Transient Heating Events in the Protoplanetary Nebula

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1. INTRODUCTION

The most fundamental reason that transient heating events were important in the formation of the solar system is that they provided the energy to produce chondrules and refractory inclusions (*Beckett et al.,* 2006; *Lauretta et al.,* 2006). From standard astrophysical models for the formation of the solar system, these objects are not predicted to exist and are certainly not predicted to be part of the terrestrial-planet-forming process as has been argued by meteoriticists for decades. They do, however, comprise up to approximately 80% of the mass of ordinary chondrites and approximately 50% of the mass of most carbonaceous chondrites (*Brearley and Jones,* 1998). Thus, the ubiquity of these objects within chondrites and the abundance of chondrites suggest that transient heating must have been common. Furthermore, *Levy* (1988) estimates that the mass of chondrules melted in the inner solar system was at least 10^{24} g, which, although not a planetary mass, is a significant amount, especially considering that it is a minimum quantity.

Today, the solar system is chemically differentiated at many scales. This differentiation is reflected in the composition of planetary materials from the millimeter-scale (chondrules and refractory inclusions) to meter-scale (chondrites), to planetesimals (asteroids) and finally the planetary scale. The compositional differences include both elemental and, in some cases, isotopic abundances, and arose from physical and chemical processes in the nebula and on parent bodies. The major issue is, did transient heating events that produced chondrules and refractory inclusions contribute, at least in part, to the chemical differentiation observed in planetary materials within the solar system? If indeed the bulk of these planetary materials are the same type of materials from which the terrestrial planets were produced, understanding the mechanism that melted chondrules and refractory inclusions is an important component to constraining solar system formation.

Numerous reviews of the petrographic and geochemical characteristics of chondrules and refractory inclusions have been published in the last decade (*Beckett et al.,* 2006; *Brearley and Jones,* 1998; *Connolly and Desch,* 2004; *Jones et al.,* 2000, 2005; *Hewins,* 1997; *Krot et al.,* 2004a,b; *Lauretta et al.,* 2006; *MacPherson,* 2004; *MacPherson et al.,* 2005; *Rubin,* 2000; *Zanda,* 2004). Many assumptions exist in the literature when discussing these objects that we will attempt to clarify as part of our goal to communicate to a wide audience within this chapter. First, when discussing chondrules, most researchers are referring to those objects dominated by FeO- and MgO-rich silicate minerals such as olivine $(Mg,Fe)_2SiO_4$ and enstatite $(Mg,Fe)SiO_3$, with varying abundances of glass, Fe,Ni-rich metal, iron sulfide, and other minor phases. These are referred to as ferromagnesian chondrules.

Refractory inclusions are divided into calcium-aluminum-rich inclusions (CAIs) and amoeboid olivine aggregates (AOA). Typically, the centimeter-sized igneous CAIs known as type B are what comes to mind for most researchers when discussing CAIs, largely due to their striking appearance, resulting in their size, color, and coarse grain-size and consequent popularity in the earlier days of CAI research on the carbonaceous chondrite Allende. It is important to note that all but the fluffy type A (FTA) CAIs experienced some degree of melting and are arguably, in some cases undisputedly, igneous. Because of their highly diverse chemistries and textures we refer the reader to reviews by *Brearley and Jones* (1998), *MacPherson et al.* (1988), *MacPherson* (2004), and *Krot et al.* (2004a) for detailed discussion of these objects.

Throughout this text we will mostly focus discussion on how ferromagnesian chondrules and those refractory inclusions that have experienced melting can constrain the nature and history of transient heating events. Igneous objects such as chondrules and type B CAIs found within chondrites have textures reflective of their thermal histories. The differences in igneous textures of chondrules and CAIs combined with the elemental fractionations within crystals provide powerful constraints on their melting temperatures, duration of melting, and rate of heat loss or cooling rate that they experienced. These same data tell us that many chondrules and type B CAIs have been heated and cooled multiple times, and in specific cases evidence suggests that such reheating or melting occurred after a period of alteration occurred, attesting to their complex petrogenesis (*Beckett et al.,* 2000, 2006; *Connolly and Desch,* 2004; *Connolly et al.,* 2003; *Davis and MacPherson,* 1996; *Jones et al.,* 2000; *Lauretta et al.,* 2006; *Rubin,* 2000; *Zanda,* 2004).

The importance of transient heating events is summed up as (1) they produced chondrules and refractory inclusions; (2) the chemical differences in chondrules, refractory inclusions, chondrites, asteroids, and planets may have, at least in part, been produced through transient heating; (3) they may have processed the majority of rocky planetary materials that were the precursors to terrestrial planets; and (4) the accretion of planets does not, from astronomical theories, have to include a phase of high-temperature processing of chondritic materials, yet meteoritics argues that it must have. Hence, assessing and investigating potential relationships between transient heating events and planet formation will enable us to put constraints on viable planet-formation mechanisms and to further understand meteorite evolution. Large energetic heating events implied by meteorite data place significant constraints on protoplanetary disk evolution not currently accommodated by astrophysical models, especially if most planetary materials went through a high-temperature processing phase before terrestrial planet formation occurred.

In this chapter, we (1) explore the evidence that transient heating events occurred (section 2), (2) discuss time and temperature constraints on transient heating (section 3), (3) investigate ideas and models of mechanisms that may have produced the heating (section 4), and (4) offer a blueprint for issues that must be addressed through further research (section 5).

2. EVIDENCE FOR TRANSIENT HEATING EVENTS

In this section, we review the evidence from the meteorite record and observational astronomy that transient heating events occurred early in solar system history. We make the reasonable assumption that events observed to occur in association with young stellar objects (YSO) with predicted masses similar to that of the Sun also occurred in the early stages of solar system formation. We divide the discussion into evidence that is well established and that which can be interpreted or is implied to support transient heating.

1.1. The Rock Record

2.1.1. Well-established evidence. The most compelling evidence for transient heating within the lifetime of the protoplanetary nebula is the presence of chondrules and refractory inclusions in primitive meteorites. These objects formed on timescales of several hours to a few days (e.g., *Beckett et al.,* 2006; *Connolly and Desch,* 2004; *Hewins et al.,* 1996; *Lauretta et al.,* 2006). Although there is currently some discussion within meteoritics as to the extent of melting many chondrules experienced, in order to at least partially melt they must have experienced temperatures at or above their solidus (conservatively ~1300–1500 K). Many chondrules (as we discuss in more detail below) experienced temperatures near or slightly above their liquidus temperatures [~1700–2000 K (*Lofgren and Lanier,* 1990; *Radomsky and Hewins,* 1990)]. Similarly, refractory inclusons, in particular type B CAIs, experienced melting at ~1700 K (*Stolper and Paque,* 1986), which is within the range of temperatures experienced by chondrules.

