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The importance of experiments: Constraints on chondrule formation models

Steven J. DESCH[1*], Melissa A. MORRIS[1], Harold C. CONNOLLY, Jr.[2,3,4], and Alan P. BOSS[5]

[1]School of Earth and Space Exploration, Arizona State University, P.O. Box 871404, Tempe, Arizona 85287–1404, USA
[2]Kingsborough Community College and the Graduate Center of the City University of New York, 2001 Oriental Boulevard, Brooklyn, New York 11235–2398, USA
[3]American Museum of Natural History, Central Park West at 79th Street, New York, New York 10024–5192, USA
[4]Lunar and Planetary Laboratory, 1629 E. University Blvd., The University of Arizona, Tucson, Arizona 85721–0092, USA
[5]Department of Terrestrial Magnetism, Carnegie Institution of Washington, 5241 Broad Branch Rd NW, Washington, DC 20015–1305, USA
[*]Corresponding author. E-mail: steve.desch@asu.edu

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Abstract–We review a number of constraints that have been placed on the formation of chondrules and show how these can be used to test chondrule formation models. Four models in particular are examined: the "X-wind" model (sudden exposure to sunlight <0.1 AU from the proto-Sun, with subsequent launching in a magnetocentrifugal outflow); solar nebula lightning; nebular shocks driven by eccentric planetesimals; and nebular shocks driven by diskwide gravitational instabilities. We show that constraints on the thermal histories of chondrules during their melting and crystallization are the most powerful constraints and provide the least ambiguous tests of the chondrule formation models. Such constraints strongly favor melting of chondrules in nebular shocks. Shocks driven by gravitational instabilities are somewhat favored over planetesimal bow shocks.

INTRODUCTION

Chondrules are igneous inclusions found in abundance in chondrites, unmelted meteorites. Their properties have been extensively reviewed (Grossman et al. 1988; Jones et al. 2000, 2005; Connolly and Desch 2004; Hewins et al. 2005; Rubin 2005, 2010; Connolly et al. 2006; Lauretta et al. 2006). Chondrules typically are hundreds of microns in size and are comprised of ferromagnesian silicates, olivines, and pyroxenes. Their textures indicate that each chondrule was (almost) completely molten and then crystallized from a melt. The timing of their melting is inferred from Al-Mg isotopic systematics to have occurred at the birth of the solar system, ~ 2 Myr after the formation of calcium-rich, aluminum-rich inclusions, or CAIs (Wadhwa and Russell 2000; Amelin et al. 2002). That is, chondrules were melted during the gas-rich stage of the solar nebula. In ordinary chondrites they make up as much as 80% of the mass of the chondrite, and an initial mass of chondrules $>10^{24}$ g (Grossman et al. 1988), and conceivably $>10^{27}$ g (Morris and Desch 2009) has been inferred. The energy required to melt even $\sim 10^{24}$ g of rock (roughly 3,000,000,000,000,000,000,000,000,000 chondrules!) exceeds 10^{34} erg. Chondrules bear witness to the earliest events in the solar system, during the epoch of planetary growth. Their testimony is that the solar nebula experienced energetic processes strong enough to melt planets' worth of rock distributed among a myriad grains freely floating in space.

Ever since their igneous textures were recognized (Sorby 1877), models for the melting mechanism have been sought to better understand the environment and processes relevant to planet formation. Models can be categorized according to the energy sources they tap to melt the chondrules. Some models invoke melting by virtue of being near the Sun, either due to sunlight and solar flares (the X-wind model of Shu et al. 1996, 1997, 2001) or by ablation in the bipolar outflow that accompanies the proto-Sun (Skinner 1990; Liffman and Brown 1996; Liffman 2009). Some models identify chondrules as melt droplets produced during collisions between planetary bodies (Urey and Craig 1953; Urey 1967; Sanders 1996; Sanders and Taylor 2005; Asphaug et al. 2011). All other models take place in the gas of the solar nebula. Some invoke electromagnetic phenomena, such as magnetic flares (Levy and Araki 1989), current sheets (Joung et al. 2004), or lightning (Morfill et al. 1993; Pilipp et al. 1998; Desch and Cuzzi 2000). Others invoke shock fronts passing through the gas (Wood 1963, 1996; Iida et al. 2001; Ciesla and Hood 2002; Desch and Connolly 2002; Desch et al. 2005; Miura and Nakamoto 2006; Morris and Desch 2010). Physical mechanisms for triggering shock waves that have been proposed include: X-ray flares impinging on the top of the disk (Nakamoto et al. 2005); clumpy accretion (Boss and Graham 1993) or an accretion shock onto the top of the disk (Ruzmaikina and Ip 1994); accretion shocks in a Jovian subnebula (Nelson and Ruffert 2005); shocks produced by planetesimal impacts (Hood et al. 2009); bow shocks around eccentric planetesimals (Hood 1998; Weidenschilling et al. 1998; Ciesla et al. 2004; Hood et al. 2005, 2009); and shocks driven by gravitational instabilities in the disk (Wood 1984, 1985, 1996; Desch and Connolly 2002; Boss and Durisen 2005; Boley and Durisen 2008). Suffice it to say that theorists have not suffered from a lack of imagination as they have attempted to model chondrule formation.

Conclusively identifying the mechanism(s) that melted chondrules requires elimination of those models that do not predict observed properties of chondrules. Chondrules are amenable to many types of analyses, including studies of their petrology and mineralogy, their compositions, their magnetizations, as well as isotopic studies that can be used to date their formation, among other things. Besides direct measurements of chondrules, experimentalists can also prepare and melt chondrule analogs in a controlled fashion. Such analyses lead to a number of constraints on chondrule formation, which we group into two types: those that constrain chondrule thermal histories before, during, and after melting; and all other, ''non-thermal,'' constraints. In the Constraints on Chondrule Formation section we review these constraints.

The constraints on chondrule formation can be used to discriminate between viable and nonviable models of chondrule formation, provided the models make quantitative predictions. Of the many models listed above, not all have been developed to the point where they can make quantitative, testable predictions. An impact origin seems likely for a subset of chondrules, those from CH/CB chondrites, as we discuss in the Asteroid Collisions section. We limit all other discussion to more well-developed models: the X-wind model (Shu et al. 1996, 2001); nebular lightning (e.g., Desch and Cuzzi 2000); planetesimal bow shocks (e.g., Hood et al. 2009); and nebular shocks driven by gravitational instabilities (e.g., Morris and Desch 2010). In the Chondrule Formation Models section, we review the physical basis of each model and outline the predictions or assumptions each makes about chondrule formation.

In the Comparison of Model Predictions and Constraints section, we compare and test these models against the experimental constraints. We show that the constraints not pertaining to thermal histories leave some ambiguity, but the constraints on thermal histories are especially diagnostic. The crucial constraints come from furnace experiments on chondrule analogs. An origin in shocks, probably large-scale shocks, such as those driven by gravitational instabilities, is strongly favored by these experiments.

CONSTRAINTS ON CHONDRULE FORMATION

Constraints on Thermal Histories

It is useful to first discuss the constraints on chondrule thermal histories. It has been widely recognized for about a decade and a half that chondrules, with their igneous textures, were ''flash heated'' from low temperatures to above their liquidus (Lofgren and Lanier 1990; Radomsky and Hewins 1990; Hewins and Connolly 1996; Lofgren 1996; Hewins 1997; Connolly and Love 1998; Jones et al. 2000; Connolly and Desch 2004; Ciesla 2005; Hewins et al. 2005; Connolly et al. 2006; Lauretta et al. 2006), then cooled at a rate slow enough to allow crystals to form (see Desch and Connolly 2002; Hewins et al. 2005; Connolly et al. 2006; Lauretta et al. 2006; Miyamoto et al. 2009). But quantification of ''flash heated'' and ''slowly cooled'' have required careful study of the melting of chondrule analogs.

The chondrule precursors, before they were melted, must have formed in a region with temperature <650 K (depending somewhat on total pressure and sulfur fugacity). This is inferred from the fact that they contain S in the form of primary sulfides that are poikilitically enclosed in phenocrysts in the chondrules (Rubin 1999). This requires S to exist in the melt, and S only condenses (as troilite) below 650 K.

