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Chondrules: The Canonical and Non-canonical View

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\textbf{Key points:}

\begin{itemize}
  \item Chondrule formation
  \item Chondrites
  \item Evolution of solids in the early Solar System
\end{itemize}
Millimeter-scale rock particles called chondrules are the principal component of the most common meteorites, chondrites. Hence, chondrules were arguably the most abundant components of the early Solar System at the time of planetesimal accretion. Despite their fundamental importance, the existence of chondrules would not be predicted from current observations and models of young planetary systems. There are many different models for chondrule formation, but no single model satisfies the many constraints determined from their mineralogical and chemical properties, and from chondrule analog experiments. Significant recent progress has shown that several models can satisfy first-order constraints, and successfully reproduce chondrule thermal histories. However, second- and third-order constraints such as chondrule size ranges, open system behavior, oxidation states, reheating, and chemical diversity, have not generally been addressed. Chondrule formation models include those based on processes that are known to occur in protoplanetary disk environments, including interactions with the early active Sun, impacts and collisions between planetary bodies, and radiative heating. Other models for chondrule heating mechanisms are based on hypothetical processes that are possible but have not been observed, like shock waves, planetesimal bow shocks, and lightning. We examine the evidence for the canonical view of chondrule formation, in which chondrules were free-floating particles in the protoplanetary disk, and the non-canonical view, in which chondrules were the by-products of planetesimal formation. The fundamental difference between these approaches has a bearing on the importance of chondrules during planet formation, and the relevance of chondrules to interpreting the evolution of
protoplanetary disks and planetary systems.
Chondrules would not be predicted to exist if they did not exist. This may seem like an odd statement, but it is true. The millimeter-sized igneous spheres known as chondrules are the dominant structural component of chondritic meteorites (Fig. 1), the oldest rocks in our collections [Grossman, 1988; Brearley and Jones, 1998; Amelin et al., 2002; Connolly and Desch, 2004; Lauretta et al., 2006; Jones 2012]. However, from the point of view of astrophysics, astronomy, planetary science, and even geology, no one would predict that the most abundant objects within the hypothesized building blocks of the Earth-like planets would have been processed into small molten silicate spheres before accumulating in the earliest planetesimals. But they were. For over 150 years, science has puzzled over what process (or processes) could have produced them? Was the process that produced abundant melt droplets, which cooled into individual rock beads, something non-intuitive to science, to our common understanding of how planets were formed, or was their production merely the byproduct of forming planets so that it is totally understandable that they should have been produced? To answer these questions we can turn to the petrologic and geochemical record in chondrules themselves. What information can we use to constrain their origin and, perhaps more importantly, to constrain chondrule thermal histories, the environments in which they formed, and the origin and evolution of their chemical compositions? What do we really know for certain about chondrules and what lies in the realm of hypothesis and speculation? Do chondrules have any significance outside of the Solar System, and might we potentially...
observe the chondrule-forming phenomenon in other protoplanetary disks or young planetary systems?

We investigate chondrules to understand their significance in the rock record, their potential relationship to other processes that helped shape the early Solar System, and to solve a clear mystery: Why do chondrules exist? Merrill (1920) was the first to produce a practical review of proposed chondrule forming mechanisms, of which he reviewed at least twelve hypotheses that existed at the time of his writing. One of the best ways to make friends within meteoritics, and one of the best ways to make enemies in meteoritics, is to propose a new mechanism for the formation of chondrules. Proposed mechanisms range from hypotheses such as lightning, chemical reactions (essentially a kind of spontaneous combustion), nebular shock waves, magnetic current sheets, impacts or collisions of planetesimals, gamma ray bursts, and most recently radiative heating from planetesimals with molten surfaces, to name just a few [Sonett, 1979; Clayton, 1980; McBreen and Hanlon, 1999; Desch and Connolly, 2002; Ciesla and Hood, 2002; Joung et al., 2004; Desch et al., 2012; Sanders and Scott, 2012; Johnson et al., 2015; Herbst and Greenwood, 2016]. The key, however, is to know what constraints are of greatest importance when developing any hypothesis for a formation mechanism for chondrules. There are lots of variables that need to be accounted for when understanding how chondrules were formed, but it is the zero to first-order ones that are actually the critical ones to define (see Connolly and Desch, 2004). The major advances in the field of chondrule research within the last decade have included numerous analytical observations that add to the detailed inventory of chemical and isotopic constraints. More fundamentally, the exciting recent advances lie in the realm of modeling. Within this
review we focus our exploration of chondrules on what we need to know in order to constrain their formation, recent advances in modeling, and a discussion of what we know, don’t know, and would like to know about chondrules and their formation.

2. What we know about Chondrites

To begin, we need to place chondrules into context. *We know* that chondrules are found within most types of chondrites (Fig. 1). The name chondrite was coined by Gustav Rose in 1863, but he did not give chondrules their name [Rose, 1863; Connolly and Desch, 2004]. The name chondrite comes from the Greek word, chondros, and it is only slightly later that the word chondrule appears in the literature [Tschermak, 1885; Connolly and Desch, 2003]. Rose (1863) termed chondrules ‘kleine kugeln’, which was later altered by Tschermak (1885) to Kugelchen and chondren, which soon after was adopted by American and English scientists as chondrule and quickly gained popularity. There have been proposals to call other similar kinds of objects chondrules, such as lunar spherules. However, the suggestion never gained popularity within the scientific community [Symes et al., 1997]. For the purpose of this review, we will follow the historical definition of chondrules—they are found only in chondrites.

