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Semarkona: Lessons for chondrule and chondrite formation

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ABSTRACT

We consider the evidence presented by the LL3.0 chondrite Semarkona, including its chondrule fraction, chondrule size distribution and matrix thermal history. We show that no more than a modest fraction of the ambient matrix material in the Solar Nebula could have been melted into chondrules; and that much of the unprocessed matrix material must have been filtered out at some stage of Semarkona's parent body formation process. We conclude that agglomerations of many chondrules must have formed in the Solar Nebula, which implies that chondrules and matrix grains had quite different collisional sticking parameters. Further, we note that the absence of large melted objects in Semarkona means that chondrules must have exited the melting zone rapidly, before the chondrule agglomerations could form. The simplest explanation for this rapid exit is that chondrule melting occurred in surface layers of the disk. The newly formed, compact, chondrules then settled out of those layers on short time scales.

1. Introduction

There have been many recent advances in the field of planet formation, including an improved understanding of the earliest stage of growth where subcomponents are held together by electrostatic forces and chemical bonds. This stage starts with sub-micron interstellar dust and ends with planetesimals held together by gravity. Numerical simulations and experiments have allowed us to probe this coagulation regime (Güttler et al., 2010; Pan and Padoan, 2013), and have lead to the confirmation of collective behavior such as the Streaming Instability (SI, Youdin and Goodman, 2005; Johansen et al., 2007).

We apply this recent understanding to the chondritic meteorite Semarkona (see Fig. 1). An LL3.0 meteorite (Grossman and Brearley, 2005), Semarkona experienced very little parent body alteration, which means that it is an excellent record of the solids in the Solar Nebula. Of particular note is the fact that Semarkona is mostly made of chondrules about 0.5 mm in diameter, with the remainder being fine-grained matrix (Lobo et al., 2014). While these chondrules are certainly small from an every-day perspective, we will show that they are also too small to fit well with our current understanding of planetesimal formation. This is even more troubling because, as an LL chondrite, Semarkona's chondrules are relatively large (Weisberg et al., 2006). Constructing a theory for the formation of Semarkona's parent body is further complicated by the low temperatures recorded in the matrix.

These difficulties mean that Semarkona's components put significant constraints on models of the Solar Nebula and the earliest stages of planet formation, while those models conversely constrain our interpretations of laboratory investigations of Semarkona. We take some early steps in combining the laboratory data with analytical and numerical studies of dust dynamics in the Solar Nebula, considering formation scenarios in which chondrules were made by melting free-floating clumps of dust, and subsequently proceeded to parent body formation via gravitational collapse of dust clouds.

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2. Matrix processing fractions

2.1. Semarkona's chondrules and matrix

Semarkona is an LL3.0, shock stage 2 meteorite made up mostly of chondrules about 0.5 mm in diameter, plus about ~27% fine grained matrix by surface area (Grossman and Brearley, 2005; Lobo et al., 2014; Friedrich et al., 2014, see also Fig. 1). In this paper we assume that the chondrules were made by melting free-floating dust clumps, which requires ambient temperatures above 1700 K (Hewins and Radomsky, 1990). We use the term matrix to refer not only to the existing matrix material in Semarkona today, but also any dust in the Solar Nebula which would today be classified as matrix (i.e. not a chondrule) were it incorporated into Semarkona. Our model considers a time span during which heating converts matrix into chondrules, so the fraction of material labeled as matrix decreases over the interval we consider.

This free-floating dust was likely not pure pristine ISM material, presumably including already thermally processed material such as relict grains (Jones, 2012). For simplicity we assume that most of the thermal processing experienced by the non-chondrule portion of Semarkona was part of the chondrule forming process, and not a contaminant from elsewhere/elsewhen. In our framework this is a conservative hypothesis: if external heating is significant, then the amount of not-chondrule forming heating allowed in Eq. (4) is reduced, imposing stricter constraints.

