Chondrules and calcium- and aluminum-rich inclusions (CAIs) are small pieces of rock that probably formed in the solar nebula when fine-grained dustballs were melted and crystallized in short-lived heating and cooling events. Many different models have been proposed to explain the heat source for these events. Studies of the mineralogical, compositional, and isotopic properties of chondrules and CAIs provide important observational constraints that any viable model must explain. Several models may be dismissed, at least in their current formulations, because they are unable to meet fundamental constraints. We examine three currently popular models for chondrule and CAI formation in more detail: nebular lightning, the shock wave model, and the x-wind model. None of the models is entirely satisfactory, and the origin of chondrules and CAIs remains enigmatic.

I. INTRODUCTION

Chondrules are nearly round, submillimeter-sized objects consisting mainly of Mg-Fe silicates. They appear to have solidified by the quick cooling of melt droplets in the early solar system. They are the dominant component in the most common and primitive classes of meteorites, the chondrites, occupying as much as 80% of the total volume (Fig. 1). A second group of similar, but less abundant, objects is the Ca-Al-rich inclusions (CAIs), which consist mainly of Ca-Al silicates and oxides. Because chondrites are considered to be the building blocks of the terrestrial planets, the formation of chondrules (and CAIs) is an important episode in the formation of our solar system (Hewins et al. 1996). Most researchers agree that solid precursors of chondrules and CAIs were melted during rapid heating events that lasted for intervals of the order of minutes; then the molten droplets cooled rapidly, over intervals of hours to days. Some chondrules and CAIs appear to have gone through this cycle more than once. However, most questions concerning the origin of chondrules and CAIs still lack definitive answers. The most fundamental question is, Where and how did the heating take place? Most researchers favor an environment in which chondrules and CAIs were free-floating objects within the solar nebula, but some still prefer planetary surface environments. Wherever they formed, there is no agreement on the most viable heating mechanism.

In the last decade, substantial progress toward solving the riddle of chondrule and CAI origins has been made. The improved understanding of the formation history of sunlike stars and their accretion disks means that chondrule formation can be addressed in a more rigorous astrophysical framework. There have also been major advances in microbeam tech-

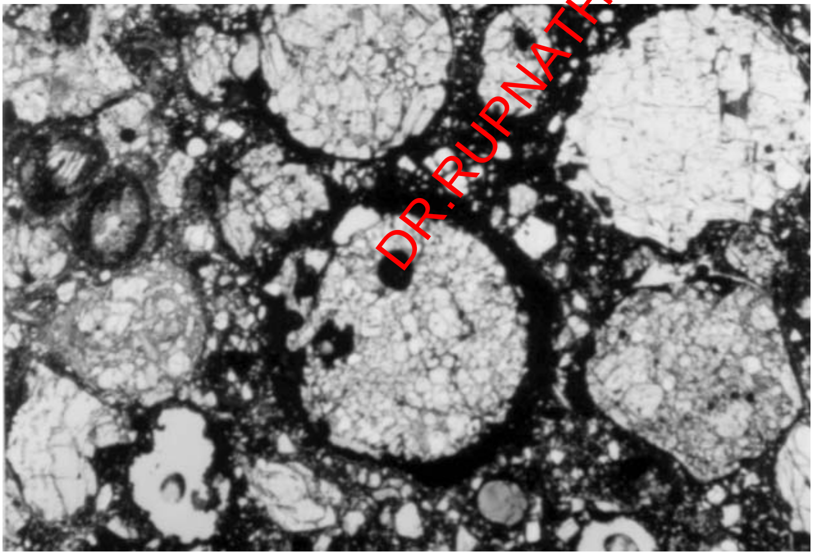

Figure 1. Texture of an unequilibrated ordinary chondrite (Ragland, LL3), showing chondrules (light) and fine-grained silicate-rich matrix which shows as black. In this transmitted-light image, metal and sulfide minerals are opaque and are also black. The chondrule in the center has a well-defined, fine-grained rim. Photo is 3 mm across.

niques that perform *in situ* analyses of the chemical and isotopic compositions of chondrule constituents on a scale of tens of micrometers or less. A third impetus has come from more sophisticated simulation experiments that have explored the effect of different parameters such as crystallization seeds, chemistry, and thermal history on the formation of chondrule textures, compositions, and phase relationships.

In this chapter we first distill a set of constraints for chondrule and CAI formation models from simulation experiments, petrographic examination, and *in situ* analyses. Then we briefly discuss why many proposed models, at least in their most naïve form, can be dismissed, because they violate some of the most critical observational constraints. Finally, we explore in more detail the three models we consider to be most viable: lightning, the nebula shock model, and the x-wind model. We suggest additional petrographic information that could potentially be used as discriminatory tests for these models.

II. OBSERVATIONAL CONSTRAINTS

In Table I, we summarize the constraints for the chondrule and CAI formation models described below and the observations that support them. The interpretation of some observations is more ambiguous than others, and we have indicated those that are not generally accepted.

Note that there are several different types of CAIs. Types B and C CAIs are coarse-grained and crystallized from melt droplets (Fig. 2). Other types of CAIs are fine-grained and have irregular shapes. In this chapter we discuss only the formation of molten (igneous) CAIs; this restriction is implied in most of the discussion where we use the term CAI.

A. Chondrites

Chondrule properties should be regarded in the context of the chondritic rocks in which they are observed. In brief, there are three main classes of chondrites: ordinary (O), carbonaceous (C), and enstatite (E). Within these classes there are 12 well-established groups. In addition, there are two less well-established groups, Rumuruti-like (R) and Kakangari-like (K) (see Table II). The groups are characterized by properties such as sizes and abundances of various components (chondrules, CAIs, matrix, etc.), bulk chemistry, and O isotopic composition (e.g., Brearley and Jones 1998), and the variation between the groups indicates that each one formed in a localized region. Each chondrite group may represent a sample as restricted as a single parent body from the asteroid belt.

B. Abundances of Chondrules and CAIs

Chondrules are the most abundant component of most types of chondrites (up to 80 vol%: Table II), providing evidence that chondrule formation affected a large proportion of the material that accreted at 2–4 AU. We infer

TABLE I
Observational Constraints for Chondrule and CAI Formation Models

Constraint	Supporting observations
Essential constraints for which a model must account:	
High efficiency	High chondrule abundances
Nebular timescales only	Isotopic dating
Low ambient temperature	Presence of volatiles
Short heating time (minutes)	Retention of volatiles; preservation of relict grains; experimental reproduction of textures
Peak temperatures ~2000 K	Experimental reproduction of textures
Short cooling time (hours)	Experimental reproduction of textures; zoning in minerals; presence of glass
Localized process	Limited size range in each chondrite group; differences in O isotopic composition
Multiple episodes; recycling	Relict grains; compound chondrules; igneous rims
Magnetic field	Remanent magnetization
Constraints not firmly accepted by meteoriticists:	
Chondrule formation ~2 Myr after CAI formation	Short-lived radioisotope data
Elevated gas pressure	Stability of molten chondrule
Variable nebular oxidation states	Variable oxidation states of chondrules
Well-defined observations for which a heating model does not necessarily need to account:	
Size sorting	Restricted size range in each chondrite group
Presence of dust that escapes heating	Fine-grained rims

that the chondrule-forming process was common and efficient, although the high abundance of chondrules is also consistent with an additional process that selectively concentrates millimeter-sized particles in chondritic parent bodies. In comparison, CAIs are far less abundant. Igneous CAIs occur almost exclusively in CV chondrites, in which Type B CAIs constitute ~3 vol% and Type C CAIs are very rare. Chondrule abundances are reported differently by different authors, because of some lack of agreement about defining what constitutes a chondrule. Chondrules are usually recognizable as having at least some properties derived from a droplet origin, such as partially rounded outlines, the presence of glass, and tex-

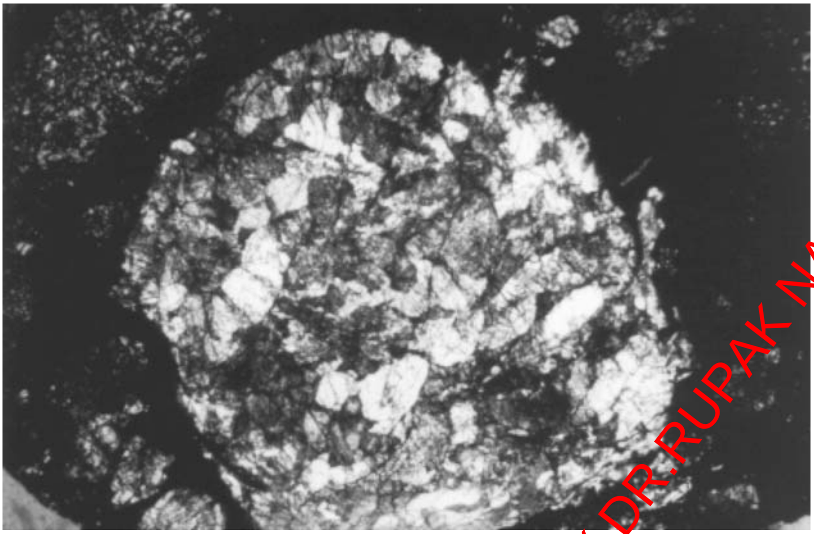

Figure 2. A Type B CAI from the CV3 meteorite Leoville (inclusion 3537–2). This object is approximately 8 mm across and is composed largely of melilite and pyroxene with minor amounts of spinel and anorthite. The chondrite matrix is black.

tures indicating crystallization from melts (igneous textures). In addition to chondrules, many chondrite groups also contain a volumetrically significant population of isolated grains and mineral fragments (usually olivine and pyroxene), which, in many cases, are inferred to be broken pieces of chondrules. Mineral fragments are included in the chondrule abundance data for the various chondrite groups in Table II.

C. Sizes of Chondrules and CAIs

Chondrules from all chondrite groups show a very restricted size range. Mean diameters range between 0.2 and 1.0 mm in all known chondrite groups, with the exception of CH chondrites (Table II). The highly reduced CH chondrites are an extraordinary chondrite group in many respects; there is some doubt that they are true chondrites formed in the solar nebula (Wasson and Kallemeyn 1990). The actual spread in chondrule sizes is wide, from "microchondrules" ($<40\ \mu$m) (Krot and Rubin 1996; Krot et al. 1997) to extraordinarily large ones, up to 5 cm across (Prinz et al. 1988; Weisberg et al. 1988), but such extreme sizes are rare. The restricted size range indicates either a heating mechanism that is specific to the submillimeter size range or the presence of a concentration mechanism for this size range that may be independent of the heating mechanism. Possible size selection mechanisms include turbulent eddies (Cuzzi et al. 1996; Paque and Cuzzi 1997) and aerodynamic coupling

TABLE II
Chondrule Abundances and Sizes in the Various Chondrite Groups

	Carbonaceous (C) chondrites							Ordinary (O) chondrites			Enstatite (E) chondrites		Other chondrite groups	
	CI	CM	CR	CO	CV	CK	CH[b]	H	L	LL	EH	EL	R	K
Chondrule abundance[a] (vol%)	≪1	20	50–60	48	45	15	~70	60–80	60–80	60–80	60–80	60–80	>40	27
Chondrule mean diameter (mm)	—	0.3	0.7	0.15	1.0	0.7	0.02	0.3	0.7	0.9	0.2	0.6	0.4	0.6

[a] Chondrule abundance includes mineral fragments.
[b] Properties of the CH group may not reflect nebular processes.
The names of the O and E chondrite groups indicate the relative abundances of metallic iron present: high (H and EH), low (L and EL), and low total iron, low metal (LL). For the C class, the groups are named after a typical chondrite fall in the group, e.g., CI chondrites are similar to the Ivuna meteorite.

of gas and dust. Metallic particles also show restricted size ranges in individual chondrite groups, and silicate and metal particle size distributions may be consistent with aerodynamic sorting (e.g., Skinner and Leenhouts 1993). Chondrules in individual chondrites show lognormal size-frequency distributions, and the mean chondrule diameter is very well defined for each chondrite group. The mean chondrule size for each group must be observed empirically and is not related to any other chemical or physical properties. If a size-sorting mechanism was operative, it must have been localized and efficient. Sorting may have taken place before, during, or after chondrule formation.

