

Papers Presented to
**Chondrules and the
Protoplanetary Disk**

**October 13–15, 1994
Albuquerque, New Mexico**

PAPERS PRESENTED TO
CHONDRULES AND THE PROTOPLANETARY DISK

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Preface

This volume contains papers that have been accepted for presentation at the conference on Chondrules and the Protoplanetary Disk, October 13–15, 1994, in Albuquerque, New Mexico. The Program Committee consisted of R. H. Hewins, Chair (*Rutgers University*), A. P. Boss (*Carnegie Institution*), P. Cassen (*NASA Ames Research Center*), R. H. Jones (*University of New Mexico*), A. E. Rubin (*University of California, Los Angeles*), E. R. D. Scott (*University of Hawaii*), and J. T. Wasson (*University of California, Los Angeles*).

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Abstracts

PRODUCING CHONDRULES BY RECYCLING AND VOLATILE LOSS. C. M. O'D. Alexander, McDonnell Center for Space Sciences, Washington University, St. Louis MO 63130, USA, and Department of Terrestrial Magnetism, Carnegie Institution of Washington, 5241 Broad Branch Road NW, Washington DC 20015, USA.

Interelement correlations observed in bulk chondrule INAA data, particularly between the refractory lithophiles, have led to the now generally accepted conclusion that the chondrule precursors were nebular condensates [e.g., 1]. However, it has recently been suggested that random sampling of fragments from a previous generation of chondrules could reproduce much of the observed range of bulk chondrule composition [2,3].

The exploration of a recycling model is motivated by several observations. First, there is scant mineralogical evidence that traditional equilibrium condensation occurred. Certainly, the presence of presolar grains in all chondrite groups shows that at least some nebular material did not experience nebularwide heating and recondensation. In addition, the rims and matrices of chondrites do not contain the equilibrium condensate mineral assemblages one would predict from the chondrule refractory precursor compositions deduced by [1]. Nor do the refractory condensates ever survive unmelted in chondrules despite the presence of less refractory relict olivine. Second, there is petrologic evidence for recycling of chondrules; these include most relict grains apparently having come from chondrules [4], compound chondrules with one enclosing the other [5], reheating of chondrules [5,6], and chondrule rims containing chondrule fragments [7]. Last, ion probe measurements show that the refractory lithophiles, which make up the most important group of intercorrelated elements in the INAA data, are, with the exception of Mg, all highly incompatible in silicate melts. As a result, the refractory lithophiles are concentrated in chondritic relative abundances in the chondrule glasses [2,3].

The latter observation suggests a very simple means of producing the correlations among the refractory lithophiles, namely that chondrules formed by randomly sampling fragments of a previous generation inherit variable amounts of glass. Thus, while the relative abundances of the refractory lithophiles would be fairly constant from chondrule to chondrule, their absolute abundances would vary according to the amount of glass the chondrules received. Almost all the other reported correlations among the lithophile elements in the bulk chondrule data can also be reproduced by the random sampling model [2,3]. However, a more complete model of chondrule formation would probably have to include incorporation of rim/matrix, reduction/oxidation, and, as discussed below, volatile loss.

The only elemental correlation in the INAA data that poses a significant problem to the recycling model is the one between Mg and the other refractory lithophiles. This correlation is not particularly strong but is, nevertheless, statistically significant. Recycling cannot easily produce the Mg-refractory lithophile correlation because most of the Mg is in the olivine and pyroxene while the other refractory lithophiles are in the glass. The correlation is not evident in EMPA data but this may be due to a thin section being an unrepresentative sample of a whole chondrule [1].

One means of producing the correlation without recourse to condensate precursors is the volatile loss of Si from some chondrules [3,8]. At temperatures $\leq 2000^\circ\text{C}$, Fe and Si are the two most volatile major elements in a chondritic melt [9]. Volatile loss of Fe and Si might explain why the most magnesian chondrules, the type Is, are metal poor despite being highly reduced, why they tend to be smaller (higher surface/volume ratios facilitate evaporation), and why chondrule rims in UOCs often have very fayalite-rich normative compositions.

