PLANETESIMAL INITIAL MASS FUNCTIONS AND CREATION RATES UNDER TURBULENT CONCENTRATION USING SCALE-DEPENDENT CASCADES.

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Introduction: The initial accretion of primitive bodies from freely-floating nebula particles remains problematic. Traditional growth-by-sticking models in *turbulent* nebulae encounter a “meter-size barrier" due to both drift and destruction [1], or even a mm-to-cm-size “bouncing" barrier [2]. Recent suggestions have been made that some “lucky" particles might be able to outgrow the collision and/or drift barriers, and lead to so-called “streaming instabilities" or SI [3]. However, new full models of growth by sticking in the presence of radial drift [4] show that lucky particles (the largest particles, at the tail of the size distribution, that grow beyond the nominal fragmentation and drift barriers) are far too rare to lead to any collective effects such as streaming or gravitational instabilities.

Thus we need to focus on *typical* radii r_M which contain most of the mass. Our models of disks with weak-to-moderate turbulence [4,5], which include all the most recent experimental constraints on collisional growth, erosion, bouncing, and fragmentation, as well as radial drift, find that growth stalls quite generally at sizes r_M which are too small to settle into layers which are dense enough for any collective effects (streaming or gravitational instabilities) to arise.

Even if growth by sticking could somehow breach the nominal barriers (perhaps if the actual sticking or strength is larger than current estimates for pure ice or pure silicate, with specific grain sizes), turbulent nebulae present subsequent formidable obstacles to incremental growth through the 1-10km size range [6]. On the other hand, *nonturbulent* nebulae ($\alpha \ll 10^{-4}$) may form large asteroids too quickly to explain long spreads in formation times, or the dearth of melted asteroids (see, however, [7]). Thus, the intensity of nebula turbulence is critical to the entire process from the earliest stages of sticking, through the planetesimal formation stage.

Theoretical understanding of nebula turbulence is itself (it seems, perennially) in flux; recent models of MRI (magnetically-driven) turbulence favor low-or-no-turbulence environments [8], but purely hydrodynamic turbulence is making a comeback with two recently discovered mechanisms generating robust turbulence which do not rely on magnetic fields at all [9-11]. Nebula turbulence is described by its Reynolds number $Re = (L/\eta)^{4/3}$, where $L = H\alpha^{1/2}$ is the largest eddy scale, with eddy timescale $t_K \sim$ the orbit period, H is the nebula gas vertical scale height, α the turbulent viscosity parameter, and η is the smallest scale in turbulence (typically about 1km), with eddy turnover time $t_\eta \sim$ an hour. The mechanisms of [9-11] lead to $\alpha \sim$ a few times 10^{-4}. In the actual nebula, for values of α in this range, Re is far larger than any fully resolved numerical simulation can currently handle, so some physical arguments and models are needed to extend the results of numerical simulations to nebula conditions (see “Cascade models and thresholds.." below).

Our models indicate that because of limits to particle growth by sticking, the midplane solids density falls short of the SI threshold by a factor of about 100, at least until 4×10^5 years, a time when sizeable planetesimals are already known to be forming in the terrestrial planet region [4 (figure 20), 5]. If growth *were* possible, the midplane solids density would grow as $\sqrt{r_M}$ until the particle size is about a dm, and then linearly, so SI would require further particle growth by 3 orders of magnitude in the terrestrial planet region (to about 1m radius) for SI to occur for values of $\alpha \sim 10^{-4} - 10^{-3}$. The situation is *slightly* more favorable just outside the snowline at 4-7AU in these models, where “stickier" ice particles can grow to larger sizes. Work reported at this meeting [5] shows that particle porosity can vary these outcomes in significant ways.

Important clues regarding planetesimal formation include an apparent 100km diameter peak in the pre-depletion, pre-erosion mass distribution of asteroids [12]. Scenarios leading directly from independent nebula particulates to large objects of this size, which avoid the problematic m-km size range, could be called “leapfrog" scenarios of which SI is one [for a recent review see 13]. There is also a range of evidence suggesting that the parent bodies of the primitive chondrites, even at ∼100km diameter, were originally *homogeneous throughout* in particle size and in chemical and isotopic properties [13]. Acceptable “leapfrog" models of planetesimal formation must account for all of these observed properties.

Cascade models and thresholds together determine the planetesimal “IMF": The “leapfrog" approach we have pursued [14,13] envisions turbulent concentration (TC) of certain particle sizes in moderate turbulence, into dense zones that can lead directly to planetesimal formation with the properties noted above, given a range of initial parameters. The spatial distribution of particle concentration can be captured statistically by a *cascade model* [14], based on full 3D numerical simulations, which predicts the volume fractions of the nebula with different combinations of local solids mass density and gas vorticity. The *conditions* that *allow* planetesimal formation are functions of spatial scale, and we modeled them using estimates of “thresholds" which these local properties must satisfy. The combination of cascade-derived volume fractions, and crude-physics-based threshold estimates, leads to predictions of planetesimal *Initial Mass Functions* (IMFs) and formation rates [14]. Here we show how new understanding of the cascade affects planetesimal IMFs, and has implications about the initial sticking process.