For CAIs, size data have not been quantified very clearly, but the largest (up to 2.5 cm in size: Clarke et al. 1970) are found in the CV chondrites, which also have the largest chondrules; CO, CM, and ordinary chondrites contain smaller CAIs ($<$1 mm).

D. Chondrule and CAI Compositions

Most chondrules are ferromagnesian chondrules, dominated by Fe, Mg, Si, and O. There is considerable compositional variation, particularly in terms of FeO/MgO ratios and SiO_2 contents (e.g., Grossman et al. 1988). FeO-poor chondrules are reduced and contain metallic Fe as well as FeO-bearing silicate minerals, whereas FeO-rich chondrules are more oxidized and contain only minor metallic Fe. Within each of these types, higher SiO_2 contents lead to crystallization of a higher ratio of pyroxene relative to olivine. Most ferromagnesian chondrules also contain glass. There are arguments that all ferromagnesian chondrule compositions can be derived from FeO-rich material by a combination of evaporative loss and loss of metal beads during prolonged melting events (e.g., Sears et al. 1996). However, the siderophile ("metal-loving") element and other fractionations observed in chondrules cannot be explained entirely by such a process (Grossman et al. 1988; Grossman 1996). Also, this scenario is inconsistent with the very short heating times that chondrules experienced (see section II.G below).

Aluminum-rich (Al-rich) chondrules constitute $<$5% of all chondrules and occur in most chondrite types. Compositionally, they span the gap between ferromagnesian chondrules and CAIs, but their relationship to both these other types of objects is not well understood (Bischoff and Keil 1984; MacPherson and Russell 1997). They typically contain plagioclase feldspar, pyroxene, olivine, and glass.

Igneous CAIs are classified into two types, B and C, that have different proportions of the minerals melilite, spinel, pyroxene, and anorthite feldspar. Unlike chondrules, none of these CAIs contain any appreciable quantities of glass. The minerals are described as refractory, meaning that they are among the first minerals predicted to condense, under equilibrium conditions, from a cooling gas of solar composition, and among the last minerals to evaporate on heating. Although refractory during condensation, CAIs have melting temperatures lower than many chondrules. The differences between Type B and C CAIs probably reflect differences in precursor assemblages rather than a genetic relationship between the two types.

E. Oxygen Isotopic Compositions of CAIs and Chondrules

Oxygen isotopic variations are widespread in the solar system. In an oxygen three-isotope diagram (Fig. 3), different constituents of unequilibrated chondrites all have their own oxygen isotopic variation patterns. The anhydrous (water-free) minerals (AM) in carbonaceous chondrites (CC) populate a line with a slope of 1 (CCAM line). These data may be interpreted as a mixture of two or more distinct components with different oxygen isotopic compositions, such as a nucleosynthetic component from supernovae (^{16}O-rich) and the nebular gas (^{16}O-poor; Clayton et al. 1973). Alternatively, the data may also be explained as a mass-independent isotopic fractionation effect (Thiemens 1996).

Chondrules from different meteorite groups have limited ranges and plot in different parts of the O isotope diagram, suggesting different formation sites or times for chondrules in different chondrite groups (Clayton et al. 1983; Clayton 1993). Oxygen isotopic compositions of chondrules all lie relatively close to the terrestrial fractionation line (TF), although

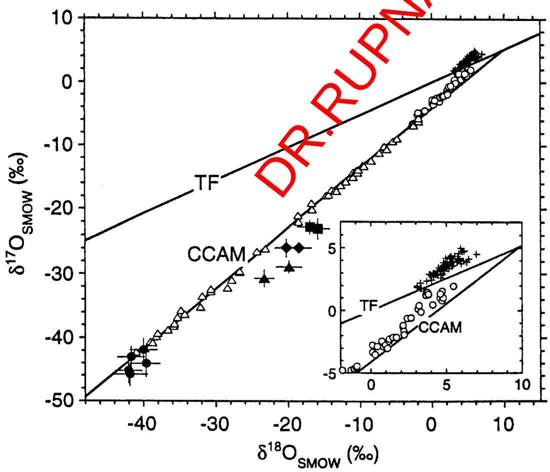

Figure 3. Oxygen isotopic compositions of chondrules and CAIs from ordinary and carbonaceous chondrites. Reprinted with permission from K. D. McKeegan et al. (1998), *Science* 280:414–418. Copyright (1998) American Association for the Advancement of Science. $\delta^{17}O_{SMOW}$ and $\delta^{18}O_{SMOW}$ refer to deviations per thousand, relative to standard mean ocean water (SMOW). Data for chondrules from ordinary chondrites (crosses) lie above the terrestrial fractionation line (TF), whereas data for chondrules from carbonaceous chondrites (circles) lie below TF (see inset). Data for whole CAIs from carbonaceous chondrites (open triangles) fall along a line of slope ~1, known as the carbonaceous chondrite anhydrous minerals (CCAM) line. Recent data for CAIs from ordinary chondrites (filled symbols) lie on the same line.

measurable compositional spreads are observed. In contrast, oxygen isotopic compositions of CAIs show a much wider spread along the CCAM line. McKeegan et al. (1998) have shown that oxygen isotopic compositions of the rare CAIs in ordinary chondrites plot near the same slope 1 line as the CAIs in carbonaceous chondrites. A possible interpretation of this result seems to be that all CAIs from different groups of meteorites share a common origin.

F. Chondrule and CAI Precursors

The immediate precursor material of chondrules probably consisted of individual dustballs, each one having a unique composition. Components of the dustball are thought to be fine-grained. In porphyritic chondrules, relict grains tens of microns in size are preserved (see subsection II.G), while the majority of chondrule precursor material melted. This suggests that most of the host chondrule precursor material was relatively fine-grained. Although there is no constraint on a lower limit for precursor grain size, porphyritic textures require preservation of crystal nuclei from the precursor dust, which probably requires initial grain sizes in the range of micrometers (see section II.G).

G. Thermal Histories of Chondrules and CAIs

Thermal histories of chondrules and CAIs are a function of four important features: ambient temperature, peak temperatures of melting, duration of melting, and cooling rates. An understanding of these variables has been achieved through a comparison of the textures, mineral chemistries (including elemental zonation within crystals), and bulk compositions of the natural objects with synthetic analogs produced in the laboratory. We use the expression "integrated T/t" when we describe the temperature and the duration of a heating process. This is an important parameter, because, for kinetically driven processes, the effect of heating to a high peak T for a short time can be equivalent to that of heating to a lower T for a longer time. The thermal histories we describe below are summarized in Fig. 4.

Earlier experiments designed to constrain thermal histories of chondrules emphasized the effect of cooling rate to produce variations in texture. However, it is now apparent that one key to interpreting chondrule and CAI textures is the number of crystal nuclei present in the melt as it begins to cool (e.g., Lofgren 1996). For example, radiating and barred textures are produced from melts with few nuclei remaining, whereas porphyritic textures are the product of a melt in which many nuclei survived (Fig. 5). One source of crystal nuclei is incomplete melting of precursor dust grains. When this is the case, all other parameters being equal, porphyritic textures represent a lesser degree of heating (lower integrated T/t) than barred textures. It is also possible, however, that chondrules collided with dust grains while they were molten and that these "seed" grains controlled the texture, especially if no nuclei derived from precursor dust survived melting (Connolly and Hewins 1995).

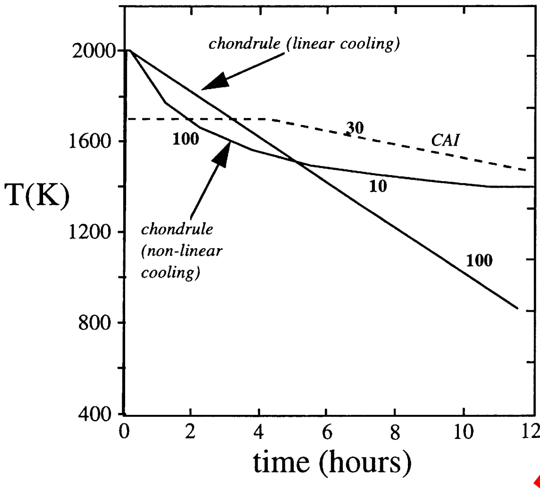

Figure 4. Schematic thermal histories for chondrules (solid lines) and igneous CAIs (dashed line). Cooling rates in kelvins per hour are indicated. Inferred thermal histories for CAIs have more extended times at peak temperatures and lower cooling rates than those for chondrules.

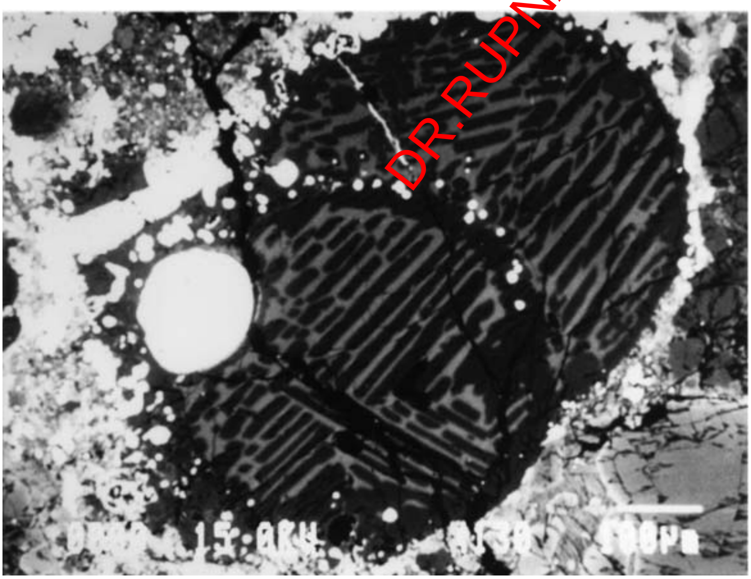

Figure 5. Textures of chondrules and experimental analogs. All the images are back-scattered electron images, in which phases with higher average atomic numbers appear brighter. (a) A compound chondrule from the Semarkona (LL3) ordinary chondrite, consisting of a pair of barred olivine chondrules. The dark gray grains are elongate olivine crystals, and the light gray interstitial material is glassy mesostasis. Both chondrules have abundant metal blebs (white) around their rims.

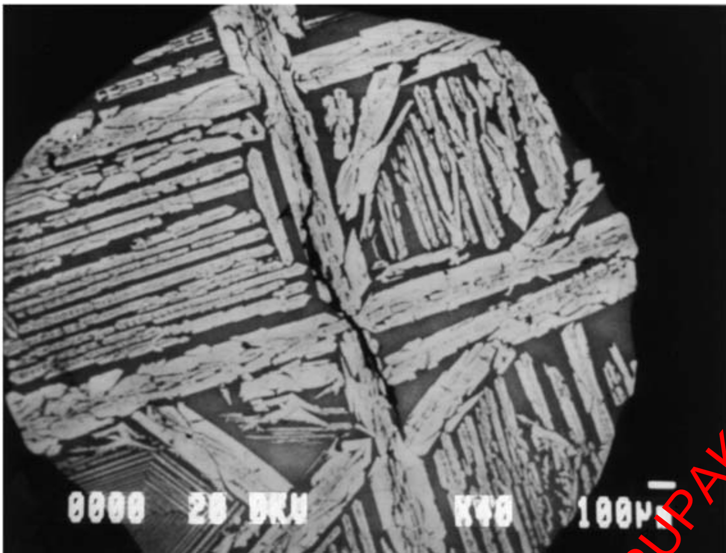

Figure 5. (b) Synthetic barred olivine chondrule showing a similar texture to (a). This texture can be produced in flash-melting experiments, in which the peak temperature is maintained for only seconds to minutes.