Evaporation of Fe and Si would also have implications for the simulation of chondrule thermal histories. For instance, in an isothermal system the composition of an originally FeO-rich melt would be driven by Fe and Si loss to increasingly magnesian and olivine-normative compositions, and therefore go from near-liquidus to subliquidus without any change in temperature. Consequently, estimates of peak temperatures and cooling rates experienced by a chondrule as deduced from comparisons with isochemical simulations may be erroneous.

If volatile loss of Fe and Si did occur, why is the evidence for loss of the more volatile alkali metals not stronger? The alkali/Al ratio in chondrules from some of the least-equilibrated UOCs vary by about 2 orders of magnitude, and for K and Rb (Na is often relatively enriched) this variation broadly correlates with chondrule type [e.g., 3]. In addition, rims and matrices in UOCs tend to be enriched in the alkalis, relative to bulk OC, consistent with alkali loss from chondrules. One exception to this is Krymka, which not only has relatively alkali-poor rim/matrix but also chondrule glasses that appear alkali enriched, particularly in Na (unpublished). Sodium is not only more volatile but also more mobile than the other alkalis, and its relative enrichment in chondrule glasses suggests it can be redistributed even in the least-equilibrated UOCs [3]. Consequently, some care needs to be taken in interpreting the alkali abundance data.

What remains to be seen is whether the kinetics of evaporation are rapid enough for significant compositional changes to take place in a reasonable length of time. From measured vacuum evaporation rates, a 250- μm -radius chondrule could lose half its Si in 3000 s at 1700°C and 120 s at 2000°C. However, the presence of an ambient gas can have a strong influence. For instance, the evaporation rate of forsterite increases by $\sim 100\times$ when the $P(\text{H}_2)$ increases from 10^{-6} to 10^{-3} atm [10]. Thus the above timescales are probably upper limits and, as such, are not unreasonable.

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CARBON, CAIs, AND CHONDRULES. R. D. Ash^{1,2} and S. S. Russell^{1,3}, ¹Department of Earth Sciences, Open University, Milton Keynes, MK7 6AA, UK, ²Present Address: Department of Geology, University of Manchester, Manchester, M13 9PL, UK, ³Present Address: Division of Geology and Planetary Sciences, Mail Stop 170-25, California Institute of Technology, Pasadena CA 91125, USA.

Chondrules are generally considered to have formed from solid precursors or “dust ball” aggregates. It has been postulated that the chondrule precursors may have been held together by some form of carbonaceous organic “glue” [1]. The effects of such material in chondrule precursors has recently been investigated experimentally [2] and has been found to have a profound effect on the resultant mineralogy and chemistry of the chondrule.

To further investigate the origin, fate, and effects of the carbonaceous material in chondrule precursors we have measured the C content and isotopic composition of hand-picked chondrules, CAIs, and matrix separates. Allende (CV3) was chosen as the subject for this study because it has a low matrix C content, which will minimize contamination to low C inclusions. Furthermore, the chemistry and mineralogy of Allende chondrules, CAIs, and matrix have been widely studied, and as an observed fall, terrestrial C contamination in Allende is minimal. The C was extracted using a stepped combustion technique, enabling the resolution of carbonaceous species according to their susceptibility to oxidation.

The matrix separates have a C content between 3000–4000 ppm, with the maximum C release at 700°C. The $\Sigma \delta^{13}\text{C}$ of the matrix is -18.4‰ and no temperature step produced C with a $\delta^{13}\text{C}$ of $>0\text{‰}$. After subtracting the known contribution from diamond, the remainder of the matrix is calculated to have a $\Sigma \delta^{13}\text{C}$ of -11.3‰ .

Both the chondrules and CAIs contain less C than the matrix samples (180 ppm and 930 ppm respectively) and both contain some C released during combustion between 300°C and 400°C. This material may, at least in part, be ascribed to terrestrial contamination. CAIs and chondrules also contain C in a refractory form that is released at temperatures of around 1000°C. For chondrules, this release makes up around 40% of the total C, and for the CAI sample, it constitutes 5% of the total C. This component is enriched in ^{13}C , having a $\delta^{13}\text{C}$ value of $28.5 \pm 0.9\text{‰}$ in the CAI and $22 \pm 1.2\text{‰}$ in the chondrule separate. The differences in bulk isotopic composition and release profiles between the matrix and other samples preclude the possibility of the C in the inclusions being merely due to adhering matrix that has been isotopically fractionated during extraction.