Chondrites are pieces of asteroids but, with one exception, we do not know precisely which chondrite groups come from what spectral type of asteroids [Bus and Binzel, 2002]. The exception is the Hayabusa sample return mission which returned pieces of S-type asteroid 25143 Itokawa: those samples are essentially identical to equilibrated ordinary chondrites (specifically LL5 chondrites: Yurimoto et al., 2011),
some of the most abundant meteorites found on Earth [Mason, 1960; Sears and Dodd, 1998; Brearley and Jones, 1998; Scott and Krot, 2005; Weisberg et al., 2006]. It is important to note that these rocks can be viewed as a kind of sedimentary, or accretionary, rock and that they contain structural components that were likely formed at different times and potentially different places within the protoplanetary disk or elsewhere. Their importance, based on what we know confidently about them, is several fold: (1) They provide a record of processes that occurred and materials that were formed before accretion of their parent asteroids [Clayton, 1981; Brearley and Jones, 1998; Scott and Krot, 2005; Weisberg et al., 2006], (2) Within a factor of two they all have a bulk composition (with the exception of the most volatile elements such as H, C, N, noble gases) similar to the Sun’s photosphere [Sears and Dodd, 1998; Brearley and Jones, 1998; Scott and Krot, 2005; Weisberg et al., 2006; Palme et al., 2014], (3) One of the structural components of chondrites known as refractory inclusions (of which, Calcium-rich Aluminum-rich Inclusions, CAIs, are the most dominant) provide the age of formation of the first solids in the Solar System at 4567 million years [Amelin et al., 2002; Bouvier and Wadhwa, 2010; Connelly et al., 2013], often referred to in meteoritics as \( t = 0 \) for the formation of Solar System solids. (4) They provide a chronological record of the evolution of rock-forming materials and rocks in the form of chondrules, which are mostly younger than refractory inclusions [Russell et al., 2006; Kita et al., 2012; Kita and Ushikubo, 2012; Bollard et al., 2013; 2014], (5) They contain organic compounds in addition to rock-forming minerals [Sephton, 2002; Pizzarello et al., 2006; Burton et al., 2012], (6) They contain presolar grains that were formed in other stars and thus preserve a record of some nucleosynthetic processes [Huss and Lewis, 1995; Brearley and Jones,
Some of them record geological processes such as thermal metamorphism and aqueous alteration that occurred within the earliest time period (tens of millions of years) after their accretion [Mason, 1967; Sears and Dodd, 1998; Brearley and Jones, 1998; Scott and Krot, 2005; Weisberg et al., 2006]. The other important aspect of chondrites that we know and thus relates to chondrules is that chondrites come from parent asteroids that found their way into Earth-crossing orbits as Near Earth Asteroids (NEAs) and were shed from such bodies, were trapped by Earth’s gravitational pull, and landed on the Earth.

3. What we know about chondrules

Before we explore potential mechanisms for chondrule formation, we need to define the pivotal variables upon which understanding anything about chondrule formation depends. The zero-order observation about chondrules is that they are igneous rocks, without question [Tschermak 1883; Merrill, 1920; Wood, 1963; Hewins, 1988; 1989; Wood, 1996; Jones et al., 2000; Connolly and Desch, 2004; Connolly, 2005; Hewins et al., 2005; Jones et al., 2005; Lauretta et al., 2006; Alexander and Ebel, 2012; Jones, 2012; Hewins and Zanda, 2012]. This means that the most fundamental variable to understand about chondrule formation, the first-order constraint, is their thermal history. An igneous rock is one that was melted and subsequently cooled. In some cases the cooling was relatively slow, slow enough for well-developed igneous textures to form. There are over 200 years of investigations on the formation of igneous rocks on Earth, an extensive literature that some chondrule researchers have capitalized on. Understanding
the thermal history of chondrules includes defining their peak melting temperatures, the
duration of melting, and the rates of cooling. The major method for constraining the
thermal history of chondrules is through a combined approach that utilizes analytical data
on natural chondrules, experimental petrology reproductions of chondrules, and
numerical modeling, with the first two being the ones that have provided the most
constraints.