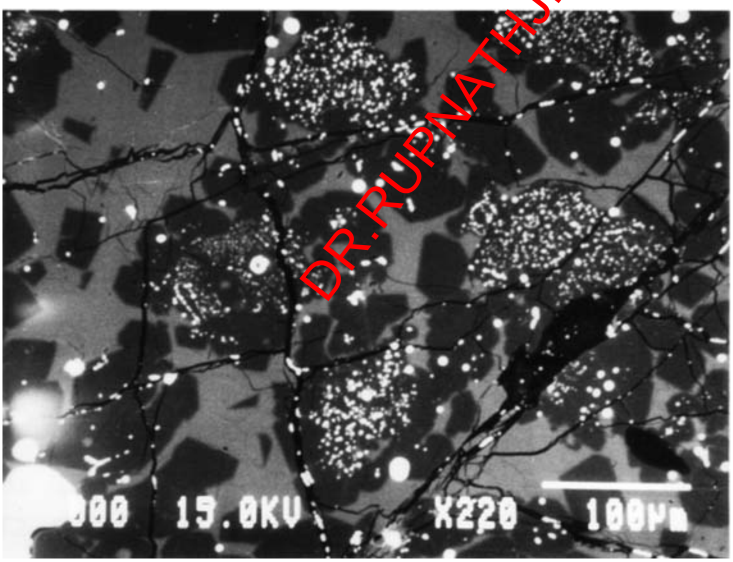

Figure 5. (c) FeO-poor (type IA) porphyritic olivine chondrule from the Semarkona (LL3) ordinary chondrite. Olivine grains are dark gray and show straight crystal faces; mesostasis glass is light gray. Metal (white) occurs in two associations: as larger blebs occurring throughout the olivine and mesostasis, and as hosts of small blebs in the interiors of "dusty" olivine grains. The small blebs were produced by reduction of more FeO-rich relict olivine grains that were incorporated into the host chondrule precursor assemblage and escaped melting.

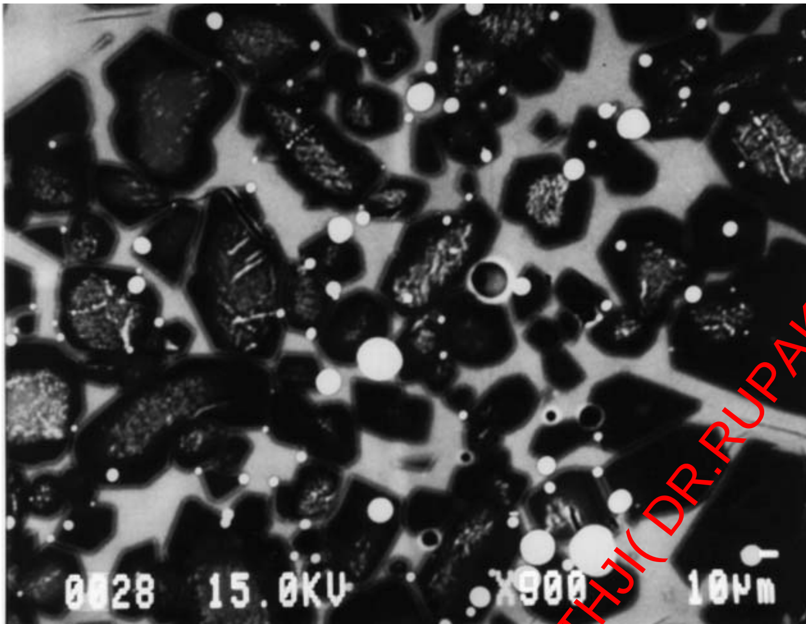

Figure 5. (d) Synthetic FeO-poor chondrule showing a similar texture to (c). This experiment contained carbon in its starting material, which, upon heating, reduced the FeO in the unmelted silicate grains to Fe metal. Scale bars in (a), (b), and (c) are 100 microns, in (d) is 10 microns.

1. Ambient Nebular Temperature. The presence of moderately volatile elements such as Na and S within chondrules, assuming that they were inherited from their precursors, provides a constraint on the premelting ambient nebular gas temperature within the region of chondrule formation (Grossman 1988; Wasson 1996; Zanda et al. 1996; Connolly and Love 1998; Rubin et al. 1999). This temperature must have been below that at which S (usually in the form of FeS) and Na evaporate: ~650 K and ~970 K, respectively (Wasson 1985).

CAIs contain almost no volatile elements. The ambient nebular temperature for CAIs is constrained to be around 1400–1500 K.

2. Duration of the Heating Event. The melting interval for chondrules was originally postulated to have lasted for several hours (Hewins 1989; Lofgren 1996) but more recent experiments have restricted this time to less than a few minutes in order to facilitate retention of moderately volatile elements such as Na and S. Experiments conducted at a range of pressures and oxygen fugacities have shown that if heating from low ambient nebular temperatures was slow, more than a few minutes, or if melting at peak T was longer than several minutes, chondrules would not retain these volatile elements (Radomsky and Hewins 1990; Yu et al. 1996; Hewins et al. 1997; Connolly et al. 1998; Yu and Hewins 1998).

Another independent constraint on the duration of chondrule melting is the presence of relict grains that were not in contact with melt for a long enough time to dissolve. Survival of relict grains in chondrules is a function of the integrated T/t close to peak temperatures, and it constrains the maximum time that appreciable melt was present to tens of seconds to several minutes (Connolly et al. 1994; Greenwood and Hess 1996; Hewins and Connolly 1996).

3. Peak Temperatures. Estimates of peak melting temperatures are obtained by comparisons between chondrule simulation experiments, the calculated equilibrium liquidus temperatures of chondrules (temperatures of complete melting) and chondrule textures (Hewins and Radomsky 1990; Lofgren 1996; Connolly et al. 1998). The total range of estimated peak temperatures of chondrule formation is from ~1800 to 2200 K. Pivotal to these estimates is the production of barred olivine textures (Hewins and Radomsky 1990), which, if no external seeds interacted during formation, require very precise melting and cooling conditions (Lofgren and Lanier 1990; Radomsky and Hewins 1990). The peak T for a given composition cannot be estimated precisely because of the importance of kinetic factors such as the duration of the heating interval and the precursor grain size.

For molten CAIs, T/t paths determined from experiments are significantly different from those determined for chondrules (Fig. 4). Based on growth characteristics of melilite, the dominant silicate mineral in Type B CAIs, the maximum melting temperature is inferred to be ~1700 K with a duration of several hours (Stolper 1982; Stolper and Paque 1986; Beckett et al. 1988; Paque and Lofgren 1993). However, initial melting conditions similar to those experienced by chondrules have not yet been fully tested on CAI compositions, and the possibility of similar heating cycles for melted CAIs and chondrules should not be eliminated (Paque 1995). Although Type B CAIs appear to contain several generations of spinel (Meeker 1995; Connolly and Burnett 1998), dissolution times have not been estimated.

Any heating mechanism that heats particles in good thermal contact with the nebular gas might be expected to produce a narrow range of peak temperatures. This is because, at nebular pressures, molecular hydrogen dissociates at temperatures comparable to chondrule and CAI peak temperatures, e.g. 1700–2000 K at 10^{-4} atm (Liepmann and Roshko 1957; Scott et al. 1996; Wasson 1996). The large energy per unit mass required to dissociate hydrogen makes it an excellent “thermostat” for both the gas and any solid materials in good thermal contact with it.

4. Cooling. Variations in cooling rate affect the textures and mineral chemistries of chondrules and CAIs, as well as bulk compositions, if evaporation occurred during this interval. In general, chondrules cooled much quicker than CAIs: Approximate linear cooling rates are 50–1000°/hr for chondrules and 2–50°/hr for CAIs (Lofgren and Russell 1986; Stolper and

Paque 1986; Radomsky and Hewins 1990; Jones and Lofgren 1993; Lofgren 1996; Hewins et al. 1997). These cooling rates are relevant to the temperature range in which a significant proportion of the object is molten (∼1600–2000 K for chondrules). Preservation of chemically zoned mineral grains and the presence of glass not only are indicators of rapid cooling but also argue that cooling continued down to low ambient temperatures and that no significant reheating or annealing occurred. Small values of the integrated T/t for a reheating or annealing event (e.g., 1200 K for a few seconds or 800 K for a few hours) would be difficult to detect. However, longer durations or a higher temperature would result in homogenization of zoning by solid-state diffusion, and glass would crystallize (devitrify) (Connolly and Hewins 1992; Jones and Lofgren 1993; DeHart and Lofgren 1996). Wasson (1996) proposed that observed chondrule textures are produced by multiple low-temperature annealing events on largely glassy precursors, but chondrule textures have not been reproduced experimentally in this manner.

Although most chondrule and CAI analog experiments have determined linear cooling rates, it is more likely that cooling curves in any natural process would be nonlinear (Yu et al. 1996; Yu and Hewins 1998). Microstructures in plagioclase and pyroxene in some chondrules record cooling rates of tens of degrees per hour in the temperature range 1450–1600 K (Weinbruch and Müller 1995). Typical nonlinear cooling curves may be like the one illustrated in Fig. 4.

Cooling rates of chondrules and CAIs are slower than would be expected from simple radiative heat loss to the surrounding ambient nebular gas, implying that some type of heat-buffering effect accompanied their formation. This is commonly attributed to high dust/gas ratios relative to a gas of solar composition, which insulates the formation regions (Wood 1984; Grossman 1988; Sahagian and Hewins 1992). Alternatively, thermal buffering could also have been achieved through a hot, compressed gas (as in the shock wave model: see section III.B.2). The estimated cooling rates, as well as short times at peak temperatures, are inconsistent with models that require heating of large volumes of dusty clouds (e.g., >100 km in size), which would not allow sufficiently rapid cooling (Sahagian and Hewins 1992; Boss and Graham 1993; Wasson 1996). This concern further supports the interpretation that chondrule formation was a fairly localized process.

H. Oxygen Fugacity and Pressure of Ambient Nebular Gas

Chondrules and CAIs provide limited information about the surrounding gas during the formation interval. During the short heating times for chondrules, there would be only limited exchange of material between chondrules and gas, even at high temperatures, and the chondrules would not necessarily achieve equilibrium with the gas. Evidence for such limited interactions comes from the fact that O isotopic compositions of some chondrules that have undergone more intense heating and melting (e.g., barred olivine chondrules) indicate a higher degree of equilibration with the gas than those of porphyritic chondrules do (Clayton et al. 1983).

The oxidation states of chondrules vary greatly. If chondrule oxidation states were controlled by the surrounding gas, FeO-poor chondrules record conditions similar to that of a gas of solar composition, but FeO-rich chondrules record much more oxidizing conditions. Increases in oxidation states have been explained by the evaporation of fine dust in different concentrations. Alternatively, the degree of reduction of an individual chondrule may be controlled to a large extent by the abundance of reducing phases, particularly C, in the precursor assemblage (Connolly et al. 1994; Hewins 1997), and hence may record only limited information about the surrounding gas.

Little is known about the oxidation state of CAIs. Determinations of the oxidation state of Ti in hibonite suggest that they formed under reducing conditions and that they could have equilibrated with a gas of solar composition (Beckett et al. 1988).

Chondrules may also provide clues concerning the local gas pressure within their formation region, although this constraint is very uncertain. During condensation, liquids of chondrule compositions are stable against evaporation only at pressures greater than $\sim 10^{-3}$ atm (Wood and Hashimoto 1993; Ebel and Grossman 1997, 1998), significantly higher than canonical values of $\sim 10^{-6}$ atm. Synthetic chondrules lose most of their Na within 10 minutes of melting at pressures of 10^{-5} atm (Yu and Hewins 1998), so retention of Na in chondrules also implies an elevated pressure. Local pressures of 10^{-3} atm may be obtained by enhancing the dust/gas ratio to 100–1000 times that of a gas of solar composition. Alternatively, chondrules and CAIs could have formed in a region of the nebula that was at a higher total pressure.

I. Multiple Heating and Recycling

At least 25% of chondrules provide evidence that they have experienced multiple heating events (e.g., Rubin and Krot 1996). This evidence includes the presence of (1) coarse-grained rims, (2) compound chondrules, which consist of two or more chondrules joined together (Fig. 5a), and (3) relict grains (Fig. 5c). Coarse-grained, or igneous, rims have been interpreted as partially melted dusty mantles on primary chondrules (Rubin and Krot 1996). Although many compound chondrules may be produced by collisions of partially molten objects, certain types consist of a primary chondrule that is entirely entrained in a larger secondary chondrule. The secondary chondrule is considered to have formed by heating and melting of fine-grained dust that had accreted onto the surface of the primary (Wasson et al. 1995). Relict grains have chemistries, textures, and O isotopic compositions that indicate that they are recycled from a previous generation of chondrules (Jones 1996; Jones and Danielson 1997; Jones et al. 1998). Hence, disruptive collisions occurred commonly between heating events. An estimate of the number density of chondrules in the chondrule-forming region is of the order of 1×10^{-3} cm^{-3} (Wasson 1993).