2.1.2. Supporting evidence. The existence of other evidence that can be interpreted as having been, at least in part, the result of a transient heating event (or events) is often the subject of intense debate. Because such data may be important to our discussion, we must consider them.

The bulk compositions of chondrites are diverse (*Brearley and Jones,* 1998; *Krot et al.,* 2004a; *Weisberg et al.,* 2006), as are those of chondrules and refractory inclusions. Chondrite compositions deviate from primitive solar CI values, with varying amounts of depletions of moderately volatile and volatile elements, depending on the chondrite type (*Wasson,* 1985). How these differences arose is a major question. One potential explanation relevant to this chapter is that, at least in part, chondritic components and/or their precursors (including those of chondrules and refractory inclusions) may have undergone evaporative processing during transient heating followed by partial or total recondensation of evaporated species (*Alexander,* 2004; *Cohen et al.,* 2000; *Haung et al.,* 1996; *Hewins,* 1997; *Hewins et al.,* 2005; *MacPherson et al.,* 2005). It is clear that at least some CAIs experienced mass-dependent isotopic fractionation (*Ash et al.,* 2002; *Clayton et al.,* 1988; *Galy et al.,* 2000; *Richter et al.,* 2002); however, the extent to which chondrules experienced evaporation while molten is unknown (*Hewins,* 1997; *Connolly et al.,* 2001; *Cohen et al.,* 2000; *Cohen and Hewins,* 2004). There is no isotopic evidence for Rayleigh fractionation resulting from evaporation during chondrule formation, suggesting that free evaporation under canonical conditions (i.e., an ambient 10^{-3} bar gas of solar composition) did not occur as might be expected (*Humayan and Clayton,* 1995; *Galy et al.,* 2000). *Palme et al.* (1993, and references therein) argued that a chemical relationship exists between chondrules and chondrite matrix, matrix being more enriched in volatiles than chondrules, and that the chondrules lost volatiles that recondensed onto or in the form of matrix. Such a relationship may be due to the processing of chondritic materials during transient heating, but it is by no means the only explanation. Although the role that transient heating played in contributing to the bulk compositions of chondrites is a topic of debate, the potential for it to have been an important process cannot be ignored.

The existence of short-lived radionuclides (^{7}Be, ^{10}Be, ^{26}Al, ^{41}Ca, and ^{53}Mn) in refractory inclusions and potentially chondrules has been suggested to be the product of irradiation of precursor materials by the early active Sun (*Gounelle et al.,* 2001). If, as has been suggested by *Gounelle et al.* (2001), the irradiation process is also related to the mechanism that melted refractory inclusions (and perhaps chondrules), then the evidence for the existence of these isotopes is indirect evidence for transient heating, even if it does appear to be circular reasoning.

2.2. Observational Astronomy

2.2.1. Well-established evidence. From observational astronomy, clear evidence exists for transient heating events occurring during the lifetime of a protoplanetary disk. These observations, however, correspond to timescales of months to 10^3–10^5 yr, which is far longer than the kinds of transient heating that chondrules and refractory inclusions experienced. Nevertheless, from an astronomical view they are transient and their relationship to the production mechanisms of shorter transient heating events that may be the heat source for producing igneous melt spheres found within chondrites is unknown. It is therefore important that we review the observations.

FU Orionis outbursts (e.g., *Hartmann and Kenyon,* 1996; *Bell et al.,* 2000) are increases in the optical luminosity of accreting protostars by about a factor of 100. The rise in luminosity occurs on a timescale of a few years, and is followed by decay in the luminosity that takes place over several decades (*Bell et al.,* 2000; *Calvet et al.,* 2000). The increased optical luminosity is likely due to increased mass accretion of material through the disk onto the YSO. Statistics suggest that each protostar experiences about 10 FU Orionis outbursts during its evolution (*Bell et al.,* 2000; *Calvet et al.,* 2000). FU Orionis outbursts are believed to occur only during the initial stages (Class 0, I) of protostellar evolution, or the first 10^5 yr (*Bell et al.,* 2000; *Konigl and Pudritz,* 2000; *Shu et al.,* 2000). Based on this estimate and stellar statistics, the interval between outbursts is estimated at about 10^4 yr. However, from the spacing between the knots within bipolar outflows, the time between FU Orionis outbursts is estimated to be about 10^3 yr (*Bally et al.,* 1995). It would appear that every thousand years or so, protoplanetary disks spend about a century in a stage of enhanced accretion onto the protostar; this sporadic accretion continues for perhaps 10^5 yr.

Similar phenomena to the FU Orionis outbursts are Exor outbursts. They involve an increase in luminosity by a factor of approximately 30, and the timescales for the rise and fall in luminosity are months to years (*Herbig,* 1977, 1989). Exor outbursts are not restricted to the first 10^5 yr of disk evolution and appear to occur even in more classical T Tauri disks [Class 0 through II (*Konigl and Pudritz,* 2000)].

Bell et al. (2000) argued that the midplanes of protoplanetary disks are too deeply embedded to respond to the temperature increases during the outburst phases, but hypothesized that the surfaces of disks can experience significant temperature increases. These temperature increases would, however, necessarily last as long as the outburst, i.e., for years. While transient on disk evolution timescales (several million years), this is much longer than the timescales for chondrule and refractory inclusion formation (*Beckett et al.,* 2006; *Connolly and Desch,* 2004; *Hewins et al.,* 2005; *Jones et al.,* 2000; *Lauretta et al.,* 2006).

Another transient heating mechanism known to occur in protoplanetary disks is X-ray flares. X-ray emission from protostars is observed and is known to be highly variable, changing by an order of magnitude over the course of hours (*Feigelson et al.,* 2003). X-ray flares persist throughout the T Tauri stage of protostellar evolution (Class I through III). However, the actual X-ray energy output from protostars is typically no more than 0.1% of the star's luminosity. The X-rays, and possibly energetic particles (keV to MeV energies) accelerated in the flares, can interact with the surface layers of the disk and ionize local gas very effectively (*Glassgold et al.,* 2000). This in turn may trigger transient energy dissipation mechanisms that rely on coupling between the magnetic field and the gas in the disk, such as magnetic flares in the disk (*Mannings et al.,* 1996). For the X-ray flares to directly heat meteoritic material requires that that material reside close to the star. Rocky material residing in the magnetosphere of the protostar could interact and be heated with energetic particles accelerated in flares (*Shu et al.,* 2001).

