AGGREGATES: THE FUNDAMENTAL BUILDING BLOCKS OF PLANETESIMALS?

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Introduction: The initial accretion of primitive asteroids (meteorite parent bodies) from freely-floating nebula particles remains problematic. Traditional growth-by-sticking models in turbulent nebulae encounter a formidable “meter-size barrier” due to both drift and destruction, or even a mm-to-cm-size “bouncing” barrier \([1]\). Even if growth by sticking could somehow breach these barriers (perhaps if the actual sticking or strength is larger than current estimates, which are based on pure ice or pure silicate), turbulent nebulae present further obstacles through the 1-10km size range \([2]\). On the other hand, nonturbulent nebulae form large asteroids too quickly to explain long spreads in formation times, or the dearth of melted asteroids \([1]\). Thus, the intensity of nebula turbulence (or “\(\alpha\)” is critical to the entire process. Theoretical understanding of nebula turbulence continues to evolve; while recent models of MRI (magnetically-driven) turbulence favor low-or-no-turbulence environments \([3]\), purely hydrodynamic turbulence is making a comeback with three recently discovered mechanisms generating turbulence of moderate \(\alpha\) which do not rely on magnetic fields at all \([4-7]\).

Leapfrog models and planetesimal “IMFs”: An important observational clue regarding planetesimal formation is an apparent 100km diameter peak in the pre-depletion, preerosion mass distribution of asteroids \([8]\); we call direct transformations of small nebula particles into large objects of this size, which avoid the problematic m-km size range, “leapfrog” scenarios (for a recent review see \([1]\)). Unfortunately, new models show that “lucky” particles (the largest particles at the tail of the size distribution, that grow by sticking somewhat beyond the nominal fragmentation and drift barriers) are far too rare to trigger leapfrog processes such as gravitational “streaming” instabilities (SI) alone \([9]\), under conditions of weak-to-moderate nebula turbulence. We found recently that another leapfrog hypothesis (turbulent concentration or TC alone) also fails to produce 100km planetesimals unless its building blocks are considerably larger (several cm to dm radius) than individual chondrules \([10,11]\). We suggested that a combination of TC and SI working together - a “Clustering Instability” or CI (this could be thought of as a triggered or nonlinear instability) - might lead to the observed planetesimal IMF under conditions of moderate turbulence \([10,11]\).

The cm-dm nebula particle sizes upon which this process acts must reflect aggregates containing \(10^3 \sim 10^5\) or more chondrule-size particles. However, model aggregates of dustrimmed, chondrule-sized particles only grow to some mm-cm in radius, assuming sticking and strength properties of pure silicates \([12]\). Thus, growth by sticking must be slightly more robust than is generally accepted if dm-dm aggregates are to grow. It may be that “sticky” organics or frost on the rims of particles might aid in sticking. We suggested that some effort be devoted to searching for aggregates of chondrules that might have grown and remained together in the nebula, wandering around for some time before being accreted by a process such as the hypothetical CI \([10,11]\).

NWA5717: evidence for chondrule aggregates? This

![Figure 1: A 13x15 cm section of NWA5717 [14], a different slab from the same meteorite analyzed by [13] who first described the two different lithologies (a) and (b). We suggest the light clumps (b) may be surviving aggregates of chondrules whose chemical and isotopic properties are very different from those in similar aggregates (not so easily distinguished) of the more plentiful dark material (a). Our hypothesis is that chondrules of like properties formed and aggregated by sticking in regions of different chemical and isotopic composition, before the aggregates were mixed together into some region where they were incorporated into a parent body, perhaps by a “leapfrog” process [10,11]. Further study of this chondrite and others like it may show (or preclude) that chondrules can grow by sticking into clusters several cm across, larger than now generally expected.](https://ntrs.nasa.gov/search.jsp?R=20170001704)
difference might be nebular in origin, or might be explained by
mild parent body aqueous alteration (the more altered “dark”
lithology is isotopically “heavier”). For this to be the case,
it would require a very small amount of “heavy” water ice to
have been localized in the dark lithology (a) and absent from the
“light” lithology. A quantitative assessment of this possibility
has not yet been done. Even more significant perhaps is the
very different Mg/Fe ratio in the chondrule cores (but not rims)
between the dark lithology (Fa10-20) and the light lithology
(Fa< 3) [13]. Neither of the lithologies resembles common chondrite
groups, but they do bear some resemblance to other
ungrouped, metal-poor chondrites [13].