Many Type B CAIs contain a thin, multilayered rim, commonly referred to as a Wark-Lovering rim, which probably formed when the CAIs were rapidly melted and quickly cooled after the object had crystallized (MacPherson et al. 1988; Davis and MacPherson 1996). Multiple heating events may also be necessary to reproduce spinel rims (Paque et al. 1998). There is still some question as to whether CAIs contain relict grains. Some studies suggest that relict grains occur (Meeker 1995; Paque 1990; Connolly and Burnett 1998).

J. Fine-grained Rims

Many chondrules have fine-grained rims, consisting of a complex mixture of silicate, metal, and sulfide material that is similar in composition to the chondrite matrix (the fine-grained material that occurs interstitially to chondrules, CAIs, etc.). This material is interpreted as dust that adhered to the chondrules between the intervals of chondrule formation and accretion and escaped the heating process that formed chondrules. There is considerable variability in rim thicknesses between different chondrite groups, although within individual chondrite groups chondrule rim thicknesses are more uniform. Thick rims (up to ~20% of the chondrule diameter) are observed on chondrules in CM and CV chondrites, whereas in ordinary and enstatite chondrites rims are very narrow or nonexistent. Rim thicknesses generally show a positive correlation with chondrule diameters (Metzler et al. 1992; Paque and Cuzzi 1997), and this correlation has been used to argue for chondrule formation at sites local to the parent bodies (Morfill et al. 1998). Some Type B CAIs also have fine-grained accretionary rims.

K. Magnetism

Chondrules preserve a record of magnetic fields of variable strength that were present during their formation (e.g., Sugiura et al. 1979; Sugiura and Strangway 1982; Nagata and Funaki 1981; Morden and Collinson 1992). The magnetic component, which is randomly oriented, was probably acquired when chondrules cooled through the Curie temperature of their magnetic minerals. The field strengths recorded are fairly strong, between 0.1–0.7 mT (~1–10 G). CAIs do not contain magnetic minerals, so the magnetic properties of the environment in which they formed is unknown.

L. Timing of Chondrule and CAI Formation

One of the most fundamental questions about chondrules and CAIs is the timing of the formation events. There are two questions to consider: when chondrule formation occurred relative to CAI formation, and the absolute age of chondrules and CAI relative to the history of the solar system.

The question of the relative ages of CAIs and chondrules does not have a straightforward answer, because the ideal chronometer does not exist. The ^{26}Al chronometer sheds some light, but there are problems with interpreting the data. Details are discussed by MacPherson et al. (1995) and the chapter by Wadhwa and Russell, this volume. One problem with the ^{26}Al data is that most of the chondrules in which abundances have been measured are the relatively rare Al-rich variety. A simple interpretation of the ^{26}Al data is that CAIs are the oldest processed material in the solar system and that chondrules were formed at least 2 Myr later than most CAIs. The problem of mixing material formed 2 Myr apart into the same chondrite parent body constitutes a severe challenge to many nebular models as well as chondrule/CAI formation models.

Other short-lived radioisotopes that have been measured in both chondrules and CAIs include ^{53}Mn and ^{129}I (see Swindle et al. 1996 and the chapter by Wadhwa and Russell, this volume). Instead of dating chondrule and CAI formation events themselves, both systems may record secondary events that postdate formation times and occurred either in the nebula or on parent bodies. The results are not very systematic but are generally consistent with the notion that most secondary activities were over within about 10 Myr of CAI formation.

The problem with absolute age dating of CAIs and chondrules is that most action happened within the first 0.01 Gyr (i.e. 0.2%) of the 4.5-Gyr history of the solar system. To establish a chronology of events in such a short interval so long ago taxes conventional radionuclide dating techniques to their limit. So far only the $^{235}U/^{207}Pb$ system has been applied to CAI and chondrule dating successfully with time resolution approaching 1 Myr. The Pb-Pb age of CAIs most often quoted is 4.566 Gyr (Allègre et al. 1995), which is slightly higher than the earlier results of Chen and Wasserburg (1981), 4.559 Gyr. No suitable minerals for U/Pb dating occur as crystallization products of chondrule melts. However, phosphate minerals that occur in chondrites as a secondary product of thermal metamorphism are suitable and can be used to define lower limits for chondrule formation ages. The oldest chondritic phosphate ages have been determined in H4 meteorites (Göpel et al. 1994) and are only 3–5 Myr younger than the Allende CAI age.

All chronometers point to chondrule and CAI formation very early, within about 10 Myr of initial CAI formation. This timescale is comparable to the lifetime of the nebula (Podosek and Cassen 1994). Because many planetary processes that have been suggested for chondrule formation would also be expected to persist later in solar system history, even up to the present day, this evidence suggests that chondrules and CAIs formed in the solar nebula.

M. Chondrule and CAI Formation: The Same Process?

One question that arises from the above discussion is whether molten CAIs and chondrules were formed by the same process. Despite the obvious differences in precursor mineral compositions, several other properties distinguish the two processes: CAI formation apparently occurred in a significantly earlier epoch than chondrule formation, and CAIs appear to have undergone slightly different thermal histories, including slower cooling rates, compared with chondrules. At present it is not possible to distinguish between two possibilities: (1) a single process that was operative over a period of several million years in the solar nebula and was sufficiently variable in nature to incorporate the constraints of both types of objects, or (2) different processes for CAI and chondrule formation. This question is left open in the following discussion.

III. THEORETICAL MODELS FOR CHONDRULE AND CAI FORMATION

A. Models We Dismiss

Many diverse heating mechanisms for chondrules have been proposed over the last century, but no single model is clearly preferable to all others. Most models have not addressed formation of CAIs specifically. The status of a variety of models was summarized by Boss (1996). In this section we briefly discuss the predictions of some of the models that we consider to be less viable. Each of these has one or more serious inconsistencies with the observational constraints summarized in Table I.

One model that has been investigated repeatedly is the impact model. In this scenario, chondrules are spheres of melt produced in impacts between planetesimals at relative velocities of 5 km s^{-1} or more, possibly analogous to crystalline spherules observed in the lunar regolith (e.g., Symes et al. 1998). Several difficulties with this mechanism have been discussed by Taylor et al. (1983). This model produces the observed restricted range of chondrule peak temperatures only by coincidence, and it is inconsistent with multiple episodes of chondrule recycling. Although recent models (Hood 1998; Weidenschilling et al. 1998) support planetesimal velocities sufficient for impact melting, impact melt production rates on asteroids are extremely small (Keil et al. 1997). The preponderance of chondrules in common meteorites argues for a more efficient process.

A related model is one in which chondrules are produced as droplets formed in the collision of molten kilometer-sized planetesimals (Sanders 1996). This model has many of the same difficulties as the impact melt hypothesis, with the additional challenges of preserving chondritic compositions and maintaining relict grains in melt for the very long timescales associated with kilometer-sized bodies.

Another potential chondrule formation model is ablation of molten droplets from meteors entering transient protoplanet atmospheres, from high-speed planetesimals traversing the nebula, or from planetesimals caught in the young Sun's bipolar outflow jets (Liffman 1992). Support for the requisite high velocities was cited above. A difficulty with this model is a droplet's predicted cooling time once free of its parent body. The cooling time should be similar to the drag heat pulse durations of the shock wave model: tens of seconds rather than minutes to hours. Chondrule recycling is also difficult to imagine in the context of this model.

Chondrules may also have been heated in a locally hot inner protoplanetary nebula. This model is difficult to reconcile with cold precursors, short heating and cooling times, variations among chondrules from different parts of the nebula, elevated pressures, and variable oxygen fugacities.

It has been suggested that chondrules were heated by periodic activity on or near the young Sun, analogous to FU Ori outbursts (e.g., Huss 1988; Bell et al. 1995, and the chapter by Bell et al., this volume). The observed outbursts, however, last very much longer than the allowed range of chondrule heating and cooling times: Outbursts have peak durations of months followed by decades-long declines.

Chondrules could also be interstellar precursors thermally processed in the accretion shock, the discontinuity where infalling molecular cloud material struck the protoplanetary disk (Wood 1984; Ruzmaikina and Ip 1996). This scenario has difficulty explaining locally variable chondrule compositions. It also is inconsistent with chondrule recycling, because each chondrule could only encounter the shock exactly once.

B. More Viable Models

We consider three models to be more viable for chondrule and CAI formation: lightning, the shock wave model, and the x-wind model. All of these models describe processes that only occur in the nebula, so they all automatically conform to the constraint of occurring only on nebular timescales.

1. Lightning. The popularity of lightning as a chondrule formation mechanism has waxed and waned for some time (e.g., Cameron 1966; Whipple 1966; Love et al. 1995; Horanyi et al. 1995; Horanyi and Robertson 1996; Pilipp et al. 1998; Gibbard et al. 1997; Desch and Cuzzi 1999). In a terrestrial thunderstorm, hailstones that have grown to millimeter size and begun falling under the influence of gravity collide with 100-μm ice crystals, which are too small to fall efficiently. In each collision, $\sim 10^5$ electrons are preferentially transferred to the ice crystal (e.g., Keith and Saunders 1989). The continuing rainout of positively charged hailstones leads to a growing large-scale separation of charge and an increasing vertical electric field. When the field reaches a critical threshold value ($\sim 10^5$ V m^{-1}), the electrical resistance of the air breaks down and current, in the form of a lightning bolt, flows to cancel the charge separation.

Lightning in the asteroidal region of the protoplanetary nebula is envisioned to operate analogously. Here, gas turbulence, gas convection, or vertical (i.e., perpendicular to the midplane) solar gravity produces size-segregated motions of chondritic-composition particles, which are assumed to transfer charge as do ice particles in earthly thunderclouds.

Large-scale charge separation builds until the nebular gas breaks down. Reports of lightning in terrestrial volcanic plumes and dust storms (with diverse particle properties) and in outer planet atmospheres (with compositions similar to the protoplanetary nebula) support the idea of nebular lightning. So do observations of “red sprites” and “blue jets” (e.g., Sentman et al. 1995), discharges observed in the clear air above active terrestrial thunderstorms, some of which are seen at altitudes where the pressure ($\sim 10^{-5}$ bar) is comparable to that of the nebula.

Lightning is attractive as a chondrule formation mechanism, because it is consistent with most of the observed characteristics of chondrules. Lightning works in cold environments. The formulation of Morfill et al. (1993) suggests that durations of nebular discharges should be $\sim$100 s, much longer than those of terrestrial lightning bolts and consistent with chondrule peak heating times. Discharge temperatures could have been buffered by hydrogen dissociation. The spatial scale of nebular discharges is not well constrained and could have been large enough to produce the observed chondrule cooling rates. Lightning can work locally and repeatedly and can produce magnetic fields that might explain the remnant magnetism of chondrules. Fine dust caught in lightning bolts would have been more strongly heated than millimeter-sized chondrule precursors (because of the former’s greater ratio of cross-sectional area to mass). The dust might have evaporated, recondensing immediately after the discharge along with volatiles boiled from neighboring chondrules. The gas pressure within the hot discharge channel would be higher than in the surrounding nebula.

Despite its good agreement with the observations, concerns about the model’s physical feasibility have kept lightning from being broadly accepted as the source of chondrules. Some lightning models (e.g., Desch and Cuzzi 1999) suggest discharge durations of milliseconds (as in terrestrial lightning), which are difficult to reconcile with chondrule textures (e.g., Brownlee et al. 1983) and cooling times. The electrical conductivity of the nebula may have been high enough to “short-circuit” large-scale charge separation, effectively preventing nebular lightning (e.g., Gibbard et al. 1997). If lightning did occur, its energy flux may have been too small to melt silicates (e.g., Love et al. 1995). Some models of nebular turbulence provide too little energy to produce the inferred preponderance of chondrules (e.g., Weidenschilling 1996, 1997). Many of these difficulties, however, remain in dispute (e.g., Desch and Cuzzi 1999). Better understanding of terrestrial lightning and of the nebula’s electrical properties will be needed to judge finally whether nebular lightning could have formed chondrules.

2. Shock Wave Model. The idea that chondrule and CAI materials were processed within the protoplanetary nebula by a shock wave has been discussed for more than 30 years (Wood 1962; Stolper and Paque 1986; Hood and Horanyi 1991, 1993; Boss 1996; Cassen 1996; Hood and Kring

1996; Connolly and Love 1998; Hood 1998; Weidenschilling et al. 1998). Shock waves have recently gained favor with the meteorite community as a potential chondrule/CAI-forming mechanism (Boss 1996). As discussed below, the predictions of the model agree well with observations of chondrules and their host meteorites.