As chondrules heated to their melting temperatures, the rate of heating was apparently rapid. Once chondrules exceeded their solidus temperatures and were partially melted (roughly 1400 K; Hewins and Radomsky 1990; Hewins and Connolly 1996), volatiles such as Na and K should have escaped within a matter of minutes (Yu et al. 2005; Yu and Hewins 1996, 1997, 1998). Likewise, the lack of isotopic fractionation of volatile species, such as K, S, and even Fe, indicates they did not have time to evaporate significantly, and so the chondrules must have been heated above their solidus temperatures in a matter of minutes (Yu et al. 1998; Tachibana et al. 2002; Tachibana and Huss 2005). It is important to note here and elsewhere the important caveat that volatile species lost from the chondrule may re-enter the chondrule from the gas phase. A high partial pressure of volatile vapor, such as Na or K can suppress evaporation and prevent Rayleigh distillation. As the chondrule cools, more of the volatile vapor can recondense into the chondrule melt and diffuse through it, likewise erasing volatile depletions and isotopic fractionation in the chondrules. The extent to which volatiles recondense into chondrules is not known. If substantial recondensation occurs, the rate of heating is less well constrained. We return to this point below.

The peak temperatures reached by chondrules are constrained by their textures. In radial pyroxene and barred olivine chondrules, which comprise 10–13% of all chondrules in ordinary chondrites (Gooding and Keil 1981), nearly all nucleation sites must be destroyed, which requires peak temperatures at least 150–400 K above the liquidus. Assuming a liquidus temperature $T_{\rm liq} \approx 1400$–1700°C (~1670–1970 K; Hewins and Radomsky 1990), this implies barred or radial textures require $T_{\rm peak}$ in the broad range ≈1820–2370 K. In barred olivine chondrules, the need to retain just a few nucleation sites restricts this stage of peak heating to minutes only (Hewins and Connolly 1994; Tsuchiyama et al. 2004). Radial pyroxene textures are produced by crystallization from a supercooled melt in which no nucleation sites remained and therefore provide few constraints on the time scale of heating (Lofgren and Russell 1986; Connolly and Hewins 1995). Porphyritic textures, which are found in about 84% of chondrules in ordinary chondrites (Gooding and Keil 1981), require retention of many (hundreds of) nucleation sites, and peak temperatures 80–120 K above the liquidus, i.e., $T_{\rm peak} \approx 1750$–2100 K, for only minutes (Hewins and Connolly 1996). The textural constraints on duration of heating and peak temperature are somewhat degenerate, in that more intense heating for a shorter time may yield the same textures.

Upper limits to the duration of heating come from the retention of volatiles. Chondrules retain primary Na, which would completely and rapidly evaporate from a molten chondrule above the liquidus. In their furnace experiments using chondrule analogs, Yu et al. (1995) and Yu and Hewins (1998) found that Na was lost in about 20 min at 1725–1760 K, in an H_2 atmosphere at pressure 10^{-5}atm. S can be lost under similar conditions in only 2–10 min (Yu et al. 1995; Cohen and Hewins 2004). In these experiments, retention of Na or S at elevated temperatures—roughly speaking, the liquidus—requires cooling rates exceeding $\sim 10^3$ K h^{-1}. In these same experiments, the chondrule analogs were allowed to cool at slower rates ≈ 250 K h^{-1} below the liquidus. Volatile loss was not found to be significantly affected by prolonged cooling at lower temperatures.

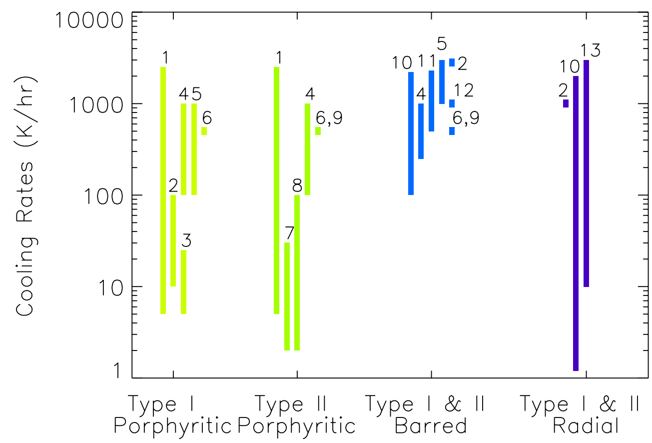

Fig. 1. Cooling rates of chondrules of various textures. The shaded bars represent combinations of compositions and cooling rates that have successfully produced various chondrule textures in different experiments. Produced textures include type I porphyritic textures (PO/POP), type II porphyritic textures (PO/POP/PP/PPO), barred textures (BO/BP), and radial textures (RP). The numbers denote different experimental investigations: 1. Lofgren and Russell (1986); 2. De Hart and Lofgren (1996); 3. Wick et al. (2010); 4. Radomsky and Hewins (1990); 5. Lofgren (1989); 6. Connolly and Hewins (1991); 7. Weinbruch and Müller (1995); 8. Jones and Lofgren (1993); 9. Connolly et al. (1998); 10. Kennedy et al. (1993); 11. Lofgren and Lanier (1990); 12. Tsuchiyama et al. (2004); 13. Hewins et al. (1981).

Here, we repeat the caveat that evaporation of volatiles like S and Na may have been suppressed by high partial pressures of these species in the gas. Alexander et al. (2008) have argued for high partial pressures of Na vapor during chondrule formation, based on the existence of unzoned Na in olivine phenocrysts in some porphyritic chondrules. This Na must have been present in the melt as the crystal grew. Based on the partitioning of Na in the melt, high partial pressures of Na, $> 10^{-4}$ bar, can be inferred from the data presented by Alexander et al. (2008). As these partial pressures are comparable with the *total* pressure of gas in the chondrule-forming region, this constraint must be viewed with suspicion; nevertheless, the presence of Na in the olivine must be explained. To the extent that evaporation was suppressed by high partial pressures of Na, this constraint on the rapid cooling above the liquidus is loosened.

Chondrule textures and chemical zoning profiles of single crystals provide further constraints on the thermal histories of chondrules, and reveal that below the liquidus temperature, chondrules very clearly cooled at a much slower rate than the rates above the liquidus temperature alluded to above. Figure 1 summarizes these experimental investigations. For each investigation referenced, a range of cooling rates is shaded that yielded textures and/or mineral chemical zoning consistent with observations of chondrules. The results have been separated by chondrule textural type; from left to right these are: type I (reduced Fe) porphyritic olivine/porphyritic olivine-pyroxene; type II (FeO-rich) porphyritic; type I and II barred olivine/barred pyroxene; and type I and type II radial pyroxene. Porphyritic chondrules of both type I and II apparently cooled at rates that did not exceed a few $\times 10^3$ K h^{-1}. Faster cooling rates result in skeletal, cryptocrystalline, or glassy textures that are not common in the chondrule population. The lower end of the range of cooling rates that are consistent with porphyritic textures is not as well constrained. Weinbruch et al. (1998) attempted to establish a minimum cooling rate consistent with little loss of Fe from the chondrule melt, and concluded that a few K h^{-1} probably represented a lower bound. There is some evidence that cooling rates nearer to this lower bound are more consistent with the specific chemical zoning profile grains in porphyritic chondrules for both type I and type II chondrule compositions (Jones and Lofgren 1993). Barred chondrules also cannot cool faster than a few $\times 10^3$ K h^{-1}, but unlike porphyritic chondrules, their textures and chemical zoning profiles seem to require a minimum cooling rate of a few $\times 10^2$ K h^{-1}. Radial pyroxene chondrules apparently are produced by sudden crystallization of a supercooled melt, and can be reproduced in furnace experiments by a wide range of cooling rates (Lofgren and Russell 1986; Hewins et al. 2005). As such, they are probably less diagnostic of the conditions in the chondrule-forming region.

Altogether, the constraints on thermal histories paint a detailed picture of how chondrules were melted. Chondrule precursors started at the ambient temperature of the nebula, <650 K. If retention of volatiles like Na or S is diagnostic of cooling rates, chondrules were then heated rapidly, reached peak temperatures in the range 1700–2300 K, and then cooled very rapidly, at 10^3–10^4 K h^{-1}, remaining above their liquidus temperatures for no more than about 10 min. In any event, after cooling several hundred K, the chondrules then crystallized over a range of temperatures $\approx$1400–1800 K, at rates that probably were different for the different textural types. Barred olivine chondrules cooled in less than an hour, at rates $\sim 10^3$ K h^{-1}. Porphyritic chondrules, which comprise the majority of chondrules, cooled at rates in the range 10–10^3 K h^{-1}, with the chemical zoning favoring a cooling rate at the lower end of that range.