Cascade models and scale dependence: Cascade models are well known in turbulence physics [14], and are based on the underlying cascade of energy from large scales to small. A cascade model calculates the fractional volume occupied by some value of a property (like particle concentration) by repetitive application of certain partition functions, envisioned as applying over a range of descending scales of the turbulence. Previously we assumed that these functions were scale-independent, but disagreement with results of others at higher Re led us to an in-depth study using even more highly resolved fluid simulations [15]. That work has been completed [16,17] and we find that the partition functions for particle concentration *are* scale dependent. Fortunately, the *dependence* itself *obeys a simple scaling* involving lengthscale and stopping time [16,17]. We have now run new, *level-dependent cascades* and combined them with our previous threshold estimates, to recalculate planetesimal IMFs. We find they differ significantly

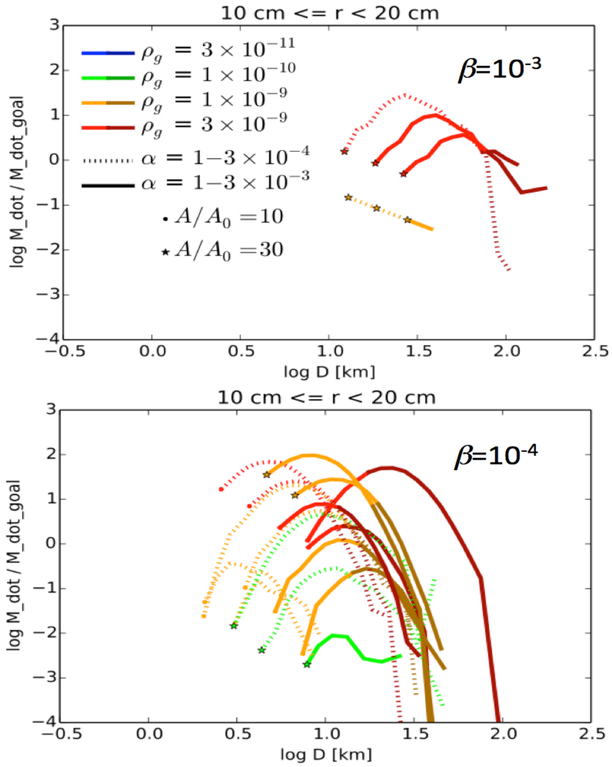

Figure 1: Planetesimal Initial Mass Functions (IMF's) as in [14], but using new level-dependent cascades. Top and bottom panels differ only by β, the headwind parameter. A/A_o, denoted by a symbol at the end of each curve, is the surface mass density ratio of solids to gas ($A_o = 10^{-2}$). Results are shown for a wide range of α and gas density ρ_g. The lighter colors along some part of some curves represent cases where the local solids mass density exceeds values where turbulence damping may occur, which we regard as questionable. Modal values of planetesimal diameter are in the 10-60km range.

from our previous results and have important implications.

Results and speculations: After re-running the full cascade models, using the new level-dependent partition functions (also called multipliers) of [16,17], while retaining the same threshold physics as [14], we find that sizeable planetesimals with a fairly well-defined size mode can still arise from turbulent concentration alone. **Figure 1** shows the mass creation rate $\dot{M}$ of planetesimals of a given diameter *relative to* the rate needed to provide the primordial asteroid belt mass, prior to dynamical depletion ($\dot{M}_{goal}$). That is, a value of $\dot{M}/\dot{M}_{goal} = 1$ provides the needed amount of planetesimal mass in the asteroid belt over the several Myr it appears to take, based on age-dating evidence. The strength of the background "headwind" parameter β encountered by the clumps could be lower in a solids-dominated midplane (bottom panel) than for an isolated particle (top panel)[14]. Several of the models provide more mass than needed, allowing for unmodeled inefficiencies. For instance, mass loading can damp turbulence [14], and this effect is not included in these cascades; lighter colors along some of the curves indicate where the underlying particle concentrations may be overestimates for this reason.

However, the nebula particle sizes to which these results refer are in the dm-radius range, and must reflect aggregates of chondrule-size particles in the terrestrial planet region. Contrary to our prior results [14], no 10-100km diameter planetesimals are formed directly from turbulent concentration of individual, free-floating, chondrule-size particles under nebula conditions close to nominal. This difference arises because of the previously unmodeled scale dependence of the multipliers, or partition functions. Rare objects of sub-km size may be formed, but these will be vulnerable to disruption by gravitational scattering [6].

In the light of figure 20 of [4] and corresponding results of [5], we can see a disconnect *at least* in the terrestrial planet region between the largest objects which the best current models can grow in weak to moderate turbulence by incremental sticking (mm), and the sizes needed for planetesimal formation to begin (dm). Particles of dm radius, which figure 1 shows *can* lead to *some* planetesimal formation by TC, are *still* too small to permit planetesimal formation by SI alone at least in the inner solar system [5, and above] unless $\alpha \ll 10^{-4}$.

However, the underlying conditions for planetesimal formation by SI and by TC seem to be converging, leaving open the possibility that the two mechanisms might work synergistically. We might call this hypothetical regime "clustering instability" - a *nonlinear* instability triggered in *SI stable* midplane layers of cm-dm size particles *by the fluctuations caused by TC*. Still, this scenario can only occur if sticking is slightly more robust than currently believed [5]. It has been shown [18] that aggregates of dust-rimmed, chondrule-sized particles may grow to perhaps mm-cm in radius, assuming pure silicates. If some amount of "sticky" organics or frost were present on the rims of silicate particles, or if grain size/shape effects played a role, perhaps dm-size aggregates may not be unrealistic.

Future work: damping of turbulence needs to be included, and the simple "thresholds" of [14] need to be replaced by actual simulations. Experimental work on sticking and strength for aggregates of mixed media, including refractory organic materials and ice rims, could be conducted. Evidence for aggregates could be sought in the most primitive chondrites.

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