Collisional growth of aggregates:
The physics of collision rates and outcomes involves the so-called “kernel” \( K = n^2(r)\pi r^2 \nu_{rel}(r) \), where \( r \) is the particle radius, \( n \) is its lo-
cal volume density, and \( \nu_{rel}(r) \) is a typical relative velocity
at collision. Some typical global average \( n \) and \( \nu_{rel}(r) \) are
usually adopted [9,15] which neglect subtle effects of particle clus-
tering in turbulence. Yet, the theory of turbulent concentra-
tion (TC; [1,16]) already anticipates that the particle density
can vary strongly from place to place because of the way par-
ticles of different size respond to turbulence, and the collision
velocity does too. One can ratio the “observed” kernel from
very large numerical simulations to the “naive” kernel which
accounts for none of these effects, and separate the ratio into
a local concentration term \( g(r) \) (the Radial Distribution Func-
tion), and the ratio \( \nu_{rel}(r)/u_\eta \) (where \( u_\eta \) is the velocity on the
smallest scale of the turbulence - the Kolmogorov scale \( \eta \)).

Two recent and relevant studies [17,18] both show signifi-
cant (order of magnitude or more) increases in the \( g(r) \) term as
the spatial scale decreases to the collision scale of chondrules,
showing that a given chondrule-size particle is embedded in a
local density much higher than “average”. However, there is
some disagreement about whether and how much the compan-
tion term \( \nu_{rel}(r) \) decreases to small scales. Thus, predicting
collision kernels in the nebula for particles with radius \( r \ll \eta \)
quantitatively is not easy or well understood. Current stud-
ies have been done at low Reynolds Number \( Re \) (or turbulent
intensity) and spatial scales far larger than the collisional (par-
ticle size) scale. It does seem [17,18] that relative velocities
at collision are significantly lower (by a factor of at least sev-
eral) than the current estimates, making sticking easier and
forestalling bouncing, thus allowing growth of aggregates to
larger sizes than as modeled by, eg. [9] or [15]. On one hand
[17], increasing volume densities (through \( g(r) \)) might over-
come decreasing velocities and the kernel might be orders of
magnitude larger than currently expected, with a very sharp
preference for equal-sized particles having stopping time \( t_s \)
comparable to the Kolmogorov Kolmogorov eddy time \( t_\eta \), or
Stokes number \( St = t_s/t_\eta = 1 \). On the other hand [18], the
decreasing velocity may exactly cancel the increasing density,
leaving the kernel and collision rates close to current estimates,
but still with very low relative velocities that significantly favor
sticking over bouncing. The outcomes would be different in
detail, but both tend to support growth to larger aggregates than
in current models [9,12]. This conclusion would be consistent
with the suggestion that the light colored lithologies of figure
1 are indeed large \((10^6 \sim 10^8 \text{ chondrule})\) aggregates. Both
[17,18] find that collision rates between particles which have
\( St \ll 1 \), are lower by \( St \) to some power; that is, particles aero-
dynamically selected for high collision rates and high sticking
coefficients are likely to be those with \( St \sim 1 \) (estimated at
roughly chondrule size in the asteroid belt region by [19]).

Chondrule size distributions can help us understand these
aerodynamic effects. It was thought by [19] that chondrule size
distributions were quite narrow, and that this was in agreement
with direct TC into self-gravitating assemblages that quickly
became planetesimals. More recently and almost simultane-
ously, new observations of chondrule size distributions in Al-
lende [20,21] showed the size distribution to be much broader
than previously thought, and new models suggested collisional
growth to the cm-dm scale, resulting in a broader size distribu-
tion [10,11]. The most recent observations of NWA517 [14]
show size distributions having good agreement in shape, if not
in mean size, with those in Allende [20,21].

Cometary aggregates:
An unrelated observation may be relevant in this regard. It has been shown [22] that in cometary aggregate lumps and Wild 2 aggregate particles, the silicate and sulfide monomers (which have very different densities) have equal radius-density product within each aggregate. On the face of it, this is highly suggestive of aerodynamic sorting (see [23] for other examples). However the monomer grains
involved are 0.03-0.2 \( \mu m \) in radius, and nominal nebula gas
densities and turbulent \( \alpha \) in the outer solar system suggest that
such particles would have \( St \ll 1 \), making it very hard for
them to grow by collisional sticking with others of the same
\( St \) (by the Kernel behavior described above). The paradox
could be resolved if the local gas density in the regions where
cometary aggregates formed were one or two orders of magni-
tude smaller than canonical model predictions, or the nebula \( \alpha \)
were one or two orders of magnitude higher, or some combi-
nation. These submicron grain monomers would then play
the role of “chondrules” in those rarified regions, forming aggre-
gates by collisions. Moreover, if this situation were the case,
the aggregates made up from these monomers, which are tens
to hundreds of times larger than the monomers, would become
the analog of the chondrule aggregates in the light lithology
of figure 1, and could for the same reason have a large enough \( St \)
to be concentrated by TC (or CI) directly into planetesimals. References: 