial mass distribution.

Model and Preliminary Results:

We use a 1D (radial), vertically-isothermal model for the disk gas, including evolution by viscous spreading and accretion. We use a static temperature profile of $T = T_0 R^{-1/2}$, where $T = 280$K at 1 AU. We use a standard $\alpha$ parameterization for the disk viscosity, setting $\alpha = 10^{-2}$. The disk is initially compact with a starting mass of 0.03 $M_\odot$ and a $t = 0$ profile of

$$\Sigma_{g,t=0} = \frac{M_\odot}{3\pi \nu} \left(1 - \frac{R_{\text{in}}}{R}\right) \exp\left(-\frac{R}{R_d}\right),$$

where $R_{\text{in}}$ is the inner edge of our gridded disk space at 0.1 AU, and $R_d$ is the exponential fall-off radius. We consider both the nominal disk model and the most compact disk model of [8], using $R_d = 20$ AU and 5 AU, respectively.

We randomly seed an initial distribution of 10,000 particles to follow the $t = 0$ distribution of the disk-gas mass. We allow the particle ensemble to evolve under the influence of gas drag (in the Epstein drag regime) and the averaged radial accretion flow of the gas, which is largely inward, but produces an outward flowing region at the outer disk edge where the disk is expanding. As the disk evolves both gas and dust are lost inward onto the parent star. The fraction of gas and dust remaining in the disk with time are plotted in Fig. 1.

Figure 2 displays the change in the relative concentration of particles in our simulation using the nominal disk model and a particle size of 20 $\mu$m (density of 3 g cm$^{-3}$). In this case we find that the particles and gas maintain a roughly even mixture out to about 100 AU for the first 500,000 years of disk evolution. This time period corresponds to the peak in radial mixing and outward transport of high-temperature materials as modeled in [7]–[8]. However, between $t \sim 0.6$–1.5 Myr the dust-to-gas concentration is roughly doubled in the disk region out to ~25 AU due to the infall of particles from the thinning outer disk. According to the work of Youdin and Shu [2] this concentration factor may be marginally sufficient to induce the clumping of solids beyond the snow.
Here, the more rapid processing of the disk mass causes a slightly more rapid evolution of the particle-to-gas concentration, but the radial extent of the region of enhanced concentration is maintained for this particle size. Therefore, inward drift and disk accretion may be able to concentration particles sufficiently for the planetesimal formation mechanisms discussed in [1]–[3]. However, the evolution and loss of disk mass places constraints on how long such concentration enhancements may be maintained.