"Non-Thermal" Constraints

In addition to the constraints on the thermal histories of chondrules during their melting, there are many other constraints on chondrule formation that constrain the timing and frequency of chondrule formation, as well as the physical conditions in the chondrule formation region. The density of chondrules is constrained by the frequency of compound chondrules. A fraction $f_c \approx 5\%$ of all chondrules in ordinary chondrites are compound (Ciesla et al. 2004), meaning they stuck together while still plastic, i.e., above the solidus temperature $\approx$1400 K. Assuming chondrules cooled at rates of $t_{\rm plast} \sim 0.6$–60 h, they would have been above 1400 K and remained plastic for a duration $t_{\rm plast} \sim 0.6$–60 h. An upper limit to the relative velocity of chondrules is $V_{\rm rel} < 10^4$ cm s^{-1}, as collisions at higher relative velocities would shatter the chondrules (Ciesla et al. 2004), but a more likely relative velocity (based on turbulent motions) is $\sim 10^2$ cm s^{-1} (Cuzzi and Hogan 2003). Given a chondrule radius $a_c \sim 300\,\mu$m, it is straightforward to show that the number density of chondrules must have been $n_c \sim f_c(4\pi a_c^2 V_{\rm rel} t_{\rm plast})^{-1} \sim 2$ m^{-3}, and the mass density $n_c m_c \approx 7 \times 10^{-10}$ cm^{-3} (for $t_{\rm plast} = 6$ h and $m_c = 3.7 \times 10^{-4}$ g). The existence of compound chondrules also constrains the size of the chondrule formation region: to achieve these compound chondrule frequencies, the region must be large enough that chondrules stood a reasonable chance of colliding. As the mean free path of chondrules is $l_{\rm mfp} = (n_c \pi a_c^2)^{-1}$, a region $\gg 10^3$ km is demanded.

A size of the chondrule formation region $\approx$150–6000 km in radius also can be inferred by the limits on volatile loss experienced by chondrules (Cuzzi and Alexander 2006). Chondrules should have experienced evaporation of K, Fe, Mg, and Si-containing vapor during their long heating stage, and while they are relatively depleted in these species (Alexander 2004; Davis et al. 2005), they do not exhibit the systematic isotopic fractionations indicative of Rayleigh distillation (Cuzzi and Alexander 2006). Thus, it is presumed that the vapor lost from chondrules remained in the vicinity of the chondrules, raising the partial pressures of these volatile species in the gas, and limiting further evaporation and isotopic fractionation. As the chondrules cooled, these species could recondense onto chondrules or matrix grains. To avoid evaporation of volatile species, such as Na and K, and especially S, high gas pressures $>10^{-3}$atm also are inferred (Ebel and Grossman 2000; Miura et al. 2002; Alexander 2004). This interpretation also requires that the volatile-enriched gas does not diffuse away from the heated chondrules while they are molten. Estimates of the rate of diffusion in the gas led Cuzzi and Alexander (2006) to conclude that the chondrule-forming region was $>10^3$ km in extent.

The existence of type I chondrules in which Fe exists as reduced metal or sulfides, and type II chondrules in which Fe is oxidized (usually as fayalite), has sometimes been interpreted as a constraint on the oxygen fugacity of the nebular gas (Huang et al. 1996; Hewins 1997). In contrast, Krot et al. (2000) conclude that these phases are not controlled by an equilibrium between the chondrule melt and the nebula gas, instead representing internally buffered systems. They interpret the variable oxidation of Fe as reflecting different chondrule precursor compositions. For example, some FeO-poor chondrules show evidence for reduction of FeO by internal C (Connolly et al. 1994). The existence of type I and type II chondrules therefore does not place unambiguous constraints on the nebular conditions or even the chondrule formation process, but may place constraints on the starting compositions of chondrules.

An important, if debated, constraint on the chondrule formation region is the chemical complementarity between chondrules and matrix grains. This term refers to the fact that chondrules and matrix grains may each deviate in their chemical abundances from a standard chondritic abundance pattern, but together their sum lies much closer to solar (CI). This strongly implies that the chondrules and matrix are cogenetic and formed in the same environment. Evidence for chondrule-matrix complementarity and cogeneticity has been observed in various chondrite classes, such as OC (Wood 1985), CV (Palme et al. 1993; Murakami and Ikeda 1994; Hezel and Palme 2008), CR (Klerner and Palme 1999), and other carbonaceous chondrites (Bland et al. 2005). It is essential in such studies to correct for parent-body redistributions of species from the chondrules to the matrix, e.g., by aqueous alteration, which also produce the chondrule-matrix complementarity pattern. Such redistributions certainly have occurred (e.g., Krot et al. 1995; Zanda et al. 2009). It is currently debated how much complementarity can be attributed to preaccretionary redistributions.

The chondrule formation process was not a one-time event, but rather was a repeated process. Relict chondrules (or fragments thereof) are commonly found inside other chondrules, speaking directly to at least two chondrule-forming events (Jones 1996; Jones et al. 2000; Ruzicka et al. 2008). Besides chondrules, relict grains may also contain fragments of asteroidal clasts or even planetary materials (Libourel and Krot 2007; Libourel and Chaussidon 2011), although this interpretation is currently debated. If established, this would place strong constraints on the timing of planetary formation.

The timing of chondrule formation is well established from isotopic analyses of chondrules. Al-Mg systematics of chondrules in carbonaceous and unequilibrated ordinary chondrites reveal a variety of initial $^{26}Al/^{27}Al$ values; if interpreted chronologically, these data suggest that extant chondrules in these chondrites formed any time starting 1.5 Myr after CAIs, ending 3–4 Myr after CAIs, with the bulk of chondrules having formed 2–3 Myr after CAIs (Kurahashi et al. 2008; Villeneuve et al. 2009). There is marginal evidence in that data set for clustering of chondrule ages at specific times (Kurahashi et al. 2008; Villeneuve et al. 2009). These ages are consistent with absolute U-Pb dating of chondrules and CAIs, which likewise reveal an age difference of 2 Myr between CAIs and chondrules, albeit from different chondrite classes (Amelin et al. 2002; Connelly et al. 2008). A general caveat to these investigations is that chondrules may have been forming earlier than 2 Myr after CAIs, yet simply did not survive. A chondrite parent body forming < 2 Myr after CAIs would contain so much ^{26}Al that it should completely melt (Grimm and McSween 1993), erasing most of the earlier chondrule record. Indeed, Bizzarro et al. (2004) have argued for contemporaneous formation of CAIs and chondrules. What is clear is that chondrule formation was a repeated event occurring over a timespan lasting several million years.

Finally, remanent magnetization of chondrules in the past has been used as a constraint on the chondrule formation environment. Previous studies have suggested that chondrites (e.g., Allende) experienced unidirectional paleofields of strength 0.1–1 G, and chondrules experienced nonunidirectional paleofields of strength 1–10 G (see review by Weiss et al. [2010] and references therein). Sophisticated modern techniques of characterization of remanent magnetization (Weiss et al. 2010) have shown that in fact very few chondrites actually record paleofields. Allende itself does record a paleofield, but of strength $\sim$1 G, and in components that formed 8 Myr after CAIs. As such, it would appear that the remanent magnetization is recording a parent-body dynamo, with interesting consequences (Weiss et al. 2010). Evidence for a high-temperature and nonunidirectional (i.e., preaccretionary) magnetization of chondrules exists, and is very suggestive that chondrules were individually magnetized as they cooled through their Curie temperatures but not conclusive at this time (Weiss et al. 2010).

CHONDRULE FORMATION MODELS

Asteroid Collisions

Production of chondrules as melt droplets produced during collisions of asteroids has long been suggested (Urey and Craig 1953; Urey 1967; Sanders 1996; Sanders and Taylor 2005; Asphaug et al. 2011). Such models have not been developed to the point that they can be quantitatively matched against even such fundamental constraints as the cooling rate through the crystallization temperatures. For example, a simple estimate of the cooling rate would place an isolated melt droplet in free space, in which case it would cool at a rate

$$\frac{dT}{dt} \sim \frac{4\pi a_c^2 \sigma T^4}{m_c C_P} \sim 10^6 \mathrm{K\,h^{-1}}, \quad (1)$$

where $a_c \approx 300\,\mu$m, $m_c \approx 3.7 \times 10^{-4}$ g, and $C_P \approx 1.4 \times 10^7 \mathrm{erg\,g^{-1}\,K^{-1}}$ are reasonable values for the droplet's radius, mass, and heat capacity. Unless moderated somehow, this cooling rate is far too fast to match chondrule textures. The cooling rate would be moderated by the presence of some gas, but unlike nebular models of chondrule formation, here the ratio of droplet mass to gas is not fixed. The cooling rate would also be moderated by the radiation emitted from nearby droplets, but here the details depend on the mass of ejected droplets, their geometrical distribution, and the speed with which they move away from the impact, as well as many other factors. Although these parameters could in theory be determined, no models to date include such factors, so it is simply not possible at this point in time to quantitatively test the asteroid impact hypothesis.

