PLANETESIMAL FORMATION IN THE PROTOPLANETARY DISK BY TURBULENT CLUSTERING.
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Introduction: The formation of the first sizeable primitive bodies in the Solar System’s protoplanetary disk is still an active research topic, and many questions remain unanswered. An emerging consensus is that during planetesimal formation the solar nebula was weakly turbulent, likely with turbulence levels $-10^{-5} < \alpha < 10^{-3}$ [1]. Under such conditions, traditional growth-by-sticking models starting with sub-μm dust particles encounter various growth barriers including fragmentation, drift, and erosion/fragmentation [2,3,4]. Currently accepted limits of growth via sticking also reflect a mm-to-cm size bouncing barrier [5]. Collective effects have been proposed that may “leapfrog” over these growth barriers and form large, 10-100 km size objects directly from small particles [6]. The most popular of these, the streaming instability, has recently been found to be suppressed or limited by nebula turbulence in the plausible range [7,8], for particles with sizes that can plausibly grow in such levels of turbulence [5]. This motivates a closer look at alternate planetesimal formation mechanisms that can function under turbulent conditions.

Turbulent Clustering (TC): In this work we consider the spatial variations of particle densities caused by turbulence. In a turbulent flow, particles too large to be completely trapped to the gas motions are not distributed homogeneously but tend to cluster in regions of high strain and low vorticity. This is sometimes described as being “spun out of eddies”, but the physics is more subtle. Depending on particle size (or actually the particle’s aerodynamic stopping time) and nebula conditions, particle-rich regions on scales of hundreds to thousands of km may form with some (small) probability, which are dense enough to sediment under their own gravity directly into planetesimals [9]. However, the determination of these probabilities by the “cascade” formulation used by [9] was incorrect [10]. A cascade model calculates the fractional volume occupied by some value of (e.g.) particle concentration, by repetitive application of certain partition functions, applied over a range of descending scales of the turbulence.

We have now re-modeled this clustering process of planetesimal formation [11,12] using a new cascade model which correctly predicts the probability distribution function (PDF) of particle concentration and flow vorticity in the protoplanetary nebula. Our new cascade model is based on an in-depth study [13] using highly resolved fluid simulations [14]. [13] found that the partition functions for particle concentration obey a simple scaling in the inertial range of turbulence, involving length scale and stopping time, and were predictable.

Results: We report two primary conclusions of [11].

(a) The newly calculated Particle Concentration PDFs are by themselves of interest as they help understand the formation environment of chondrules (by whatever heating mechanism), since the oxidation state of the ferromagnesian silicates that result, as manifested in their Mg/Fe ratios, is a sensitive indicator of the local solids/gas ratio. Figure 1 shows the cumulative particle fractions, as functions of enhancement, in regions with concentrations above some value, for two particle sizes. We imagine that the several-cm size objects are aggregates of individual chondrule precursors, that become disaggregated in the formation process. A combination of these concentrations, at least for the larger particles, combined with vertical settling, can approach typical enhancements in chondrule formation regions [15].

(b) Planetesimal formation occurs in regions with much smaller volume fractions. In order to derive initial mass functions (IMFs) and formation rates of planetesimals, we combine the new cascade-based probabilities with simple, physics-based thresholds to determine the conditions under which dense zones can successfully undergo gravitational sedimentation, as in [9]. We derive new planetesimal production rates and IMFs, both for the asteroid-forming region in the inner nebula and for the outer nebula region where Kuiper belt objects (KBOs) are believed to have formed.

One notable characteristic of our models is that the IMF of planetesimal sizes has a distinct mode — a peak at some diameter — rather than being a powerlaw. The distribution of "fossil" asteroids shows such a mode [9], but that of the KBOs is less well known.

Our current models [11] show that under reasonable assumptions for disk turbulence and possible nebula conditions, ~10-100 km diameter objects can be formed directly from cm-to-dm size particles by this physics (Figure 2). Such initial particles are significantly larger than chondrules, and we have suggested the possibility that chondrules (or chondrule precursors) form aggregates [16]. Although such particle sizes may be slightly larger than achievable in current models of growth by sticking [5], the differences are not large, and better understanding of the collision physics in turbulence may alleviate some of these issues [12].

In the outer nebula, particles in the few-mm to cm range are needed to form sizable planetesimals, more
compatible with current understanding of dust coagulation and sticking strength [2,5,6].

Generally speaking, in the new models, larger particles form larger planetesimals, and planetesimals are slightly larger for stronger turbulence (larger $\alpha$ values) but are produced at a lower rate. The smallest particles for which our model produces planetesimals (at our nominal thresholds) have a Stokes number $S_{\text{St}}$ of 0.01 ($S_{\text{St}}$ is the ratio of the particle’s aerodynamic stopping time to the characteristic time of the largest eddy in the turbulence). For example, individual sub-mm chondrules may have $S_{\text{St}}=10^{-4}$ or so.

The current standalone turbulent clustering model can only provide a crude approximation to a full, 3D model including self-gravity and “peloton” or other collective effects associated with streaming instabilities. It is possible that a combination of the two effects would be more powerful than either acting alone [16]. Other interesting avenues of future research may include the hierarchical fragmentation or bifurcation of these rotating, but strengthless, dense clumps [17].


Figure 1. Cumulative fraction $F_p(>C)$ of particles lying in regions where the concentration is larger than some value $C$, for 1.5cm (top) and 1mm (bottom) radius particles in a nebula with $F_p = 10$ (10x enhancement in the gas density compared to a Minimum-mass solar nebula) at 3 AU and two different values of the turbulent $\alpha$. In this context, concentration refers to the ratio of the local particle density (averaged on some length scale $l$) to its global average, but does not account for any other enhancement effects such as settling towards the midplane, or various kinds of radial enhancement.

Figure 2. Model results for the inner nebula, showing the peak of the planetesimal IMF, $D_{\text{peak}}$, and the rate of formation, $M_{\text{peak}}$, relative to the expected rate, $M_{\text{goal}}$, for a range of nebula parameters and particle sizes. The panels show results for two values of $\alpha$, while colors, symbol shapes and fill styles denote gas density factor $F_p$, enhancement $A/A_0$ in the abundance of solids (relative to a cosmic solids-to-gas ratio of 0.01), and a scale factor for the headwind parameter, $F_w$. The size of the symbols scales with the particle radius $r_p$. Symbols that have been greyed out in the legend denote parameters that did not produce results in the plot range.