Using a classic single-stage thermal history, the preponderance of data for the
thermal history of chondrules has been determined for the most abundant type of
chondrule, Fe,Mg-rich porphyritic chondrules [Jones and Scott, 1988; Jones, 1990, 1994,
1996; Connolly and Desch, 2004; Zanda, 2004; Scott and Krott, 2005; Lauretta et al.,
2006; Jones, 2012], meaning those chondrules dominated by well-formed crystals of
solid-solution minerals rich in MgO and/or FeO such as olivine and low-Ca pyroxene
(Figs. 2, 3, and 4). It has been shown that the extent of melting of chondrule precursors
depends on the peak melting temperature experienced, the duration of the melting event,
and the specifics of a chondrule’s composition, which defines the liquidus temperature,
i.e. the temperature of complete melting [Hewins et al., 2005]. Defining the peak melting
temperature of chondrules depends on the production of a non-porphyritic textural type
known as barred olivine (BO; Fig. 2a). Producing BO textures in the laboratory requires
very precise melting conditions from a peak temperature just slightly under or at the
liquidus temperature of an analog chondrule composition. The implications for natural
chondrule formation are that the production of BO chondrules means that they
experienced peak melting temperatures from 1750 to 2200°C, the range of liquidus
temperatures of BO chondrules [Hewins and Radomksy, 1990; Lofgren and Lanier, 1990;
The majority of chondrules, however, have porphyritic textures (Fig. 2b, c, d) requiring, depending on the duration of the heating events, an average peak temperature of approximately 1550°C. These experimental results largely depend on the fact that the chondrules are only partially melted and crystal growth occurs due to nucleation on existing mineral substrates that remain throughout the melting period. Nucleation sites may be (sub)microscopic. Alternative methods for crystal nucleation exist within chondrule melts, such as injection of seed grains [Connolly and Hewins, 1995], however, partial melting is the more widely accepted hypothesis for porphyritic chondrule formation. Factors that affect melting dynamics can include such variables as bulk composition, grain size, abundances of non-silicate phases, etc., however, these are all second to third-order variables that ultimately are not as important as maximum temperature of heating or heating duration for constraining chondrule formation models [Connolly and Desch, 2004].

Upon achieving peak temperatures, chondrules could not have been heated for an extended duration, and heating was limited to times on the order of many minutes to hours, unless specific conditions we discuss below were met. Prolonged heating would essentially have resulted in loss of all their volatile to moderately volatile elements such as Na, K, and S, which is not the case [Hewins et al., 2005]. Another first-order issue related to chondrule thermal histories is that there is strong evidence in the form of petrographic and geochemical features that multiple heating events occurred in chondrule-forming regions. At least 15% of all Fe,Mg-rich chondrules provide evidence for this repetitive heating process in the form of relict grains
(Fig. 3), igneous rims, and perhaps some types of compound chondrules [Nagahara, 1981; Rambalidi, 1981: Wasson and Rubin, 2003; Jones, 1996; Connolly and Desch, 2004; Jones, 2012]. Recently, studies by Bigolski et al. [2016] and Dobrica and Brearley [2016], who have investigated the nature of micro-chondrules and their formation, point to the formation of these tiny chondrules during repeated thermal recycling of chondrules. Survival of relict grains in chondrules also supports a short duration for heating at the peak temperature, because grains that are not in equilibrium with the host chondrule melt are resorbed into chondrule melts in timescales of minutes to hours [Hewins et al., 2005; Jones, 1996, 2012].

In order for chondrules to crystallize, they must have lost their heat. The loss of heat in an igneous system translates into a defined cooling rate. The cooling rate of an igneous rock is constrained by the following: (1) The overall silicate igneous texture exhibited by the rock, (2) Silicate crystal morphology, (3) Elemental zoning in individual mineral grains, (4) The presence or absence of glassy mesostasis, (5) Stability of metastable silicate polymorphs (such as clinoenstatite in chondrules). Since chondrules are igneous rocks, constraints on the rates at which they cooled can be obtained by investigating each of these variables. An extensive data set from natural samples and experiments defines cooling rates within chondrules [Jones and Scott, 1989; Jones, 1990, 1994, 1996; Jones and Lofgren, 1993; Connolly and Desch, 2004; Hewins et al., 2005; Miyamoto et al., 2009; Jacquet et al., 2015]. With the established data set, research founded in experimental petrology has established analog conditions that most closely reproduce chondrules in the laboratory, providing constraints on the natural conditions experienced by chondrules. Most porphyritic chondrules cooled between 0.5 and
100°C/hr, [Jones and Lofgren, 1993; Desch and Connolly, 2002; Hewins et al., 2005; Wick and Jones, 2012]. The slower end of the cooling rate spectrum is specific to type I chondrules as they cool through temperatures around 1000°C, and is required for crystallization of primary anorthite, the last phase to crystallize from an FeO-poor melt [Wick and Jones, 2012]. Also, diffusion profiles for Cu and Ga within FeNi-rich metal grains from chondrules in CR chondrites [Humayun, 2012] constrain cooling rates to 10–1000°C/hr for a temperature of 1200 ± 100°C with a maximum possible range of 0.1–400°C/hr over the temperature range of 926-1526°C. The view here is that the silicate and metal portions of chondrules record a similar thermal history. The use of metals as probes of chondrule cooling rates also provides some insight into their subsolidus histories.

Faster cooling rates, on the order of 1000 to 3000°C/hr, may have been necessary in order to produce non-porphyritic chondrules. However, no confident data set exists on how to actually constrain their cooling rates since for some of them it is impossible to know definitively at what temperature nucleation occurred.

