TOWARDS A SCENARIO FOR PRIMARY ACCRETION OF PRIMITIVE BODIES.
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Introduction: In [1], we identified a process whereby chondrule-sized particles are sorted by nebula gas turbulence into narrow size distributions based on their aerodynamic stopping time t_S, and locally concentrated by orders of magnitude relative to the average particle mass density. We speculated that these high degrees of mass concentration led directly or indirectly to primary accretion of primitive bodies directly from these size-sorted components – perhaps helping us understand the properties of primitive chondrites (see also [2]). Key open issues include (a) the local damping of nebula turbulence *by* particle mass loading, which tends to limit the degree of concentration; (b) the generally unrealized difficulty of collapsing even extremely dense clumps of small particles under self-gravity, and (c) the 1-2 Myr duration of planetesimal formation, suggesting a temporally extended, and thus inefficient, process. We have taken several steps towards understanding these issues, and here sketch the outline of a scenario that might lead to observed kinds of primitive bodies on observed timescales.

The Cascade Model: To address issue (a), the role of particle mass loading, and to obtain the occurrence statistics of clumps having the density and size needed to address issues (b) and (c), we developed a *cascade model* which simultaneously treats the local particle mass density C and the local vorticity ω (expressed as enstrophy $S = \omega^2$). Work by ourselves and others [3] has shown that regions of high particle mass density avoid fluid zones of high enstrophy. A cascade model (see figure 1) mimics the statistics of a full 3D fluid model by using statistically defined multipliers m

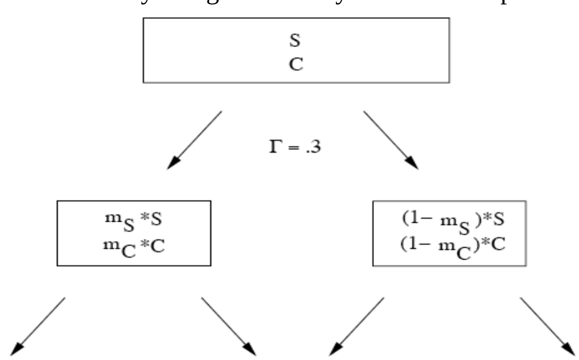

Figure 1: Schematic showing one bifurcation of a cascade model in which the properties C and S are sequentially repartitioned into smaller parcels or sub-eddies using the statistically determined multipliers m_S and m_C. The parameter Γ accounts for the spatial anticorrelation of C with S ([4]).

with some probability distribution (PDF) $p(m)$. Both C and S have their own set of $p(m)$. In [4], we showed that $p(m)$ is actually also a function of C: *i.e.*, $p(m|C)$ (figure 2). Here, $C = \rho_p/\rho_g$, the ratio of particle mass density to gas mass density. The multiplier PDFs can be very well fit by analytical functions of a single parameter; narrower $p(m|C)$ - peaked at 0.5 - lead to unchanging C and S, because partitioning 50% of C or S into a partition half the original size results in no change in its local value. In this limit turbulent concentration reaches an asymptote. Mass loading has very little effect until $C > 10$, but when $C > 100$, multiplier PDFs become so narrow that little further increase in local C is possible.

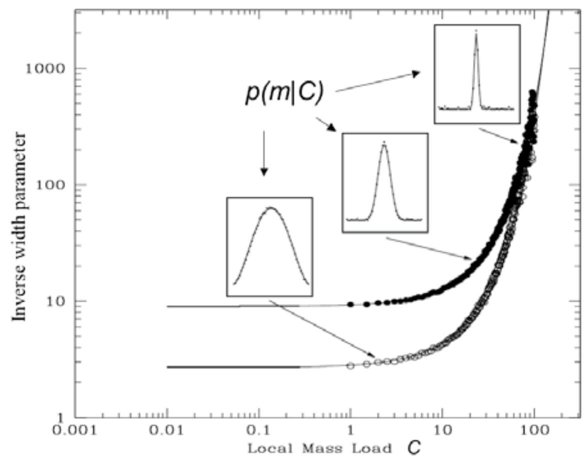

Figure 2: The PDFs of m_S and m_C (inserts) vary with local mass loading C. The PDFs can be described by an inverse width parameter and become narrower as C increases. Increasingly narrow PDFs result in an asymptotic limit for C of approximately 100.

We then used these *conditioned multiplier* PDFs (figure 2) in cascade models to obtain the *global joint* PDFs of particle concentration and local fluid vorticity, $P(C,S)$. Each $P(C,S)$ is associated with some number of bifurcations, which is in turn identified with some spatial scale in a broad inertial range of scales at some nebula Reynolds number (or viscosity parameter α). Cascade model PDFs were compared with actual DNS simulations over their overlap range, and good agreement was found. For details the reader is referred to [4]. Cascade models were then generated for much larger Reynolds numbers, comparable to plausible nebula values; typical results are shown in figure 4 below. The contours of $P(C,S)CS$ are effectively volume density of the nebula occupied by particle clumps of the given mass loading, at the given local vorticity. Naturally, most of the volume is at low (canonical) mass loading and normalized S~1. The various straight lines represent different stability or instability thresholds, above which dense clumps become bound objects and can evolve towards actual planetesimals.