In summary, there are several events taking place in protoplanetary disks that imply transient heating. FU Orionis events take place over decades, but Exor events occur with smaller amplitude and faster variation. It is tempting to suggest that even smaller heating events related to these different outbursts might occur in disks on even shorter timescales. Observations of DG Tau show that it exhibits behavior over timescales of only months that may suggest some type of transient heating (*Wooden et al.,* 2000). X-ray flares are observed around protostars and could heat material, although it is unclear how efficient such energetic events would be for producing chondrules and refractory inclusions.

2.2.2. Supporting evidence. Bipolar outflows alone cannot be considered the transient heating events that processed materials within the disk. They are far too hot (*Konigl and Pudritz,* 2000) to have been the direct source of the melted materials found in meteorites. However, winds are hypothesized to occur during the outflow stages and there may be interactions between outflows and disks (*Konigl and Pudritz,* 2000; *Shu et al.,* 2000). Although the winds themselves do not directly heat or melt solid materials, heating may occur when particles are entrained within the winds and irradiated in the optical and X-ray wavelengths by the YSO (*Shu et al.,* 1996, 1997, 2000; *Gounelle et al.,* 2001).

A lesser energetic component of the outflow is not directed along the protostar's poles and could potentially interact with the disk, although it is not yet observed. This process may produce shocks as the wind collides with the disk gas and thus produces heating of gas and any rocky materials or dust grains (*Nakamoto et al.,* 2004). Such heating would be restricted to a very thin surface layer of the protoplanetary disk ($\ll$1 g cm^{-2}) and has yet to be defined numerically in detail.

The exact timing of the start of planet formation is only constrained to within a few million years (*Nichols,* 2006). If it began very early in the disk's lifetime, then the process of accretion would itself have produced transient heating events. The energy associated with accretion, largely through collisional events, could have processed primitive planetary materials at high temperatures. As we discuss below, however, a collisional mechanism for the production of chondrules and refractory inclusions is problematic for several reasons.

3. CONSTRAINTS ON TRANSIENT HEATING EVENTS: TEMPERATURE/TIME VARIABLE

Of critical importance to understanding the energetic nature of transient heating events is gaining some understanding of the temperatures and durations of the events. It is difficult to quantify with confidence the exact peak temperature and duration of any given transient heating event(s). We do not have direct measurements for all aspects of astronomically observed events and in meteorites only an indirect record of these events. Both petrographic and experimental investigations of chondrules and refractory inclusions provide constraints on the temperature and heating duration these objects experienced. As a framework to explore the temperature/time variable of transient heating, we discuss two different aspects of timescale: the first is the hours to days during which individual chondrules and refractory inclusions formed, and the second is the 10^5–10^6 yr over which the mechanism or mechanisms must have operated.

Most constraints on the temperatures and times of transient heating events within the protoplanetary nebula are derived from comparing natural materials with the results of experimental investigations of chondrule and refractory inclusion formation (e.g., *Beckett et al.,* 2006; *Connolly and Desch,* 2004; *Hewins,* 1997; *Hewins et al.,* 2005; *Lofgren,* 1996). Since the chondrules and refractory inclusions we discuss are igneous, we can use their chemical and physical characteristics to constrain the thermal conditions that characterize their melting and crystallization, and this, in turn, can constrain the heating regime of these objects. The thermal histories of chondrules and igneous refractory inclusions (compact type A, type B, type C, and some AOAs) comprise four stages: (1) pre-melting, (2) melting, (3) cooling and crystallization, and (4) post-crystallization. Numerous factors affect each one of these stages and we discuss some of the more important issues below or refer the reader to an appropriate reference.

As was briefly mentioned above, it is important to understand the types of objects we are discussing. Chondrules are diverse, both in their textural types and bulk chemistry (*Grossman et al.,* 1988; *Hewins et al.,* 1996; *Brearley and Jones,* 1998; *Connolly and Desch,* 2004; *Lauretta et al.,* 2006). To date, the only chondrules that have been investigated through experimental petrology in enough detail to provide clear constraints on their thermal history are the Fe,Mg-rich chondrules (*Connolly and Desch,* 2004; *Grossman et al.,* 1988; *Hewins et al.,* 2005; *Lauretta et al.,* 2006). The formation of Al-rich or any other chondrule type is essentially experimentally unconstrained; thus our discussion is limited to the origin of Fe,Mg-rich chondrules (*Connolly and Desch,* 2004). The majority of constraints on the thermal histories of chondrules have not fully integrated free evaporation (elemental fractionation) from the molten chondrules or back-reactions between molten spheres and gas. We are therefore forced to limit our discussion to data on the thermal histories of chondrules that experienced negligible evaporation while molten.

As with chondrules, refractory inclusions are diverse in both their textures and bulk chemistry. To date, only an average type B1 CAI bulk composition has been investigated experimentally in detail (*Beckett et al.,* 2006; *Stolper,* 1982; *Stolper and Paque,* 1986; *Connolly and Burnett,* 2003). The role of free evaporation from molten type B CAIs is not yet well constrained, although evidence is compelling that it did occur (*Richter et al.,* 2002).

3.1. Thermal Histories

1. The pre-melting thermal conditions of chondrules and, to an even greater extent, igneous refractory inclusions are poorly constrained. The primary constraint on pre-melting temperatures that chondrules experienced is derived from the abundance of moderately volatile elements such as S and Na. Chondrules contain varying abundances of volatile and moderately volatile elements. Sulfur is observed mainly in the form of troilite, which is argued to be primary in a small percentage of chondrules (*Rubin et al.,* 1999; *Jones et al.,* 2000; *Tachibana and Huss,* 2005; *Zanda,* 2004). The presence of primary S within chondrules suggests that these chondrules did not experience prolonged heating (more than a few hours) between ~650 and 1200 K before, or more than several minutes at, their peak temperatures (*Hewins et al.,* 1996; *Connolly and Love,* 1998; *Jones et al.,* 2000; *Lauretta et al.,* 2001; *Tachibana and Huss,* 2005). However, it should be noted that the quoted temperature range is dependent on the total pressure and dust/gas ratio of the system during heating and these calculations make certain assumptions about the diffusion and kinetics of reactions of S in a silicate melt at the tested pressures and dust/gas ratios (*Lauretta et al.,* 2001; *Tachibana and Huss,* 2005). Thus, some caution must be taken when using the temperature/time constraints as further experiments might refine these data.

The pre-melting thermal conditions experienced by type B CAIs are essentially unconstrained. These objects contain a very minor amount of S-rich phases argued to be troilite, but it is rather unlikely that such a phase is primary in these objects. Because these objects are composed of refractory phases compared with Fe,Mg-rich chondrules, it is possible that they or their precursors experienced premelting thermal conditions that were hotter than Fe,Mg-rich chondrules for longer periods than the chondrules. However, this issue is essentially quantitatively unconstrained.

