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Chondrule formation during planetesimal accretion

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ABSTRACT

We explore the idea that most chondrules formed as a consequence of inefficient pairwise accretion, when molten or partly molten planetesimals ~30–100 km diameter, similar in size, collided at velocities comparable to their two-body escape velocity ~100 m/s. Although too slow to produce shocks or disrupt targets, these collisions were messy, especially after ~1 Ma of dynamical excitation. In SPH simulations we find that the innermost portion of the projectile decelerates into the target, while the rest continues downrange in massive sheets. Unloading from pre-collision hydrostatic pressure P_0~1-100 bar into the nebula, the melt achieves equilibrium with the surface energy of chondrule-sized droplets. Cooling is regulated post collision by the expansion of the optically thick sheets. on a timescale of hours–days. Much of the sheet rains back down onto the target to be reprocessed; the rest is dispersed.

1. Introduction

The formation of terrestrial planets left thousands of unaccreted bodies whose remnants are represented by chondrites, the majority of meteorites that fall to Earth. Chondrites consist predominately of ~0.1-1 mm igneous silicate spherules known as chondrules (e.g. Hewins et al., 1996; Ringwood, 1961; Scott, 2007; Scott and Krot, 2005; Sears, 2004; Sorby, 1864; Urey, 1967; Wood, 1963). What was the widespread cause of melting of these small spherules, in a nebula whose pressures were far too low for liquids to be stable? Why did they solidify in hours to days, instead of tens of seconds as expected for sub-mm droplets? Why are they so compositionally and texturally diverse, when whole-rock chondrites are similar in aggregate chemistry (c.f. Hezel and Palme, 2010)? Why are chondrules ≳1 Ma younger than most of the iron meteorite parent bodies (Amelin and Krot, 2007; Wadhwa et al., 2007)? In light of the significant deficiencies in all chondrule-forming models, including the presently popular idea that they formed in nebular shocks, we propose a new answer to these questions.

1.1. Background

Physical models for chondrule formation must accommodate several facts. Chondrules formed as a rather narrow size distribution of spherules that were embedded in a fine-grained heterogeneous matrix. This matrix is complementary (Hezel and Palme, 2010) in that chondrite meteorites are much closer to solar composition than chondrules or matrix separately (Wood, 1963). Chondrules solidified in hours (Desch and Connolly, 2002) compared to seconds for a silicate droplet radiating into space. They are found to have crystallized in evaporative equilibrium with sodium and other volatiles (Alexander et al., 2008) and show evidence for plastic (almost-molten) pairwise collisions (Gooding and Keil, 1981) and mergers. These latter aspects argue significantly for their formation in dense, self-gravitating particle swarms (Alexander et al., 2008).

Lead isotope ages of certain chondrules have been determined to high precision (Amelin and Krot, 2007; Villeneuve et al., 2009; Wadhwa et al., 2007). They postdate CAIs by ≳1 Ma and appear well represented only after the first 1–2 Ma of solar system history. Iron meteorites sample ~50–100 core-bearing parent bodies that melted ≳0.5–1 Ma prior to chondrule formation (Bizzarro et al., 2005; Kleine et al., 2005; Qin et al., 2008), so the late time of formation and the widespread presence of magmatic planetesimals frames the debate.

1.2. Nebular models

Nebular models of chondrule formation (Wood, 1963) have evolved into the presently popular idea that low density mechanical aggregates of solar-composition dust, or pre-chondrules of some sort, were melted when the nebula was heated by powerful shocks (e.g. Boss and Durisen 2005; Ciesla and Hood, 2002; Desch and Connolly, 2002; Morris and Desch, 2010) whose cause is much debated. Planetesimals that had already formed by then, including the iron meteorite parent bodies, were bystanders or formed elsewhere (Bottke et al., 2006), or were instrumental in causing the shocks.

