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.

Keywords:
Asteroids, Asteroids, composition, Disks, Planetary formation, Solar Nebula

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 & Padoan, 2013), and have lead to the confirmation of collective behavior such as the Streaming Instability (SI, Youdin & Goodman, 2005; Johansen et al., 2007).

We apply this recent understanding to the chondritic meteorite Semarkona. An LL3.0 meteorite (Grossman & 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.

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 & Brearley, 2005; Lobo et al., 2014; Friedrich et al., 2014; see also Figure 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 & 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 Equation 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 chondrules show signs of several melting events interleaved with collisional growth (Weisberg & Prinz, 1996; Rubin, 2013, see also Figure 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 & 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:

$$k_h = g k_c.$$  \hspace{1cm} (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

$$m_t \simeq (1 - [1 + g]b)^n,$$

and

$$m \simeq (1 - b)^n,$$

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

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

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

$$n([-b - gb] - [-b]) \gtrsim - \ln 2, \quad (5)$$

so

$$bn \lesssim \ln 2^{1/g}. \quad (6)$$

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

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

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 $\sim 75\%$ 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

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

Solving for the filtering fraction $f$, we arrive at

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

plotted in Figure 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 ($\sim 1700$ K) and the matrix heating temperature ($\sim 800$ 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 bow shocks, 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 & Palme, 2010).

If a given element evaporated during the chondrule melting process, a significant fraction of the evaporated...
the shape of which is plotted in Figure 3.

Figure 3: Shape of the volatile depletion curve (Equation (10) with $e = 1$).

the 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 $e c / m$ and the final bulk abundances depleted by a fraction

$$e c / (e c + m),$$

Equation (10) implies that dust dynamics depends solely on the drag parameter. For filtering to have occurred, the ambient matrix grains and the chondrules (or chondrule assemblies) that went into Semarkona had to have had different Stokes numbers. The chondrule melting process itself can alter $St$ (Hubbard & Ebel, 2014). Dust Stokes numbers at the midplane of a disk are (assuming Epstein drag, appropriate for naked Semarkona chondrules):

$$St = \frac{\sqrt{2 c a \rho_s}}{\Sigma_g},$$

where $a$ is the dust grain radius, $\rho_s$ the dust solid density and $\Sigma_g$ the gas disk surface density. The chondrule melting process eliminates the matrix’s porosity, and so increases the grains’ densities $\rho_s$. This in turn increases the Stokes numbers of the chondrules as compared to the Stokes numbers of the matrix precursors.

3.2. Dust gravitational instabilities

At some point the cloud of chondrules which would make up Semarkona must have become gravitationally unstable, allowing the formation of Semarkona’s parent body. Using the observed Semarkona chondrule mean radius $a = 0.25 \text{mm}$, and a chondrule solid density of about $\rho_s = 3 \text{g cm}^{-3}$, Equation (13) implies that a naked chondrule has

$$St \approx 2 \times 10^{-3} \left( \frac{100 \text{g cm}^{-2}}{\Sigma_g} \right).$$

Note that $\Sigma_g = 100 \text{g cm}^{-2}$ is well below the Hayashi Minimum Mass Solar Nebula (MMSN) value of $\Sigma_g = 430 \text{g cm}^{-2}$ at $R = 2.5\text{AU}$, which in turn is far smaller than the more recent Desch MMSN value (Hayashi, 1981; Desch, 2007). Accordingly, Equation (14)’s value for chondrule Stokes numbers is a significant overestimate.

Even the largest, $\sim 1 \text{mm}$ diameter, chondrules in Semarkona have midplane $St \ll 10^{-2}$ for reasonable gas surface densities. We also note that at most half the solids could have been melted into chondrules ($g \geq 1$ implies $c < 0.5$, see Figure 2). This means that the expected chondrule-to-gas surface density ratio is less than half the
0.5% rock-to-gas mass ratio expected for the overall Solar Nebula, itself less than the 1.5% ice+rock-to-gas mass ratio (Lodders2003).

