PLANETESIMAL FORMATION IN THE OUTER NEBULA IN THE PRESENCE OF TURBULENCE.
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Introduction: Many questions remain unanswered in our understanding of how the very first planetesimals formed in the Solar System's protoplanetary disk. In light of the recent close encounter of NASA's *New Horizons* spacecraft with the Kuiper belt object (KBO) 2014 MU_{69}, informally named *Ultima Thule* [1], we here consider the formation of such objects in the outer nebula.

Consensus is building that during planetesimal formation the solar nebula was weakly turbulent with turbulence levels ~ $10^{-5}<\alpha<10^{-3}$, and this has important consequences [2]. In traditional growth-by-sticking models sub-μm dust particles grow by coagulation to ever larger particles until they begin to gravitationally interact [3]. In a turbulent medium, however, this process encounters various barriers to growth including: fragmentation, drift, and erosion/fragmentation [4,5,6]. Currently accepted limits of growth via-sticking also pose a mm-to-cm size bouncing barrier [7]. However, several collective effects may "leapfrog" over these growth barriers and form large, 10-100km sized objects directly from small particles [8].

Turbulent Clustering (TC): A scenario we have pursued is based on the fact that in a turbulent flow inertial particles are not distributed homogeneously but, instead, cluster in regions of high strain and low vorticity. Under the right conditions, such zones may become both large and dense enough to sediment under their own gravity to form planetesimals directly [9].

The turbulent clustering or preferential concentration effect is particle-size dependent, and specifically depends on the particles' aerodynamic stopping time t_s or Stokes number $St_L = t_s / t_L$ where t_L is the eddy time of the largest eddy in the turbulence. We have modeled this concentration or clustering process with a so-called "cascade" model which allows us to predict the probability distribution function (PDF) of particle concentration and flow vorticity in the protoplanetary nebula [9,10]. The 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 [9], but disagreement with results of others at higher Reynolds numbers [11] led us to an in-depth study using even more highly resolved fluid simulations [12]. That work has found that the partition functions for particle concentration are scale dependent but obeys a simple scaling involving lengthscale and stopping time [10].

Thresholds and initial mass function (IMF): Somewhat crude but physics-based thresholds have been derived to determine the conditions under which dense zones can successfully undergo gravitational collapse [9]. We retain the threshold methodology from [9] and have derived new planetesimal production rates and IMFs using the new cascade model. One notable characteristic of our model is that the IMF of planetesimal masses has a distinct mode - a peak in the mass distribution 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 determined.

Results and Speculation: The most refined models show that under reasonable assumptions for disk turbulence and a range of possible nebula conditions, we can produce ~10-100km objects in the outer nebula from particles in the sub-cm to several-cm range (Figure 1), right at the limit of our current understanding of dust coagulation and the sticking strength [5]. Objects are slightly larger for stronger turbulence (larger α values) but are produced at a lower rate. The smallest Stokes number for which the model produced planetesimals was 0.01.

Results for the inner nebula are similar but typically require larger initial particle sizes in the several cm to dm range. This is much larger than the size of chondrules and currently accepted limits of sticking [7]. For the TC scenario to work in the inner nebula, some growth beyond chondrules is necessary. We have suggested the possibility that chondrules may have formed aggregates [13].

The size range of planetesimals produced by the model can be understood in simple physical terms. On the one hand, objects much smaller than ~10km diameter are not possible in this model since such clusters would be disrupted by the ram pressure between the solids and the nebula gas which orbits at sub-Keplerian speeds. On the other hand, objects larger than a few 100km are not possible either since the turbulent clustering process stalls at high mass-loading (high solids to gas density) which limits the total amount of solids in a dense zone.

Lastly, observations of cold classical KBOs appear to indicate that a large fraction of them are binaries [14]. We note that in our simplified formation models entire dense zones are assumed to collapse, but whether this collapse results in single or multiple objects remains to be determined. It seems plausible, for instance, that variations in the particle concentration in dense zones could cause multiple objects to form, although this can only be answered by numerical simulations, see further discussion in [15].