Interestingly, while Semarkona's chondrules have a size spread, there are almost no 1 mm diameter chondrules in Semarkona, and no chondrules significantly larger than that (Lobo et al., 2014). This means that agglomerations of many average chondrules were not themselves melted, even though some of Semarkona's condrules show signs of several melting events interleaved with collisional growth (Weisberg and Prinz, 1996; Rubin, 2013, see also Fig. 1).

About half of Semarkona's matrix material was heated enough, above circa 800 K, to release the P3 gas component from the (likely) pre-solar nano-diamonds (Huss and Lewis, 1994), and other temperature probes suggest similar matrix temperatures for chondrites (Brearley, 1999). Of course, the heating that did occur may have happened after parent-body formation: more heavily altered meteorites show much more matrix heating. Nonetheless, even though these measurements provide only upper limits to the heating experienced by matrix material before parent body assemblage, they still allow us to construct a simple model to estimate how much of the ambient dust was melted into chondrules. We define c as the mass ratio of chondrules to all solids, m as the mass ratio of all matrix material to all solids ($c + m = 1$) and m_l as the mass ratio of non-heated (P3 not released) matrix material to all solids.

2.2. Thermal processing rates

We assume that solids encounter regions hot enough to make chondrules at a rate k_c. These regions have warm sheathes, too cool to melt chondrules, but hot enough to liberate the P3 component of the gas from the matrix, so every chondrule melting event will also process additional matrix material without melting it.

We can parameterize the rate k_h at which matrix loses the P3 component while remaining matrix material in terms of the chondrule melting rate:

$$k_h = gk_c. \tag{1}$$

We will quantify our results in terms of the (poorly constrained) parameter g which measures the rate at which dust is heated enough to release the P3 component, but not to melt. In many scenarios g reduces to the ratio of the volume of the warm sheathes around chondrule melting regions to the volume of those melting regions.

We also assume that the total system has a lifetime t, which we decompose into n intervals with $t = n\delta t$ and n large enough that $b = k_c\delta t$, with $b,\ gb \ll 1$. This allows us to estimate that, after a time $n\delta t$, the fraction of non-heated matrix to total solids and the fraction of total matrix to total solids are

$$m_l \simeq (1 - [1 + g]b)^n, \tag{2}$$

and

$$m \simeq (1 - b)^n, \tag{3}$$

respectively. From the pre-solar grain noble gas measurements we know that

$$\frac{m_l}{m} = \frac{(1 - [1 + g]b)^n}{(1 - b)^n} \gtrsim \frac{1}{2}. \tag{4}$$

Taking the logarithm of Eq. (4) and using $b,\ gb \ll 1$ we find

$$n([-b - gb] - [-b]) \gtrsim -\ln 2, \tag{5}$$

so

$$bn \lesssim \ln 2^{1/g}. \tag{6}$$

Finally, we find that the fraction of material not turned into chondrules is

$$m \simeq \exp(\ln[(1 - b)^n]) \gtrsim \frac{1}{2^{1/g}}. \tag{7}$$

We assume equality henceforth both for simplicity, and as an lower limit for the strength of the constraint.

2.3. Need for filtering

However, Semarkona is ~75% chondrule, so the fraction of non-chondrule to chondrule material in Semarkona is 1/3. If the planetesimal formation process makes use of all the chondrules and a fraction f of the matrix material, then

$$\frac{mf}{c} = \frac{2^{-1/g}f}{1 - 2^{-1/g}} = \frac{1}{3}. \tag{8}$$

Solving for the filtering fraction f, we arrive at

$$f = \frac{1}{3}(2^{1/g} - 1), \tag{9}$$

plotted in Fig. 2. Note that if $g < 0.5$, then chondrules make up more than 75% of the solids, so they, not matrix, need to be filtered out.