Clouds of very low $St$ dust can be self-gravitating, but achieving that is difficult. If there is any background turbulence, it will stir the dust, preventing the onset of gravitational instabilities (Weidenschilling1980). Even if there is no background turbulence, the dust will need to have settled into a very thin, Kelvin-Helmholtz unstable layer. Our current understanding is that if dust is nearly perfectly coupled to the gas ($St \ll 1$), it can become gravitationally unstable only for significantly, $> 4 \times$, super-Solar Nebular solid-to-gas mass ratios (Weidenschilling2006; Lee et al.2010). However, because most of the solids were in the free floating matrix, Semarkona’s chondrules have a much lower chondrule-to-gas mass ratio: that ratio for the chondrule population is $c/3 < 1/6$ for $g > 1$; where the factor of 3 converts between rock+ice to just rock as noted above. Direct formation of planetesimals through unaugmented gravitational instabilities of naked Semarkona chondrules is therefore ruled out.

3.3. Collective behavior

The above constraints can be alleviated by collective behavior such as the Streaming Instability (SI). In the $St < 1$ regime however, collective behavior between dust grains that lead to gravitational interactions still require significantly higher dust-to-gas surface density ratios, closer to 3% (two times the expected value for the Solar Nebula), and, further, those interactions only set in once the dust grains grow large enough that their Stokes numbers are $St > 10^{-2}$ (Johansen et al.2009; Bai & Stone2010). In the case of naked Semarkona chondrules, that would mean a gas surface density less than 20 g cm$^{-2}$, less than 5% of the Hayashi MMSN value, combined with an, at minimum, order of magnitude enhancement in the local chondrule-to-gas surface density ratio above values suggested by Lodders2003.

From Equation (13), we can see that to reach the minimum $St \gtrsim 10^{-2}$ required for the SI to act, non-porous objects with $\rho_s = 3 \text{ g cm}^{-3}$ in a MMSN with $\Sigma_g = 430 \text{ g cm}^{-2}$ would need to have a radius

$$a \gtrsim \frac{10^{-2} \Sigma_g}{\sqrt{2 \pi \rho_s}} \simeq 0.6 \text{ cm}, \quad (15)$$

more than 20 times larger than (and more than $10^4$ times as massive as) Semarkona’s $a = 0.25 \text{ mm}$ chondrules. Allowing for $\sim 50\%$ porosity, the radius increases to above 1 cm. Distinct clusters of chondrules, cluster chondrites, much closer to the size required by the SI (a significant fraction of 1 cm) are found in the meteoritical record, although their abundance in Semarkona is as yet unmeasured (Metzler2012). While not a dominant feature of their host chondrites, these clasts may represent the agglomerations required to proceed to the gravitational collapse of dust clouds in the Solar Nebula.

We conclude therefore that, even considering collective behavior such as the SI, naked Semarkona chondrules could not have proceeded to gravitational collapse into a parent body without significant intervening collisional growth: current dust dynamical theory does not otherwise allow for parent body formation. This also means that any changes in $St$ that resulted from melting cannot explain the filtering out of matrix material because those were not the $St$ values of the dust grains when gravity took over.

Significantly, the agglomerations that must resulted from collisional growth are not dominant in the meteoritical record, and the results of melting such agglomerations are not present. It follows that the chondrule melting location and the chondrule-agglomeration assembly location must have been distinct, either in space or time.

4. Collision resilience

The sizes, and hence Stokes numbers, reached by collisionally growing dust grains are controlled by bouncing and fragmentation. Dust grain collision speeds are determined by their Stokes numbers, with radial drift collision speeds scaling with $St$ (Weidenschilling1977). Turbulent induced collision speed scales as

$$v_c = \beta \sqrt{\alpha St} c_s \quad (16)$$

where $\alpha$ is Shakura-Sunyaev $\alpha$ parameter, here used to parameterize the turbulent diffusivity (Shakura & Sunyaev1973) and $\beta$ a factor of order unity. Equation (16) can be obtained on dimensional grounds (Voelk et al.1980) and numerical simulations have confirmed that $\beta \lesssim 1$ (Hubbard20122013; Pan & Padoan2013; Pan et al.2014). Combining these scalings with Equation (13) we can see that dust growth results in faster collisions.

