CHONDRULE FORMATION BY PARTIAL ACCRETION OF PLANETESIMALS.

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Summary: We introduce a simple mechanism for ubiquitous chondrule formation during the partial accretion of planetesimals. The mechanism requires an expected level of dynamical excitation, and melted or partially melted colliding bodies, but is otherwise a natural consequence of early planetary growth.

At the onset of terrestrial planet formation the random motions among swarming planetesimals were damped by gas and dust to much slower than their dominant escape velocity, $v_{rand} << v_{esc}$. If so then the earliest pairwise collisions were efficient mergers. After the dust and gas cleared, most of the mass was in planetesimals, so that gravitational stirring excited the random motions to $v_{rand} \sim v_{esc}$ (~100 m/s assuming ~100 km largest planetesimals). This increased the collisional energy and caused a subtle but fundamental shift from efficient mergers to partial accretion and hit and run collision [1], forming chondrules from unaccreted colliding projectile material.

Collisions during accretion are too slow to disrupt the largest bodies. But when $v_{rand} \sim v_{esc}$ a projectile a few times smaller in size typically has enough kinetic energy to overshoot the target. If molten or partially molten, the unaccreted projectile erupts downrange as through a nozzle, leading to swarms of chondrule-sized droplets that expand and cool on a timescale of hours.

Theory: There is abundant evidence for widespread melting of planetesimals during the time of chondrule formation [2]. Models based on the ^{26}Al budget [3] show that planetesimals ~10-30 km diameter are molten for the first few Ma if they accrete in the first ~1 Ma. Small molten planetesimals can maintain chondritic chemistry; the greatest obstacle to forming chondrules out of planetesimal melts [4] is physical. Proposed mechanisms are either implausible during the quiescent state of early accretion, or ad hoc.

The chemistry and thermal state of solidifying chondrules indicates their formation in dense, probably self-gravitating [5] swarms. This is important to our model, where gravity provides energy (or enthalpy) to chondrule formation in addition to the copious thermal energy available from the decay of ^{26}Al, by randomly stirring the population to $\sim v_{esc}$, and by generating hydrostatic pressure $P_0 \sim G\rho^2R^2$ inside each planetesimal.

Once this characteristic random velocity is achieved, then hit and run collisions and partial accretions are more common than mergers [1]. The target functions (with varying degrees of effectiveness) as a gravitational-mechanical nozzle to disperse the unaccreted projectile materials from P_0 into space, producing a cloud of droplets. We study this using hydrocode models and a droplet formation analysis.

Numerical Method: We have run a number of simulations at high resolution in 3D (~10^6 particles) using an established smoothed-particle hydrodynamics (SPH) technique [e.g. 6]. We apply a grid-based self-gravity solver. We use the Tillotson equations of state for iron and basalt, starting at an internal energy corresponding to molten silicate, and treat both colliding bodies as liquids. According to Eq. 17 in [2], a liquid treatment is appropriate if a ~10 km radius planetesimal has Newtonian viscosity <10^{11} poise; other caveats will be addressed at the conference. Iron is representative of core material, and at these low impact velocities basalt is a suitable placeholder for materials of more primitive silicate composition of density ~2.7 g/cm^3.

Formation of Droplets: Droplets form when a pressurized liquid is released into space. $V\mathrm{d}P$ is added to the available enthalpy, where $\mathrm{d}P \sim P_0$, and this is readily accommodated by the addition of surface energy (droplets). Assuming that a fraction E of the magmatic enthalpy converts to droplet surface energy, a simple relationship is possible between the radius R of a disrupted planetesimal, and the radius r of characteristic chondrules that derive from its unloaded melted materials. Equating $P_0 \sim G\rho^2R^2$ to the Laplace pressure $2\gamma/r$ across a droplet interface gives $R = 1/\rho\sqrt{2\gamma/GrE}$. Much physics and chemistry is hidden in E, although its uncertainties are under the square root. We suggest E is the ratio of chondrule-forming mass to non-chondrule matrix in a chondrite.

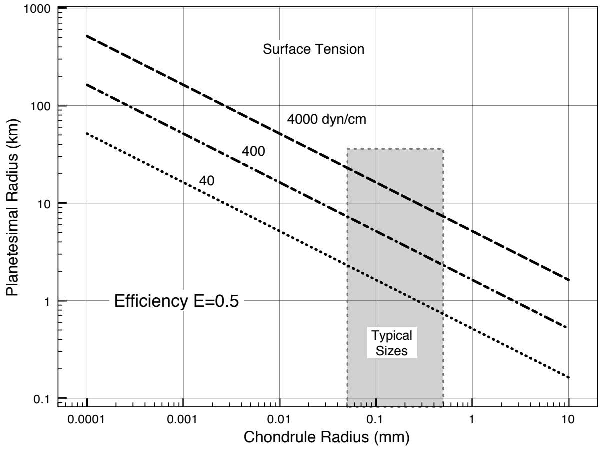

Figure 1 By assuming that the Laplace pressure is equal to a fraction E of the pre-disruption pressure P_0, chondrule radius can be related to the radius of the disrupted planetesimal from which it formed.

Typical surface tension for terrestrial melts at 1 bar, for a rather wide range of temperature and pressure, is 400 dyn/cm. Adopting this value, and considering the sizes of chondrules (Figure 1), we find a characteristic chondrule-forming planetesimal diameter of tens of km.