While the parameter g is as yet unstudied, the large difference between the chondrule melting temperature (~1700 K) and the matrix heating temperature (~800 K) suggests that hot sheathes around chondrule melting zones should be large. Boley et al. (2013), a study of planetesimal bow shocks as a chondrule formation mechanism, did not quantify the parameter g, but its figures suggest that 800 K is reached for impact parameters at least twice that required for melting chondrules, or $g > 3$. The initial conditions used in McNally et al. (2014), a study of magnetic heating, are above 800 K, which limits its ability to constrain g when interpreted as a model for a full disk as opposed to surface layers. However, that work also suggests large warm regions, i.e. a respectable g. Further, while there are quite a few mechanisms proposed to reach temperatures above 1700 K, those mechanisms can also fail, resulting in heating episodes that never achieve chondrule melting temperatures raising g even higher (McNally et al., 2013). The authors think that $g > 1$ is a quite conservative estimate; and even that value requires $f < 1/3$, which means that more than 2/3 of the matrix material must have been filtered out.

2.4. Complementarity

If the matrix and chondrules originally had different abundances from each other, then filtering would have altered the abundances of the assembled whole as compared to the mean abundances of the Solar Nebula's total solids. In particular, chondrule melting presumably evaporated volatiles which (in part) recondensed onto the matrix, some of which survived as matrix up to the parent body assemblage stage. If some of that surviving matrix was filtered out, the resulting chondrite would be volatile depleted.

As an LL chondrite, Semarkona is noteworthy for its low iron (and siderophile) abundances, a topic beyond the scope of this paper. However (once normalized to magnesium) Semarkona is approximately Solar in lithophile abundances down to the moderately volatile elements such as sodium and potassium (Weisberg et al., 2006), even though its matrix and chondrules have moderately different abundances from one another (Lobo et al., 2014). This anti-correlation between matrix and chondrules is known as "complementarity" (Hezel and Palme, 2010).

If a given element evaporated during the chondrule melting process, a significant fraction of the evaporated element would have recondensed onto the newly formed chondrules due to physical proximity. Nonetheless, we can approximate that a fraction e of the element would have both evaporated from the chondrules and recondensed on the matrix, which would otherwise have had identical abundances of that element. This results in the chondrules being depleted in the element by a fraction e, the matrix being enriched in the element by a fraction ec/m and the final bulk abundances depleted by a fraction

$$e\frac{c - fc}{c + fm}, \tag{10}$$

the shape of which is plotted in Fig. 3.

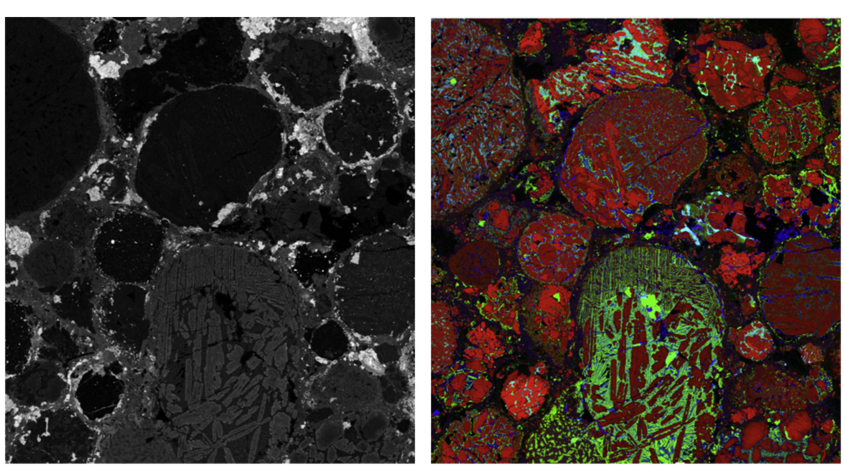

Fig. 1. Slice through Semarkona (portion of sample AMNH 4128-t1-ps1A, 3.35 × 3.65 mm). Left: Backscattered electron microscope. Right: Mg (red)–Ca (green)–Al (blue). One can see many sub-mm sized chondrules, and in the bottom-center a multi-zoned chondrule which was made by aggregating at least three chondrules. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)