When the characteristic collision speeds breach a threshold bouncing speed $v_h$, dust-dust encounters start resulting in growth-neutral bouncing events (Zsom et al.2010). This slows collisional growth, but the low velocity tail of the collision velocity distribution still allows coagulation (Windmark et al.2012). Laboratory studies have shown that $v_h$ is on the order of 1 mm s$^{-1}$ for the $\sim 10^{-4}$ g chondrules and chondrule precursors we consider (Göttler et al.2010). At an even higher collision speed threshold, $v_f \sim 100 \text{ cm s}^{-1}$, dust grains fragment, placing an effective cap on the dust grain $St$ values, and hence their sizes. A pile-up in dust sizes with $St$ values that concentrate the collision speeds above $v_h$ but below $v_f$ has been suggested as a cause of the narrowness of the chondrule size distribution (Jacquet2014).

Chondrule agglomerations must have grown collisionally in the Solar Nebula because Semarkona’s chondrules were too small to directly form parent bodies (Section 3.3). The size distribution of these agglomerations was controlled by $v_h$ and $v_f$. However, matrix grains also grew collisionally, with their own $v_h$ and $v_f$. To achieve filtering, the final, collisionally determined, $St$ distribution of
the matrix must have been different from that of the chondrule agglomerations.

Collision velocities themselves are only a function of \( St \), so if chondrule assemblages interacted with each other with the same critical \( v_b \) and \( v_f \) velocities as the matrix, then both the chondrule assemblages and the matrix would have grown to the same \( St \). If that were the case, matrix material could not have been filtered out at the planetesimal formation stage because the matrix and the chondrule assemblages would have obeyed identical dynamical equations. It follows that the fragmentation speed \( v_f \) (and likely the bouncing speed \( v_b \)) of chondrule assemblages must have been significantly higher than that of the matrix. Further laboratory experiments will be required to quantify this difference.

5. Chondrule melting location

Given that large chondrule agglomerations must have formed in the Solar Nebula (Section 3.3), it is surprising both that no melted high \( St \) agglomerations are seen in Semarkona, and that even unmelted distinct assemblages of chondrules are not dominant. Indeed, while there is evidence of small, mm-sized melted chondrule agglomerations or chondrule-matrix agglomerations (Rubin 2013, see also Figure 1), Semarkona’s chondrules have a conspicuously narrow size range (Lobo et al. 2014). This implies that, once melted, chondrules must have exited the melting zone on short timescales, before they could grow collisionally and be remelted. Semarkona chondrules were however limited in their ability to move large distances radially: their very low \( St \ll 1 \) means that they were well coupled to the gas, and so their radial motion was tied to the accretion flow of the disk.

Observations of extrasolar protostars suggest that the quasi-steady state accretion rate through the Solar Nebula was between \( 10^{-10} \) and \( 10^{-7.5} \) \( M_\odot/\text{yr} \) (Ingleby et al. 2013). This rate can be surpassed only briefly, for example during brief episodic accretion events such as FU Orionis type events (Hartmann & Kenyon 1996). For an Hayashi MMSN at \( R = 2.5 \text{ AU} \), the upper end of that accretion rate range implies an accretion velocity \( v_r = 20 \text{ cm s}^{-1} \) and a characteristic radial transport time \( r/v_r = 60 \text{ kyr} \). Those values are consistent with a viscous alpha disk with \( 10^{-3} < \alpha < 10^{-2} \) (Shakura & Sunyaev 1973). This means that removing chondrules from even a narrow radially demarcated melting zone would have taken too long to avoid melting large chondrule agglomerations.

Vertical settling is a more plausible way to have removed the chondrules from the melting zone. The vertical distribution of dust grains is controlled by the competition between gravity pulling the grains to the midplane and turbulence stirring the grains upwards. Dust, especially at the sub-mm size scale considered here, is expected to be very porous (Ormel et al. 2007, Blum & Wurm 2008), so non-porous chondrules have higher \( St \) than their (porous) precursor matrix grains. If the melting was restricted to surface layers, then the higher \( St \) chondrule would have settled out of the melting layer on sub-century time scales (Hubbard & Ebel 2014). Subsequently formed chondrule agglomerations, with even higher \( St \) values, would have been unable to reenter the melting layers. Settling does not further complicate complementarity because it requires that the matrix material is vertically well mixed by turbulence.

