FRACTAL GROWTH AND RADIAL MIGRATION OF SOLIDS: THE ROLE OF POROSITY AND COMPACTION IN AN EVOLVING NEBULA. P. R. Estrada[1] and J. N. Cuzzi[2], [1] *Carl Sagan Center, SETI Institute, Mountain View CA 94043, USA, (Paul.R.Estrada@nasa.gov),* [2] *NASA Ames Research Center, MS 245-3, Moffett Field, CA 94043, USA..*

Introduction: The manner in which solids in the primordial nebula can proceed from sub-micron dust to larger bodies remains problematic due to the various barriers to growth grains may encounter. These include the bouncing (e.g., [1]), and fragmentation barriers (e.g., [2-4]) which, depending on nebula properties can nearly grind the process of incremental growth to a halt long before planetesimal sizes can be achieved. Moreover, a rather detrimental effect of the slowed growth rate of solid particles is that they cannot hope to overcome the radial drift barrier (often referred to as the "meter-sized" barrier) as they radially drift faster than they can grow (e.g., [5-6]).

One can bypass these issues by simply assuming that the nebula was not turbulent. Indeed, non turbulent nebulae can work under certain conditions [7]. But, this simple-minded view is inconsistent with observations such as, e.g., the formation ages of primitive meteorites [8-9], and the duration (and evolution) of "dusty-gas" protoplanetary nebulae [10]. Thus the evidence for mixing at least in the early nebular environment argues for some form of angular momentum transport. The most viable turbulence mechanism up until now remains MRI, but it cannot operate over large radial expanses of the disk (e.g., [11]). However, new mechanisms have been proposed that may operate under the right conditions ([12-13], see Umurhan et al., this conference).

Global models for solids evolution under moderately turbulent conditions were explored by [6] who found that growth to larger sizes ($\sim$ mm-cm-sized) in significant numbers is difficult, posing a problem for "leap frog" methods such as the streaming instability (SI, e.g., [14]) and turbulent concentration (TC, e.g., [15]) which require locally large solids-to-gas ratios (see Cuzzi et al., this conference). Here we consider that outside the snow line, icy particles are not only "stickier" than non-icy particles (reflected in larger strengths Q_*), but also growth, at least initially, is fractal where particles become quite porous and their radial drift velocities remain low (consistent with, e.g., [16]) because their Stokes numbers St remain low, allowing them to overcome the radial drift barrier. However, we expect that compaction will play a role increasing their drift rates. Here we explore models with fractal growth and an up-to-date compaction model [17] in order to assess the possible pathways to larger sizes, perhaps even planetesimals.

Brief Global Model Description: We employ a 1+1D global gas and solids evolution code that we have developed that simultaneously treats self-consistently the growth and radial drift of material of all sizes, accounts for vertical diffusion and settling of small grains, radial diffusion of dust and vapor phases of multiple species, and incorporates a self-consistent calculation of opacity and disk temperature which allows us to track the evaporation and condensation of various species at their respective evaporation fronts (EFs) as they are transported throughout the disk [6].

Results Assuming Solid Particle Growth: In Figure 1, we show a simulation of the protoplanetary disk over 2×10^5 years which includes the a full range of collisional dynamics (see [6]), with an initial disk mass of $0.2\ \mathrm{M}_\odot$ ($M_\odot$ is a solar mass), for $\alpha_t = 5\times10^{-4}$. The particle strengths Q_*, which determine the fragmentation size r_*, are compositionally dependent. The model includes several species in cosmic abundance, all of which are solid outside the water-ice EF located between $\sim 4-7$ AU. In the top panel, black curves depict particles sizes of interest (see caption). Inside the water ice EF, $r_L \gg r_M$, but these largest particles are few in number and are considered "lucky particles" arising from incremental growth (a PDF in collisional velocities is used to determine their destruction probabilities). The relatively constant St (blue) in the outer disk and the shape of the r_L curve is indicative of particles not overcoming the radial drift barrier (see [6]). In the bottom panel are plotted the fractional masses at two different times.

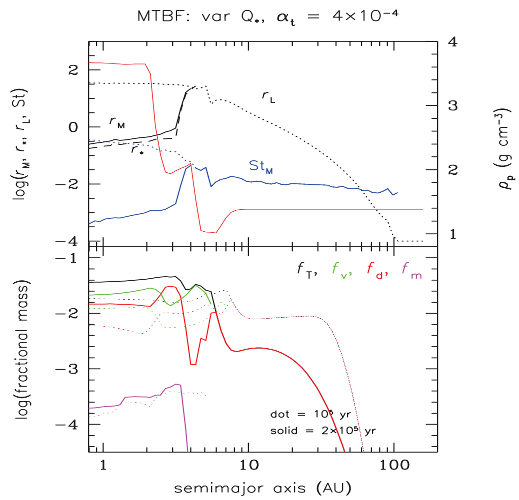

Figure 1: Model for solid particle growth that includes bouncing, fragmentation and mass transfer. Upper panel: Fragmentation radius r_* (dashed), particle radius that carries most of the mass r_M (solid black) and largest particle radius r_L (solid black curve). The Stokes numbers for r_M and r_L are shown in blue. Also plotted are the mean particle densities (red). lower panel: Fractional masses shown at two different times. From [6].

The key point here is that radial drift depletes the outer disk rather quickly, and enhances the inner nebula by as much as a factor of ~ 5 over the initial value. Longer simulations continue this trend, while the inner disk enhancements do not increase much further for this moderate value of α_t.