A new area of research is focused on defining the subsolidus cooling rates experienced by chondrules, based on analysis of metal and sulfides, and referencing these data to that determined for the silicate part of chondrules. Most cooling rates that have been defined for chondrules only use the data generated from their silicate portion. Furthermore, experimental constraints do not generally apply to subsolidus temperatures—few such constraints have been generated (e.g. Weinbruch and Müller, 1995). The presence of opaque phases such as Fe,Ni metal and FeS allow constraints to be developed in the subsolidus temperature range (between 600-400°C); these fall around a few $10^2$ °C/hr for FeO-rich chondrules [Schrader et al., 2016; Mori et al., 2016].
cooling rates can be viewed as fairly consistent with data obtained for the silicate portion
of FeO-rich chondrules and may confirm a one-stage cooling process, which has always
been an underlying hypothesis for understanding chondrule cooling rates.

In order for any potential mechanism for forming chondrules to be taken
seriously, it must, first and foremost, quantitatively reproduce chondrule thermal
histories. To make an igneous rock, it is required that their precursors become melted and
cooled, it is that simple.

4. What we would like to know about chondrules: Formation mechanisms.

We would like to know precisely what mechanism produced chondrules, but we do
not, at least not yet. The list of hypothesized mechanisms for forming chondrules is long
and does not decrease over time. Connolly and Desch [2004] and Desch et al., [2012]
provide detailed reviews of the many different kinds of proposed chondrule-forming
mechanisms. We have categorized the various kinds of formation hypotheses into two
types of mechanisms: (A) Processes known to have occurred and (B) Processes unknown
to have occurred but possible. In order to evaluate these categories effectively, we need
to keep in mind our zero order observation, that chondrules are igneous, and the first-
order constraint that any model must satisfy quantitatively - chondrule thermal histories.

4.1. Known processes

4.1.1. Interactions with the early active Sun
It makes total sense to link chondrule formation to what had to be the most powerful energy source in the protoplanetary disk, the early active Sun. Sorby [1877] is generally given credit for linking chondrule formation to the Sun, but at the time of his publication there was no way to understand the nature of an embedded star in a protoplanetary disk. Also, he could not address chondrule thermal histories. Many models have been proposed over the years, most of them linking at least some of the work done in the production of chondrules to aspects of molecular outflow in young stellar objects [Skinner, 1990; Liffman, 1995; Liffman and Brown, 1996; Shu et al., 1996, 1997, 2001].

Although some of these researchers attempted to reproduce the first-order constraint on chondrule formation—thermal histories—they were not entirely successful. With each model some aspect of chondrule thermal histories is undeveloped, such as defining exactly the thermal histories of chondrules, what specifically is the work done by the mechanism on chondrule precursors to melt them, etc. (see Connolly and Desch, 2004; Desch et al., 2012). For more recent proposed models, such as those by Ireland and co-workers (2016) the jury is still out as to whether the models will be developed further and successfully reproduce chondrule thermal histories. Thus, the models can be considered promising hypotheses, but that is all that can be covered within this review.

4.1.2. Impacts and Collisions Between Planetary Bodies

Without question, we know that the pathway to creating a planetary body is to accrete material. The Earth would not exist if it were not for the accretion process. We know with a very high level of confidence that collisions occurred in the earliest time periods of the Solar System. But the question is: Could collisions during accretion have
produced chondrules? Until the very recent past, the production of chondrules via some kind of collision model, first reviewed in detail by Merrill [1920], has essentially been within the realm of unsupported hypotheses or ideas that often were qualitatively described, with little or no quantitative predictions attached to them (e.g. see Connolly and Desch, 2004). This all changed with the publication of a model by Asphaug et al. [2011] for chondrule formation during planetesimal accretion. Asphaug et al. [2011] produced a solid first attempt at answering the question and clearly their findings stimulated other groups to undertake further efforts. In their model, they assume that chondrules formed from the collision of molten or partially molten planetesimals. However, the details of how chondrules were heated to their peak melting temperatures and the value of those peak melting temperatures are not captured in their model. Thus the major issue with the model is that it does not meet our first-order requirement, which is accurately reproducing chondrule thermal histories. It is an excellent first attempt at quantitatively modeling chondrule formation via some kind of collisional event, but we cannot consider their model any further at this time because the thermal histories were not well constrained. The same argument can be applied to the work of Sanders and Scott [2012], who have championed the hypothesis of the collision of molten planetesimals.