2. Constraints on the melting history of chondrules and type B CAIs have been determined from experimental petrology studies using analog compositions. These experiments are generally performed at total pressures of 1 atm and an f_{O_2} controlled to be comparable to those experienced by natural chondrules.

An essential concept for understanding the melting of chondrules is that the degree of melting and the survival of potential nucleation centers depends, to a great extent, on a temperature/time function, which, in part, constrains the type of texture that can be produced. For example, a shorter heating time at a higher temperature may leave many nucleation sites as a longer heating time at somewhat lower temperatures. Hence, there is rarely a unique thermal regime solution for any observed texture (*Jones et al.,* 2000). However, some constraints can be placed from experimental petrology. Peak melting temperatures experienced by the majority of chondrules were between 1770 and 2120 K and these temperatures were maintained for several seconds to minutes (*Connolly and Desch,* 2004; *Connolly and Love,* 1998; *Hewins,* 1997; *Hewins and Connolly,* 1996; *Hewins et al.,* 2005; *Jones et al.,* 2000; *Lofgren,* 1996; *Lofgren and Lanier,* 1990; *Lauretta et al.,* 2006; *Radomsky and Hewins,* 1990). For barred olivine chondrules (BO) it is possible that with very short heating times the absolute maximum temperature was somewhat higher [2200 K (*Connolly et al.,* 1997)]. The number of crystal nuclei that must survive the melting event determines this peak temperature range. Nucleation may also be produced by collisions of molten chondrules with dust particles or other chondrules (*Connolly and Hewins,* 1995), in which case, because survival of nuclei is not required to produce textures, the *peak temperature* might be higher (at least 2200 K).

The duration of heating must be on the order of several seconds to a few minutes. This constraint was determined mainly from the abundance of volatile and moderately volatile elements such as Na and S (*Yu et al.,* 1996; *Yu and Hewins,* 1998). The only alternative to rapid, or flash, melting of chondrule precursors and chondrules is if the ambient nebular gas was enriched in volatile or moderately volatile elements. If this was the case, molten chondrules could have exchanged with the gas during melting and cooling to replenish these elements (*Lewis et al.,* 1993). It is important to note that parent-body processing (hydrous alteration and metamorphism) can also redistribute moderately volatile elements, thereby complicating evidence from volatile-element abundances (*Grossman and Brearley,* 2005). The implication of this parent-body redistribution process is that great caution is needed when assuming that observed moderately volatile-element abundances in chondrules represent only a signature of melting and cooling history.

The time a chondrule spends at peak temperature affects the amount of relict material, be it crystals or nuclei that remain in a melt after heating (*Connolly and Desch,* 2004; *Hewins et al.,* 2005; *Lofgren,* 1996). The number of nuclei remaining in a melted chondrule constrain the type of texture that is produced if nucleation is not affected by external sources such as collisions with dust grains (*Connolly and Hewins,* 1995). Another independent constraint on chondrule heating times is derived from the dissolution rates of silicates in silicate melt (*Greenwood and Hess,* 1996; *Jones et al.,* 2000). Approximately 15% of chondrules in ordinary chondrites contain grains that are interpreted to be relict (*Jones,* 1996), meaning they survived the melting of the chondrule in which they are observed. Since these grains did not melt or completely dissolve, their existence constrains the temperature/time variable of heating to tens of seconds to several minutes.

The presence of relict grains also demostrates that chondrules experienced multiple melting events. Texture and chemistry of these grains imply that they were derived from a previous generation of chondrules. Those chondrules where such grains were originally formed were broken up and their contents found their way into the precursors of another generation of chondrules. Thus, chondrule formation occurred many times and is not restricted to a single heating and cooling episode.

Based on the studies of the crystallization of melilite, the major phase in type B CAIs, these objects experienced peak melting temperatures of ~1700 K (*Beckett et al.,* 2006; *Stolper,* 1982; *Stolper and Paque,* 1986). However, it is possible that heating for shorter times to higher peak temperatures could also have produced similar textures, but detailed experimental data for such a thermal history are not yet available. *Connolly and Burnett* (2003) place limits on the maximum duration of type B CAI heating to less than a few tens of hours based on the inhomogeneous concentrations of V, Ti, and Cr within spinel grains. Like chondrules, type B CAIs contain evidence that they experienced multiple melting events (*Beckett et al.,* 2000, 2006; *Davis and MacPherson,* 1996; *Connolly and Burnett,* 1999; *Connolly et al.,* 2003): In some cases this reheating or remelting occurred after an epoch of alteration (that occurred while the objects were free-floating wanders) was experienced by the object (*Beckett et al.,* 2000, 2006; *Simon et al.,* 2005).

3. The cooling and crystallization of chondrules and type B CAIs is to some level well understood. *Desch and Connolly* (2002) reviewed in detail the experimental data on cooling rates and discussed the limitations of these data. To summarize, the cooling rates of chondrules are constrained from the development of chondrule textures (the arrangement and shape of the crystals) and the major- and to a lesser extent the minor-element zoning behavior within individual crystals. Overall the cooling rates experienced by chondrules based on their texture and chemistry are constrained to a range of 10–3000 K h^{-1}, with the majority of chondrules (i.e., porphyritic textures) cooling at 100 K h^{-1} or less through the temperature range between their liquidus and solidus. Cooling from above the liquidus temperature was very rapid, at least 5000 K h^{-1}. Although in reality chon-

drules probably did not cool linearly, most of their crystallization likely occurred in a temperature range that was approximately linear. Recent research has questioned these cooling rates as being far too slow (*Wasson and Rubin,* 2003), but the faster rates proposed, which are up to 1000°/s, have not been widely accepted and are difficult to reconcile with other observations of natural materials and experimental analogs.

Type B CAIs have been constrained to cool between 0.5 and 50 K h^{-1} with perhaps the most reliable cooling rates appearing to be ~2 K h^{-1} (*Stolper and Paque,* 1986; *MacPherson et al.,* 1984; *Simon et al.,* 1996).

4. The post-crystallization, pre-parent-body-accretion thermal regimes for chondrules and igneous CAIs are largely unconstrained experimentally. For petrological studies of natural samples, the major challenge has been to determine chemical overprints from parent-body processes on these objects. It is not, however, known if chondrules and igneous CAIs could have experienced prolonged heating from subsolidus temperatures (e.g., <1300 K) before accretion. The preservation of igneous zoning profiles (for chondrules and refractory inclusions) and abundant glass (in chondrules) is evidence that any post-formation regime of elevated temperature was limited. The issue has not been quantified in any detail and requires additional research in the future.