Further, this scenario also helps explain the fact that Semarkona’s chondrules are both small and have a narrow size distribution. With \( St \) numbers well below \( St = 10^{-3} \), the precursors to Semarkona’s chondrules would naively be expected to collide slowly enough to grow for all but the most violent turbulent stirring (see Section 4). However, dust grains of a given midplane \( St \) are well mixed with the gas up to a height

\[
H_d = \sqrt{2 \ln \left( \frac{1 + \alpha}{St} \right) H_g}
\]

where \( H_g \) is the gas scale height and \( \alpha \) the Shakura-Sunyaev \( \alpha \) parameter used to measure the turbulent diffusivity of the dust as in Section 4 (Dubrulle et al. 1995, Takeuchi & Lin 2002). This behavior is well fit by numerical simulations of turbulent disks (Fromang & Papaloizou 2006, Carballido et al. 2006). This means that only matrix grains with small enough \( St \) values could be lofted into the melting zone and provides a complement to the bouncing barrier in limiting the size distribution of chondrules (Jacquet 2014).

These constraints remain even when the ability of large dust grains to survive the melting process is considered. In the planetesimal bow shock model (Hood 1998), dust grains find themselves moving through gas at high velocity. Susa & Nakamoto (2002) considered the competition between ram pressure and surface tension for chondrule melts, and their results imply that \( a \sim 1 \text{ cm} \) grains could survive the shocks invoked by, e.g., Morris et al. (2012). That size is well above the observed chondrule size for Semarkona, so the fragmentation of melted chondrules by shocks is not an explanation for the lack of large chondrules.

6. Discussion and conclusions

We have identified three important constraints on the formation of Semarkona (and other chondrites). Firstly, laboratory studies have shown that Semarkona is a mixture of high temperature chondrules and cold matrix. Any reasonable chondrule melting mechanism will also heat a significant amount of matrix material enough to have experimental consequences, so this allows us to conclude that the chondrule-to-matrix ratio in the Solar Nebula must have been low. This is the case even though the experimental limits on the matrix's thermal history are weak, and quite possibly dominated by parent body processing rather than nebular processing (Huss & Lewis 1994). As a
result, for our uses the constraints are upper limits on the chondrule-to-matrix ratio in the Solar Nebula. The large amount of matrix material that was never heated to high temperatures (above 800 K) also rules out large scale spiral waves (Boss & Durisen 2005) as a chondrule melting mechanism for Semarkona because such waves would spare nothing.

Secondly, analytical and numerical studies of dust concentration have shown that naked Semarkona chondrules were too small to have directly proceeded to parent body formation. This problem is exacerbated by the modest chondrule melting efficiency mentioned above. It immediately follows that large chondrule agglomerations must have been made, where “large” means more than 20 average chondrule radii in size (so larger than the agglomerations considered in Weisberg & Prinz 1996). Finally, Semarkona’s chondrule-to-matrix ratio is much higher than the small nebular chondrule-to-matrix implied by the requirement that the matrix have remained cold. It follows that some form of filtering out of matrix material during parent body formation occurred.

From these constraints we can infer two significant consequences. Firstly, the results of melting large chondrule agglomerations is not seen in the meteoritical record (Friedrich et al. 2014), even though the agglomerations must have formed. We can therefore conclude that chondrules exited the melting region rapidly, before the agglomerations reached their final size. Due to the difficulty in moving objects the size of Semarkona’s chondrules radially in the Solar Nebula, we suggest that this motion was probably vertical settling to the midplane, assisted by the reduction in the drag parameter associated with melting a porous dust grain into a non-porous chondrule. This disfavors planetesimal bow shocks (Hood 1998; Morris et al. 2012) as the chondrule melting process for Semarkona because a significant number of the planetesimals producing those shocks must have been on low inclination orbits, resulting in midplane heating. On the other hand, magnetic heating mechanisms such as the short-circuit instability are well suited to surface layer heating (Hubbard et al. 2012; McNally et al. 2013). Protoplanetary disks are expected to have radially extended magnetically dead-zones where the ionization fraction is too low to support magnetic fields. However, these dead-zones are bounded above and below by magnetically active layers where non-thermal ionization is sufficient for magnetic fields to couple to the gas (Gammie 1996). This would naturally result in magnetically-mediated chondrule formation mechanisms having operated in upper layers of the Solar Nebula but not at the midplane.

