Primary Accretion: The Birth Population in the Asteroid and KBO regions

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Introduction: The initial creation of today's primitive bodies (asteroids, KBOs, etc) from freely-floating nebula particles remains problematic. Traditional incremental growth models (steady growth by sticking) encounter a formidable meter-size barrier due to rapid removal by drift and destructive collisions in turbulent nebulae, but nonturbulent nebulae incur an embarassment of riches in forming large asteroids too quickly by this path to satisfy both long spreads in formation times required to satisfy radiometric age-dating and thermal evolution constraints [1,2]. Primitive bodies in the outer solar system pose their own set of puzzles: they seem too large and too abundant to have grown in place by traditional incremental accretion unless the surface mass density were larger than currently observed [3,4,5].

A scenario has been advanced to help resolve some of these puzzles in the asteroid belt region, while also explaining the peculiar and characteristic chondrule-dominated fabric of most primitive meteorites [6,7; see below]. A prediction of this scenario is a minimum threshold size for primary bodies, required to allow their precursor dense particle clumps to survive destruction by the differentially moving gas; this minimum size (10-50km radius, depending on parameters) is intriguingly close to the proposed dominance of the primordial asteroid belt by 100km diameter objects [8]. An alternate scenario has been advanced which also operates in turbulence and produces large planetesimals, but starts with boulder-sized objects rather than with chondrule-sized objects [9,10]. Here we further explore the scenario of [7] as to its predictions for the primary accretion birth function in both the inner and outer solar system, and compare predictions with asteroid and KBO size distributions.

Turbulent concentration (TC) and primary accretion: In the scenario described in [7], turbulence selects aerodynamically sorted particles for concentration by large factors (see [11] for selection physics and preferred particle sizes as a function of nebula parameters). The predicted size distributions are a good match to chondrule size distributions [11,12]. If outer nebula primary bodies formed from porous grain aggregates, this "fingerprint" might be hard to detect in the final, compacted bodies. The outcome of TC can be captured statistically in a *cascade model* [7] which predicts probability distribution functions $P(\Phi, S)$ for dense clumps, where Φ is the particle/gas mass loading factor and S is the local enstrophy ω^2, with ω a local vorticity or eddy frequency. $P(\Phi, S)$ is a function of level N in a cascade to smaller scales, where N maps into a nebula lengthscale l (see below). Preliminary results presented in [6], reproduced schematically in figure 1, show how the model predictions of $P(\Phi, S)$ can be combined with two different particle mass loading thresholds to assess the formation probability of primary bodies by this path. The thresholds Φ_1 and Φ_2 are associated with self-gravity overcoming (a) local coriolis force, and (b) ram pressure disruption by the differentially rotating gas. Application of the Φ_2 threshold by [7] led to a rough similarity with a "typical" primordial mass [8] mentioned above. Here we report progress in refining these thresholds and exploring their dependence on distance from the sun, to determine if the scenario is capable of explaining primary accretion of both asteroids and TNOs.

Model predictions as a function of various parameters: Expressions for $\Phi_1(S)$ and Φ_2 can be written in terms of the radial variation of their constituent parameters. The primary threshold physics involves the product $\Phi_2 l$, where l is a clump diameter, rather than Φ_2 alone [7]. In assessing the "birth function" for primary accretion, allowance must be made for the values of probability $P(\Phi, S)$ as a function of l and thus $M = \Phi\rho_g l^3/6\pi$; the cascade model (which has its own uncertainties) gives $l = H\alpha^{1/2}2^{-N/3}$ [7], where H is the nebula gas vertical scale height and α is the standard turbulent intensity parameter. Results can be generalized to a simple function Φ_2 which depends on distance from the sun, gas density, radial pressure gradient, α, and N. The physics of turbulence damping by concentrated particles leads to saturation of Φ at roughly 100 [7]. Thus, values of $\Phi_2 > 100$ are prohibitive to primary accretion and smaller values are more permissive (occur at larger values of $P(\Phi, S)$). The largest accessible values of $P(\Phi, S)$ occur near where $\Phi = \Phi_1(S) = \Phi_2$ (figure 1) and thus a typical mass might be $M^*(l(\alpha, N)) = \Phi_2\rho_g l^3/6\pi$, although other masses are also being formed. To ascertain the *most common* or *characteristic* mass, we need to assess $P(\Phi, S)$ for a range of N (or l). Results will be presented for inner and outer solar system conditions.