3.2. Long-Term Timescales: The Epoch of Chondrule and Igneous Calcium-Aluminum-rich Inclusion Formation

By making certain reasonable assumptions, temporal constraints can be made for the epoch of processing chondritic rock-forming materials into chondrules and refractory inclusions within the nebula. As discussed elsewhere within the volume, the inferred initial $^{26}Al/^{27}Al$ in igneous CAIs of 5×10^{-5} is taken as the solar system initial value (*Bizzarro et al.,* 2004; *Galy et al.,* 2000). Lower values observed in chondrules have been used to argue that chondrules (both Fe,Mg-rich and Al-rich) may have begun to form some 0.7 m.y. later (*Tachibana et al.,* 2003; *Russell et al.,* 1996). The data also suggest that chondrule production lasted for at least 2.4 m.y. after formation of most CAIs (*Tachibana et al.,* 2003; *Huss et al.,* 2001) and potentially up to 5 m.y. later (*Russell et al.,* 1996). Timescales for chondrule forma-tion of several million years are also suggested by Pb-Pb ages (*Amelin et al.,* 2002). There is currently some uncertainty about whether there is a hiatus between CAI and chondrule formation (*Amelin et al.,* 2002). It is important to point out that not all authors of this chapter agree on the interpretation of the relative abundance of ^{26}Al within chondritic material. The apparent age gap between CAI and chondrule formation may or may not be real, depending on whether there was a uniform distribution of ^{26}Al throughout the solar system, which is an assumption that is being actively questioned. With more analyses of minerals with lower Al/Mg and high-precision Pb-Pb dating, the apparent time difference between CAIs and chondrules is diminishing. Interestingly, two amoeboid olivine aggregates (AOAs) have $^{26}Al/^{27}Al$ ratios that correspond to inferred ages of 0.3 and 0.5 m.y. after CAI formation, thus their ages appear to fall between CAI and chondrule formation (*Krot et al.,* 2004b). One of these AOAs experienced very low degrees of melting, suggesting that some processing of planetary materials was occurring after CAI formation but before chondrule formation. A critical point to remember is that the data is widely interpreted as demonstrating that CAI formation was apparently short-lived, whereas chondrule formation lasted for potentially millions of years. Future data may dramatically change our current thinking on the time frame of chondrule and refractory inclusion formation, but for now we are con-strained to work with available data.

Several important implications arise from the discussion of the ages of refractory inclusions and chondrules. First, such data essentially provide no constraint on the mechanism that melted chondrules and CAIs, but on the duration of the process. The zero-order constraint is that transient heating within the disk (CAIs) occurred very close to t = 0 and then definitively at 0.7 m.y. later for a period of at least 2.5 m.y. later. We cannot state with any confidence if the mechanism that produced the heating and melting lasted continuously for at least 2.5 m.y. or if it was episodic, turning off and on. It is not possible at this time to determine if more than one mechanism was responsible for CAI and chondrule production, or even if all chondrules were formed by the same process. Age data on AOAs, intermediate in composition between CAIs and chondrules, suggests that the processing of chondritic material may have been continuous from t = 0 and that the composition of the material being processed changed or evolved from more refractory to less so with time. Simply stated, there is no *a priori* reason that these objects cannot have been melted by the same mechanism or type of mechanism. Unfortunately, this is not a unique solution because no compelling evidence exists to eliminate the potential that refractory inclusions and chondrules were melted by different mechanisms. We stress that this does not mean that the environments of formation were the same, and the reader is cautioned not to automatically equate the environment of formation with a mechanism because they may not be intimately linked.

4. THE PRODUCTION OF CHONDRULES AND REFRACTORY INCLUSIONS

We categorize the numerous proposed transient heating events into three major paradigms that represent various environments associated with protoplanetary disks (*Connolly and Desch,* 2004): (1) collision or impact events between asteroid- to planetary-sized bodies in the earliest stages of planet formation, (2) linking the formation of chondrules and refractory inclusions to the YSO, and (3) what we consider to be mechanisms that are purely hypothetical. The first two paradigms have some undisputed bases in linking the formation of chondrules and refractory inclusions to events or processes that are known to occur in protoplanetary disks or did occur in the solar system. In the following section we explore these models and their merits and weaknesses for producing heating events in the contexts of our criteria established above.

4.1. Chondrules as Objects Formed by Collisional Interactions of Planetary Bodies

The idea of chondrules being the product of some kind of planetary setting rather than free-floating wanderers is not new, appearing as far back as *Tschermak* (1895). A big advantage to invoking this kind of setting for chondrule and refractory inclusion production is that it is well established that, to build planetesimals and planets, collisions and impacts occurred. Many different types of planetary settings for the formation of chondrules have been proposed in the last 100 years (*Connolly and Desch,* 2004, and references therein). Such ideas include magmatic processes, presumably in planetary bodies; ejection from planetary bodies by such forces as volcanos (*Merrill,* 1920; *Lugmair and Shukolyukov,* 2001); and collision events between two bodies, either solid, partially molten, or fully molten in the interior (*Urey and Craig,* 1953; *Urey,* 1967; *Sanders,* 1996). Many of the impact or collision ideas typically involve small bodies or planetesimals, the size of asteroids, colliding with one another or impacting into Moon-sized bodies. It may have been the case that Moon-sized bodies were also colliding into each other in the early nebula. Astrophysical models of hierarchical accretion in the protoplanetary disk provide a plausible basis for hypotheses involving collisions. On the other hand, astrophysical models of these accretion stages are incomplete, and currently there are no models that constrain the magnitude, frequency, or effects of the collisions. The data discussed in previous sections do not refute the planetary collision paradigm, but neither can they be used to support it. However, we know that these events occurred and we know that, in some cases, they produced melts. These melts appear as shock-melt veins in chondrites (*Dodd and Jarosewich,* 1979; *McCoy et al.,* 1995), as meteorites interpreted as crystallized impact melts, and, in some cases, as melt spheres, e.g., in diogenites (*Mittlefelt et al.,* 1998), in howardites, on the Moon, and on Earth [e.g., Lonar Crater (*Fredriksson et al.,* 1973)]. However, the geological and astronomical conditions under which these were formed are quite different from those expected on a chondrite parent body and there are key differences in all these compared with chondrules. But without more sophisticated numerical models of impact melting and chondrule production from a chondritic parent body, this remains a potential mechanism for chondrule and possibly refractory inclusion formation.

