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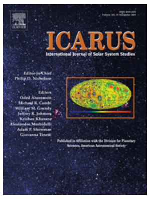

Impact splash chondrule formation during planetesimal recycling

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ABSTRACT

Chondrules, mm-sized igneous-textured spherules, are the dominant bulk silicate constituent of chondritic meteorites and originate from highly energetic, local processes during the first million years after the birth of the Sun. So far, an astrophysically consistent chondrule formation scenario explaining major chemical, isotopic and textural features, in particular Fe,Ni metal abundances, bulk Fe/Mg ratios and intra-chondrite chemical and isotopic diversity, remains elusive. Here, we examine the prospect of forming chondrules from impact splashes among planetesimals heated by radioactive decay of short-lived radionuclides using thermomechanical models of their interior evolution. We show that intensely melted planetesimals with interior magma oceans became rapidly chemically equilibrated and physically differentiated. Therefore, collisional interactions among such bodies would have resulted in chondrule-like but basaltic spherules, which are not observed in the meteoritic record. This inconsistency with the expected dynamical interactions hints at an incomplete understanding of the planetary growth regime during the lifetime of the solar protoplanetary disk. To resolve this conundrum, we examine how the observed chemical and isotopic features of chondrules constrain the dynamical environment of accreting chondrite parent bodies by interpreting the meteoritic record as an impact-generated proxy of early solar system planetesimals that underwent repeated collision and reaccretion cycles. Using a coupled evolution-collision model we demonstrate that the vast majority of collisional debris feeding the asteroid main belt must be derived from planetesimals which were partially molten at maximum. Therefore, the precursors of chondrite parent bodies either formed primarily small, from sub-canonical aluminum-26 reservoirs, or collisional destruction mechanisms were efficient enough to shatter planetesimals before they reached the magma ocean phase. Finally, we outline the window in parameter space for which chondrule formation from planetesimal collisions can be reconciled with the meteoritic record and how our results can be used to further constrain early solar system dynamics.

1. Introduction

Chondrules are igneous-textured spherules, typically 0.1–2 mm in diameter, and largely composed of the silicate minerals olivine and pyroxene. They are abundantly found in chondritic meteorites, together with other disk materials, such as Ca,Al-rich inclusions (CAIs) and the fine-grained matrix that includes presolar grains and primitive organics (Scott and Krot, 2014). Chondrules are often surrounded by or close to beads of Fe,Ni metal (e.g., Wasson and Rubin, 2010; Jones, 2012) and show specific features, such as high abundances of moderately volatile elements like Na, K and S (Alexander et al., 2008; Scott and Krot, 2014; Connolly and Jones, 2016) and diverse chemical and isotopic signatures (Jones and Schilk, 2009; Hezel and Palme, 2010; Olsen et al., 2016). Their peak temperatures were ~ 1900 K or higher (Alexander et al., 2008; Connolly and Jones, 2016) with subsequent cooling in minutes to days (e.g., Hewins et al., 2012; Desch et al., 2012; Wick and Jones, 2012). Most chondrules were formed during the earliest phases of the solar system within the first 3–4 million years after the formation of CAIs (e.g., Villeneuve et al., 2009; Connelly et al., 2012) and show clear evidence for multiple melting cycles (Rubin, 2017, and references therein).

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Because of their enigmatic features coupled with high-energy processing, chondrule formation is considered to be intimately linked to the physical processes in the protoplanetary disk or planetary accretion and spawned a multitude of proposed formation mechanisms. The often underlying view of how chondrules are intertwined with the planet formation process is that they were formed before accretion and therefore represent the fundamental building materials of the planets and asteroids (Connolly and Jones, 2016). In this case, chondrules are formed before parent body accretion, either by melting dust aggregates by nebular shocks (Desch and Connolly, 2002; Morris and Desch, 2010; Morris et al., 2016), for example related to global disk instabilities (Boss and Durisen, 2005; Lichtenberg and Schleicher, 2015), or condensation of melts and crystals (Blander et al., 2004; Nagahara et al., 2008). In contrast, if chondrules formed via processes involving already formed planetesimals, the interpretation of their role would shift to a ‘by-product’ of planet(esimal) formation (see discussion in Section 4).

Recently proposed chondrule formation scenarios considered melt spray from subsonic collisions (‘splashes’) between similar-sized planetesimals, which were fully melted by decay heat from ^{26}Al (Asphaug et al., 2011; Sanders and Scott, 2012) or impact ‘jetting’ via collisions of planetesimals with undifferentiated protoplanets (Johnson et al., 2015; Hasegawa et al., 2016; Wakita et al., 2017). Collisional mechanisms were suggested previously and offer attractive solutions to many chondrule features (Krot et al., 2005; Sanders and Scott, 2012; Stammler and Dullemond, 2014; Dullemond et al., 2014; 2016; Marrocchi et al., 2016). From a dynamical point-of-view, collisional interactions of planetesimals and embryos during accretion are inevitable and expected to create a vast amount of continuously reprocessed debris (Bottke et al., 2006; Carter et al., 2015; Jacobson and Walsh, 2015; Asphaug, 2017; Bottke and Morbidelli, 2017) that inherits the geochemical features from previous planetesimal generations.