Recently, however, considerable advances have been made in quantitatively reproducing chondrule thermal histories through impact jetting models, specifically the work of Johnson et al. [2014; 2015] and Hasegawa et al. [2016]. In these models, extreme pressure at the contact point of collision produces a jetting of molten material. In the 2015 paper, Johnson et al. demonstrate that the jetting model can achieve the first order
The above discussion is focused on the production of all chondrules in all chondrite groups by some kind of impact/collision scenario. An entirely separate discussion describes formation of chondrules and chondrule-like objects in the metal-rich CB and CH chondrites in an impact setting, but models for CB-CH components have not been reconciled with the models described above for more typical chondrules of C, O and E chondrites. There is wide agreement, but not universal, that individual components of the CB and CH chondrites were formed within a metal-rich impact plume [Kallemeyn et al., 1978; Campbell et al., 2002, 2005; Rubin et al., 2003; Goldstein et al., 2011; Fedkin et al., 2013]. The hypothesis is based both on the chondrules, many of which are non-porphyritic, and Fe,Ni metal particles, a population of which shows zoning that indicates condensation of solid metal from the gas phase. Chondrules in CB chondrites are also significantly younger than those in typical C, O and E chondrites, and it has been suggested that the young ages are consistent with an impact origin after the nebular gas had dissipated (Krot et al., 2005). However, CB and CH chondrites also contain CAIs and other nebular components, which are not considered to have formed in the impact plume as discussed by Krot and co-workers [2002], and this results in a need for complicated scenarios. At present, the state of the field is that impacts are called upon to explain features in CH-CB chondrites that differ from “typical” chondrules, whereas impact models such as those described above aim to explain “typical” chondrules. There does not appear to be a rational argument, that dictates that chondrules in one group of chondrites must have had their chondrules formed by impact, and chondrules in other
groups did not. Modeling through collision or impact of rocky bodies needs to be focused on the production of all chondrules (and we argue even igneous CAIs, see below) in all types of chondrites, if collisional models are to be considered as the dominant chondrule-forming mechanism.

The next step in modeling impact mechanisms for chondrule formation should be to focus on meeting the second and third-order constraints on chondrule formation, and account for constraints such as chemical and isotopic diversity among chondrules (see below).

4.1.3. Radiative heating

A very recent development in chondrule formation models is the proposal that chondrule formation occurred via radiative heating of dust clumps, in the vicinity of planetesimals that had incandescent lava at the surface (Herbst and Greenwood, 2016). Herbst and Greenwood (2016) show that this scenario reproduces the first-order thermal history constraints on chondrule formation. It does, however, remain to be evaluated within the community at large. It is not clear whether hot rocks on the surface of moving planetesimals will remain hot long enough for radiative heat to be a heat source for producing large volumes of chondrules, especially when considering it is an airless body. Furthermore, a more detailed treatment of how such radiative heat would interact with the gas within the disk, as well as the radiative effects between the gas and particles in the disk, would be helpful in evaluating this model for chondrule formation. As for impact and collision models, this model does show some promise in constraining the first order
variables of chondrule formation and now needs to focus on meeting second and third-
order constraints.

4.2. Chondrule-forming mechanisms based on hypothetical processes that we do not
know to have occurred but are possible.

The majority of hypothesized mechanisms for forming chondrules are not known
to have occurred. In contrast to the known phenomena of an active early Sun and impacts/
collisions, we do not know if lightning occurred within the protoplanetary disk, or if
nebular shock waves existed, if magnetic current sheets happened, if planetesimal bow
shocks occurred, and the list goes on (Jones et al., 2000; Connolly and Desch, 2004;
Connolly et al., 2006). These processes are predicted and plausible, but have not been
directly observed or inferred from independent phenomena. Chondrule formation via
nebular shock waves has been modeled extensively since the quantitative models of Iida
et al., [2001], Desch and Connolly [2002], and Ciesla and Hood [2002] were published
(see Desch et al., 2012 for a detail review) and this model remains a viable mechanism
for forming chondrules. Recently, significant advances have been made modeling
chondrule formation via planetesimal bow shocks and magnetic current sheets [McNally
et al., 2013; Morris and Desch, 2010; Morris et al., 2012; Boley et al., 2013; Mai et al.,
2016; Mann et al., 2016]. Like with nebular shock waves, magnetic current sheets and
planetesimal bow shocks meet the first-order requirement on chondrule formation,
quantitatively reproducing chondrule thermal histories. For all these models, diving
deeper into the variables that models should explain for chondrule formation is
warranted. However, the major issue with these genres of models is that they are and
might remain unknown to have occurred. Thus, the models proposed are reproducing chondrules without knowing what actually produced them (in the case of nebular shock waves) or if the proposed mechanisms actually existed. For some researchers this may be uncomfortable, but it is a scientifically sound approach.

5. The Canonical vs. the Non-canonical View: Is there resolution?

The base-line hypothesis for models that are linked to the early active Sun, as well as most models that lie in the realm of purely hypothesized, is that chondrules were free-floating wanderers within an environment in the protoplanetary disk. Since this assumption underlies most interpretations of chondrules, it has become a canonical, or well-accepted, viewpoint. Chondrule formation is, in the meteorite and cosmochemistry community, traditionally linked to planet formation in that chondrules are thermally processed before they are accreted to small asteroids and thus the process that formed them is a step towards forming planets. The vast majority of solids that went into accreting planetesimals were therefore processed at high temperature before accretion. This view has, with some exceptions, been the prevailing view in the community. It may also afford chondrules a special place in science: arguments for local gravitational collapse and rapid accretion following chondrule formation [Alexander et al., 2008; Alexander and Ebel, 2012; Jones 2012] offer a solution to the problem of growing km-sized bodies which are essential to planet formation (e.g. Youdin and Shu, 2002). Another way to view the importance of the hypothesis that chondrules were free-floating wanderers is that if you want to make an asteroid/planetesimal, and thus a planet, you
must first make chondrules. The interesting exception to this hypothesis is that in order for planetary bow shocks to have occurred, planetesimals must have existed. Yet the models basically assume that chondrule precursors were free-floating wanderers that were caught up in the shock wave produced by the planetesimals moving. Although this sounds like a chicken-and-egg argument, there is no reason to exclude the possibility that the earliest generation planetesimals were themselves formed from chondrules. We do not know whether the materials that formed the earliest differentiated asteroids (e.g. timescales of <1 million years after CAI formation for iron meteorites – Kleine et al., [2009]) were processed through chondrule-forming events: by definition, we only see chondrules from chondritic parent bodies that escaped large-scale melting.

