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Compound chondrules fused cold

Alexander Hubbard

Department of Astrophysics, American Museum of Natural History, New York, NY 10024-5192, USA

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ABSTRACT

About 4–5% of chondrules are compound: two separate chondrules stuck together. This is commonly believed to be the result of the two component chondrules having collided shortly after forming, while still molten. This allows high velocity impacts to result in sticking. However, at $T \sim 1100$ K, the temperature below which chondrules collide as solids (and hence usually bounce), coalescence times for droplets of appropriate composition are measured in tens of seconds. Even at 1025 K, at which temperature theory predicts that the chondrules must have collided extremely slowly to have stuck together, the coalescence time scale is still less than an hour. These coalescence time scales are too short for the collision of molten chondrules to explain the observed frequency of compound chondrules. We suggest instead a scenario where chondrules stuck together in slow collisions while fully solid; and the resulting chondrule pair was subsequently briefly heated to a temperature in the range of 900–1025 K. In that temperature window the coalescence time is finite but long, covering a span of hours to a decade. This is particularly interesting because those temperatures are precisely the critical window for thermally ionized MRI activity, so compound chondrules provide a possible probe into that vital regime.

1. Introduction

Chondrules are sub-millimeter sized igneous inclusions found in chondritic meteorites which were melted in the Solar Nebula, the gas and dust disk from which our Solar System formed. Usually distinct objects within their host meteorite, they are sometimes found as part of a compound chondrule: two distinguishable chondrules fused together (see Fig. 1). While compound chondrules (*cc*s, lower-case to distinguish from carbonaceous chondrites) are rare, with a frequency of about 4–5% of chondrules (Gooding and Keil, 1981; Ciesla et al., 2004), they are nonetheless common enough for some basic statistical information about their nature to be well established (Gooding and Keil, 1981; Wasson et al., 1995). Wasson et al. (1995) distinguishes between sibling and independent *cc*s, depending on whether the primary and secondary chondrules either have or do not have similar composition and textural types. One of the greatest difficulties in studying compound chondrules is the difficulty in correcting 2D information from thin sections to 3D properties (Ciesla et al., 2004), which makes determining their precise frequency difficult, and establishing other parameters, such as the size ratio of the secondary chondrule to the primary, fraught.

Gooding and Keil (1981) proposed that compound chondrules were made by collisions between still molten chondrules shortly after they were formed from ambient dust. If so, then the *cc* frequency is an important constraint because it links the chondrule–chondrule relative velocity and cooling times to the chondrule number density (e.g. Desch et al., 2012). However, sibling and independent *cc*s occur at similar frequencies, implying that if the *cc* fusing process occurred at temperatures where the chondrules were molten, that process must have been able to maintain the structural integrity of droplets of nearly identical liquids in close contact with each other. This requirement is exacerbated by the observation that small contact angle *cc*s dominate the statistics (Wasson et al., 1995; Ciesla et al., 2004), i.e. the radius of the neck between the two component chondrules is generally much smaller than the radius of the individual chondrules, see Fig. 2.

Wasson et al. (1995) suggest that at least some compound chondrules could have been made by melting nebular dust that had accreted onto a chondrule, which is a good model for enveloping *cc*s, a rare class of *cc*s so named because the second chondrule mostly envelopes the first. Miura et al. (2008) instead suggests a model where very large dust grains (far larger than observed chondrules) had their surfaces melted and stripped by a shock in the nebular gas. The stripped surface separated into droplets which in turn collided with each other, creating compound chondrules.

Excepting the production of enveloping *cc*s by melting an accretionary dust rim, the above models all require that molten droplets remain in contact, with very small contact angles, for significant

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E-mail address: ahubbard@amnh.org