We nevertheless discuss this scenario because there is strong evidence for an impact origin of some chondrules, namely those in the CB (Bencubbin-like) and related CH (carbonaceous, high-metal) chondrites, and the chondrite Isheyevo, which shares properties of both and therefore indicates a common origin for the CB and CH chondrites (Ivanova et al. 2006) These chondrites are remarkable for their very high metal content ($>40\%$), extreme depletions in even moderately volatile elements, and extreme enrichments in ^{15}N (Weisberg et al. 2001). Most (CBa and CH) do not contain fine-grained matrix, only distinct clasts of finer material, arguing for a planetary rather than nebular setting. A distinct origin for the CH/CB chondrites is also indicated by the very late formation of the CB chondrites Gujba and Hammada al Hamra 237, as measured by Pb-Pb ages: some 5–6 Myr after CAIs (Krot et al. 2005). CH chondrites contain only very small chondrules, $\approx 20\,\mu$m in diameter (Campbell et al. 2005), an order of magnitude smaller than nearly all other chondrules (e.g., Grossman et al. 1988). Nearly all of the chondrules in CBa chondrites are cryptocrystalline (Campbell et al. 2005), in marked contrast to chondrules in ordinary chondrites, which are nearly all ($>80\%$) of porphyritic texture, with only a few percent of cryptocrystalline texture (e.g., Grossman et al. 1988). CBb chondrites also contain abundant zoned metal spherules that appear to have condensed from a hot gas (Petaev et al. 2001). All of these factors indicate an origin quite distinct from other chondrules and chondrites, but consistent with formation in an impact plume (Krot et al. 2005).

Quantitative models of chondrule formation in CH and CB chondrites are to be encouraged to more strongly make the case that these objects formed in an impact plume following a collision between asteroids. Should such an origin be established, although it does not follow that most chondrules formed during asteroid impacts, as the CH/CB chondrites, are so different from other chondrites. In fact, an impact origin for the CH/CB chondrites would tend to argue against an impact origin for the majority of chondrules, even as it might establish multiple formation mechanisms for chondrules. The lack of detailed modeling precludes further conclusions about the role of impacts in chondrule formation, and we turn our attention instead to more quantitative models.

X-Wind

One proposed setting for chondrule formation is in the disk near where the proto-Sun's magnetosphere truncates the protoplanetary disk. The interaction between the disk and the Sun's magnetic fields yields an "X"-shaped geometry for the magnetic field at this location, called the X point. Typically the X point is predicted to lie <0.1 AU from the Sun. The bending of the magnetic field lines, coupled with the rotating geometry, yields a magnetocentrifugal outflow that carries off gas and angular momentum. The combination of the geometry and the outflow have led this model to be named the X-wind model. In a series of studies, Frank Shu and collaborators developed the X-wind model, first to explain protostellar bipolar outflows (Najita and Shu 1994; Shu et al. 1994, 1995; Ostriker and Shu 1995), and later to explain chondrule and CAI formation (Shu et al. 1996, 1997, 2001).

In the context of the X-wind model, chondrules are heated as they are lofted from the disk in the magnetocentrifugal outflow. Temperatures in disks, at least those not being heated by active accretion, are much lower than the blackbody temperature at that radius, for the simple fact that disks absorb starlight obliquely yet radiate it from their entire surface areas. Shu et al. (1996) estimated temperatures in the disk at 0.1 AU would be 1160 K (for a disk in the "embedded" stage), and chondrules within the disk would start at these temperatures. After the chondrule is lofted as part of the upward outflow, it is exposed to direct sunlight and reaches a higher temperature, 1700 K at 0.1 AU. The time it takes for this temperature rise is the time it takes for a chondrule to cross a scale height, which may be as short as hours to days. Upon reaching the peak temperature, the chondrule cools at a rate dependent upon how fast it can move away from the Sun. As the blackbody temperature of an object varies with heliocentric distance r as $T(r) \propto r^{-1/2}$, $\mathrm{d}T/\mathrm{d}t = -(T/2r)\, V_r$, where the radial velocity $V_r \approx 50\,\mathrm{km\,s^{-1}}$. A chondrule therefore necessarily cools through the crystallization temperature range at a steady rate $\sim(1800\,\mathrm{K})\ (2 \times 0.05\,\mathrm{AU})^{-1}(50\,\mathrm{km\,s^{-1}}) = 6\,\mathrm{K\,h^{-1}}$.

Desch et al. (2010) have recently critiqued the X-wind model and its ability to explain CAI and chondrule formation, and short-lived radionuclide production in manners consistent with the meteoritic record. Other estimates of physical parameters in the X-wind environment have been discussed extensively and can be found in the study by Desch et al. (2010).

Nebular Lightning

A different proposed setting for the melting of chondrule precursors is near lightning bolts in the solar nebula. As in terrestrial lightning, charge separation in the nebular gas may occur and increase electric fields to the point where the gas suffers electrical breakdown. Electrons are always accelerated by the electric field between collisions with molecules; in an electrical breakdown situation, the electric field is great enough that electrons acquire sufficient energy to ionize the next molecule they hit; each new collision increases the number of electrons exponentially in a runaway process. The increased electron density increases the electrical conductivity, allowing large amounts of charge to be moved between the charge centers in the nebular gas through a thin, ionized channel. (In terrestrial lightning this channel is typically only 10–10^3 electron mean free paths wide, or a few millimeters; Desch et al. 2002.) Ultimately, the movement of charge through the channel neutralizes the opposite charges in the separate charge centers in the nebular gas, but along the way Ohmic heating in the channel raises the temperature to many $\times 10^3$ K. Where terrestrial lightning hits sandy soil, fulgurites (melted rock) can be produced. It is reasonable to suppose nebular lightning could melt chondrules too.

Examples of nebular lightning models include those of Gibbard et al. (1997) and Pilipp et al. (1998), which rely on separation of charge across the scale height of the nebula, and that of Desch and Cuzzi (2000), which relies on separation of charge by turbulent eddies. All models involve channels at least hundreds of km long, possibly much longer. Given the mean free paths of electrons at typical nebular pressures ($P \sim 10^{-5}$atm), the channel widths are probably 1–10 m wide. Most models of nebular lightning focus on the prerequisite charge separation and initiation of electrical breakdown, and on the total energy liberated per lightning bolt, but not on the modeling of how chondrules are melted in the channel.

Based on lightning models, we infer how chondrules would be melted and what their thermal histories would be. Desch and Cuzzi (2000) estimated that a single lightning bolt would liberate $\sim 3 \times 10^{17}$ erg of energy into a channel >300 km long and >10 m wide, yielding an energy density $\sim 3000\,\mathrm{erg\,cm^{-3}}$, about 50 times higher than the energy density of the surrounding gas. This energy is carried by electrons, with a number density $\sim 10^{15}\,\mathrm{cm^{-3}}$ and temperature $T \sim 10^4$ K. The energy flux delivered by electrons to chondrules is sufficient to vaporize the chondrules in the channel; chondrules outside the channel are not immediately affected, except by radiation that may be emitted during this stage. Due to its overpressure, although the channel rapidly expands at a fraction of the sound speed (several $\mathrm{km\,s^{-1}}$), until its density drops and the pressure has dropped by a factor ∼50, so that the heated gas is in pressure equilibrium again with the nebula gas. This requires the expansion of the channel radius by a factor < 10, i.e., to a radius $\sim 10^2$ m. The expansion must take on order < 0.1 s. During this expansion of the channel, chondrules may or may not be pushed outward.