The non-canonical view, which has existed since the dawn of meteoritics but has only recently been gaining wide popularity, is that chondrules are the byproducts of forming planetesimals. Chondrules may not have a special place in science with regards to building planets. As has been pointed out by Connolly and Desch [2004] and recently Johnson et al. [2015], if chondrules are formed by some kind of collision process they become the by-products of making planetesimals and thus their perceived importance in the formation of planets becomes rather insignificant. The issue of whether chondrules formed before planetesimals or are a by-product of forming planetesimals becomes even more complex to resolve if we bring into the equation the formation of igneous CAIs. The only type of igneous CAI for which we have any compelling constraints on their thermal histories is type B. Thermal histories of type B CAIs are constrained by the major element distributions in the major minerals, combined with the appearance temperature of the Ti-rich pyroxene phase colloquially known as fassaite. These thermal histories
overlap with conditions that type I chondrules experienced [Desch and Connolly, 2002; Desch et al., 2012; Wick and Jones, 2012]. Cooling rates for type B CAIs are on the order of 0.5-50°C/hr [Stolper and Paque, 1986; see Beckett et al., 2006], whereas type I chondrules cooled at rates 0.5-100°C/hr (see above). It should be noted that these cooling rates were determined from laboratory experiments and that higher cooling rates are possible. However, the quoted rates are the ones that best reproduce type B CAIs and type I chondrules, both with respect to their igneous textures and elemental distributions in individual mineral phases. Therefore, with reference to our zero-order observation of chondrules, igneous CAIs are just that, igneous. Yet the meteorite and cosmochemistry community at large do not model igneous CAI formation through any type of collisional model. The ‘party line’ is that CAIs are ‘more important’ than chondrules largely due to the fact that they have important isotopic anomalies (e.g., relatively high abundance of light oxygen (16O), significant evidence for live 26Al, etc.) and that they are significantly older than chondrules, by about 2 My (Kita et al., 2005; Russell et al., 2006). Without question they are thought of as precursors to planetesimals, harboring live 26Al needed for early melting and differentiation. This results in an assumed need to provide one mechanism to form igneous CAIs and perhaps a second to form chondrules, when it is completely unknown what might have formed either set of objects. Occam’s razor dictates that if both objects are igneous and experienced similar thermal histories, the mechanism that formed these objects was the same, with the key issue being the evolution of composition over time (assuming the objects were not formed contemporaneously) and / or space.
It is important for an understanding of the mechanism that produced chondrules, and arguably that which produced other igneous objects within chondrites, to constrain the two major hypotheses as the starting state of chondrules: Were they free-floating wanderers or the by-product of events such as collisions? Can we definitively determine constraints that can refute one of these two hypotheses? Currently, there appears to be no firm way to discern which one is stronger and whether one can be firmly refuted. The main reason for this conundrum is because each genera of models makes a basic assumption: either chondrule precursors existed as individual objects, (usually considered to consist of mineral aggregates with a somewhat fractal range of grain sizes), before melting, or they were not, requiring their precursors were housed as part of some kind of parent body.

6. What we would like to know about chondrules: Second and third order constraints on chondrule formation.

It is important when attempting to model chondrule-forming mechanisms that we follow a hierarchy of variables, and that we do not get stuck in details related to certain variables that we term second or third order constraints on chondrule formation until the first-order constraints have been satisfied.

*We would like to know* if, at least in part, chondrules formed as open systems as defined by Wood (1996), meaning they both lost and gained elements (or oxides) to and/or from gases within the environment, while they were molten [Yu and Hewins, 1998; Hewins et al., 2005; Lauretta et al., 2006; Libourel et al., 2006; Alexander et al.,
Isotopic exchange between chondrule melts and gas is quite possible: in particular, experiments have demonstrated that oxygen isotope exchange could have taken place between molten chondrules and the surrounding gas [Yu et al., 1995; Di Rocco and Pack, 2015]. However, the extent of chemical changes that may have occurred during the chondrule-forming process is more difficult to quantify. The bottom line is that all the constraints generated to solve this issue are if-then statements, with perhaps one exception. One petrographic/petrologic fact is inescapable: chondrules record variability in redox conditions potentially due to either differences in their precursors, changes in environmental conditions, or a combination of both. [Wood, 1963; Nagahara, 1981a; McSween et al., 1983; Grossman, 1988; Hewins, 1989; Connolly et al., 1994; Jones, 1996; Jones et al., 2005; Lauretta et al., 2006; Villeneuve et al., 2015]. Some chondrules have minerals rich in FeO, others do not, and the latter are often rich in opaque mineral phases such as FeNi metal or FeS, providing additional evidence for low oxygen fugacity (fO2) before and/or during formation.