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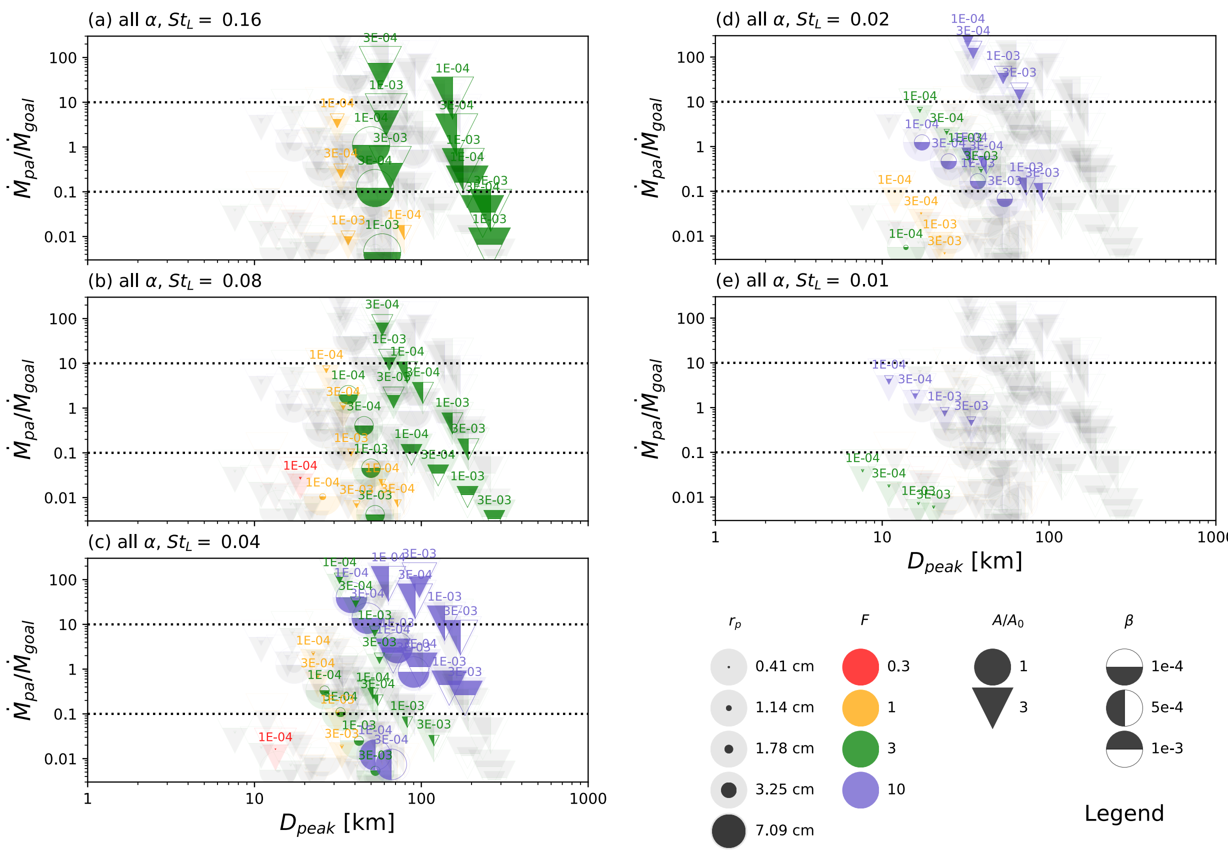

Figure 1: Model results for the outer nebula. The symbols show the peak of the planetesimal size distribution, D_{peak}, vs the rate of formation (mass per time) relative to the expected rate for a range of possible nebula parameters and particle sizes. Each panel highlights in color particles of a given Stokes number (which corresponds to different physical sizes depending on nebula conditions) while the grayed out symbols show all other Stokes numbers. Colors, shapes and symbol fillings denote gas density enhancement factor F (relative to MMSN), solid abundance enhancement factor A/A_0 (relative to a nominal value of 0.01 solids to gas ratio), and headwind parameter β, respectively. The size of the symbols scales with the particle size. Results for particles up to 10 cm radius are shown. Numbers next to each symbol indicate the turbulence intensity (α value). The specific results shown here are for planetesimal formation between 16 and 30 AU where KBO may have formed before migrating further out, but preliminary tests indicate that results don't change all that much for formation distances further out in the nebula.