After the expansion of the channel, the gas will cool on a slightly longer time scale. As it does, the surrounding gas will compress it until the original density and temperature are restored. Chondrules may be heated by the initial pulse of radiation associated with the lightning bolt, but otherwise they are primarily heated by exchange with the gas. Desch (2000) argued that the chemical energy of H_2 recombination may more directly heat chondrules during this stage. Regardless, it is unlikely that this stage lasts very long. In a heated cylinder of gas 300 km long and just 100 m in radius, assuming a gas density $\sim 10^{-9}\,\mathrm{g\,cm^{-3}}$ and a chondrule-to-gas mass ratio $\sim 0.5\%$, there would be $\sim 10^8$ chondrules of radius 300 μm. For a chondrule temperature of 1500 K, each radiates at a rate $\sim 3 \times 10^6\,\mathrm{erg\,s^{-1}}$. Thus, the heating of chondrules alone must cause the region to cool at a rate $\sim 3 \times 10^{14}\mathrm{erg\,s^{-1}}$. Comparing with the total energy of the system $\sim 10^{16}$ erg, the lightning-heated region must cool in < 1 min. The mean free path of photons (or chondrules) within the cloud of chondrules is $> 10^2$ km, so the cloud of heated chondrules is optically thin.

The models of Pilipp et al. (1998) and others involve different mechanisms for generating charge separation and invoke different lengths of channels. Nevertheless, the heated region will necessarily be only an order of magnitude larger than the channel itself, which is only some number 10–10^3 times the electron mean free path. The cylinder in which chondrules are heating must therefore be optically thin to the radiation emitted by chondrules. As discussed by Desch and Cuzzi (2000), the energy of the bolt will be proportional to the length of the channel. The prediction of a short cooling time scale seems to be a robust prediction of the lightning model.

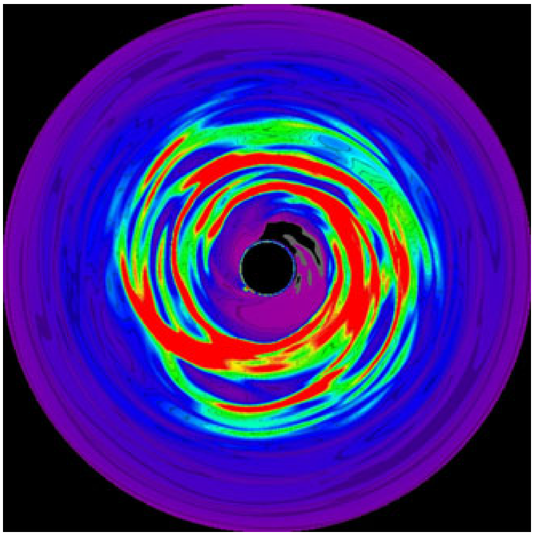

Fig. 2. False color representation of the midplane densities in the gravitationally unstable disk model of Boss and Durisen (2005). Region shown is 20 AU in radius, and a 1 $M_{\odot}$ protostar lies at the center of the disk, whose inner boundary is 2 AU in radius. A strong shock between very low-density material (black) and moderate-density material (purple) is seen at the 12 o'clock position, extending from 2 AU to about 4 AU in radius.

Gravitational Instability-Driven Shocks

Shock fronts associated with spiral arms in the solar nebula, driven by gravitational instabilities (GIs), have long been suggested as a site for chondrule formation (e.g., Hood and Horanyi 1991; Wood 1996). It is likely that the disk mass approached that necessary to trigger GIs, $\sim 0.1\,M_{\odot}$, based on the models of the mass distribution in the disk (Desch 2007), as well by models of Jupiter's formation either by core accretion or GI (Boss and Durisen 2005). Hydrodynamical calculations of the evolution of disks undergoing GIs show that shocks are a natural outcome (Boss 2002; Pickett et al. 2003). The Boss and Durisen (2005) model shows that GI-driven shocks are transient events in a chaotic disk, not permanent features. In addition, GIs in the solar nebula were likely intermittent, probably due to the episodic build up of mass in a "dead zone" where radial transport by magnetohydrodynamic turbulence was inhibited (e.g., Gammie 1996; Armitage et al. 2001). Episodes of rapid transport by gravitational instabilities may have been associated with FU Orionis outbursts (e.g., Miller et al. 2011), leading to strong inner disk shocks sporadically over millions of years.

Boss and Durisen (2005) showed that disks in which Jupiter forms at 5.2 AU are not only GI-unstable and capable of generating sporadic shocks over many Myr, they are also able to drive these shock fronts into the asteroidal regions ($\sim$2.5 AU). One-armed ($m = 1$ modes) spiral arms at 5 AU and beyond are able to drive spiral waves right down to the surface of the central protostar, as seen in Fig. 2, depicting the three-dimensional model calculations of Boss and Durisen (2005). In this model, a strong shock front is observed between 2 and 3 AU, driven by the gravitational forces associated with the clumps and spiral arms that have formed primarily between 5 and 10 AU in the disk. Once Jupiter forms, either by core accretion or by disk instability, it will continue to drive similarly strong shock fronts in the inner disk as long as the inner disk gas remains, i.e., over the lifetime of the inner solar nebula. GI-driven shocks are thus seen to be tied to the formation of Jupiter, and to be global in extent, potentially processing much of the material in the inner disk.

As discussed by Boss and Durisen (2005), the spiral pattern producing the inner shock front rotates at a speed governed roughly by the Keplerian angular velocity of the clumps and arms orbiting beyond 5 AU, resulting in a large difference in orbital velocity between the spiral pattern and dust aggregates moving with the gas on nearly Keplerian orbits at orbital radii inside the distances of the clumps (Wood 1996). If the spiral pattern is driven at 5.2 AU, gas and chondrules orbiting at 2.5 AU will encounter the shock front at speeds $\approx 12\,\mathrm{km\,s^{-1}}$. The component of this velocity that is normal to the shock front is the speed of the shock. Because the spiral shocks are tightly wound, the shock speed is usually much smaller than the maximum $12\,\mathrm{km\,s^{-1}}$. Figure 2 depicts a time when the inner shock is oriented at an angle of $\approx 60°$ to the direction of motion of orbiting solids, leading to a perpendicular shock speed of $\sim$10 km s^{-1}, more than sufficient for melting chondrule precursor dust aggregates. The midplane gas density increases by a factor of 100 across this shock front.

Shocks like these (as well as planetesimal bow shocks, discussed below) heat chondrules through three physical mechanisms. Before the shock hits, the chondrule and the surrounding gas are moving at the same speed, but after the shock passes, the gas is instantly compressed and accelerated; or, the gas is slowed if one considers the more useful frame comoving with the shock front. The chondrule is accelerated by drag forces as well, but these require a finite time $\sim \rho_s a_c/(\rho_g c_s)$ $\sim$1 min to act, where $\rho_s \approx 3\,\mathrm{g\,cm^{-3}}$ is the chondrule density, $a_c \approx 300\,\mu\mathrm{m}$ is the chondrule radius, $\rho_g \approx 6 \times 10^{-9}\,\mathrm{g\,cm^{-3}}$ is the postshock gas density, and $c_s \approx 3\,\mathrm{km\,s^{-1}}$ the postshock thermal velocity. During these tens of seconds that the chondrule is experiencing supersonic drag, frictional forces are heating the chondrules. Chondrules are also heated by thermal exchange with the shocked gas, for as long as the gas can remain hot. The combined gas/chondrules system will cool only as fast as it can radiate away its combined energy to more distant, cooler gas. As discussed in Desch (2000), the major store of energy is the gas, but radiation emitted by chondrules themselves is the predominant coolant. Thermal energy is exchanged from gas to chondrules, whereupon it is radiated. Finally, chondrules far downstream from the shock are heated when they absorb the infrared radiation emitted by hotter chondrules closer to the shock.