Disks around sun-like stars persist for millions of years (Meyer et al., 2008). Planetary embryos excited by Jupiter (Weidenschilling et al., 1998) plowing supersonically through a dense nebula (e.g. ρ_{nebula} ~ 10^{-9} g cm^{-3}, v ~ 8 km/s; Morris and Desch, 2010) can lead to shocks capable of melting dust and compressing the gas by a factor of ~10. However, Cuzzi and Alexander (2006) calculate that the

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chondrule-forming shocks must have been 100s to 1000s of km across in order to experience limited isotopic fractionation; if so then chondrule formation might require regional shocks, as are triggered by density waves and gravitational instabilities (Boss and Durisen 2005). To accommodate the timing of chondrule formation (Wadhwa et al., 2007) instabilities must take place for millions of years. If dynamically-excited embryos set up the chondrule-forming shocks, then likewise the cause of eccentric forcing, and the disk, must have persisted for millions of years.

The origin of pre-chondrule agglomerations is a puzzle. Parceling 'dust bunnies' into monodisperse ~10–1000 μg accumulations requires size-dependent processing prior to melting, for instance aerodynamical sorting (see Wood, 1988). It is more difficult to explain in this context the stunning diversity of chondrule types and compositions over intimate spatial domains (see e.g. Ciesla, 2010). All chondrite groups show a wide range of chondrule compositions, and the ratio of olivine to olivine + pyroxene in porphyritic (the most common) chondrules ranges from <1% to >99% (see Scott and Krot, 2005). Why should one dust bunny's chemistry or its shock be so different from the one adjacent?

Chondrule-forming nebular shocks must leave behind a self-gravitating swarm according to the formation densities calculated by Alexander et al. (2008). Assuming shock compaction by a factor of ~10, the pre-shocked swarms must be within an order of magnitude of instability already. Cuzzi et al. (2008) and Johansen et al. (2007) show how particles might coalesce in turbulent eddies into local-scale accumulations that might be close to self-gravitating, and like Morbidelli et al. (2009) we regard turbulent clumping as the likely cause for the rapid accretion of the first planetesimals, bypassing the problematic 'one meter barrier' (Benz, 2000; Weidenschilling et al. 1977).

If this turbulent clumping happened after chondrule formation, the chondrules could not have formed in self-gravitating densities: the clumping would have occurred gravitationally already. If clumping coincided with the shock, then the turbulence must be tied to the long range gravitational forcing (disk instability or forcing by distant planets). We favor the scenario where turbulent clumping leads directly to planetesimal formation, with chondrules forming later from the planetesimals.

One challenge to nebular models is the inclusion of Mg-rich silicate grains that formed at elevated temperatures and pressures (Libourel and Krot, 2007; Villeneuve et al., 2011) within various CV-class chondrules. These might have derived from a precursor body, later disrupted and incorporated into chondrules. However, massive and energetic collisions—reversing accretion—are required to disrupt ≳10 km planetesimals into tiny bits. We favor an alternative where these inclusions derive from crusts and unmelted components (with their own complicated histories) of the same disrupted planetesimals that form the chondrules.

Nebular models require circumstances that have specific implications for nebula physics and planet formation (e.g. Chambers, 2004; Ciesla, 2010; Desch et al., 2005). The early nebula was a complex place with diverse and coinciding processes competing for dominance. That said, we now turn to a process that certainly occurred in the first few Ma of solar system history: the pairwise accretion of molten planetesimals.

1.3. Planetesimal models

If chondrules formed in collisions or igneous eruptions (see Hutchison et al., 2005; Sorby, 1864; Urey and Craig, 1953) then the nebula played a background role, damping the relative motions and contributing to the chondrite matrix. These models have not ascribed a satisfactory physics to their process. Appendix I of Wood (1963) debunks planetesimal models, and his arguments have been convincing. While Krot et al. (2005) reason that some of the latest (~5 Ma post-CAI) iron-rich (CB, CH) chondrules formed in a single large impact, these chondrule types are uncommon; at question is not whether impacts *ever* formed chondrules, but whether the majority of common chondrites derive from disrupted planetesimals.