One of the biggest problems for the shock wave model is determining how the hypothetical shocks were produced. There is no current observational evidence for producing powerful, reliable, repeatable, and astrophysically realistic shocks. Several recent suggestions, largely theoretical, include clumpy accretion to the nebula (Boss and Graham 1993), outbursts from the protosun analogous to FU Orionis events (Boss 1996), spiral arm instabilities in the disk (Morfill et al. 1993; Wood 1996), and eccentric planetesimals moving at hypersonic speeds through the protoplanetary disk (Hood 1998; Weidenschilling et al. 1998). Although the lateral size and distance traveled by shock waves may have almost any values, their spatial scales must be limited to events that can produce the localized processes indicated by the observational constraints for chondrule formation.

A shock wave is a sharp discontinuity between hot, compressed, high-speed gas (moving faster than the local speed of sound) and cooler, less dense, slower-moving gas. The nebular shock wave model envisions nebula gas that is overrun by a shock wave and becomes abruptly heated, compressed, and accelerated. The kind of shock is assumed to be a thin, flat surface (a plane) that moved through an initially cool, quiet (turbulent velocities of $\sim$50 m s^{-1} or less, Cuzzi et al. 1996) region of the nebula composed dominantly of H_2 gas and silicate dust. For simplicity the shock is assumed to be normal (i.e., traveling in a direction perpendicular to its front surface).

Given the Mach number of the shock and the ideal gas equation of state, analytical relations govern the postshock density, pressure, velocity, and temperature in the gas, as illustrated in Fig. 6 (Hood and Horanyi 1993; Cassen 1996; Hood and Kring 1996; Scott et al. 1996; Connolly and Love 1998). Temperature and density increase moderately behind the shock wave, while pressure increases significantly. For example in a Mach 5 shock, pressure increases by a factor of 29, density by a factor of 5, and temperature by a factor of 5.8 (Fig. 6).

The major hurdle to overcome with the shock wave model is showing rigorously that such a mechanism could have melted chondrule and CAI precursors. As was determined by Hood and Horanyi (1993) and discussed by Cassen (1996) and Connolly and Love (1998), a solid particle that is overrun by a shock suddenly finds itself in a blast of wind moving at several km s^{-1}. At this time the particle begins to heat due to friction with the postshock gas, which is forcing the particle to match speeds with the gas. Heating by thermal radiation from hot neighboring particles also occurs. In addition, particles can be heated radiatively and conductively

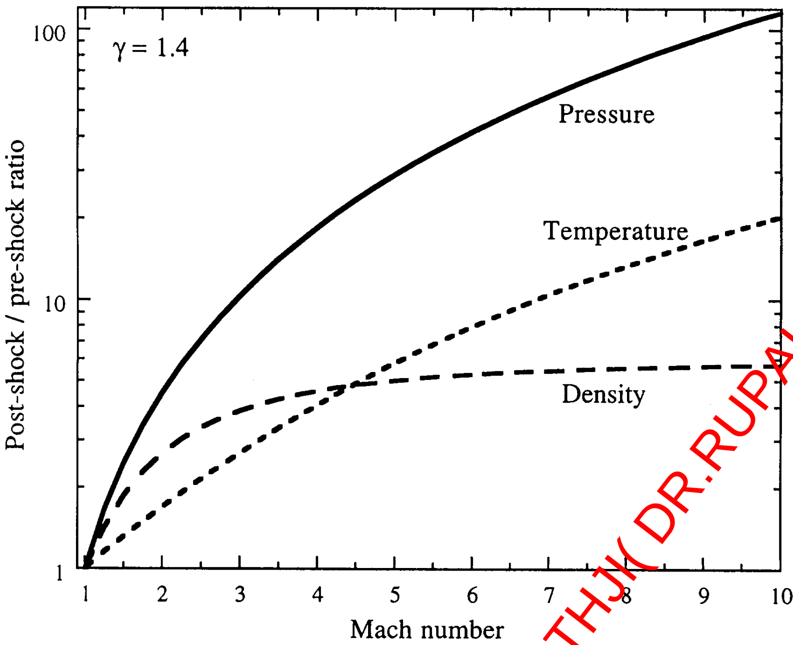

Figure 6. Post- to pre-shock pressure, temperature, and gas density ratios as a function of shock strength expressed in Mach number M. Shocks of M 3 to 8 are thought to be capable of forming chondrules. An M 5 shock increases the density by a factor of 5, the temperature by a factor of 5.8, and the pressure by a factor of 29.

by the hot postshock gas until cooling begins or a postshock rarefaction wave follows.

During the heating process, the flux of kinetic energy absorbed by a particle (drag) must at least balance the radiative loss of heat from that particle if melting is to be achieved. At the melting point, this relation can be expressed by the equation $\frac{1}{2}\rho_s V^3 \pi a^2 > 4\pi a^2 \sigma T^4_{\mathrm{melt}}$, where V is the velocity of the particle relative to the postshock gas, a is the particle radius, T_{melt} is the particle temperature, and ρ_s is the density of shocked gas (Cassen 1996). Initially the heating is mainly due to drag or friction, which will begin to approximate zero once the particle has achieved the speed of the shock. In theory, frictional heating occurs only for a finite distance and time, which is related to the stopping distance of a particle, expressed as $l_{\mathrm{stop}} = d_p \rho_p / 2\rho_s$, where d_p is the particle diameter, ρ_p is the particle density, and ρ_s is the postshock gas density. Inserting typical values into the above relations yields drag heat pulse durations of a few tens of seconds. Chondrule formation via shocks in an optically thin medium, however, cannot prevent the solidification of the molten chondrules within seconds (Cassen 1996; Hood and Horanyi 1993). For drag heating alone to produce cooling rates comparable to those of chondrules, shock waves with unreasonable speeds (~Mach 60) are required (F. Shu, personal communication, 1998).

The petrologic and geochemical constraints on chondrule formation require, however, that chondrules formed within the presence of other chondrules and fine-grained silicate dust. The mass density of chondrules and other dust particles may have exceeded that of the gas before chondrules were heated and may have provided an opaque "blanket" that slowed radiative heat loss rates to values comparable to those experimentally determined for chondrules (e.g., Hood and Kring 1996). In this optically thick scenario, shock waves of Mach 3 to 8 (a physically realistic range) produce peak temperatures and cooling rates that match those of chondrules (Cassen 1996; Hood and Horanyi 1993; Hood and Kring 1996). It should be pointed out, however, that a full analysis of cooling within an optically thick medium composed of different-sized particles has yet to be performed.

Because of space limitation, it is impossible for us to describe in detail the comparison between the predictions of the shock wave model and the meteorite evidence. Connolly and Love (1998) and Hood and Kring (1996) showed that the predictions of the model agree well with the petrologic and geochemical constraints on chondrule formation. Although the predictions of the shock wave model for chondrule formation also agree with many observations and constraints on the formation of igneous CAIs, the longer cooling times required for CAIs are difficult to reconcile with the model. Below we highlight some of the more important issues on forming chondrules by the nebular shock wave model.

The first constraint we examine is the intensity and duration of particle heating. Nebular shocks of Mach 3 to 8 can heat initially cold chondrules (as mandated by the petrologic observations discussed above) to melting temperatures for times consistent with those determined experimentally. Shock wave heating is also virtually instantaneous; particles are heated to their centers on timescales limited by their size and thermal diffusivities, ~1 s for 1-mm silicate spheres (Love and Brownlee 1991), satisfying the need to melt chondrules quickly to prevent the loss of volatile phases or elements. In addition to melting, postshock cooling rates similar to those experienced by chondrules have been determined (Hood and Kring 1996). A potential weakness of the shock wave model is that if shock waves stronger than Mach 8 occurred, they might have heated chondrules to temperatures above their experimentally derived formation temperatures. This weakness may be offset by hydrogen dissociation (see section II), which absorbs orders of magnitude more energy than simple caloric heating (Wasson 1996), and may be effective in limiting chondrule peak temperatures to the observed range even in shock waves substantially stronger than Mach 8.

An important petrological test of the shock wave model is the fact that chondrules have been recycled. Because shock waves need not be singular or identical events, they can provide the multiple heating episodes of varying intensity indicated by the texture and chemistry of some chondrules. Collisions within shock waves would also have broken up chondrules, assisting in the recycling process and potentially producing their observed fine-grained accretion rims.

3. X-wind Model. The suggestion that chondrules and CAIs may have an astrophysical origin has stimulated the study of solid material in relation to the observed phenomena of young sunlike stars. Well-documented physical processes in young, low-mass stars may contribute to the formation of chondrules and CAIs. Sorby (1877) first proposed that melting of chondrule precursors occurred near the surface of the Sun and those molten spheroids were later flown outwards in solar flares. Herbig (1977) proposed that the enhanced stellar radiation in an FU Orionis outburst melts chondrule or CAI precursors, and the ensuing mass loss drags the grains to interplanetary space. Energetic events occurring in the vicinity of young stars, such as jets and outflows, have motivated more modern investigations (e.g. Skinner 1990*a*,*b*; Liffman 1992; Liffman and Brown 1996). The x-wind model (see the chapter in this volume by Shu et al.) has the potential to meet the astrophysical criteria to be a jet-bearing wind that drives the molecular outflow, and is therefore worthy of more detailed discussions for its meteoritic connections.

The x-wind arises as a result of the interaction between a disk and a strongly magnetized central star in the early evolution of a sunlike star. The stellar magnetosphere truncates the surrounding accretion disk at an inner edge of radius R_x as the gas presses onto the magnetic fields. A fraction of the accreting mass blows open the magnetic field lines to form the x-wind, and the rest funnels onto the star on the closed field lines that connect the star and the disk. Making a star of 1 $M_\odot$ requires a total mass of between 0.33 and 0.5 $M_\odot$ to be lost in the x-wind. A detailed treatment and a schematic drawing of the x-wind environment are presented in the chapter by Shu et al., this volume.

In the steady state, the stellar dipole rotates at the same Keplerian angular speed as the inner edge of the disk at R_x. On the other hand, in the time-dependent x-wind environment the edge of the disk fluctuates about the equilibrium position as the magnetosphere undergoes cycles, analogous to the solar example (Shu et al. 1997). In the high states of the magnetic cycles, the magnetosphere is relatively stronger than the accretion gas flow, and the inner edge of the disk is pushed outward until a balance is found, at which point the star rotates faster than the inner edge of the disk. In the low states the disk can intrude further inward, and the inner edge rotates faster than the star. Violent magnetic reconnections can occur, releasing the wrapped-up magnetic fields accumulated by inequalities in rotation rates, on sites of magnetic reversals (Linker and Mikic 1995). In addition to the soft X-rays produced steadily from the coronal fields, flares contribute many more hard X-rays, UV radiations, and MeV-energy cosmic ray particles powered by the magnetic energy release (see the chapters by Shu et al. and Glassgold et al., this volume).

At the truncation point R_x of the disk, only gas will be stopped by the magnetosphere, while rock/dust continues spiraling in until the evaporation point of the most refractory material. Millimeter- to centimeter-sized molten droplets may have dropped out from the funnel gas on the way to the star. These rocks make a ring of particles under the funnel flows, known as the reconnection ring. The extension of the dust/rock disk inward of the gas disk is supported by the observations that some classical T Tauri stars require the inner edges of optically thick dust disks to be as close as $0.5R_x$ (Meyer et al. 1997). If left alone, the ring of particles would eventually spiral inward through the equatorial plane and accrete onto the Sun as vapor.