Radiation is such an important component of chondrule thermal histories, it is useful to further quantify its role. An individual chondrule heated to $T = 2000\,\mathrm{K}$ would radiate away its heat energy on a time scale $(4\pi/3\rho_s a_c^3 c_P T)/(4\pi a_c^2 \sigma T^4)$, where $c_P \approx 1.4 \times 10^7\,\mathrm{erg\,g^{-1}\,K^{-1}}$ is the heat capacity and σ the Stefan-Boltzmann constant. This time scale is about 1 s comparable with the time an ember from a fireplace can stay hot. Assuming a solar solids-to-gas ratio, for every gram of chondrules heated to $\approx 2000\,\mathrm{K}$, there are 100 g of H_2 gas, with heat capacity $\approx 5 \times 10^7\,\mathrm{erg\,g^{-1}\,K^{-1}}$, heated to a comparable temperature. In addition, much (10%) of that H_2 gas can be dissociated, providing a chemical store of energy comparable with the thermal energy. Effectively, gas can store 10 times the energy per mass as chondrules, thereby extending the cooling time to $\sim 10^3\,\mathrm{s}$, even for an optically thin patch of gas and chondrules. In a large-scale shock like those driven by GIs, these cooling time scales are extended even more because the one-dimensional nature of the shock front, whose lateral extent exceeds $10^6\,\mathrm{km}$. In such shocks the radiation cannot escape to free space, but must escape to regions far from the shock front. In essence, gas and chondrules must move several optical depths past the shock front, before they can cool. Because fine dust almost certainly evaporates even prior to the arrival of the shock front (Morris and Desch 2010), the postshock opacity is provided by chondrules themselves. For this reason, the higher the density of chondrules, the faster chondrules can move several optical depths from the shock front, and the faster the chondrules can cool. Chondrule cooling rate is thus robustly predicted to be proportional to the local chondrule density (Desch and Connolly 2002; Morris and Desch 2010).

Planetesimal Bow Shocks

A final proposed setting of chondrule formation is in the bow shocks surrounding planetesimals that are on eccentric orbits, as proposed by Hood (1998), Weidenschilling et al. (1998), Ciesla et al. (2004), and Hood et al. (2005, 2009). The majority of extant chondrules formed 2 Myr after CAIs (Villeneuve et al. 2009), but many planetesimals formed before that time (Wadhwa and Russell 2000). Several mechanisms have been identified that would allow growth of bodies $>100\,\mathrm{km}$ in diameter within the first $\sim 10^6\,\mathrm{yr}$ of the solar nebula (Johansen et al. 2007; Cuzzi et al. 2008; Weidenschilling 2011). As chondrules also record nebular gas, these planetesimals necessarily would have had bow shocks around them, if they moved at supersonic speeds relative to the gas.

The velocity differences between the gas and planetesimal depend on the orbital excitation of the planetesimal. Gas in orbit around the Sun at a distance r will orbit very nearly at the Keplerian speed $V_K = (GM_\odot/r^3)^{1/2}$. A planetesimal in a circular orbit with semimajor axis a will also orbit at the Keplerian orbital speed $V_K = (GM_\odot/a^3)^{1/2}$. A planetesimal in resonance with Jupiter, however, may be driven to high eccentricity e (and comparable inclination), so that especially at aphelion and perihelion it may have a large velocity with respect to the gas. It is straightforward to show that if the planetesimal's aphelion is at a heliocentric distance r, then this velocity difference is $\approx e v_K(r)$. For aphelia at 2.5 AU, where $V_K \approx 19\,\mathrm{km\,s^{-1}}$, $\Delta V > 8\,\mathrm{km\,s^{-1}}$, the shock speed thought necessary to melt chondrules (Morris and Desch 2010), provided $e > 0.4$ (if the orbit is inclined, a smaller e may lead to the same ΔV). That is, a planetesimal with $a = 1.8\,\mathrm{AU}$ and $e = 0.4$ will have a velocity difference with respect to the gas $> 8\,\mathrm{km\,s^{-1}}$ when it reaches aphelion at 2.5 AU. Because of the need for the planetesimals to be gravitationally excited to achieve high e, it is quite likely they require the formation of Jupiter to begin forming chondrules. If Jupiter took $\approx 2\,\mathrm{Myr}$ to form, this would explain the time delay between CAI and chondrule formation.

Thermal processing of chondrules in planetesimal bow shocks is nearly identical to thermal processing in GI-driven shocks, with one exception. Because the scale of the shock front is comparable with the size of the planetesimal itself (e.g., Ciesla et al. 2004), radiation can be emitted in the lateral direction; i.e., radiation does not have to escape to regions far ahead or behind the shock front to cool the heated region. Chondrules moving at $\sim 10\,\mathrm{km\,s^{-1}}$ through a heated region $< 10^3\,\mathrm{km\,s^{-1}}$ in extent, must cool significantly (several hundred K) in $\sim 10^2\,\mathrm{s}$ or at rates 10^3–$10^4\,\mathrm{K\,h^{-1}}$. More careful calculations confirm this back-of-the-envelope estimate that chondrules in planetesimal bow shocks cool at rates no less than $\sim 10^3\,\mathrm{K\,h^{-1}}$ (Morris et al. 2010).

COMPARISON OF MODEL PREDICTIONS AND CONSTRAINTS

"Non-Thermal" Constraints

Although the four models described above are not equally developed in their ability to predict chondrule formation, they are each sufficiently developed to be tested. We begin by testing each model's ability to match

Table 1. Nonthermal constraints on chondrule formation.

Constraint	X-wind	Lightning	Bow shocks	GI shocks
$L \gg 10^3$ km [a]	✓	X	?	✓
$n_c \sim 10$ m^{-3} [b]	✓	?	?	?
$P > 10^{-3}$ atm	✓	X	✓	✓
fO_2 variable, oxidizing	?	?	?	?
Chondrules, matrix cogenetic	X	✓	✓	✓
Form ≈ 1.6–3 Myr after CAIs	X	✓	✓	✓

[a]L = radius of chondrule-forming region.
[b]n_c = number density of chondrules following melting.

each of the "non-thermal" meteoritic constraints. The results are compiled in Table 1.

First, do the models invoke a sufficiently large ($\gg 10^3$ km) region in which chondrules form? These large sizes are easily consistent with formation in the X-wind environment and with formation in GI-driven shocks. Planetesimal bow shocks are comparable in size to the planetesimal itself, so if the planetesimal is especially large (e.g., Ceres-sized, $>10^3$ km in diameter) then it may be possible to just meet the requirement. The heated region associated with lightning, being <1 km in radius, appears to fail to match the constraint.

Second, is each model consistent with a (postheating) chondrule density $n_c \sim 10\,\mathrm{m}^{-3}$? Assuming each chondrule is 300 μm in radius and has a mass $\approx 3 \times 10^{-4}$ g, this corresponds to a density of chondrules $\rho_c \approx 3 \times 10^{-9}$ g cm^{-3}. The solids-to-gas ratio of a solar composition is 5×10^{-3} (Lodders 2003), and most but not all of these particles are chondrules; we write $\rho_c/\rho_g = (3.75 \times 10^{-3})C$, where ρ_g is the gas density and C is a concentration factor of chondrules. Values $C > 1$ are plausible, but it is not likely that C can exceed $\sim 10^3$ (i.e., the solids-to-gas ratio exceeds unity), either by settling of material to the midplane (see Weidenschilling and Cuzzi 1993) or turbulent concentration (Cuzzi et al. 2001, 2008). The constraints imply $\rho_g \sim 10^{-6} C^{-1}$ g cm^{-3}. For $C < 10^2$ this density is high, but may be consistent with the gas densities near the X point (Desch et al. 2010). At 2–3 AU, the gas densities are lower, $\sim 10^{-10}$ g cm^{-3} in a minimum-mass solar nebula (Weidenschilling 1977), but $\sim 10^{-9}$ g cm^{-3} in a more massive disk (Desch 2007). Concentration of chondrules is a key component of the lightning model of Desch and Cuzzi (2000), and $C \sim 10^3$ is argued for. In the shock models, the nebular gas is compressed by an order of magnitude in the postshock region, so smaller concentrations $C \sim 10^2$ are required. These are likely to be achieved by settling to the midplane in the absence of turbulence (e.g., Weidenschilling and Cuzzi 1993) or by turbulent concentration in the presence of turbulence (Cuzzi et al. 2001). So far, models of nebular densities, degree of turbulence, and settling of solids do not yet provide sufficient detail to judge whether the chondrule densities in each model match the constraints. We judge that all models appear potentially viable, but only if chondrules are melted at the disk midplane. The X-wind model seems to best match the high-density constraint.

Next, we consider the pressure in the chondrule-forming region, which is inferred to be $>10^{-3}$ atm. For "typical" temperatures $\sim$2000 K, a pressure 10^{-3} atm is achieved only for gas densities $\sim 2 \times 10^{-8}$ g cm^{-3}, which is similar to the density constraint. These high pressures are likely to be achieved in the X-wind environment (Desch et al. 2010), but are also clearly predicted to occur in the postshock gas, due to the compression of the gas (Ciesla and Hood 2002; Desch and Connolly 2002). In the lightning model, however, gas pressures remain in equilibrium with the ambient nebula, for which $P \sim 10^{-5}$ atm (for $\rho_g = 10^{-9}$ g cm^{-3}).