What we do not know is if chondrules reacted with their surrounding gas with respect to other elements exchanging, such as Na or Si. They may well have: for example, mineralogical zonation of chondrules that have olivine in the interior surrounded by a shell of pyroxene has been attributed to condensation of SiO during chondrule formation [Tissandier et al., 2002; Krot et al., 2004; Libourel et al., 2006; Friend et al., 2016]. Also, there is no clear isotopic anomaly within chondrules that points unequivocally to whether evaporation or condensation-exchange must have occurred [Cuzzi and Alexander, 2006]. In addition to not completely understanding the extent of exchange that took place, we do not know whether exchange was purely an effect related
to the environment of chondrule formation or was it also a consequence of the mechanism that produced them, or both?

We would like to know how molten chondrules remained stable within a protoplanetary disk environment. Melt droplets in such a disk, where the total pressure of H$_2$ (the predominant gas species) must have been exceedingly low, should have evaporated to gas and not formed molten silicate droplets. And even though silicate melts are not thermodynamically stable in this environment, we know from chondrule cooling rates that melts persisted during chondrule formation for periods of at least several hours. But chondrules formed. Thus something about our basic astrophysical framework for understanding total pressure within the protoplanetary disk is not intuitive when we factor chondrules (and igneous CAIs) into the equation. Many mechanisms have been proposed to stabilize chondrule liquids through a variety of alterations to the partial pressure of ambient gas, but in the end we simply do not know how chondrule melts survived their heating cycles. An obvious question to explore is: Was the environment in which chondrules formed controlled, at least in part, by the mechanism that formed them, or was it independent of any kind of mechanism and simply reflects local environmental conditions? For example, an elevated gas pressure, needed to retain volatiles in chondrule melts, could have been produced by the chondrule formation event, by evaporating fine-grained dust [Desch and Connolly, 2002].

The abundance of Na within olivine phenocrysts of FeO-rich chondrules has been interpreted to suggest that the overall abundance of Na in the chondrule forming region was considerably higher than expected for a gas of solar composition, and this may require a high abundances of solids in the area during chondrule formation [Alexander et
The model suggests that the solids would evaporate, increasing the gas in elements such as Na. The needed environment for chondrule formation may have been produced by some kind of collision event as suggested by Alexander et al., [2008], although other hypothesis for chondrule-forming mechanisms such as nebular shock waves cannot be ruled out. Thus, although there is no unique solution yet offered for the retention of high amounts of Na in chondrule olivines observed by Alexander and co-workers [2008], it is important to note that the environments where FeO-rich chondrules formed were not devoid of moderately volatile elements such as Na. This fact strengthens an important concept—chondrules formed as systems that were not isolated from their surroundings.

We would like to know why chondrules are chemically diverse. As stated above, chondrules are in general similar to solar compositions within a factor of two, but this fact hides a lot of complexity. The various different chemical and textural types of chondrules are present in almost all chondrite groups. But individual chondrules have diverse compositions and they are clearly not all derived from a homogeneous precursor. The relative abundances of different textural types of chondrules within different chondrite classes and groups have been reviewed elsewhere (Brearley and Jones, 1998; Jones, 2012). As discussed above, CH and CB chondrites are an exception because they have high abundances of non-porphyritic chondrules (e.g. Lauretta et al., 2006): there is strong support for formation of chondrules in these groups in an impact plume following collisions of two planetesimals [Kallemeyn et al., 1978; Campbell et al., 2002, 2005; Rubin et al., 2003; Goldstein et al., 2011; Fedkin et al., 2013]. For the mainstream carbonaceous, ordinary and enstatite chondrites, the fact that different textures exist
points to the clear conclusions that not all chondrules had the same homogeneous source material, or experienced the same thermal and redox conditions during their formation. If they did, they would all have similar or identical textures. An obvious issue raised is: What was controlling the overall chemical composition of chondrules? And whatever it was, does it have anything to do with the mechanism that melted them?

We know that the overall relative size range for chondrules is from a few tens of μm (micro-chondrules: Bigolski et al., 2016; Dobrica et al., 2016) to cm in size [Prinz et al., 1988], but we would like to know why this is the case. Large chondrules on the order of several mm to cm-sized are rare. Chondrule sizes vary significantly among different chondrite groups, and in some cases their sizes are so diagnostic of a specific chondrite group that they can be used for classification purposes (Jones, 2012). Overall the mean size for chondrules in different carbonaceous, ordinary, and enstatite chondrite groups varies from approximately 0.2 mm to 1 mm. The important issues to explore related to chondrule size range are: Why is there so much variation between chondrule sizes from different chondrite groups? Why are there not abundant larger chondrules (e.g., cm-sized)? Is the production of their size ranges informing on the general relationship between how chondrules were produced, their local formation environment, something about the availability of material being processed into chondrules, a sorting mechanism that operated after (and independently of) chondrule formation, or some or all of the above factors?

We know that chondrules were recycled, as discussed above. The recognition of previous generations of chondrule olivine and pyroxene, igneous rims and possibly micro-chondrules are powerful constraints that indicate that chondrules experienced more
than one heating event and that during each event not every chondrule experienced the
same thermal histories as they did during the previous event that produced them. But
important questions remain: We would like to know how many times chondrules were
recycled. Can we constrain the thermal conditions of the repeated heating? What
constraints do the compositions of relict grains and igneous rims provide about chondrule
precursor compositions and the evolution of their compositions?