Simple Prescription for Fractal Growth: For a fractal dimension D, the growth of particles by low velocity collisions of monomers of mass m_0 and radius r_0 can be described by $m = m_0(r/r_0)^D$, $r = r_0(m/m_0)^{1/D}$, where $D = 3$ refers to the usual solid particle growth. For $D < 3$, the particle density decreases with radius and their porosities ϕ increase such that $\rho_p/\rho_0 = 1 - \phi = \psi^{-1}$, where ψ is the filling factor, and the monomer density $\rho_0 = 3m_0/4\pi r_0^3$. For $r > r_*$, we implement a crude compaction such that $\psi = \psi_*$ remains

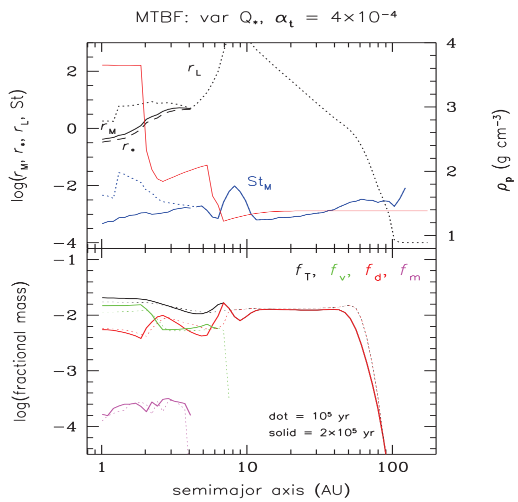

Figure 2: Complementary model to that shown in Fig. 1 for fractal growth. Description for the various curves are the same. Fractal growth leads to porous particles whose St in the outer disk are considerably lower. Their reduced drift rates thus allow them to overcome the radial drift barrier and much larger aggregate sizes are reached.

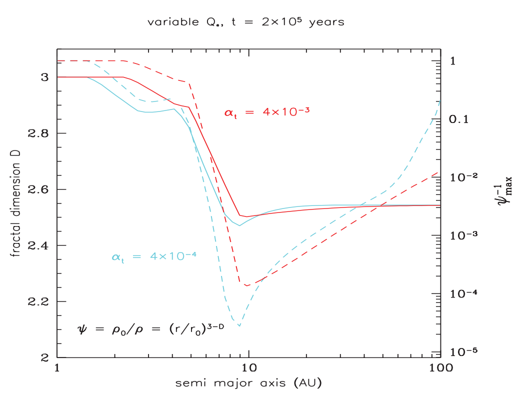

Figure 3: Plot of the mean fractal dimension D and maximum filling factor ψ for the simulation shown in Fig. 2 (cyan), as well as a case where the turbulence is an order of magnitude stronger (red). Only a crude compaction scheme is implemented (see text). Outside the snow line, as the region becomes rich in water, the stickiness of particles increases as D decreases.

constant, and $r = r_0(\psi_* m/m_0)^{1/3}$. Note that the particle stopping times $t_s \propto m_0^{2/D} m^{1-2/D}$. Thus in the extreme case of $D = 2$, aggregates drift at the same rate as a monomer.

Results Assuming Fractal Growth: In Figure 2, we show the complementary case in which we have included fractal growth as described above. The main points to take here is that outside the snowline, particles can grow to much larger sizes ($\sim$ 50 m outside the water ice EF) and in a much shorter time scale. Furthermore, the slow radial drift of solids allows the outer disk to retain its material. Thus, in the solid particle growth case ($D = 3$), the dust disk has become depleted significantly whereas with porous particles, the solids fraction remains similar to the initial value over the same time scale. As a consequence, however, the enhancements in the inner disk are muted because much less material has been transported there due to drift. This effect is further illustrated in Figure 3 where we show the D and ψ as a function of semi major axis (red curves) for the model in Fig. 2. As solids are evaporated at the EF and diffuse outwards, they condense outside the front making the particles icier there, and a feedback effect ensues decreasing D and increasing particle aggregate sizes.

This results suggests that progressively larger aggregates can be produced, especially just outside the snow line, while preventing the rapid loss of material to the inner disk. However, this may make it even more difficult to produce the large enhancements required (solids-to-gas ratio near unity), e.g., to satisfy the SI, unless a another mechanism is at work that is efficient at removing the gas. Whether radial drift of material is important or not has broad implications. For example, if radial drift is not important, one would predict a core for Jupiter (assuming it formed near the snow line) that is not very enriched in water relative to cosmic, whereas if drift is important, then Jupiter's core should be very much enhanced in water.

Recipe for Compaction: Our simulation above does not include realistic compaction. Collisional compaction can begin to occur when the collisional energy $E \gtrsim E_{roll}$ where E_{roll} is the energy needed to roll two monomers over an angle of 90^o [18]. Aggregates can also only withstand some external pressure before being compressed from the surrounding gas and self-gravity. For this talk, we will implement a more realistic model based on [17,19] that treat these compression effects.

Discussion: Our simplified fractal growth and compaction model in Figs. 2 and 3 demonstrates that fractal growth could play a very important role in allowing particle growth to overcome the radial drift barrier. We expect that implementing the more sophisticated compaction scheme above will provide us a more realistic constraint on particle growth, though we acknowledge that more experimental studies are required under, e.g., different circumstances of grain size, and mixed composition to better understand the compaction process. We will present simulations that incorporate these new physics, and will run longer duration nebula evolutions to see how the conditions within the disk change over time. Continued stalled growth might then argue for mechanisms that systematically remove gas from the disk.

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