We now outline the theoretical framework of the x-wind model for forming chondritic meteorites (Shu et al. 1996, 1997). A continuous flow of gas and dust accretes through the disk. The disk is self-shielded from the direct rays of the protosun and is relatively cool. The dust component becomes the precursors of chondrules and CAIs. When the accreting material meets the magnetosphere at the x-point, the gas is launched from the inner edge, R_x, as the x-wind. Precursors are also lifted with the gas into the wind by strong gas-grain coupling in the x-region. Out of the shade of the disk, they are immediately exposed to full sunlight. In the protosolar radiation field, if heated to temperatures above ~1700 K lasting for several hours to days, molten CAIs form and cool in the wind, in radiative equilibrium with the sunlight as the spheroids move further from the protosun. However, the prolonged high temperatures of the mean radiation field would have evaporated all chondrule components. In the steady state, the production of chondrules may need subsolar heating on the rotating dustballs to reach local high melting temperatures when the mean radiation field becomes weaker. In the time-dependent x-wind model, chondrules may be irradiated by flares during the high states of the magnetic cycles when the x-region is further from the Sun. They are flash-heated by enhanced luminosity in all wavelengths, on a timescale of minutes to hours, to temperatures approaching 2200 K. The cooled and solidified particles are thrown into space by the wind like stones from a sling. Large particles fall back into the disk not far from the launch point, whereas small particles remain well coupled to the gas and are carried to interstellar space. Intermediate-sized particles are well enough coupled to the x-wind that they fall back to the disk at interplanetary distances, where they then accumulate along with the ambient dust grains in the nebular disk to form the parent bodies of chondritic meteorites.

To quantify the scenario outlined, we refer to two sets of fiducial numerical examples that correspond to typical evolutionary stages of low-mass star formation. The first set represents the embedded stage, when the young star is still deeply embedded inside its infalling envelope of gas and dust; the second one represents the revealed stage, when the outflowing wind has reversed the infall over almost all solid angles and revealed the star and the disk as optical and infrared objects (Shu et al. 1987).

As the system evolves, as a result of stronger dynamo action, reduced accretion rates, or both, the magnetic fields become relatively stronger, and R_x gradually recedes. The parameters are listed in Tables 1 and 2 of Shu et al. (1997). The embedded stage (mass of protostar, $M_\star = 1 \times 10^{33}$ g; stellar radius, $R_\star = 2.1 \times 10^{11}$ cm; $R_x = 4R_\star$; mass loss rate at x-wind outflow, $M_w = 3 \times 10^{19}$ g s^{-1}) lasts for about 2×10^5 yr, and the revealed stage ($M_\star = 1.6 \times 10^{33}$ g; $R_\star = 2.1 \times 10^{11}$ cm; $R_x = 5.3R_\star$; $M_w = 2 \times 10^{18}$ g s^{-1}) for about 3×10^6 yr, in rough agreement with the observational lifetimes of the young stellar objects.

CAIs can form in the steady-state x-wind environment. The surface-averaged temperature of a millimeter-sized sphere can be estimated from the general radiation equilibrium condition with the contributions from the direct and the diffuse radiation. The diffuse radiation field can be estimated as half of a blackbody from the underlying disk characterized by the disk temperature T_x at the x-point. When R_x is very small, no solid material can survive. As R_x increases, the temperature around the launch point falls and the most refractory material starts to survive. Peak temperatures reached in the fiducial embedded and revealed cases are 1800 K and 1300 K for T_x equal to 1200 K and 800 K, respectively. The first value is high enough to melt CAIs and some chondrules. Lifted molten droplets will stay near liquidus temperatures for an interval of a few days, when the radial distances of the CAIs increase from about 1 R_x to 1.5 R_x. The inferred cooling rates along the trajectories in a direct radiation field are $>$3 K hr^{-1} in the embedded phase and $>$2 K hr^{-1} in the revealed phase.

For chondrules, we need a fluctuating system (Shu et al. 1997). In varying magnetic cycles, the high states and the low states of the star-disk system can create significantly different thermal environments corresponding to the same average states discussed in the previous paragraph. In the embedded phase the disk temperature has a range of 750 K $< T_x <$ 1600 K, and in the revealed phase the range is 500 K $< T_x <$ 1100 K. The peak temperature oscillates between 1300 K and 2200 K in the embedded phase and between 950 K and 1600 K in the revealed phase. In the low magnetic and average states, T_x is high enough to drive off moderately volatile elements from chondrule precursors. When launched, the rocks remain near peak temperatures for days. On the other hand, in the high states of the revealed phase, T_x (500 K) is low enough to retain volatiles in the chondrule precursors. During flight, the peak temperature reached is insufficient to melt the magnesium-iron silicates completely. The production of chondrules may peak slightly towards the high states, although it would be mixed with the production of CAIs in the low states.

Observations of young stellar objects show that typical X-ray flares rise in a short time and decay on a timescale of up to few hours (chapter by Glassgold et al., this volume). Flare heating can result in doubling or tripling of the base temperatures because of a favorable geometry that does not involve very oblique rays (from the helmet streamers) and is close to chondrule precursors (in the reconnection ring). In the embedded state, tripling of T_x results in a temperature rise to 2250 K, and cooling to 1300 K in an hour equals a cooling rate of 950 k hr^{-1}. In the revealed state, the peak temperature is 1500 K, and the cooling rate is 550 k hr^{-1}. Near the x-region both in and out of the disk, the particle density is high, and collisions of (partially) molten chondrule droplets may occur fairly frequently. After launch in the wind, chondrules would acquire magnetization, recording magnetic fields with intensities of 0.09–0.3 mT. This scenario is consistent with several of the observational constraints for chondrules.

For prolonged flares or an extended heating environment in the reconnection ring, the protochondrules may vaporize, and the constituent atoms will condense as rims onto preexisting CAIs. These CAIs would have already undergone at least one launch cycle, when they were formed, and subsequently dropped back down into the midplane. This process may occur many times before the particles are relaunched by an encroaching x-wind, resulting in accumulation of the thick layered mantles seen in many CAIs. Many flares in the right range of strengths may also reheat chondrule material, accounting for recycling observations.

The aerodynamic drag provides a size sorting mechanism for both chondrules and CAIs. The x-wind sprays particles according to the inverse product of densities and radii. The sizes of the solidified spheroids that return to the disk in the region of the asteroid belt can be calculated. Particle diameters are 3.0 and 0.14 mm from the high states and 4.9 and 0.22 mm from the low states, for the embedded phase and revealed phase, respectively. Within the same average evolutionary stage, subsequent (and rapid) inclusion of CAIs and chondrules in larger (sub)planetary bodies will preserve the narrow size distribution. The x-wind theory specifically predicts that small chondrules and CAIs should exist in comets.

The x-wind environment has the potential of reviving the explanation of producing meteoritic-level ^{26}Al by young solar cosmic ray bombardment (Lee et al. 1998; but see also the chapter by Goswami and Vanhala, this volume). The proton and α particle fluence sufficient to synthesize ^{41}Ca and ^{53}Mn at levels corresponding to those observed in chondrites fails, by one to two orders of magnitude, to produce enough ^{26}Al. However, impulsive flares arising from the reconnection ring accelerate numerous ^{3}He nuclei to MeV energy per nucleon, and this process may yield an enhanced abundance of ^{26}Al. Producing ^{26}Al within the solar system would remove the difficulties of having to form CAIs a few million years earlier than chondrules.

The general framework of the x-wind model addresses several of the observational constraints for CAIs and chondrules. However, some important and essential constraints still remain to be examined in the context of the model. These include the O isotopic compositions of chondrules and CAIs as well as the proportion of material in a chondrite that would be derived from dust that had not been processed through the x-wind.

IV. DISCRIMINATORY TESTS

We now turn our attention to suggesting some discriminatory tests that would be helpful in evaluating the viable models. One such test requires understanding the relationship between chondrule size and the degree of heating experienced. Although chondrule recycling might complicate this matter somewhat, if every heating event produces the same size dependence, the sum of many such events should also. In shock wave models, larger chondrules are predicted to be heated more strongly than smaller ones; in lightning and x-wind models, smaller ones are heated more; and in most other models there is no predicted correlation between size and heating intensity. Lightning and x-winds heat material with radiation, light, or ion bombardment. The heat input is proportional to the cross-sectional area, but the energy required to heat and melt is proportional to the particle's volume. In contrast, in a shock wave, larger particles take longer to come up to speed with the postshock gas than smaller ones, thus experiencing a longer drag-heat pulse duration and a higher integrated T/t.

A second discriminatory test that would be useful in evaluating formation models is the relationship between the abundances of opaque minerals (metal and sulfides) in chondrules and the degree of heating experienced. In a model that heats chondrules with light (lightning, x-wind), heating effects should be strongest in objects rich in opaque minerals because these would absorb more light than transparent materials (silicates). In models such as the shock wave model, there would be no expected correlation between opaque abundance and degree of heating, although particles with high opaque abundance would be denser and have longer stopping distances (and thus heating durations) than particles of similar diameter that were poor in opaques.

Unfortunately, these two potentially valuable constraints are difficult to evaluate from the chondrule record. It is hard to create a semiquantitative scale for the degree of heating experienced by an individual chondrule, because the unique texture and composition presently observed is a function of the grain size of precursor material, bulk composition, peak T relative to the liquidus, the influence of fine-grained dust as nucleation seeds, and many other variables. One type of chondrule that may provide an opportunity to examine these questions is the so-called agglomeratic olivine (AO) or dark-zoned (DZ) chondrules (Weisberg and Prinz 1996; Zanda et al. 1996). These chondrules are very fine-grained and have not been melted extensively, but their bulk compositions span a wide range from FeO-poor to FeO-rich. The problem of determining initial opaque abundances is complicated by the possibilities of volatilization and centrifugal loss of metal beads during formation. Nevertheless, an attempt to address these parameters would be a profitable exercise for future research efforts.

V. SUMMARY

Despite several significant advances in our understanding of chondrules and CAIs and in our theoretical models, the puzzle of providing a viable and acceptable model for formation of these objects is still not resolved. The authors of this paper do not all agree on some of the points presented, and it is clear that the debate about heating mechanisms will continue for some time. Lightning matches observational constraints for chondrule formation well, but there are still some concerns about the feasibility of lightning in the nebula. Shock wave models are well developed and are consistent with many of the observational constraints, but the source(s) of the shock waves needs to be defined. The x-wind model has the advantage of being an observed phenomenon in disks, and it addresses many of the constraints for CAI formation. However, it needs to be considerably better developed (by addressing more of the observational constraints) if it is to be considered a viable model for chondrule formation. Other models fail to satisfy observational constraints in one or more critical aspects and must therefore be considered to be flawed in their current formulations.

Acknowledgments We are most grateful to Jeff Cuzzi and John Wasson for thoughtful and constructive reviews of this manuscript. This work was partially funded (R. H. J.) by the Institute of Meteoritics, University of New Mexico, and NASA grant MRA-97-282 (J. J. Papike, PI). H. C. C.'s contribution was supported by NASA grant NAG5-4319 (D. S. Burnett, PI), and H. S.'s contribution by NASA grant NAG5-4851.

REFERENCES

Allègre, C. J., Manhès, G., and Göpel, C. 1995. The age of the earth. *Geochim. Cosmochim. Acta* 59:1445–1456.

Beckett, J. R., Live, D., Tsay, F.-D., Grossman, L., and Stolper, E. 1988. Ti^{+3} in meteoritic and synthetic hibonite. *Geochim. Cosmochim. Acta* 52:1479–1495.

Bell, K. R., Lin, D. N. C., Hartmann, L. W., and Kenyon, S. J. 1995. The FU Orionis outburst as a thermal accretion event: Observational constraints for protostellar disk models. *Astrophys. J.* 444:376–395.

Bischoff, A., and Keil, K. 1984. Al-rich objects in ordinary chondrites: Related origin of carbonaceous and ordinary chondrites and their constituents. *Geochim. Cosmochim. Acta* 48:693–709.

Boss, A. P. 1996. A concise guide to chondrule formation models. In *Chondrules and the Protoplanetary Disk,* ed. R. H. Hewins, R. H. Jones, and E. R. D. Scott (Cambridge: Cambridge University Press), pp. 257–263.

Boss, A. P., and Graham, J. A. 1993. Clumpy disk accretion and chondrule formation. *Icarus* 106:168–178.

Brearley, A. J., and Jones, R. H. 1998. Chondritic meteorites. In *Planetary Materials,* Reviews in Mineralogy Vol. 36, ed. J. J. Papike (Washington D.C.: Mineralogical Society of America), pp. 3-1–3-398.

Brownlee, D. E., Bates, B., and Beauchamp, R. H. 1983. Meteor ablation spheres as chondrule analogs. In *Chondrules and their Origins,* ed. E. A. King (Houston: Lunar and Planetary Institute), pp. 10–25.