The key problem of the planetary setting paradigm is that it is based on untested ideas. Many objections to forming chondrules in some kind of planetary setting and collision process have been discussed by *Taylor et al.* (1983), *Grossman et al.* (1988), and *Hewins et al.* (1996); these objections include the need for multiple heating events, the production of rims around chondrules, etc. Although these authors raise interesting and important points against such models, the main difficulty in assessing any kind of planetary setting for the production of chondrules is that no quantitative model has yet been developed and ideas have not been developed beyond the cartoon and idea stage. The thermal histories of chondrules — their peak temperatures, durations of heating, and cooling rates — have simply never been computed in the context of a planetary setting. This is also precisely the main reason not to reject or quickly dismiss such ideas. At this point in the investigation of chondrule and refractory inclusion formation it is simply unknown if any of these ideas have merit in a rigorous quantitative treatment.

Apart from the scientific issues discussed above, another major challenge for any model that ties chondrule formation to a planetary setting is the implicit assumption almost universally made in the field of meteoritics that chondrules (and potentially refractory inclusions) predate planetesimals. This is an understandable deduction, since the majority of primitive chondrite materials are composed almost entirely of chondrules. However, the age of chondrules, refractory inclusions, and magmatic processing on asteroids could be interpreted to suggest that this is not the case (*Nichols,* 2006), and continued research into this important issue is needed.

4.2. Linking the Formation of Chondrules with the Early Active Sun

Relating the Sun or the byproduct processes of an early active star to the formation mechanism of chondrules was first proposed by *Sorby* (1877) with his suggestion " . . . that some at least of the constituent particles of meteorites were originally detached glassy globules, like drops of fiery rain . . . when conditions now met with only near the surface of the sun extended much further out from the centre of the solar system." A major advantage to linking chondrule formation with the early active Sun is that many of the processes that the early active Sun is thought to have experienced are observed in other YSOs. Linking the Sun's early activity to chondrule and refractory inclusion formation has significant merit in that it can potentially lead to testable, quantitative predictions.

Several ideas that link chondrule production with the early active Sun have been proposed (*Grossman,* 1988), including FU Orionis outbursts (*Boss,* 1996) and magnetic flares (*Levy and Araki,* 1989; *Morfill et al.,* 1993). In the last few years, however, one idea has received considerable attention: chondrules as byproducts of the bipolar outflow stage of the YSO. The idea can first be attributed to *Skinner* (1990), although his model was purely qualitative. *Liffman and Brown* (1996) produced a quantitatively detailed model for the formation of chondrules by ablation off larger bodies in outflows. Their model attempted to quantitatively reproduce chondrule thermal histories but did not successfully reproduce the maximum temperatures experienced by Fe,Mg-rich chondrules or the duration of melting. Furthermore, in their model chondrules are produced as ablation spheres from larger rocks that find their way into the outflows and are pushed along the edge regions of the flow. There is no *a priori* reason to assume that chondrules were or were not formed by ablation from larger bodies. This does add an extra step to chondrule formation: the formation of meter- to kilometer-sized bodies before chondrule production. These models attempt to reproduce chondrule cooling rates quantitatively, but it is not clear whether the required chondrule cooling rates of 10–100 K h^{-1} can be achieved and sustained throughout the chondrule crystallization temperature range. The model tends to predict chondrule cooling rates on the order of a few 1000 K h^{-1}, far too fast to reproduce porphyritic textures. Other problems with this model are that it is not clear how remelting or reheating of chondrules would occur or how CAIs and chondrules would be related to each other. Several other unaddressed issues exist, as outlined by *Jones et al.* (2000). These include total pressure or partial pressure of different elements such as O during chondrule formation.

Of chondrule formation models that rely on the Sun's early activity, the one that has stimulated the most interest is the X-wind model of *Shu et al.* (1996, 1997, 2001). This model hypothesizes that chondrule and CAI precursors were transported radially through the protoplanetary disk to the X-wind region, where they were irradiated by energetic flares and/or optical photons from the Sun, then carried by a magnetocentrifugal outflow and flung outward to land back into the disk in the 2–3 AU region. Even though the X-wind model has received significant attention in the last few years, no one has yet calculated the thermal histories of chondrules and CAIs in the context of the X-wind. Chondrule melting is attributed to X-ray flares, which heat the chondrules and CAIs directly, or which may heat the surrounding disk material. Rough estimates of the peak temperatures and cooling rates have been made (*Jones et al.,* 2000) under the somewhat arbitrary assumptions that X-ray flares triple the temperature of the disk gas, and that the flare decays in about an hour. While data on protostellar X-ray flares make these assumptions plausible, no effort has been made to tie chondrule heating and cooling to the substantial literature on the statistics of protostellar X-ray flares (e.g., their peak luminosities and decay timescales). Important details such as the response of the disk to a flare, its thermal inertia, and its vertical structure, have not been computed in detail. The X-wind model provides a framework in which predictions of chondrule peak temperatures, heating durations, and cooling rates could be made, and the details of pre- and post-melting thermal histories examined. For the most part this potential has remained unfulfilled.

In addition to the absence of calculated thermal histories, the X-wind model is also in apparent conflict with other constraints discussed by *Connolly and Desch* (2004), in particular the fact that the solar bulk composition of chondrites is due to the presence of chondrules and matrix. Each of these components alone does not constitute a solar bulk composition. It has thus been suggested that chondrules and matrix formed and/or experienced thermal processing in very close proximity, if not together (*Palme et al.,* 1993). While calculations of particle trajectories in the X-wind have not been presented in great detail in the refereed literature, it is clear from *Shu et al.* (1996) that micrometer-sized dust grains launched by the X-wind will almost certainly escape the solar system. They will never be able to accompany chondrules flung by the X-wind to the asteroid belt. This begs the question of how chondrules entering the disk at 2–3 AU could be complementary in composition to the matrix grains located and likely formed at 2–3 AU when the chondrules themselves formed at 0.1 AU. Dust and chondrules will not be transported together in the X-wind model. Their size and density are considerably different and thus they are not coupled together when entrained in the wind. This apparent conflict might be resolvable within the context of a detailed model. In its current form, however, the X-wind model remains an association of interesting concepts that makes few specific predictions about chondrule or refractory inclusion properties that can be tested, especially regarding the thermal histories of chondrules.

However, within the last few years the community has stimulated discussion on the formation of CAIs by the X-wind model (or a similar type of mechanism) and chondrule production by another mechanism, potentially by shock waves (the current favorite contender). The concept of X-wind production of CAIs that are subsequently flung out to pepper the protoplanetary nebula as exotic materials does not face the same chemical objections as does the genesis of chondrules in this manner. Calcium-aluminum-rich inclusions do not have any complimentarity with their host rocks; indeed their primary chemistry and isotope systematic bears more resemblance to other CAIs than they do to anything else. Hence, a strong argument may be made that they were formed in one place and then scattered among the chondrite-forming region. An X-wind-like model may shed considerable light onto this issue if future detailed numerical modeling is performed.

