CHONDRULE FORMATION BY PAIRWISE ACCRETION OF MELTED PLANETESIMALS

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Summary: We have introduced a new mechanism for chondrule formation [1] where primitive igneous droplets are a dynamical consequence of sloppy pairwise accretion of melted planetesimals. The idea of splashing molten planetesimals has long heritage [e.g. 2]; our mechanism is unique in starting from the hydrostatic pressure within an igneous primitive planetesimal, as massive sheets of melt are ejected from ~tens of bars in hit-and-run and graze-and-merge collisions [3, 4]. Chondrule diameters are regulated by magmatic surface tension in our model, producing ~0.1 mm-sized spheres from ~30-100 km diameter planetesimals. Chondrule formation is as common as accretion, so long as the colliding bodies have significant melt reservoirs; later collisions form breccias and rubble piles. The story of chondrules is more complicated than our simple scenario can predict, so we review and expand upon our treatment of collisions, evaluate plausible scenarios and their implications, and explore caveats and testable aspects.

Motivation: There is substantial evidence for widespread melting of planetesimals during the timeframe of chondrule formation, and models based on the ^{26}Al budget [e.g. 5] show that planetesimals ~30-100 km diameter are molten for the first few Ma if they accrete in the first ~1 Ma. We find [1] that molten planetesimals of milligravity size can easily maintain chondritic chemistry. The greatest obstacle to forming chondrules out of melted or partly melted planetesimals [2] has been physical, motivating us to uncover a mechanism rooted in pairwise accretion, and aligned with the evidence that CB chondrites formed in relatively late collisions [6].

The interpreted formative chemical and thermal state of chondrules indicates their solidification in dense, probably self-gravitating [7] swarms. Gravity is an important aspect of our model, providing energy to chondrule formation in addition to the copious thermal energy from radionuclides, by generating hydrostatic pressure $P_0 \sim G\rho^2 R^2$ inside each planetesimal.

Slow and messy: Collisions at tens of meters per second – car-crash velocities, by objects the size of small states – are never simple mergers. Initial contact takes hours, and the long term aftermath takes days to weeks. The large time scales and spatial scales, and microgravity conditions, have placed them beyond what is attainable in a laboratory, although with modern hydrocodes we are able to explore these scenarios in some physical detail. Pairwise planetesimal collisions differ from the better-studied scenarios for the impact origin of the Earth-Moon system, an event that has been modeled as a 'graze and merge' collision [e.g. 8] using similar techniques but at vastly higher energy. At tens of meters per second, there are no shocks.

We find [1] that pairwise planetesimal growth is accompanied by repeated evisceration and pressure-unloading of planetesimals that overshoot their targets [9]. Unaccreted material includes bound ejecta which can remain in orbit or within the Hill sphere, and escaping ejecta. Ejecta are composed primarily of unaccreted downrange projectile material, with more energetic collisions dredging up increasing fractions of target material. If molten, this unaccreted material disrupts into swarms of chondrule-sized droplets that expand and cool on a timescale of hours.

The droplets formed are thus subject to a variety of fates. The model predicts their sizes, where surface accommodates the hydrostatic pressure prior to the collision, and cooling rate, as regulated by the swarm's diminishing opacity.

The model: We use high resolution SPH simulations (~10^6 particles) to model colliding bodies. These are of varying size ~10-100 km and either liquid, or liquid beneath a massive solid carapace, with an iron core. A liquid treatment is appropriate [3] for a ~10 km radius planetesimal of Newtonian viscosity <10^{11} poise; but there would be nonlinear complications to the rheology, e.g. bubbles, shear softening, etc.

Figure 1 shows a typical outcome for an escape-velocity collision (36 m/s) between two bodies 30 km and 70 km diameter with notional cores. The characteristic feature is the release of the unaccreted sheet, mostly projectile material, from hydrostatic pressure. $V\mathrm{d}P$ is added to the available enthalpy, where $\mathrm{d}P \sim P_0$, the initial hydrostatic pressure. ΔH can be accommodated by vapor dissolution and outgassing, but these require free surfaces (bubbles, droplets) and the associated energy γ. A simple relationship is attained between the radius R of a disrupted planetesimal, and the radius r of characteristic chondrules that derive from unloaded melted materials. Equating $P_0 \sim G\rho^2 R^2$ to the Laplace pressure $2\gamma/r$ across a droplet interface gives $R = 1/\rho\sqrt{2\gamma/GrE}$, where E is an efficiency that we take to be the ratio of chondrule-forming mass to non-chondrule matrix in a chondrite. Surface tension of terrestrial melts for a rather wide range of T, P is $\gamma \sim 400$ dyn/cm. For this value, the characteristic chondrule-forming planetesimal is tens of km diameter. Because the droplet swarm is molten, original droplet diameters are smaller than the final chondrules, so factoring in that chondrules might more than double in size through accretion and Ostwald ripening, a ~30-100 km progenitor planetesimal would be typical.

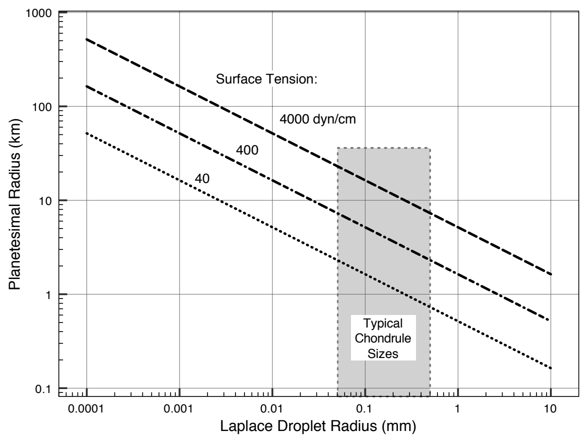

Figure 1 Equating Laplace pressure to the pre-disruption hydrostatic pressure P_0 gives droplet radius as a function of planetesimal radius [1]. Droplets then grow into chondrules.