Sizes of Primitive Bodies: Figure 2 shows a histogram of (large) asteroid sizes, created by binning the numbers of asteroids in the IRAS diameter-albedo file [13] into bins differing by a factor of two in mass. There are dozens of objects in all of the bins smaller than 150 km diameter, so the peak appears to be real. Objects

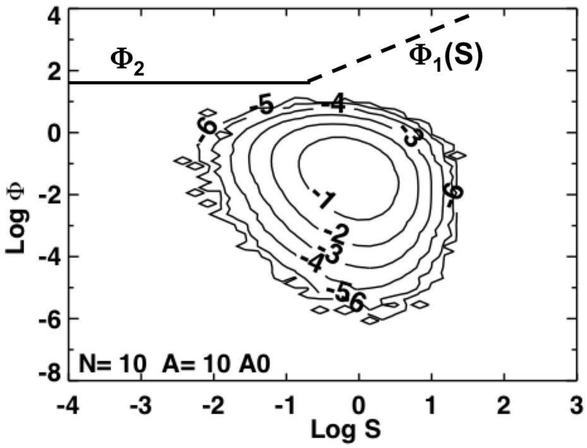

Figure 1: Occurrence probability or volume density $P(\Phi, S)$ (contours) from the cascade model ([7]). Clumps in the range of (Φ,S) above the boundary defined by Φ_2 and $\Phi_1(S)$ (which vary with N and nebula parameters) can survive to become primary bodies. Their mass is determined by the local solid density $\Phi_2\rho_g$ and their lengthscale l, which is a function of nebula α, semimajor axis, and cascade level N. Plots like this can be constructed for a range of cascade levels N, and the range of contours expanded by averaging. The small values of volume density are not in an implausible range (see [6]). The relative abundance of objects of mass $M^* = \Phi_2\rho_g l^3/6\pi$ will then provide the birth function of primary objects. For example, the case shown ($N = 10, l \sim 3 \times 10^4$km) yields primary body diameter of 100km for $\alpha = 3 \times 10^{-4}$, pressure gradient parameter $\beta = 10^{-3}$, and $\rho_g = 10^{-9}$ g cm^{-3}at 2.5AU. Parameters are poorly known of course, and [7] noted a range of primary body diameters between 20-200 km.

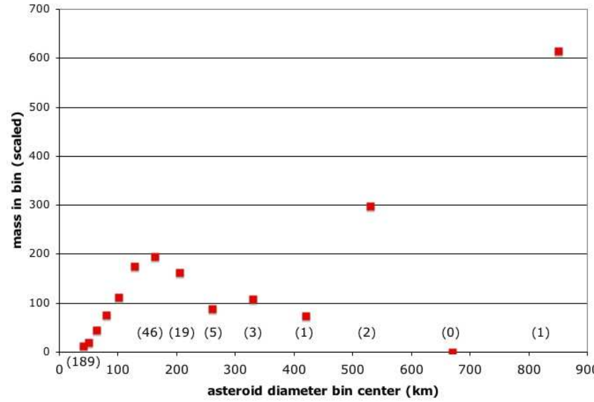

Figure 2: A rendition of the mass histogram of large asteroids, determined by binning asteroid diameters [13] into bins which differ in central mass by factors of two, ranging downward from Ceres (the largest bin). The points are labeled by the number of objects in each bin. There seems to be evidence for a population with typical diameter slightly larger than 100km. Bottke et al ([8]) have argued that objects of this size are impervious to collisional erosion over the age of the solar system and may represent a primordial population.

of these sizes are not seriously affected by collisional destruction over the age of the solar system [8]. This mass peak is distinct from the mass peak represented by Ceres (most of the mass of the current asteroid belt lies in its largest members). Bins larger than 300km have few members so their statistics are uncertain. Because it is hard to see how the 150km mass peak could have derived from an initial population of still larger primary bodies, we suspect it somehow manifests a signal of primary accretion. The situation is less clear for the TNO population; recent results suggest mass peaks in the 60-100km diameter range [14,15,16] - perhaps marginally consistent with simple erosional processing at weak strengths [17,18] or perhaps a signature of primary accretion (19]).

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