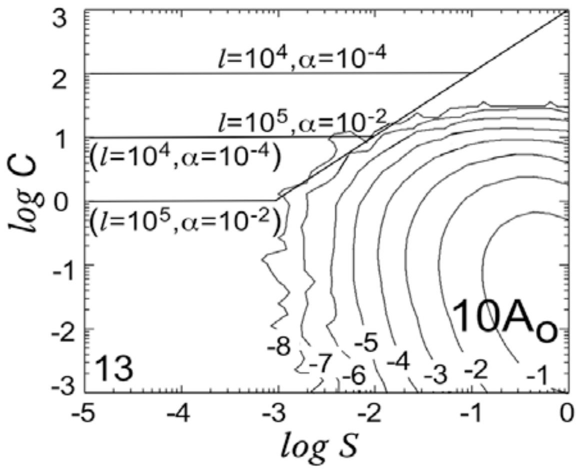

Figure 4: Typical PDFs expressed as the product *P(C,S)CS*, the volume density for a region having *(C,S)*, in a nebula where the average background mass density of solids is enhanced by a factor of 10 over the canonical nebula value A_o (for purposes of illustration). The diagonal line is the traditional gravitational instability threshold. The horizontal lines are stability thresholds against disruption by nebula headwinds, functions of the diameter of the clump *l* and the nebula turbulent intensity α.

Stability and instability of dense regions: G*ravitational instabilities* (GI) have long been advocated in the context of a dense nebula midplane [5-8]; even mild nebula turbulence precludes sufficient particle settling for GI to occur near the midplane as usually envisioned, but it is in principle applicable *wherever* dense zones form. GI is usually thought to lead to a rapid collapse of a dense region on the dynamical time $t_G = (G\rho_p)^{-1/2}$, where G is the gravitational constant, typically on the order of an orbit period, faster than the constituents of the clump can be dispersed. This threshold is shown by the diagonal line in figure 3.

However, this is *not the case* in the chondrule-sized particle regime (see [2] for a more detailed discussion). It was first shown by [6], but apparently neglected by all subsequent workers until we recently encountered it in our own numerical modeling work, that dense clumps in which $t_s << t_G$ *cannot* collapse on the dynamical timescale, but can only sediment towards their mutual center on a much longer timescale. This is because the particles, in attempting to collapse, compress the entrained gas until it acquires an outward pressure gradient that stalls the collapse of both the gas and the entrained particles. Chondrule clumps are squarely in this regime; thus while the dense clump does remain bound ([6] called this state an "incompressible mode"), it remains vulnerable to processes of disruption for the hundreds of orbits required for slow inward sedimentation to occur.

Indeed there is one obvious disruptive process which acts on the several-orbit timescale: the ram pressure due to the differentially-rotating nebula gas. For an object with no internal strength, this relative velocity of $\Delta V \sim \eta V_K$, where $\eta \sim 10^{-3}$, is quite potent and capable of disrupting dense clumps after less than 2 orbits (figure 5).

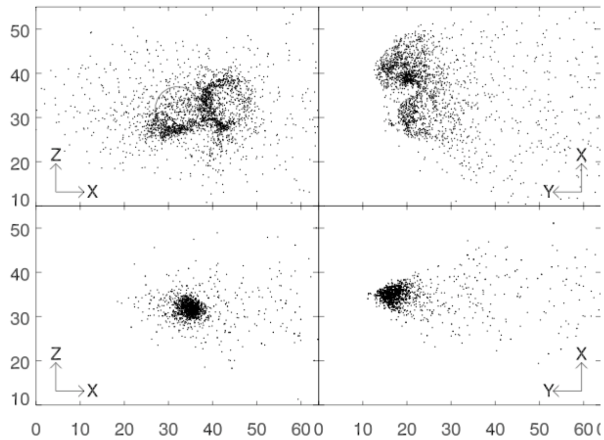

Figure 5: Front (left pair) and side (right pair) views of particle clumps experiencing nebula gas ram pressure without (top pair) and with (bottom pair) the benefit of their own self-gravity, after 1.75 orbits. The circle in the top left panel shows the initial diameter of the clump. The nongravitating clump is being disrupted, while the gravitating clump is retaining its integrity and slowly shrinking even while spalling off a small number of particles.

Figure 5 shows clumps with a combination of parameters which are indicated to be transitional by a simple analytical model we have developed, which is analogous to the *Weber number* criterion governing the stability of fluid drops settling through less dense media and is of the form $C\ l > \eta a(\rho_R/We^*\rho_g)^{1/2}$, where a is the distance from the Sun, ρ_R and ρ_g are the Roche density and local gas density, and *We** is some critical constant of order unity (to be determined numerically). In the traditional application (*ie.,* raindrops) the restoring force which stabilizes the drop against ram pressure is surface tension; in our case it is self gravity. Thus it appears that issues (a) and (b) of the Introduction can both be understood. Whether, under the $C <$ 100 constraint set by mass loading, clumps having large enough *size l* to survive ram pressure in regions characterized by η occur sufficiently often to satisfy issue (c) of the introduction, will be established using results such as shown in figure 4. Preliminary indications are promising but considerable work remains.

[1] Cuzzi J.N. *et al.* 2001 *ApJ, 546,* 496; [2] Cuzzi J.N. and S.J. Weidenschilling 2006, in "Meteorites and the Early Solar System II"; D. Lauretta and H. McSween eds.; [3] Fessler J.R., J.D. Kulick, and J.K. Eaton 1994, *Phys. Fluids 6,* 3742; [4] Hogan R.C. and J.N. Cuzzi 2007, *Phys. Rev. E.,* in review; [5] Goldreich P.M. and W.R. Ward 1973 *ApJ, 183,* 1051; [6] Sekiya M. 1983, *Prog. Theor. Phys. 69*, 1116; [7] Sekiya M. 1998 *Icarus, 133*, 298; [8] Youdin A and F. H. Shu 2002 *ApJ, 580,* 494