Results: Shown in Figure 2 a 30 km diameter body impacts a 70 km body at impact angle 60° from normal, at contact velocity v_{imp}= 51 m/s (v_{rand}=v_{esc}=36 m/s). There are no shocks. The simulation is characteristic of hundreds of similar partial accretions which send projectile material downrange, depressurized. SPH particles are plotted 1.1 hr after initial contact, showing two views sliced down the symmetry plane. Pressure remains close to hydrostatic inside the target. About 20% of the impactor emerges as a depressurized sheet, in a process similar to a garden hose nozzled by a gardener's thumb. Pressures are millibars throughout the sheet, which if molten coalesces into an initially highly opaque swarm of silicate droplets.

Cooling of chondrules is limited by opacity [7] and thus regulated by the expansion timescale. The downrange velocity ($v_{\rm rand}$~$v_{\rm esc}$) of the overshooting part of the projectile is only slightly decelerated by the impact, while the rest is stopped abruptly; this gives an expansion and cooling timescale $\tau \sim R/v_{\rm esc} \sim \tau_{grav}$, of order 1 hr.

Half of the sheet is not bound to the target in this simulation; the other half reaccumulates back onto the target body, a rain of chondrules lasting for hours to days. Re-accumulating chondrules would likely be solidified on this timescale, before impacting. They might experience a secondary heating episode after they are piled into massive layers upon the partially molten target. In many hit and run collisions and partial accretion events the downrange materials forms self-gravitating clumps. Dispersed chondrules eventually are dragged along by the diminishing nebular gas, 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.

References: [1] Asphaug, *Chemie der Erde* **70**, 199-219 (2010). [2] Bizzarro et al., *Ap.J* **632**, L41-L44 (2005). [3] Hevey & Sanders, *MAPS* **41,** 95-106 (2006). [4] Sanders & Taylor, *ASP Conf. Series* **341**, 915-932 (2005). [5] Alexander et al., *Science* **320**, 1617- 1619 (2008). [6] Jutzi et al., *Icarus* **198**, 242-255 (2008). [7] Cuzzi & Alexander *Nature* **441**, 483-485 (2006).

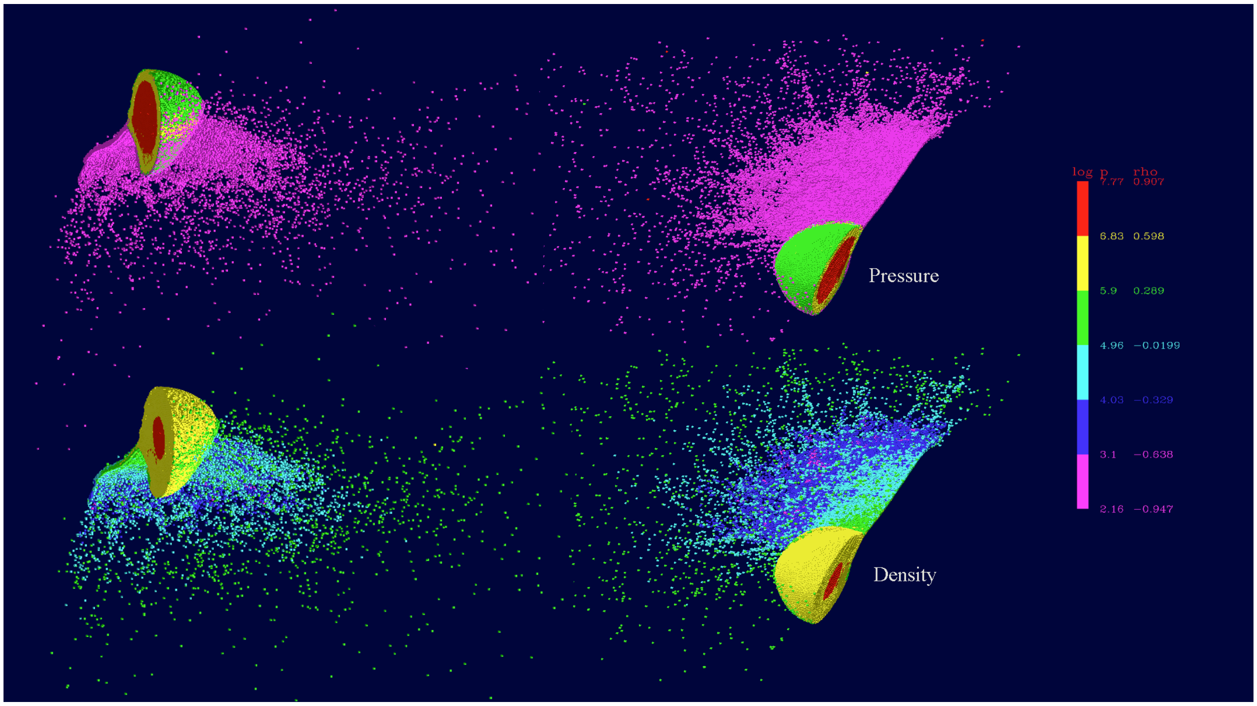

Figure 2 During accretion it is impossible to catastrophically disrupt the largest members of the population. But impactors are commonly disrupted when they overshoot the target. Shown are 30 km and 70 km diameter planetesimals colliding at 51 m/s (a massive scale car crash) at 1.1 hr after initial contact. Pressure (top) and density (bottom) are on log scales; max P=60 bars. The unaccreted fraction of the projectile disperses downrange into a thin sheet of material, depressurized from equilibrium (P~millibars), its melted components forming droplets.