4.3. Transient Heating Mechanism Hypothesized to have Occurred Within the Disk

Numerous hypothetical transient heating mechanisms that essentially have no bases in observations have been proposed over the last 100 years (*Boss,* 1996; *Connolly and Desch,* 2004; *Grossman,* 1988). Such mechanisms include processes like a hot inner nebula (*Boss,* 1983; *Cameron and Fegley,* 1982; *Morfill,* 1983), nebular lightning (*Desch and Cuzzi,* 2000; *Eisenhour et al.,* 1994; *Eisenhour and Buseck,* 1995; *Horanyi et al.,* 1995, *Love et al.,* 1995), magnetic sheets (*Joung et al.,* 2004), and shock waves (*Boss and Graham,* 1993; *Ciesla and Hood,* 2002; *Connolly and Love,* 1998; *Desch and Connolly,* 2002; *Hood and Horanyi,* 1991, 1993; *Hood and Kring,* 1996; *Iida et al.,* 2001; *Miura and Nakamoto,* 2005; *Miura et al.,* 2002; *Ruzmaikina and Ip,* 1994; *Weidenschilling et al.,* 1998; *Wood,* 1963, 1984). As of the writing of this chapter, the most popular of all these models is the nebular shock wave model. The main reason for the popularity of this model is two-fold: (1) it is testable in that what is predicted is observed in the rock record (*Connolly and Love,* 1998), and (2) it is to date the most quantitative of all models for chondrule formation and it reproduces the thermal histories of the objects in detail.

In summary, the nebular shock wave model hypothesizes that a shock wave of compressed, hot gas moves through a dust-rich region of the nebula at supersonic speeds. It assumes that the dust component is individual dust grains that make up chondrule precursors and chondrules. Numerical modeling of the shock encountering chondrule precursors, chondrules, and their associated gas predict that the gas is compressed and the grains encounter gas drag for a short duration (seconds) after contact with the shock front. This is the first pulse of heating experienced by materials as they enter a shock wave. During this drag-heating phase, mineral grains and chondrules are rapidly or flash heated to liquidus to superliquidus temperatures (2000–2300 K). After the grains and chondrules achieve the same speed as the gas (also known as their stopping distance), the drag-heating phase ends (and no more work is performed on the particles due to frictional heating between atoms and mineral grains or chondrules) and infrared radiation of hot particles to other particles and of hot, compressed gas to solid particles becomes the dominant heating mechanism. Radiation from the shock region heats particles pre-shock passage and particles that absorbed infrared radiation post-shock are heated for considerable time (hours), but this energy is slowly lost over time to produce cooling of chondrules. Numerical models (*Ciesla and Hood,* 2002; *Desch and Connolly,* 2002) show that the shock wave model predicts cooling rates of particles (chondrules) in the range of 10–100°/h. The rate at which chondrules cool in these models through the range of temperatures where crystallization occurs is set by the overall time it takes for the gas and chondrules to move approximately 5 optical depths from the shock front. A key parameter of the nebular shock wave model is that both particles (chondrules) and gas must be modeled. The more particles that are encountered or added to the shocked region, the faster the chondrules will cool due to interactions between gas and chondrules. The nebular shock wave model robustly predicts that most chondrules would cool at rates that experiments have determined produce porphyritic textures, which are the most abundant of chondrule textural types. The model has the advantage that it naturally predicts an increase in total pressure of almost 2 orders of magnitude, which is critical in order to stabilize chondrule liquids because they are not stable at canonical pressures of 10^{-6}–10^{-5} atm (*Ebel,* 2006). Considerable research is being devoted to continuing to develop the nebular shock wave model (*Desch et al.,* 2005). The addition of evaporation and condensation of silicates from molten chondrules as well as the role H_2O may play (*Ciesla et al.,* 2003) in the calculations and hence the partial pressure of oxygen (f_{O_2}) are being modeled. It is also a goal of future models to fully incorporate the production of refractory inclusions, to which the model has only loosely been applied so far (*Desch and Connolly,* 2002).

4.4. Some Additional Discussion on Transient Heating Mechanisms

It is a priority of meteorite research to explain the existence of objects that were processed by transient heating and link their formation to an astrophysically sound process and mechanism. We summarized the various proposed mechanisms that may have produced chondrules and refractory inclusions. It would be very helpful in understanding the applicability of these models and ideas if we could clearly define the framework of hierarchical constraints on the formation of chondrules and refractory inclusions. This, however, cannot be done in an unbiased fashion. *Jones et al.* (2000) discussed in some detail the cooking recipe for making chondrules and refractory inclusions. In an ideal book chapter we would present a table with all the constraints known for chondrule and refractory inclusion formation, listed in order of importance, from zero order or the absolute ground conditions that any model must satisfy to those that are very clearly able to be tweaked, meaning they are of second or third order of importance to modeling. The only issue that all the authors of this chapter can essentially totally agree upon is that the thermal history of chondrules and refractory inclusions must be reproduced by models. If a model cannot or does not quantitatively satisfy this zero-order constraint then we adopt the conclusion that the model is not viable and we do not discuss it further. This does not mean that the model is wrong or that the authors do not agree with the model, it simply means that we cannot make an informed judgment based on the data available.

5. ADDITIONAL ISSUES AND A BLUEPRINT FOR THE BIG PICTURE

We have highlighted some important observations and models that have gained wide attention since the publication of *Chondrules and the Protoplanetary Disk* (*Hewins et al.,* 1996). Many reviews exist (including within this volume) that detail the petrography, chemistry, and constraints on the formation of both chondrules and refractory inclusions as discussed above. These provide more details on what we have learned about these issues since 1996. From this review several critical questions are raised. J. Wood (*Kerr,* 2001) has pointed out the need to see the big picture — putting the details of the petrographic and chemical analysis of these rocks into a framework for their origin and that origin's relationship to solar system formation. Below we list several issues that future research needs to address for determining additional constraints on the formation of chondrule and refractory inclusions, in order to provide a better blueprint for relating all the issues discussed herein to an astrophysical setting of the formation of the solar system. Some additional issues have been reviewed by *Wood* (1996), *Jones et al.* (2000), *Connolly and Desch* (2004), and *Connolly* (2005).