We would like to know why chondrules from different chondrite groups have
unique properties that are characteristic of that group. Within a given class or group,
chondrules have a specific size range, distribution of textural types, chemistry of silicate
minerals, oxygen isotopic compositions, assemblage of sulfide minerals, metal
abundance, and distribution of relict grains (Jones, 2012). What controls these factors,
many of which are stochastic and show no correlative relationships? And why is each
chondrite group unique – does the variability require rapid accretion of localized
accretion within chondrule-forming regions? Does each chondrite group equate to a
unique planetesimal, and if so what was the original size of that body?

We would like to know the relationship between all types of chondrules and
refractory inclusions, particularly igneous CAIs. Are they even related? How did their
very different compositions originate and evolve? If we adopt the current thinking for a
potential age difference between CAIs and chondrules of about 2 million years, with
chondrules being younger [Kita et al., 2005; Russell et al., 2006], the materials that were
being processed into igneous spheres started off being rather rare, refractory materials
and evolved to what can be considered very common minerals such as olivine and
pyroxene. Why? Was this evolution being controlled by the mechanism that melted them,
their environment of formation (for example the degree of condensation of solids from
the nebular gas at the time of heating), both, or some yet unforeseen process?

We would like to know for certain what properties of chondrules were solely
controlled by their formation mechanism, their environments of formation, or both. The
environment where chondrules were formed as recorded by them may have nothing to do
with the mechanism(s) that formed them, and science has yet to set definitive
requirements on how to determine this issue.

7. Conclusions and Wider Implications

The very existence of chondrules presents us with some fundamental questions
about the origin of the solar system and formation of the planets. The simple and obvious
problem is that we would like to know how chondrules formed. This is more than just an
intriguing, unsolved scientific puzzle. If we knew how chondrules formed, we would
have a greater understanding of whether chondrules played an essential and formative
role in planet formation, or whether they are insignificant by-products of a common
process such as collisions between planetesimals and planetary embryos. Chondrule
formation models have made significant progress recently. Several models now
successfully address the first-order constraints of thermal histories that chondrule
observations require. However, some of these models rely on processes that are
predicted, but are not known to have occurred within the protoplanetary disk
environment, so that they remain hypothetical. The challenge for chondrule formation
models is to advance to the level in which they address second- and third-order
constraints that must also be satisfied for a successful solution.
Beyond advancing our understanding of our own origins, we would like to know if chondrules have any cosmic significance outside of the Solar System. Whether they are either the basic building blocks of planetesimals and hence planets, or the by-product of their making, other solar systems that contain terrestrial-like planets should have also seen an epoch where chondrules were produced. It is unlikely that we will know in the near future if observations of evolving planetary systems contain chondrules—they may be too small to distinguish from individual groups of mineral grains. It would, however, be a fundamentally important data point in understanding the formation of terrestrial-like planets, if such a process was observed.

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**Figure 1.** A backscatter electron image (BEI) of a thin section of the unequilibrated ordinary chondrite (UOC) QUE 97008, which is an L(LL) (3.05). The L(LL) classification means that this chondrite is from the L or, less likely, the LL group of UOC, and 3.05 indicates that it has undergone very little geological processing (e.g., thermal metamorphism) within its parent body since it was first accreted. The abundant circular and fragmented objects are chondrules. UOCs contain up to 85 vol% chondrules. The difference in grey scale within a BEI indicates compositional differences: phases with higher average Z are brighter, with Fe, Ni-metal grains and FeS grains showing up as bright white grains, and silicates are grey to almost black in color.

**Figure 2.** (a) A BEI of a type I (FeO-poor) classic barred olivine (BO) chondrule from the L(LL) 3.05 unequilibrated ordinary chondrite, MET 00452. (b) A BEI of a type I BO chondrule, but with a more complex texture than that shown in Fig. 2a. Note the large metal grain within the chondrule (the white grain in the upper right corner of the chondrule) and the large circular olivine grain amongst the thin olivine bars.

**Figure 3.** (a) A BEI of a classic porphyritic olivine chondrule from QUE 97008 L 3.05 UOC, which is rich in Fe, Ni-rich metal (white grains). (b) A BEI of a porphyritic pyroxene chondrule from MET 00452, an L(LL) 3.05 UOC.

**Figure 4.** BEIs of type I chondrules from (a) MET 00542 and (b) QUE 97008 UOCs. These contain relict grains known as dusty olivines (arrows) which are grains hypothesized to have been produced in a previous generation of chondrule formation.

**Figure 5.** BEIs of classic type II (FeO-rich) porphyritic olivine chondrules from the quintessential UOC Semarkona (LL 3.00). Notice the main phase, olivine, is highly zoned (seen as changes in grey scale) indicating changes in FeO content of the phenocrysts (melt grown crystals) from initially more MgO in their cores to less MgO and more FeO by the end of their growth.
Figure 1.
Figure 2.
Figure 3.
Figure 5.