Secondly, because matrix material had to have been filtered out at some stage of planetesimal formation, we conclude that the matrix dust must have had different drag parameters than the chondrule agglomerations. Theory predicts that collisional coagulation continues until dust grains grow large enough that their collisions result in bouncing or fragmentation, so we suggest that chondrule agglomerations were significantly more collision-resistant than chondrule-free matrix grains. This is not surprising, as chondrules, solid sub-mm objects, could develop coatings of fine dust (Flynn et al. 2013), which have been shown to dramatically increase the ability of chondrule analogs to stick (Beitz et al. 2012). Fractal matrix grains, made of sub-micron constituents, would not have been able to accrete such a coating. Further, chondrules could act as the weights of a bola, wrapping up chondrule agglomerations into low porosity, high contact area objects. This would be convenient because experiments performed for matrix-like material have found a fragmentation speed \( v_f \sim 100 \text{ cm s}^{-1} \) (Güttler et al. 2010). Those fragmentation speeds are difficult to reconcile with models of collective behavior and dust gravitational instabilities because they predict that dust grains large enough to trigger the collective behavior would be destroyed in dust-dust collisions for the bulk of protoplanetary disk model parameter space. Higher \( v_f \) chondrule agglomerations therefore provide an easier route to self-gravitating dust.

Our picture of surface layer chondrule melting is in tension with the picture put forward in Alexander et al. (2008) to explain the sodium found in Semarkona’s chondrules. They found that the distribution of sodium within Semarkona’s chondrules implies that they were melted in a dust cloud dense enough be gravitationally unstable, while high altitude melting would suggest relatively low dust densities. In this paper we have shown that concentrating naked Semarkona chondrules to a gravitationally unstable density is impossible under our current theoretical understanding. The problem is even worse for matrix precursors with even lower Stokes numbers. Further, if the self-gravitating dust cloud proposed in Alexander et al. (2008) was heated enough to melt chondrules, there would not be any surviving matrix material. This is a particular problem because a not-insubstantial amount of new matrix (not just cold matrix) would need to have been mixed in before the self-gravitating dust cloud collapsed to fit Semarkona’s chondrule-to-matrix ratio.

Other scenarios, such as chondrule melting in impact plumes which locally enhance the sodium partial pressure (Fedkin & Grossman 2013), have been proposed to explain sodium measurement. However, many chondrules do not possess abundant sodium (Weisberg et al. 2006), so some chondrule formation did result in the loss of volatiles. The diversity of chondrules means that multiple formation scenarios likely occurred; but if so, Semarkona’s chondrules could not have spent much time in a region where the volatile-depleting chondrule melting happened, or they would have been remelted and sodium depleted. This reinforces the argument that the chondrules must have exited the melting region rapidly, but the inference that melting occurred in surface layers can only be drawn if sodium-preserving melting scenarios can operate there.

While this analysis has focused on Semarkona, it also applies more generally. Semarkona’s chondrules are large for Ordinary Chondrites (OCs), and larger than chon-
drules in many Carbonaceous Chondrites (CCs) [Weisberg et al., 2006]. Accordingly, the observation that chondrules are too small to directly proceed to gravitational collapse or collective behavior such as the Streaming Instability is general. It follows that the need for forming large agglomerations is also general, although for in the case of CCs, with lower chondrule volume fractions, these agglomerations need not have been chondrule dominated. The result of melting these agglomerations is also not seen in the general meteoritical record, so the requirement of getting the chondrules out of their melting zone rapidly, before they could be incorporated into agglomerations, also remains.

While all OCs are dominated by chondrules, suggesting that filtering was needed, the chondrule mass fraction is lower in the CCs. For CCs, the need for filtering out matrix material depends much more significantly on the limits that can be placed on the matrix’s thermal history. Unfortunately, the matrix-material temperature history limits are poor, and convolved with parent body alteration, but the evidence suggests that a large fraction of the matrix material stayed quite cool across chondrites (Abreu & Brearley, 2011). However, we hope that, having shown that those temperature histories are an important clue to the nature of the Solar Nebula, we will see more experimental results constraining the maximum Solar Nebula temperature experienced by the matrix across the chondrite classifications. Further, we also hope that future numerical studies of chondrule heating will also consider the effect that lower temperatures have on the dust, and quantify the rate at which matrix material is heated.

Acknowledgments

This research has made use of the National Aeronautics and Space Administrations Astrophysics Data System Bibliographic Services. The work was supported by National Science Foundation, Cyberenabled Discovery Initiative grant AST08-35734, AAG grant AST10-09802, NASA OSS grant NNX14AJ56G and a Kalbfleisch Fellowship from the American Museum of Natural History.

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