1. What could produce shock waves in the nebula? Although clearly the nebular shock wave model is the most quantitative model to date for predicting the thermal histories of chondrules, how these shocks were produced is unknown. We cannot currently observe processes within disks, thus we cannot witness shocks or chondrule formation within the disks. Currently, no hypothesis for the production of nebula shocks has gained wide acceptance (*Boss and Durisen,* 2005). The nebular shock wave model has also not been applied in detail to the formation of refractory inclusions, although *Desch and Connolly* (2002) predict that it could be. These two major issues concerning the reality of nebular shock waves as the mechanism that produced chondrules and refractory inclusions must be solved. It is a challenge to astrophysics and astronomy to test the prediction of the nebular shock wave model — to predict a mechanism that produced shocks that could have made chondrules and igneous CAIs. Until a convincing method for producing shocks is observed or hypothesized, the nebular shock wave model remains the only quantitative and most favorable model for producing chondrules even though we do not yet know how they could have been produced.

2. The X-wind model needs detailed predictions on thermal histories. Much attention has been given to the X-wind model, but unfortunately it does not yet quantitatively predict the thermal histories of chondrules and refractory inclusions. It is the obligation of science to generate quantitative predictions and, in this case, match those predictions to the rock record. Thus we challenge interested parties to perform and present quantitative predictions for the thermal histories of chondrules and refractory inclusions in the context of the X-wind or some modified version of the model. Clearly the ideas within the X-wind model have considerable merit and must be researched further. Currently, however, it is in an infancy stage and cannot be applied rigorously to chondrule and refractory inclusion formation, but it also cannot and must not be dismissed.

3. A detailed quantitative model for chondrule and igneous CAI formation by interactions between planetary bodies is required. Any idea or model that associates the formation of chondrules and refractory inclusions with planetary bodies, regardless of their size or hypothesized means of producing melted rock, cannot be dismissed as *potentially unviable*. It may not be palatable to many, but it cannot be ignored. It is perfectly reasonable to associate the formation of these igneous meteorite inclusions with planetary bodies that were colliding within the earliest stages of planet formation. Collisions occurred; that is a fact. Some of those collisions were energetic enough to produce melted rock — as evinced by the formation of melt veins within chondrites. However, we need to have numerical models of the thermal evolution of such melt material in the nebula if we are to have informed discussion of the viability of such models for chondrule formation. At present these remain cartoon models.

4. What is the relationship between the mechanism of transient melting and the environment of formation? The nebular shock wave model has very few requirements as to where it could have occurred. It is assumed to have occurred at the 2–3 AU region, or at least that is where the melting of mineral aggregates occurred to produce chondrules and possibly refractory inclusions. The X-wind model *requires* that potentially chondrules and certainly refractory inclusions formed above the disk (although later versions of the model do form chondrules within the disk). It is unknown if the region where these two kinds of objects formed were similar or different. We do not known if the total or partial pressure of H_2 and other elements that comprised the nebular gas during chondrule formation was similar to that experienced by refractory inclusions. It appears that, at least at the writing of this chapter, a strong argument can be made that the environments where refractory inclusions and chondrules were formed had different properties. This does not mean that the mechanism had to be different. Thus, the relationship between the environments where chondrules and refractory inclusions formed and a transient heating mechanism need to be defined — if any relationship even exists. The bottom line is that we really do not understand precisely where chondrules or CAIs formed within the lifetime of the protoplanetary disk.

5. Were chondrules and refractory inclusions produced by the same or different mechanisms? The end of section 4 above presents an important issue that remains unanswered: We do not know if chondrules and refractory inclusions were formed by the same mechanisms or different ones. In the last few years it appears that a movement is afoot that suggests chondrules and refractory inclusions were produced by different transient heating mechanisms. It is, however, not clear what *data* support such an idea or hypothesis. Many in the field appear to associate refractory inclusion formation with the X-wind model and chondrule formation with the nebular shock wave model. It is not required that this be the case. It is also not required that chondrules and refractory inclusions experienced different melting histories. The cooling rates experienced by these objects overlap — no large gap in the rate exists. Is there any reason why the mechanism that produced these objects cannot have been the same? Is it possible that the mechanism was the same, but the environments in which they were produced were different in physical characteristics such as pressure or dust abundance? This issue must be resolved before any relationship between the production of chondrules and igneous CAIs, transient heating events, environments of formation, dynamical processes in the disk, and terrestrial planet formation can be accurately constrained.

6. When were chondrules and refractory inclusions produced? Earlier we discussed the current data and hypothesis for the temporal relationship between chondrules and

refractory inclusions. As we also discussed, however, the verdict is still out as to the exact nature of this relationship. It is critical that the exact nature of this relationship be illuminated. We also need to understand why, apparently, CAI formation was limited to far less than 1 m.y. whereas chondrule formation lasted for at least 1.5 up to 4 m.y. after t = 0. In addition to this issue, we do not yet understand the temporal relationship between igneous CAI and chondrule formation to the collapse of the molecular cloud and formation of the disk and the location within the disk where these objects were produced. As discussed elsewhere in this volume, the times of differentiation of planetesimals and the temporal relationship to chondrule and refractory inclusion formation needs to be clearly resolved. Defining these relationships with higher confidence will provide additional, much-needed constraints on their relationship to transient heating mechanism(s) and potentially terrestrial planet formation.

7. Will we be able to observe the processing of chondritic materials? With many new generations of observing tools coming on line in the near future, observations of disks at finer and finer resolution in the next decade or two may provide new insights into the processing of chondritic materials, either mineral grains that compose these rocks or the actual melting of mineral aggregates that are potentially chondrules and refractory inclusions. It is important to obtain an accurate survey of disks in various stages of evolution in a search for chondrule and refractory inclusio production.

8. Are current observations of dust on the edges of disks related to transient heating events? Determining the composition of dust around protoplanetary disks is a rapidly emerging field of study in observational astronomy (*Forrest et al.,* 2004; *Sargent et al.,* 2004; *Watson et al.,* 2004). In addition to determination of the composition of dust is the goal of understanding the structure of the dust — amorphous or crystalline. Such studies are indicating that amorphous dust is somehow processed into crystalline material within (or at least at the surface of) disks. An obvious question related to our discussions is whether this process could be some type of transient heating event, and whether such an event could be related to the production of chondrules and refractory inclusions? Future research with the Spitzer Space Telescope and other missions may provide powerful constraints on this issue.

9. Continued interdisciplinary approaches to solving the problem of transient heating are needed. The greatest strength in solving the problem of transient heating mechanisms, chondrule and CAI formation, and indeed the fundamental issue of planet formation within the early solar system is to continue to exploit an interdisciplinary approach that blends meteoritics, astronomy, and astrophysics.

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