Solids in the chondrule-forming region also figure into the constraint of chondrule-matrix complementarity. The X-wind model is definitely inconsistent with this constraint, as chondrules originate near the X point and then are mixed with matrix dust local to the 2–3 AU region. Nebular models, such as shocks and lightning naturally satisfy the complementarity constraint. Each mechanism forms chondrules in spatially isolated regions that are near reservoirs of dust, so that volatiles evaporated from chondrules will condense onto these grains. Dust grains also can condense directly from the rock vapor in the chondrule-forming region. Scott and Krot (2005) argue that amoeboid-olivine aggregrates represent such condensates.

Finally, we test if each model is consistent with formation of chondrules 1.6–3 Myr after CAIs, and possibly no chondrule formation up to that time. The three nebular models are all consistent with a prolonged formation, as each should continue to operate so long as gas persists in the inner disk. All three are consistent as well with a delay of a few million years, before chondrule formation starts. In the planetesimal bow shock model, planetesimals will not be driven on eccentric orbits until Jupiter forms, which may take this long. Likewise, GIs may be driven either by Jupiter itself or by the intermittent buildup of mass at bottleneck annuli (e.g., Gammie 1996). The latter process may take time as mass must build up and the disk cools. In the lightning model of Desch and Cuzzi (2000), the onset of lightning is delayed until the electrical conductivity of the gas decreases sufficiently. This requires decay of ^{26}Al, and for high gas densities ($\rho_g > 10^{-9}$ g cm^{-3}) onset at 2 Myr is predicted. The X-wind model is not consistent with either a prolonged or delayed production of chondrules, as it specifically predicts that they are formed contemporaneously with CAIs, which themselves formed over a limited duration.

To conclude, all four models considered here more or less match the nonthermal constraints or at least are not in conflict with them, with a few exceptions. The lightning model appears to be too small in extent, and to invoke too small a pressure, and may be excluded on these grounds. The X-wind model predicts chondrules and matrix are not complementary, but of all of the nonthermal constraints, this is perhaps weakest due to the difficulty of distinguishing nebular complementarities from parent-body redistributions. Only the timing constraints seem to argue strongly against the X-wind model. Here again, although it is not difficult to imagine a refinement of the X-wind model that would allow CAIs to form early on, when mass accretion rates were higher, and chondrules to form only later. That is to say, although the X-wind model as currently presented does not match the nonthermal meteoritic constraints, it is possible in principle that it could. The constraints on the time, place, and extent of chondrule formation have therefore allowed us to identify the lightning model as flawed, the X-wind model as flawed, but perhaps not irreparably so, and the shock models as viable.

Constraints on Thermal Histories

We now consider the thermal histories each model predicts, to see how well these predictions match the meteoritic constraints on chondrule melting and cooling. The results are compiled in Table 2. First, it is clear that in nebular models the chondrules start at temperatures < 650 K that are consistent with the presence of primary sulfides. In the X-wind model, temperatures at the site of chondrule formation are in excess of 900 K, and are even higher once viscous heating due to mass accretion is included (Desch et al. 2010). Chondrules formed in the X-wind environment should lack volatiles, such as S and perhaps even Na.

The next constraint is the duration of the heating, which measures the time taken for the chondrule to go from ambient temperature to its peak. In the lightning model, heating is nearly instantaneous (seconds) after the initial pulse of radiation. The duration of the heating pulse may be too short, in fact, to yield chondrule-like objects. Experiments by Güttler et al. (2008) subjected dust aggregates to heating by electrical discharge, and found that the sudden heating usually caused the aggregates to fragment and explode. Chondrule precursors outside the discharge channel would not be as severely heated, but the heating they receive, mostly from optical and ultraviolet radiation, may also be too sudden, so that chondrule precursors again might be expected to fragment and explode. In the shock models, the duration of the heating is prolonged because chondrules absorb radiation (from shocked chondrules) even before the shock front reaches them. In a large, 1-D shock like that modeled by Morris and Desch (2010), this preheating is inevitable and is the result of the radiation propagating into the preshock gas as a Marshak wave. The duration of the heating does depend, however, on the opacity, and may take tens of minutes instead of hours if, for example, a significant component of 10 μm microchondrules coexisted with chondrules (Morris and Desch 2011). The same principles apply to a planetesimal bow shock, except in this case the radiation is not as significant and the preshock heating less pronounced. Indeed, chondrules would not be expected to preheat for a time longer than about tens of minutes, the characteristic time for a large planetesimal to approach (to within its own diameter) a given chondrule. In the X-wind model, in contrast, the heating duration is necessarily the time taken for a chondrule to move one scale height, which is hours to days. The X-wind model is therefore inconsistent with the heating duration constraint. We remind the reader that the validity of this constraint depends on whether evaporation of volatiles is suppressed in the preshock environment by high partial pressures of the volatiles.

After being heated, chondrules reach a peak temperature in excess of 2000 K. Shock models specifically predict such high temperatures. Lightning

Table 2. Constraints on chondrule thermal histories.

Constraint	X-wind	Lightning	Bow shocks	GI shocks
Ambient T < 650 K	X	✓	✓	✓
Heating duration < 10 min[a]	X	✓	✓	?
Peak $T \geq 2000$ K	X	?	✓	✓
Cooling rate from peak $\sim 10^3$–10^4 K h^{-1} [a]	X	?	✓	✓
Crystallization cooling rate ~ 10–10^3 K h^{-1} (porphyritic)	✓	X	?	✓
Crystallization cooling rate $\sim 10^2$–10^3 K h^{-1} (barred)	X	X	?	✓
Cooling rate correlates with chondrule density	X	X	?	✓

[a]These constraints may not apply, if high partial pressures of volatiles in the chondrule-forming region suppress evaporation of these volatiles from chondrules.

models make no quantiative predictions, but the discussion by Desch (2000) and in the X-wind section make clear that such temperatures are achievable in principle. High temperatures are also acheived in the X-wind model, but they do not reach the peak temperatures necessary to completely melt the chondrule precursors. As discussed in Desch et al. (2010), particles launched in the X-wind reach blackbody temperatures $\approx$1360 K above the disk compared with about 1070 K within it (for the "revealed" phase, in which the mass accretion rate $\sim 10^{-7} M_{\odot} \mathrm{yr}^{-1}$). The disk is cooler than the blackbody temperature because it absorbs sunlight obliquely, but radiates from its entire area, but the difference amounts to only a few hundred K, not the $\approx$1300 K needed for chondrules to retain primary S, yet completely melt all phenocrysts.

Immediately after achieving their peak temperatures, chondrules must cool rapidly, 10^3–10^4 K h^{-1}, below their liquidus temperatures, so that they can retain volatile species like Na and S. These cooling rates from the peak are robust predictions of the shock models, a result of the loss of supersonic drag heating on the chondrules after they dynamically couple to the gas about 1 min past the shock front. The lightning model makes no detailed predictions of the cooling rates and it is difficult to judge, although cooling is likely to be rapid after the lightning bolt, on the order of hundreds of K in 1 min or $\sim 10^4$ K h^{-1}. The X-wind model, in contrast, predicts slowly changing temperatures, ~ 6 K h^{-1}, as the chondrule is exposed to direct sunlight and then moves away from the Sun on its ballistic trajectory. Here again, we remind the reader that the validity of this constraint depends on whether evaporation of volatiles is suppressed by high partial pressures of the volatiles.

After this stage, chondrules are inferred to cool at slower rates through their crystallization temperatures, 1400–1800 K. The cooling rates of chondrules in the shock model are predicted to depend on the opacity and the density of chondrules being ~ 10 K h^{-1} for regions with a "solar" abundance of chondrules, $C \sim 1$, and scaling linearly with C reaching 300 K h^{-1} for $C \sim 30$ (Morris and Desch 2010). If regions of variable chondrule density exist in the nebula, then the different cooling rates of porphyritic and barred chondrules can be explained in the shock model. The cooling rates in planetesimal bow shocks are probably higher than those in the large-scale (1-D) GI-driven shocks because of the lesser significance of radiation from other chondrules. Preliminary estimates by Morris et al. (2010) suggest cooling rates $>10^3$ K h^{-1} may be more typical. Further refinements to the bow shock model are needed to see if it complies with the constraints on cooling rates. The cooling rates of chondrules heated in lightning have not been calculated, but probably remain $>10^4$ K h^{-1}, and are thus inconsistent with either type of chondrule texture. Cooling rates of chondrules in the X-wind model remain <10 K h^{-1} during their crystallization. As such, the X-wind model is consistent with porphyritic textures but not barred olivine textures. Notably, none of the models makes detailed predictions about cooling rates below the crystallization temperature range. Models of large-scale shocks in particular make implicit assumptions about the reequilibration to ambient temperature that may or may not be justified (see Morris and Desch 2010).