Collisional models of chondrule formation considering fully-molten planetesimals, and thus highly energetic internal magma oceans with temperatures above the liquidus (Asphaug et al., 2011; Sanders and Scott, 2012), have the advantage that bodies interacting at low speeds ($\sim$ around the two-body escape velocity) can cause a melt spray ejection into the ambient disk medium that provides the inferred cooling regime for chondrules and the required solid densities to preserve primitive abundances of moderately volatile elements (Sanders and Scott, 2012; Dullemond et al., 2014; 2016).

For consistency with the observed metal abundances in and around chondrules (Wasson and Rubin, 2010; Palme et al., 2014; Connolly and Jones, 2016), droplet entrainment in a vigorously convecting magma ocean has been invoked to prevent efficient and complete metal-silicate segregation (Asphaug et al., 2011; Sanders and Scott, 2012; Asphaug, 2017). However, metal sequestration into the planetesimal core may have been rapid in magma ocean planetesimals as, for instance, supported by the old ages of iron meteorites (Kruijer et al., 2014). In this case, re-establishing post-collisional bulk Fe/Mg ratios and forming chondrites with metal beads would require a complicated and highly unlikely scenario of (i) partial oxidization of the metal cores of fully differentiated planetesimals and (ii) violent remixing of the remaining metal core material with mantle silicates during or after the collision (Palme et al., 2015). Additionally, chemical (Jones et al., 2005; Hezel and Palme, 2007; Palme et al., 2014) and isotopic (Bauer et al., 2016; Olsen et al., 2016) heterogeneities between single chondrules of the same meteorite cannot be retained if vigorous convection at low silicate viscosities homogenized the bulk volume of primitive planetesimals down to chondrule-sized microscales.

However, it is well known that the interior evolution of planetesimals alone could create a diverse range of thermal histories and interior structures (e.g., Hevey and Sanders, 2006; Lichtenberg et al., 2016a), where magma ocean planetesimals are only one end-member type. In addition, the structure and chemistry of planetary materials was potentially further altered due to repeated collision–reaccretion cycles, which may generate varying thermal and chemical histories on a cm–m scale of planetary materials. Here, we probe the thermal and chemical evolution of such debris in a dynamical setting for the early solar system, where small (<100 km) planetesimals were continuously formed over a given timeframe during the lifetime of the circumstellar disk, evolved internally due to radiogenic heating, and were subsequently destroyed by collisions. To evaluate the thermal and chemical state of the debris over time, we quantify the processes governing metal-silicate segregation and chemical diversity within molten planetesimals and model their thermal histories dependent on their sizes and initial ^{26}Al abundances. To classify the parameter space that is (in-)consistent with chondrule formation from impact splashes among similar-sized planetesimals, we calculate the combined influence of interior evolution and collisional parameters in a simple Monte Carlo model. We describe our methodology in Section 2 and show the results from our scalings and computations in Section 3. We discuss our findings and the limits of our approach in Section 4, and draw conclusions in Section 5.

2. Methods

2.1. Scaling analysis

This first part of our analysis aims to quantify the thermo-chemical processes governing the interior of planetesimals with high melt fractions above the rheological transition. The rheological transition of silicates describes the critical melt fraction $\varphi_{\rm crit} \sim$ 0.4–0.6 (Costa et al., 2009) at which the silicate viscosity drops by orders of magnitude (from rock- to water-like behavior). At this range, the dynamic state of the system changes from solid-state creep processes to liquid-like convectional motions in an interior magma ocean. Here, we describe the processes in an idealized system that represents the end-member scenario of a planetesimal that has fully melted as a result of ^{26}Al decay.

2.1.1. Metal-silicate segregation from Fe,Ni droplet rainfall

For the case of a fully-molten planetesimal, we parameterize the rain-out of Fe,Ni metal droplets following the description by Solomatov (2015). The dynamic processes in the magma ocean are determined by its viscosity, which drops by orders of magnitude at the rheological transition $\varphi_{\rm crit} \sim$ 0.4–0.6 (Costa et al., 2009), from $\eta \sim 10^{17}$ Pa s to 10^{-2} Pa s (Rubie et al., 2003; Liebske et al., 2005), as listed in Table 1. In melt regimes valid for planetesimals, the convective heat flux q of the magma ocean can be calculated via

$$q = 0.089k\frac{(T_{\rm m}-T_0)Ra^{1/3}}{D}, \tag{1}$$

with Rayleigh number

$$Ra = \alpha_{\rm Si-liq} g \rho_{\rm ref}\frac{(T_{\rm m}-T_0)D^3}{\kappa\eta}, \tag{2}$$

potential temperature $T_{\rm m}$, ambient (and surface) temperature $T_0 =$ 290 K, thermal diffusivity $\kappa = k/(\rho c_{\rm p})$, thermal conductivity of solid silicates k, silicate heat capacity $c_{\rm p}$, thermal expansivity of molten silicates $\alpha_{\text{Si-liq}}$, depth of the magma ocean D, silicate densities

$$\rho_{\rm s} = \rho_{\rm sol} - (\rho_{\rm sol} - \rho_{\rm liq})\cdot\varphi, \tag{3}$$

$$\rho_{\rm sol} = \rho_{\rm Si-sol}\cdot(1-\alpha_{\rm Si-sol}\cdot[T-T_0]), \tag{4}$$