Cooling of chondrules is limited by the swarm opacity [c.f. 10] and thus regulated by the expansion timescale. The overshooting part of the projectile continues on at downrange velocity $v_{\mathrm{rand}} \sim v_{\mathrm{esc}}$, while the rest is stopped; this gives an expansion timescale $\tau \sim R/v_{\mathrm{esc}} \sim \tau_{grav}$ of order 1 hr, which is consistent with chondrule petrographic cooling rates.

The target reaccumulates a rain of chondrules lasting for hours to days. The chondrules would likely be solidified on this timescale, before impacting, and the target surface is likely to have a solid crust of some sort. Chondrules re-impacting the target would likely experience secondary heating after they are piled into massive layers. Higher velocity hit and run collisions [3,4] would disperse chondrules downrange, many of these forming self-gravitating clumps. Dispersed chondrules would be dragged by the diminishing gas and possibly collected into other planetesimals, or swept by Poynting-Robertson drag into the Sun.

The hypothesis offers testable links between the dynamical evolution of the early nebula, the timing and physics of chondrule formation, and the thermal state of planetesimals. Improvements to the model would include better EOS, and explicit treatment of phase segregation and cavitation. It is plausible to test the model experimentally, requiring experiments using melts, or analog melts, in microgravity, expanding into low pressure on an hours-long timescale.

References: [1] Asphaug, Jutzi & Movshovitz, *EPSL* **308**, 2011. [2] Sanders & Taylor, *ASP Conf. Series* **341** (2005). [3] Asphaug, *Chemie der Erde* **70**, 2010. [4] Leinhardt & Stewart, *MNRAS*, submitted. [5] Hevey & Sanders, *MAPS* **41** (2006). [6] Krot et al., *Nature* **436** (2005). [7] Alexander et al., *Science* **320** (2008). [8] Canup & Asphaug, *Nature* **412** (2001). [9] Asphaug et al., *Nature* **439** (2006). [10] Cuzzi & Alexander *Nature* **441** (2006).

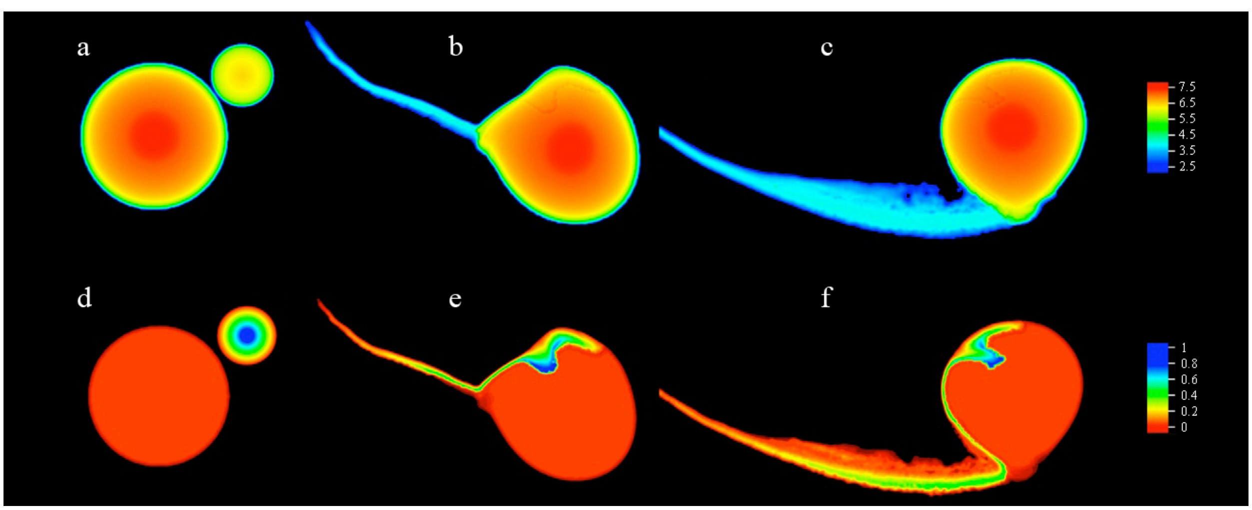

Figure 2 Planetesimal evisceration. While it is impossible to catastrophically disrupt the largest members of an accreting population, impactors are commonly disrupted when they overshoot the target [3, 4]. The unaccreted fraction disperses downrange into a thin sheet, depressurized from equilibrium (P~mbars), its melted components forming droplets in our model [1]. Shown are 30 km and 70 km diameter planetesimals colliding at v_{esc}=36 m/s at t=0, 4000 and 8000 s after contact. There are no shocks. Pressure (top) is log(P) in dyn/cm^2 from millibars (blue) to tens of bars (red); it remains hydrostatic in the target while the projectile unloads into a sheet. The bottom panel (d-f) plots the initial radius within the projectile, showing core-capture by the target, and with ~60% of the projectile mass continuing downrange. About 2% of the projectile has escaping velocity relative to the final target body; collisions >v_{esc} have much higher escaping fractions.