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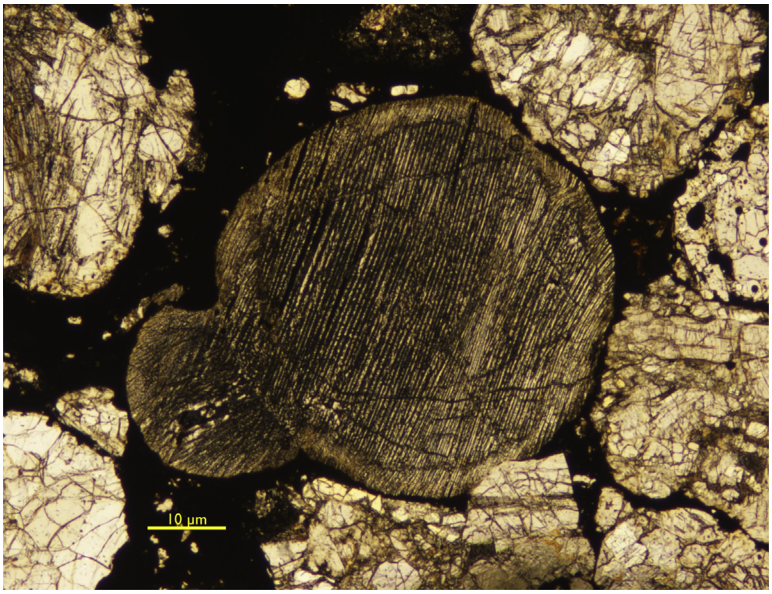

Fig. 1. A plane polarized light micrograph of a compound chondrule from the Semarkona thin section AMNH 4128-1.

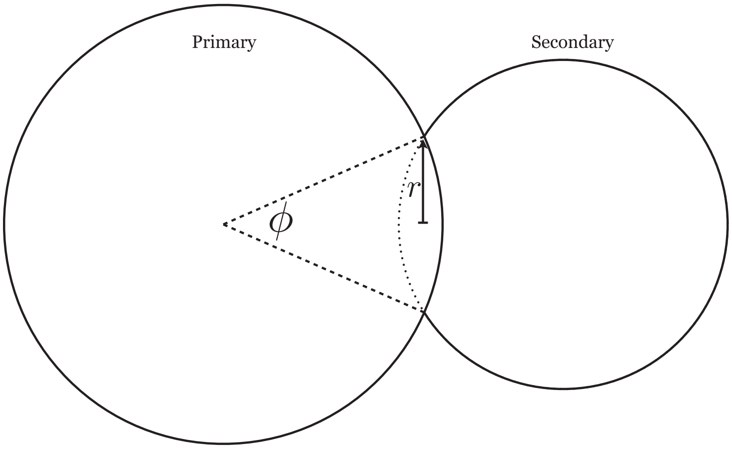

Fig. 2. Cartoon of a compound chondrule. The neck of the bridge has radius r, while ϕ is the contact angle.

collisional time scales. Note that we use the term "molten" to refer to chondrules sufficiently liquid that they collide as liquids, rather than solids. This is important because it allows the individual chondrules to collide at sufficiently elevated speeds that the observed *cc* frequency might be matched. In this paper, we consider only non-enveloping *cc*s and show that even at temperatures well below chondrule formation temperatures ($T \gtrsim 1700$ K, Hewins and Radomsky, 1990), droplet coalescence time scales are short compared to collisional time scales and that the molten-collision model cannot match the observed *cc* frequency. That means that the small contact angles observed are a major constraint, and imply that *cc* fusing had to occur relatively cold.

2. Viscosity and surface tension

Chondrules exhibit a range of sizes, compositions and textures (Weisberg, 1987; Wasson et al., 1995; Friedrich et al., 2014). Following previous studies of *cc*s (Ciesla et al., 2004; Desch et al., 2012), we adopt a characteristic chondrule radius of $a = 0.03$ cm, and a chondrule solid density $\rho = 3\ \mathrm{g\,cm^{-3}}$.

To understand the time scale on which molten chondrules in contact with each other would have flowed we need their surface tensions and viscosities. Chondrule melts had surface tensions on the order of

$$\gamma = 400\ \mathrm{dyn\,cm^{-1}} \tag{1}$$

(or $0.4\ \mathrm{N\,m^{-1}}$, Susa and Nakamoto, 2002).

We use Giordano et al. (2008) to calculate viscosities of chondrule melts.[1] Weisberg (1987) lists the composition of chondrules found in ordinary chondrites (see Table 1). We find that the viscosities for barred olivine/average chondrules in ordinary chondrites were bracketed by the values of those chondrules in H3 chondrites:

$$\log\eta = -3.55 + \frac{4557.8}{T - 618.2} \tag{2}$$

and

$$\log\eta = -3.55 + \frac{5084.9}{T - 584.9} \tag{3}$$

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[1] At the time of writing, a convenient on-line calculator can be found at http://www.eos.ubc.ca/krussell/VISCOSITY/grdViscosity.html.