Finally, one last constraint is the observed correlation between compound chondrule frequency and chondrule texture. This is a robust prediction of the shock models, in which cooling rates of chondrules depend on how quickly they can move several optical depths away from hot chondrules at the shock front (Desch and Connolly 2002; Desch et al. 2005; Morris and Desch 2010). As dust evaporates and chondrules provide most of the opacity in the postshock region, the cooling rate therefore scales with chondrule density. A large-scale shock overtaking regions of variable chondrule density (such as the regions of turbulent concentration predicted by Cuzzi et al. 2001) would then produce a variety of chondrule textures. To first order, compound chondrules will be more common in regions of high chondrule density, which will also be associated with faster cooling rates and barred textures rather than porphyritic. It remains to be seen whether the prediction is robust in the smaller planetesimal bow shocks, but is likely to hold to some degree. In the context of the lightning model, the regions involved are too small to be optically thick, and chondrules near the channel will be heated equally regardless of chondrule density, so the observed correlation between textures and compound chondrules is not predicted. Likewise, the X-wind model predicts no such correlation. If anything, regions of chondrule density high enough to be optically thick would have greater thermal inertia and would be slower to heat up upon being externally irradiated, and would be associated with lower cooling rates. At any rate, only in large-scale nebular shocks is the observed correlation robustly predicted.

To further illustrate the differences between the models, we show in Fig. 3 the likely thermal histories of chondrules melted in a large-scale nebular shock, a nebular lightning bolt, and in the X-wind. The shock model calculation is from Morris and Desch (2010), and assumes $\rho_g = 1 \times 10^{-9}$ g cm^{-3}, $V_s = 8$ km s^{-1}, and $\rho_c/\rho_g \approx 4\%$. The thermal history for the chondrule in the X-wind was taken from the discussion of Desch et al. (2010), and is appropriate for the revealed stage, when the mass accretion rate through the disk is $1 \times 10^{-7} M_{\odot} \mathrm{yr}^{-1}$. The thermal histories of chondrules near nebular lighting

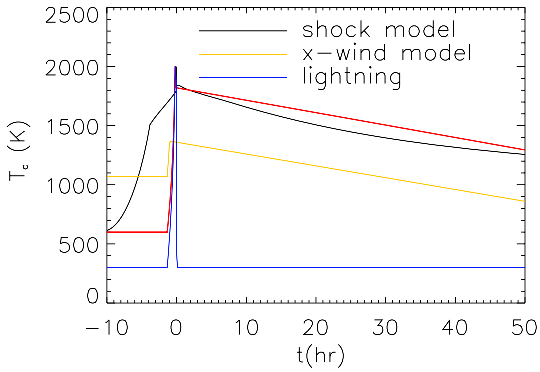

Fig. 3. Chondrule thermal histories as inferred from experimental constraints (red curve), as predicted by the shock model (taken from Morris and Desch [2010]; see text for parameters) (black curve); as predicted by the X-wind model during the "revealed stage" (adapted from Shu et al. 1996, 2001) (yellow curve); and as predicted by lightning models (e.g., Desch and Cuzzi [2000]) (blue curve).

bolts were estimated, following the discussion of X-wind section. These thermal histories are plotted against the inferred thermal histories of chondrules based on the above constraints (depicted by the red curve). Aside from the too-long duration of heating before the shock front, the thermal histories of chondrules in large-scale nebular shocks match the constraints very well. Chondrules in the X-wind start too hot and never completely melt, whereas chondrules melted by lightning simply cannot stay in their crystallization temperature range long enough to form porphyritic textures. The constraints on thermal histories strongly favor shock models.

To summarize, the constraints on chondrule formation based on their thermal histories are much more diagnostic than other constraints. The inability of lightning models to explain the slow cooling rate of chondrules, in which they took hours to crystallize, allows us to reject such models. The X-wind model also fails to match the thermal histories of chondrules: chondrules start too hot to retain primary S; they heat up over hours or days, and again should lose volatiles; they fail to reach peak temperatures sufficient to completely melt chondrules (at least in the revealed stage); and although the model allows for slow cooling rates consistent with porphyritic textures, it does not allow for the faster cooling rates of barred olivine textures. Finally, the X-wind model does not explain the observed correlation between compound chondrule frequency and chondrule texture.

CONCLUSIONS

Because of its importance to understanding the origins of the solar system and planets, many models have been proposed to explain chondrule formation. These models represent the fruitful imagination of theorists, and invoke such disparate environments as the Sun's magnetosphere, colliding asteroids, nebular lightning bolts, and shock waves driven by eccentric planetesimals, spiral density waves, solar flares, etc. Some models have been more completely developed than others. Incompletely developed models cannot be tested scientifically, and must remain merely creative ideas. Models that make quantitative predictions about chondrule properties can be tested against an abundance of experimental constraints.

In this study we tested four models for chondrule formation: melting and launching in the X-wind (Shu et al. 1996); melting near nebular lightning (Desch and Cuzzi 2000); melting in planetesimal bow shocks as suggested by Weidenschilling et al. (1998); and melting in large-scale shocks, such as those driven by gravitational instabilities, as suggested by Wood (1963). Beyond the predictions made in Shu et al. (1996, 2001), we have drawn on the analysis by Desch et al. (2010) to quantify key properties of chondrules in the X-wind. The lightning model was never fully developed, but we made estimates here about how chondrules would be melted, and also drew on estimates made by Desch (2000). Chondrule heating in the large-scale shocks is well modeled, by Desch and Connolly (2002), Ciesla and Hood (2002), Miura and Nakamoto (2006), Morris and Desch (2010), and others. Application to chondrules melted in planetesimal bow shocks is less robust due to the smaller scales. Preliminary estimates by Morris et al. (2010) show there are some relatively minor, but distinct differences. Using these quantifications, we tested predictions about chondrule formation against the experimental constraints.

Constraints on the time, place, and extent of chondrule formation, and other constraints on the chondrule formation environment, are all helpful but not completely diagnostic. Although the small scale of nebular lightning was seen as problematic, and one might exclude the lightning model on that basis, the lightning model was consistent with the majority of these constraints. Likewise, the X-wind model failed to explain chondrule-matrix complementarity, but this constraint is difficult to apply given the problem of disentangling redistribution on the parent body from nebular effects. The X-wind model only really violates the constraint on the timing of chondrule formation, but modifications to the model (CAIs form during high $\dot{M}$, chondrules during low $\dot{M}$) could, in principle, bring it into compliance. Only a preponderance of evidence favors shock models.

Constraints on the thermal histories of chondrules are much more diagnostic. Even with the caveat that recondensation of volatiles may invalidate the constraints on the duration of heating and cooling at high temperatures, the constraint on ambient temperature, and especially the textural constraints on cooling rate through the crystallization temperature range, is strong. Although melting by large-scale nebular shocks matches the chondrule thermal histories quite well, melting in the X-wind and by nebular lightning do not. Chondrules in the X-wind environment start too hot, but do not achieve the needed peak temperatures to completely melt. Chondrules melted by nebular lightning cannot cool slowly enough to produce recognizable textures. The constraints on chondrule thermal histories allow us to reject the lightning and X-wind models for chondrule formation. The ability to make such definitive statements rests on the laboratory experiments that constrain the thermal histories of chondrules.

In 1994, Roger Hewins convened a conference in Albuquerque, New Mexico, to assess the state of knowledge about chondrule formation (Hewins et al. 1996, 2005), a topic that had puzzled meteoriticists for centuries. One critical outcome of that seminal meeting was the realization that flash heating was required to explain chondrule textures (Hewins and Connolly 1996). This major constraint, coupled with almost two decades of subsequent work, has allowed the most basic questions about chondrule formation to receive at least provisional answers, although many details remain to be elucidated. We all owe a great debt to Roger for this leadership, coupled with detailed laboratory experiments, that has led us to our current state of knowledge about chondrule formation mechanisms.

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