Cameron, A. G. W. 1966. The accumulation of chondritic material. *Earth Planet. Sci. Lett.* 1:93–96.

Cassen, P. 1996. Overview of models of the solar nebula: Potential chondrule-forming environments. In *Chondrules and the Protoplanetary Disk,* ed. R. H. Hewins, R. H. Jones, and E. R. D. Scott (Cambridge: Cambridge University Press), pp. 21–28.

Chen, J. H., and Wasserburg, G. J. 1981. The isotopic composition of uranium and lead in Allende inclusions and meteoritic phosphates. *Earth Planet. Sci. Lett.* 52:1–15.

Clarke, R. S., Jarosewich, E., Nelen, J., Gomez, M., and Hyde, J. R. 1970. The Allende, Mexico, meteorite shower. *Smithsonian Contrib. Earth Sci.* 5:53pp.

Clayton, R. N. 1993. Oxygen isotopes in meteorites. *Ann. Rev. Earth Planet. Sci.* 21:115–149.

Clayton, R. N., Grossman, L., and Mayeda, T. K. 1973. A component of primitive nuclear composition in carbonaceous chondrites. *Science* 182:485–488.

Clayton, R. N., Onuma, N., Ikeda, Y., Mayeda, T. K., Hutcheon, I., Olsen, E. J., and Molini-Velsko, C. 1983. Oxygen isotopic compositions of chondrules in Allende and ordinary chondrites. In *Chondrules and Their Origins,* ed. E. A. King (Houston: Lunar and Planetary Institute), pp. 37–43.

Connolly, H. C., Jr., and Burnett, D. S. 1998. Minor element distributions in and among spinels from type B CAIs. *Lunar Planet. Sci.* 29: Abstract #1487.

Connolly, H. C., Jr., and Hewins, R. H. 1992. Chondrule modification as a possible indicator of rim-forming mechanisms. *Lunar Planet. Sci.* 23:239–240.

Connolly, H. C., Jr., and Hewins, R. H. 1995. Chondrules as products of dust collisions with totally molten droplets within a dust-rich nebular environment: An experimental investigation. *Geochim. Cosmochim. Acta* 59:3231–3246.

Connolly, H. C., Jr., and Love, S. G. 1998. The formation of chondrules: Petrologic tests of the shock wave model. *Science* 280:62–67.

Connolly, H. C., Jr., Hewins, R. H., Ash, R. D., Zanda, B., Lofgren, G. E., and Bourot-Denise, M. 1994. Carbon and the formation of reduced chondrules. *Nature* 371:136–139.

Connolly, H. C., Jr., Jones, B. D., and Hewins, R. H. 1998. The flash melting of chondrules: An experimental investigation into the melting history and physical nature of chondrule precursors. *Geochim. Cosmochim. Acta,* in press.

Cuzzi, J. N., Dobrovolskis, A. R., and Hogan, R. C. 1996. Turbulence, chondrules, and planetesimals. In *Chondrules and the Protoplanetary Disk,* ed. R. H. Hewins, R. H. Jones, and E. R. D. Scott (Cambridge: Cambridge University Press), pp. 35–43.

Davis, A. M., and MacPherson, G. J. 1996. Thermal processing in the solar nebular: Constraints from refractory inclusions. In *Chondrules and the Protoplanetary Disk,* ed. R. H. Hewins, R. H. Jones, and E. R. D. Scott (Cambridge: Cambridge University Press), pp. 71–76.

DeHart, J. M., and Lofgren, G. E. 1996. Experimental studies of group A1 chondrules. *Geochim. Cosmochim. Acta* 60:2233–2242.

Desch, S. J., and Cuzzi, J. N. 1999. The generation of lightning in the solar nebula. *Icarus,* in revision.

Ebel, D. S., and Grossman, L. 1997. Direct condensation of ferromagnesian liquids from cosmic gases. *Lunar Planet. Sci.* 28:317–318.

Ebel, D. S., and Grossman, L. 1998. Effect of dust enrichment on solid and liquid compositions in equilibrium with cosmic gases. In *Lunar and Planetary Science Conference XXIX,* Abstract #1421 (Houston: Lunar and Planetary Institute), CD-ROM.

Gibbard, S. G., Levy, E. H., and Morfill, G. E. 1997. On the possibility of lightning in the protosolar nebula. *Icarus* 130:517–533.

Göpel, C., Manhès, G., and Allègre, C. J. 1994. U-Pb systematics of phosphates from equilibrated ordinary chondrites. *Earth Planet. Sci. Lett.* 121:153–171.

Greenwood, J. P., and Hess, P. C. 1996. Congruent melting kinetics: Constraints on chondrule formation. In *Chondrules and the Protoplanetary Disk,* ed. R. H. Hewins, R. H. Jones, and E. R. D. Scott (Cambridge: Cambridge University Press), pp. 205–211.

Grossman, J. N. 1988. Formation of chondrules. In *Meteorites and the Early Solar System,* ed. J. F. Kerridge and M. S. Matthews (Tucson: University of Arizona Press), pp. 680–696.

Grossman, J. N. 1996. Chemical fractionations of chondrites: Signatures of events before chondrule formation. In *Chondrules and the Protoplanetary Disk,* ed. R. H. Hewins, R. H. Jones, and E. R. D. Scott (Cambridge: Cambridge University Press), pp. 243–253.

Grossman, J. N., Rubin, A. E., Nagahara, H., and King, E. A. 1988. Properties of chondrules. In *Meteorites and the Early Solar System,* ed. J. F. Kerridge and M. S. Matthews (Tucson: University of Arizona Press), pp. 619–659.

Herbig, G. 1977. Eruptive phenomena in early stellar evolution. *Astrophys. J.* 217:693–715.

Hewins, R. H. 1989. The evolution of chondrules. *Proc. Nat. Inst. Polar Res. Symp. Antarctic Meteorites* 2:200–220.

Hewins, R. H. 1997. Chondrules. *Ann. Rev. Earth Planet. Sci.* 25:61–83.

Hewins, R. H., and Connolly, H. C., Jr. 1996. Peak temperatures of flash-melted chondrules. In *Chondrules and the Protoplanetary Disk,* ed. R. H. Hewins, R. H. Jones, and E. R. D. Scott (Cambridge: Cambridge University Press), pp. 197–204.

Hewins, R. H., and Radomsky, P. M. 1990. Temperature conditions for chondrule formation. *Meteoritics* 25:309–318.

Hewins, R. H., Jones, R. H., and Scott, E. R. D. 1996. *Chondrules and the Protoplanetary Disk* (Cambridge: Cambridge University Press).

Hewins, R. H., Yu, Y., Zanda, B., and Bourot-Denise, M. 1997. Do nebular fractionations, evaporative losses, or both, influence chondrule compositions? *Antarctic Meteorite Res.* 10:275–298.

Hood, L. L. 1998. Thermal processing of chondrule precursors in planetesimal bow shocks. *Meteorit. Planet. Sci.* 33:97–107.

Hood, L. L., and Horanyi, M. 1991. Gas dynamic heating of chondrule precursor grains in the solar nebula. *Icarus* 93:259–269.

Hood, L. L., and Horanyi, M. 1993. The nebular shock wave model for chondrule formation: One-dimensional calculations. *Icarus* 106:179–189.

Hood, L. L., and Kring, D. A. 1996. Models for multiple heating mechanisms. In *Chondrules and the Protoplanetary Disk,* ed. R. H. Hewins, R. H. Jones, and E. R. D. Scott (Cambridge: Cambridge University Press), pp. 265–276.

Horanyi, M., and Robertson, S. 1996. Chondrule formation in lightning discharges: Status of theory and experiments. In *Chondrules and the Protoplanetary Disk,* ed. R. H. Hewins, R. H. Jones, and E. R. D. Scott (Cambridge: Cambridge University Press), pp. 303–310.

Horanyi, M., Morfill, G., Goertz, C. K., and Levy, E. H. 1995. Chondrule formation in lightning discharges. *Icarus* 81:174–185.

Huss, G. R. 1988. The role of interstellar dust in the formation of the solar system. *Earth Moon Planets* 40:165–211.

Jones, R. H. 1996. FeO-rich, porphyritic olivine chondrules in unequilibrated ordinary chondrites. *Geochim. Cosmochim. Acta* 60:3115–3138.

Jones, R. H., and Danielson, L. R. 1997. A chondrule origin for dusty relict olivine in unequilibrated chondrites. *Meteorit. Planet. Sci.* 32:753–760.

Jones, R. H., and Lofgren, G. E. 1993. A comparison of FeO-rich porphyritic olivine chondrules in unequilibrated chondrites and experimental analogues. *Meteoritics* 28:213–221.

Jones, R. H., Saxton, J. M., Lyon, I. C., and Turner, G. 1998. Oxygen isotope analyses of chondrule and isolated olivine grains in the CO3 chondrite, ALHA77307. In *Lunar and Planetary Science Conference XXIX,* Abstract #1795 (Houston: Lunar and Planetary Institute), CD-ROM.

Keil, K., Stöffler, D., Love, S. G., and Scott, E. R. D. 1997. Constraints on the role of impact heating and melting in asteroids. *Meteorit. Planet. Sci.* 32:349–363.

Keith, W. D., and Saunders, C. P. R. 1989. Charge transfer during multiple large ice crystal interactions with a riming target. *J. Geophys. Res.* 94:13103–13106.

Krot, A. N., and Rubin, A. E. 1996. Microchondrule-bearing chondrule rims: Constraints on chondrule formation. In *Chondrules and the Protoplanetary Disk,* ed. R. H. Hewins, R. H. Jones, and E. R. D. Scott (Cambridge: Cambridge University Press), pp. 181–184.

Krot, A. N., Rubin, A. E., Keil, K., and Wasson, J. T. 1997. Microchondrules in ordinary chondrites: Implications for chondrule formation. *Geochim. Cosmochim. Acta* 61:463–473.

Lee, T., Shu, F. H., Shang, H., Glassgold, A. E., and Rehm, K. E. 1998. Protostellar cosmic rays and extinct radioactivities in meteorites. *Astrophys. J.* 506:898–912.

Liepmann, H. W., and Roshko, A. 1957. *Elements of Gasdynamics* (New York: Wiley).

Liffman, K. 1992. The formation of chondrules by ablation. *Icarus* 100:608–619.

Liffman, K., and Brown, M. J. I. 1996. The protostellar jet model of chondrule formation. In *Chondrules and the Protoplanetary Disk,* ed. R. H. Hewins, R. H. Jones, and E. R. D. Scott (Cambridge: Cambridge University Press), pp. 285–302.

Linker, J. A., and Mikic, Z. 1995. Disruption of a helmet streamer by photospheric shear. *Astrophys. J. Lett.* 438:L45–L48.

Lofgren, G. E. 1996. A dynamic crystallization model for chondrule melts. In *Chondrules and the Protoplanetary Disk,* ed. R. H. Hewins, R. H. Jones, and E. R. D. Scott (Cambridge: Cambridge University Press), pp. 187–196.

Lofgren, G. E., and Lanier, A. 1990. Dynamic crystallization study of barred olivine chondrules. *Geochim. Cosmochim. Acta* 54:3537–3551.

Lofgren, G. E., and Russell, W. J. 1986. Dynamic crystallization of chondrule melts of porphyritic and radial pyroxene composition. *Geochim. Cosmochim. Acta* 50:1715–1726.

Love, S. G., and Brownlee, D. E. 1991. Heating and thermal transformation of micrometeorites entering the Earth's atmosphere. *Icarus* 89:26–43.

Love, S. G., Keil, K., and Scott, E. R. D. 1995. Electrical discharge heating of chondrules in the solar nebula. *Icarus* 115:97–108.

MacPherson, G. J., and Russell, S. S. 1997. Origin of aluminum-rich chondrules: Constraints from major element chemistry. *Meteorit. Planet. Sci. Suppl.* 32:A83.

MacPherson, G. J., Wark, D. A., and Armstrong, J. T. 1988. Primitive material surviving in chondrites: Refractory inclusions. In *Meteorites and the Early Solar System,* ed. J. F. Kerridge and M. S. Matthews (Tucson: University of Arizona Press), pp. 746–807.

MacPherson, G. J., Davis, A. M., and Zinner, E. K. 1995. The distribution of aluminum-26 in the early solar system—A reappraisal. *Meteoritics* 30:365–386.