Molten spherules can be produced directly from solids, when shock waves release during hypervelocity collisions. But impact spherules are physically and chemically distinct from chondrules (Melosh and Vickery, 1991). Furthermore, impact shock requires random velocities orders of magnitude faster than $v_{rand} \sim v_{esc}$ expected during accretion. Hypersonic collisions are characteristic of small-body populations that are eroding rather than accreting; present-day asteroids do not produce chondrules. Thus we focus on already-melted planetesimals.

1.4. Melted bodies

According to thermal models, the radioactive decay of primeval ^{26}Al, with half-life $\tau_{1/2} = 0.72$ Ma, led to the meltdown of planetesimals ≳30 km diameter that accreted in the first ~1 Ma (Hevey and Sanders, 2006; Sahijpal et al., 2007). This agrees with radioisotopic (Bizzarro et al., 2005; Kleine et al., 2005; Lee and Halliday, 1996) and petrological (Keil, 2000) records. A planetesimal might have a significant melt fraction in the timeframe of chondrule formation, beneath a solid carapace that started out thick (melting begins at the center), thinned rapidly during maximal heating, and then gradually thickened into a crust following several $\tau_{1/2}$.

Melted planetesimals can differentiate into cores and mantles. The chondrite parent bodies did experience signature variations in metallic iron ranging from metal poor (L, LL) to high (H, CB/CH), although not complete differentiation. Varying levels of partial differentiation are expected for planetesimals ~30–100 km diameter because interfacial tension is high for metals and silicates, whereas gravity is smaller than achievable on most 'zero gravity' parabolic research flights. The driving force for core segregation could well be much smaller than the interfacial stresses borne by metal percolating through silicate, or by the immiscible components in a complete melt.

Gravity acting on a metal globule of radius r is $^4/_3\pi r^3\Delta\rho g$. The density difference $\Delta\rho$ is ~4.5 g cm^{-3} for metallic iron suspended in silicates; lower for FeS. The Eödvös (Bond) number $Eo = \Delta\rho g r^2/\gamma$ is the measure of the relative importance of interfacial stress γ/r to the gravity (or other body force) per unit area. Estimating $r \sim 1$ mm, $g \sim 1$ cm s^{-1}, (a 30 km body) $\gamma \sim 400$ dyn cm^{-1}, and $\Delta\rho \sim 4$ g cm^{-3}, we find $Eo \sim 10^{-4}$. Gravity-driven percolation is thus limited until some other process first agglomerates metals into ~10 cm blobs ($m \sim 10$ kg), or increases the effective g by shaking. Capillary action can coalesce liquids if the dihedral (wetting) angle exceeds a threshold (typically ~60°), but experiments show that iron droplets remain stuck to silicate junctures until pressures exceed ~400 kbar (Takafuji et al., 2004). Molten FeS alloys drain effectively at lower pressures, corresponding to planetesimals larger than ~60 km (Yoshino et al., 2003), an interesting transition diameter.

The raining out of iron droplets may be slow even without a yield stress, for instance the case of iron droplets. Suspended in a fully melted basaltic magma (viscosity $\eta \sim 10^4$P). The Stokes settling timescale to the core is $\sim\eta/Gr^2\rho\Delta\rho$ (independent of planetesimal radius R) where ρ is the planetesimal bulk density, or ~0.1–1 Ma for 0.1-1 mm diameter droplets, and longer for more viscous magmas. The solar-composition carapace might further sustain the primitive signature in a melting body for some time. While collisional shaking might dislodge and coalesce small droplets, larger collisions would stir up the settling mixture, as might thermal and magnetically induced convection. The above calculations suggest core formation occurred with varying efficiency in melted planetesimals, consistent with the wide range of metallic iron in chondrites.