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Impact splash chondrule formation revisited

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1. Abstract

Despite continuous efforts, a conclusive and astrophysically consistent chondrule formation scenario remains elusive. Major constraints include chemical, isotopic and textural features of chondrules, in particular retained metal abundances, bulk Fe/Mg ratios, porphyritic textures and the intra-chondrite chemical diversity. Here, we propose a coupled evolution-collision scenario in which chondrules originate from the collision aftermath of low-mass planetesimals, which are only partially molten from ^{26}Al decay. The model is consistent with the vast majority of thermal and chemical constraints and invokes a diversity of pre-chondrule material compositions. The thermo-mechanical evolution-collision regime favored in our scenario constrains the timing and formation conditions of the earliest planetesimal families and thus the onset of terrestrial planet formation.

2. Where are all the debris droplets?

Collisions among planetesimals were frequent in the early solar system [1,2,3]. These bodies were sufficiently heated by the radioactive decay of ^{26}Al to undergo intense silicate melting phases and generated large amounts of melted debris as a result from two-body interactions. In low-gravity environments, such collisional debris takes the form of myriads of small magma droplets as a result of energy conversion from lithostatic load (before the impact) to droplet surface energy (after the impact) [2].

Because chondritic meteorites are the last surviving remnants of the early accretionary phase during the lifetime of the protoplanetary disk, we should be able to identify signatures of such processes in these rocks. Therefore, if chondrules would *not* represent the aforementioned magma droplets, the meteorite collection would need to be interpreted in the sense of a virtually collision-free accretionary phase, which seems unlikely [1,2,3].

3. Magma ocean planetesimals did not generate chondrules

The most serious arguments against chondrule formation from planetesimal collisions concern the occurrence of Fe-Ni metal within chondrules or in their vicinity and the chemical and isotopic diversity of individual chondrules within the same chondrite meteorite [4]. For the first 1–2 Myr after the formation of Ca-Al-rich inclusions, the collision precursor bodies are expected to have been largely molten by ^{26}Al (internal ‘magma oceans’) [5].

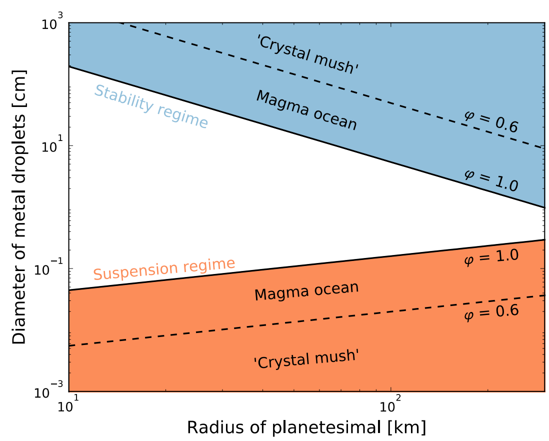

Figure 1: Metal droplets cannot be suspended in planetesimals with vigorously convecting magma oceans. The likely metal droplet sizes for various planetesimal radii and silicate melt fractions φ (‘stability’) in a magma ocean is shown versus the droplet sizes, which can be suspended in liquid magma by convection (‘suspension’).

Asphaug et al. [2] and Sanders & Scott [6] suggested in their models that chondrules may originate from low-velocity impacts among such magma ocean planetesimals. From a dynamical point-of-view, the apparent advantage of this scenario is that the planetesimals are already pre-molten, and impact velocities on the order of the planetesimal escape velocity (~m/s) are sufficient to generate magma droplets. Such low-velocity interactions in the early solar system are expected, because the high ambient gas densities may have damped mutual collision velocities [1,2]. Testing this scenario against constraints obtained from laboratory measurements, however, we show in *Figure 1* that frequent abundances of Fe-Ni metal within and around chondrules and their chemical heterogeneity rule out excessively molten (and thus differentiated) planetesimals as chondrule precursors.

4. Chondrule properties constrain planetesimal formation and dynamical timescales

However, because the case for frequent collisional interactions in the early solar system is strong [1,2], we argue that the apparent mismatch between the chemical signatures of chondrules and the expected outcome from magma ocean planetesimal collisions allows us to reverse engineer the eligible parameter space for planetesimal formation and collision timescales, which are compliant with chondrule measurements. In contrast to the previously suggested scenario, planetesimals of preferentially low mass and/or sub-canonical ^{26}Al abundances, were significantly pre-heated but did *not* differentiate extensively (*Figure 2*).

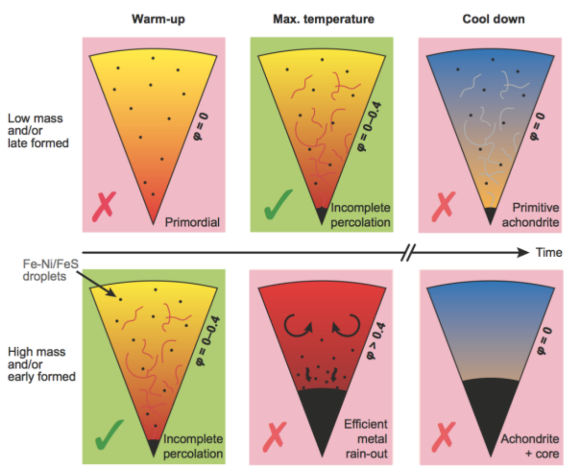

Figure 2: Suggested 'Goldilocks' regime for chondrule precursor planetesimals (green). Red scenarios are either chemically, texturally or isotopically inconsistent with laboratory measurements [4,7] or dynamical models [1,2,4].

By constructing dynamical scenarios for varying planetesimal families in the time from 0–5 Myr after CAIs, we argue that subsonic (~1 km/s) impacts of such small-size/intermediate-^{26}Al bodies are chemically, isotopically and texturally consistent with observations, and fit well to recent dynamical models of planet formation [1,3]. Furthermore, if different parent bodies accreted from isolated feeding zones without mutual mixing, potentially similar to the observed rings in extrasolar protoplanetary disks [8], chondrule-matrix complementarity [4] and distinct nucleosynthetic anomalies in individual chondrules may be retained.

5. Summary

Previously suggested models of impact splash chondrule formation offer attractive solutions to intertwine our understanding of planet formation with the ubiquity of chondritic meteorites. However, they suffer from major inconsistencies with the chemical and isotopic composition of chondrules. To resolve this mismatch we suggest that the vast majority of collisional debris feeding the asteroid main belt must have been derived from planetesimals, which were only partially molten. Therefore, the precursors of meteorite parent bodies either formed primarily small, from sub-canonical ^{26}Al reservoirs, or collisional growth mechanisms were efficient enough to shatter planetesimals before they reached the magma ocean phase.

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