McKeegan, K. D., Leshin, L. A., Russell, S. S., and MacPherson, G. J. 1998. Oxygen isotopic abundances in calcium-aluminum-rich inclusions from ordinary chondrites: Implications for nebular heterogeneity. *Science* 280:414–418.

Meeker, G. P. 1995. Constraints on formation processes of two coarse-grained calcium-aluminum-rich inclusions: A study of mantles, islands and cores. *Meteoritics* 30:71–84.

Metzler, K., Bischoff, A., and Stöffler, D. 1992. Accretionary dust mantles in CM chondrites: Evidence for solar nebula processes. *Geochim. Cosmochim. Acta* 56:2873–2897.

Meyer, M. R., Calvet, N., and Hillenbrand, L. A. 1997. Intrinsic near-infrared excesses of T Tauri stars: Understanding the classical T Tauri star locus. *Astron. J.* 114:288–300.

Morden, S. J., and Collinson, D. W. 1992. The implications of the magnetism of ordinary chondrite meteorites. *Earth Planet. Sci. Lett.* 109:185–204.

Morfill, G., Spruit, H., and Levy, E. H. 1993. Physical processes and conditions associated with the formation of protoplanetary disks. In *Protostars and Planets III,* ed. E. H. Levy and J. I. Lunine (Tucson: The University of Arizona Press), pp. 939–978.

Morfill, G., Durisen, R. H., and Turner, G. W. 1998. An accretion rim constraint on chondrule formation theories. *Icarus* 134:180–184.

Nagata, T., and Funaki, M. 1981. The composition of natural remanent magnetization of an Antarctic chondrite, ALHA 76009 (L6). *Lunar Planet. Sci.* 12:747–748.

Paque, J. M. 1990. Relict grains in a Ca-Al-rich inclusion from Allende. *Lunar Planet. Sci.* 21:932–933.

Paque, J. M. 1995. Effect of residence time at maximum temperature on the texture and phase compositions of a type B Ca-Al-rich inclusion analog. *Lunar Planet. Sci.* 26:1099–1100.

Paque, J. M., and Cuzzi, J. N. 1997. Physical characteristics of chondrules and rims, and aerodynamic sorting in the solar nebula. *Lunar Planet. Sci.* 28:1071–1072.

Paque, J. M., and Lofgren, G. E. 1993. Comparison of experimental studies on chondrule and Ca-Al-rich inclusions. *Lunar Planet. Sci.* 22:1025–1026.

Paque, J. M., Le, L., and Lofgren, G. E. 1998. Experimentally produced spinel rims on Ca-Al-rich inclusion bulk compositions. In *Lunar and Planetary Science Conference XXIX,* Abstract #1221 (Houston: Lunar and Planetary Institute), CD-ROM.

Pilipp, W., Hartquist, T. W., Morfill, G. E., and Levy, E. H. 1998. Chondrule formation by lightning in the protosolar nebula? *Astron. Astrophys.* 331:121–146.

Podosek, F. A., and Cassen, P. 1994. Theoretical, observational, and isotopic estimates of the lifetime of the solar nebula. *Meteoritics* 29:6–25.

Prinz, M., Weisberg, M. K., and Nehru, C. E. 1988. Gunlock, a new type 3 ordinary chondrite with a golfball-sized chondrule. *Meteoritics* 23:297.

Radomsky, P. M., and Hewins, R. H. 1990. Formation conditions of pyroxene-olivine and magnesian olivine chondrules. *Geochim. Cosmochim. Acta* 54:3475–3490.

Rubin, A. E., and Krot, A. N. 1996. Multiple heating of chondrules. In *Chondrules and the Protoplanetary Disk,* ed. R. H. Hewins, R. H. Jones and E. R. D. Scott (Cambridge: Cambridge University Press), pp. 173–180.

Rubin, A. E., Sailer, A. L., and Wasson. 1999. Troilite in the chondrules of unequilibrated ordinary chondrites: Implications for chondrule formation. *Geochim. Cosmochim. Acta,* in review.

Ruzmaikina, T. V., and Ip, W. H. 1996. Chondrule formation in the accretional shock. In *Chondrules and the Protoplanetary Disk,* ed. R. H. Hewins, R. H. Jones, and E. R. D. Scott (Cambridge: Cambridge University Press), pp. 277–284.

Sahagian, D. L., and Hewins, R. H. 1992. The size of chondrule-forming events. *Lunar Planet. Sci.* 23:1197–1198.

Sanders, I. S. 1996. A chondrule-forming scenario involving molten planetesimals. In *Chondrules and the Protoplanetary Disk,* ed. R. H. Hewins, R. H. Jones, and E. R. D. Scott (Cambridge: Cambridge University Press), pp. 327–334.

Scott, E. R. D., Love, S. G., and Krot, A. N. 1996. Formation of chondrules and chondrites in the protoplanetary nebula. In *Chondrules and the Protoplanetary Disk,* ed. R. H. Hewins, R. H. Jones, and E. R. D. Scott (Cambridge: Cambridge University Press), pp. 87–96.

Sears, D. W. G., Huang, S., and Benoit, P. H. 1996. Open-system behavior during chondrule formation. In *Chondrules and the Protoplanetary Disk,* ed. R. H. Hewins, R. H. Jones, and E. R. D. Scott (Cambridge: Cambridge University Press), pp. 221–231.

Sentman, D. D., Wescott, E. M., Osborne, D. L., Hampton, D. L., and Heavner, M. J. 1995. Preliminary results from the Sprites94 aircraft campaign: 1. Red sprites. *Geophys. Res. Lett.* 22:2105–2108.

Shu, F. H., Adams, F. C., and Lizano, S. 1987. Star formation in molecular clouds: Observation and theory. *Ann. Rev. Astron. Astrophys.* 25:23–81.

Shu, F. H., Shang, H., and Lee, T. 1996. Toward an astrophysical theory of chondrites. *Science* 271:1545–1552.

Shu, F. H., Shang, H., Glassgold, A. E., and Lee, T. 1997. X-rays and fluctuating X-winds from protostars. *Science* 277:1475–1479.

Skinner, W. R. 1990*a*. Bipolar outflows and a new model of the early solar system. Part I: Overview and implications of the model. *Lunar Planet. Sci.* 21:1166–1167.

Skinner, W. R. 1990*b*. Bipolar outflows and a new model of the early solar system. Part II: The origins of chondrules, isotopic anomalies, and chemical fractionations. *Lunar Planet. Sci.* 21:1168–1169.

Skinner, W. R., and Leenhouts, J. M. 1993. Size distributions and aerodynamic equivalence of metal chondrules and silicate chondrules in Acfer 059. *Lunar Planet. Sci.* 24:1315–1316.

Sorby, H. C. 1877. On the structure and origin of meteorites. *Nature* 15:495–498.

Stolper, E. 1982. Crystallization sequences of Ca-Al-rich inclusions from Allende: An experimental study. *Geochim. Cosmochim. Acta* 46:2159–2180.

Stolper, E., and Paque, J. M. 1986. Crystallization sequences of Ca-Al-rich inclusions from Allende: The effects of cooling rate and maximum temperature. *Geochim. Cosmochim. Acta* 50:1785–1806.

Sugiura, N., and Strangway, D. W. 1982. Magnetic properties of low-petrologic grade non-carbonaceous chondrites. *Proceedings of the Seventh Symposium on Antarctic Meteorites. Mem. Natl. Inst. Polar Res.* 25 (special issue):260–280.

Sugiura, N., Lanoix, M., and Strangway, D. W. 1979. Magnetic fields of the solar nebula as recorded in chondrules from the Allende meteorite. *Phys. Earth Planet. Interiors* 20:342–349.

Swindle, T. D., Davis, A. M., Hohenberg, C. M., MacPherson, G. J., and Nyquist, L. E. 1996. Formation times of chondrules and Ca-Al-rich inclusions: Constraints from short-lived radionuclides. In *Chondrules and the Protoplanetary Disk,* ed. R. H. Hewins, R. H. Jones, and E. R. D. Scott (Cambridge: Cambridge University Press), pp. 77–86.

Symes, S. J., Sears, D. W. G., Akridge, D. G., Huang, S., and Benoit, P. H. 1998. The crystalline lunar spheres: Their formation and implication for the origin of meteoritic chondrules. *Meteorit. Planet. Sci.* 33:13–30.

Taylor, G. J., Scott, E. R. D., and Keil, K. 1983. Cosmic setting for chondrule formation. In *Chondrules and Their Origins,* ed. E. A. King (Houston: Lunar and Planetary Institute), pp. 262–278.

Thiemens, M. H. 1996. Mass-independent isotopic effects in chondrites: The role of chemical processes. In *Chondrules and the Protoplanetary Disk,* ed. R. H. Hewins, R. H. Jones, and E. R. D. Scott (Cambridge: Cambridge University Press), pp. 107–118.

Wasson, J. T. 1985. *Meteorites: Classification and Properties* (New York: W.H. Freeman).

Wasson, J. T. 1993. Constraints on chondrule origins. *Meteoritics* 28:14–28.

Wasson, J. T. 1996. Chondrule formation: Energetics and length scales. In *Chondrules and the Protoplanetary Disk,* ed. R. H. Hewins, R. H. Jones, and E. R. D. Scott (Cambridge: Cambridge University Press), pp. 45–54.

Wasson, J. T., and Kallemeyn, G. W. 1990. Allan Hills 85085: A subchondritic meteorite of mixed nebula and regolithic heritage. *Earth Planet. Sci. Lett.* 101:148–161.

Wasson, J. T., Krot, A. N., Lee, M. S., and Rubin, A. E. 1995. Compound chondrules. *Geochim. Cosmochim. Acta* 59:1847–1869.

Weidenschilling, S. J. 1996. Production of chondrules by lightning in the solar nebula. *Lunar Planet. Sci.* 27:1397–1398.

Weidenschilling, S. J. 1997. Production of chondrules by lightning in the solar nebula? Not so easy! *Lunar Planet. Sci.* 27:1515–1516.

Weidenschilling, S. J., Marzari, F., and Hood, L. L. 1998. The origin of chondrules at jovian resonances. *Science* 279:681–684.

Weinbruch, S., and Müller, F. W. 1995. Constraints on the cooling rates of chondrules from the microstructure of clinopyroxene and plagioclase. *Geochim. Cosmochim. Acta* 59:3221–3230.

Weisberg, M. K., and Prinz, M. 1996. Agglomeratic chondrules, chondrule precursors and incomplete melting. In *Chondrules and the Protoplanetary Disk,* ed. R. H. Hewins, R. H. Jones, and E. R. D. Scott (Cambridge: Cambridge University Press), pp. 119–127.

Weisberg, M. K., Prinz, M., and Nehru, C. E. 1988. Macrochondrules in ordinary chondrites: Constraints on chondrule forming processes. *Meteoritics* 23:309–310.

Whipple, F. L. 1966. Chondrules: Suggestion concerning the origin. *Science* 153:54–56.

Wood, J. A. 1962. Chondrules and the origins of the terrestrial planets. *Nature* 194:127–130.

Wood, J. A. 1984. On the formation of meteoritic chondrules by aerodynamic drag heating in the solar nebula. *Earth Planet. Sci. Lett.* 70:11–26.

Wood, J. A. 1996. Processing of chondritic and planetary material in spiral density waves in the nebula. *Meteorit. Planet. Sci.* 31:641–646.

Wood, J. A., and Hashimoto, A. 1993. Mineral equilibrium in fractionated nebular systems. *Geochim. Cosmochim. Acta* 57:2377–2388.

Yu, Y., and Hewins, R. H. 1998. Transient heating and chondrule formation: Evidence from sodium loss in flash heating simulation experiments. *Geochim. Cosmochim. Acta* 62:159–172.

Yu, Y., Hewins, R. H., and Zanda, B. 1996. Sodium and sulfur in chondrules: Heating time and cooling curves. In *Chondrules and the Protoplanetary Disk,* ed. R. H. Hewins, R. H. Jones, and E. R. D. Scott (Cambridge: Cambridge University Press), pp. 213–220.

Zanda, B., Yu, Y., Bourot-Denise, M., and Hewins, R. H. 1996. The history of metal and sulfide in chondrites. In *Workshop on Parent-Body and Nebular Modification of Chondritic Materials,* LPI Technical Report No 97–02, Part 1 (Houston: Lunar and Planetary Institute), pp. 68–70.