We consider two possible explanations for the ^{13}C -enriched material: (1) isotopic fractionation in the inclusion, either during incorporation of C or in a later heating event, or (2) incorporation of components into the inclusion that have a C isotopic composition heavier than matrix CV material.

1. CAIs in CV meteorites often show high degrees of fractionation in Mg, Si, and Ca [3]. Coarse-grained CAIs are typically enriched in heavy Mg isotopes and light Ca isotopes [4]. The C data for CAIs and chondrules can also be explained in terms of fractionation, perhaps caused by volatilization. The C in inclusions could represent the isotopically fractionated residuum of the organic “glue” material, which once held the chondrule precursors together. If so, then the C has been transformed from an organic form into a more refractory mineral.

2. Carbon in the early solar system is thought to have been present in many forms, e.g., as gas, organic material, diamond, and interstellar SiC. The mix contributing to chondrules and CAIs may not have been the same as that contributing to CV matrix material. One explanation for the ^{13}C enrichment of chondrules and CAI relative to matrix is an increased proportion of SiC in the inclusion precursors. Although SiC is unlikely to have survived in chondrules and CAIs, survival in the “dusty rim” surrounding chondrules is a possibility. SiC has been observed only in the matrix of chondrites [5], but since very few grains have been found *in situ*, this could be a sampling effect. If the grains contributed to the chondrule- and CAI-forming material, but did not survive intact, they may have retained a “memory,” contributing ^{13}C -enriched C originally from SiC that has been reprocessed into a more oxidized form. Mass balance calculations suggest that if this interpretation is correct, the chondrules or their precursors may have contained up to 1 ppm SiC.

We have shown that C is present in CAIs and chondrules. It can be distinguished from matrix C both by its thermal stability and isotopic composition, which implies that it was not introduced after parent body accretion. We conclude that C must have been present in the chondrule and CAI precursor material. Thus any models of chondrule and CAI formation and inferences drawn about solar system conditions during these events must take into account the consequences of the presence of C on inclusion chemistry, mineralogy, and oxidation state.

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LARGE-SCALE PROCESSES IN THE SOLAR NEBULA.

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Theoretical models of the structure of a minimum mass solar nebula should be able to provide the physical context to help evaluate the efficacy of any mechanism proposed for the formation of chondrules or Ca,Al-rich inclusions (CAIs). These models generally attempt to use the equations of radiative hydrodynamics to calculate the large-scale structure of the solar nebula (i.e., the temperature, density, pressure, and velocity fields) throughout the planet-forming region. In addition, it has been suggested that chondrules and CAIs (= Ch&CAIs) may have been formed as a direct result of large-scale nebula processing such as passage of material through high-temperature regions associated with the global structure of the nebula. Here we assess the status of global models of solar nebula structure and of various related mechanisms that have been suggested for Ch&CAI formation.

Basic Requirements for Ch&CAI Formation: Ch&CAIs have spheroidal shapes indicative of a molten phase, with maximum temperatures in the range 1500 K–2100 K, and even as high as 2400 K for one CAI [1]. Reproducing the textures of chondrules requires cooling rates of ~ 1000 K/hr [2], while cooling rates for type B CAIs are inferred to be in the range 0.1–10 K/hr [3]. While CAIs are not

uncommon, chondrules are quite common in primitive meteorites [4], implying that Ch&CAI formation processes could not have been rare events. CAIs and chondrules are usually found separately in carbonaceous chondrites, implying independent origins, but the discovery of a relict CAI inside a chondrule implies that at least some CAIs were formed prior to chondrules [5]. Chondrules appear to be chemically complementary (in Fe, Cr) to dark inclusions and matrix, suggesting formation in a closed system [6].

Globally Hot Nebula: Midplane temperatures on the order of 1500 K inside about the 1-AU region have been calculated for minimum mass solar nebula models [7–9] and inferred on the basis of observations of young stars [10]. Midplane temperatures in the asteroidal region are likely to be only on the order of 1000 K when the nebula mass is about $0.02 M_{\odot}$ [9], not high enough to melt the Ch&CAI precursors. However, it has been suggested that Ch&CAIs formed from high-temperature condensates in the higher-temperature regions interior to 1 AU and were then diffusively transported outward [11] or upward [12], but these suggestions suffer from the difficulty of transporting significant material “upstream” in the overall inward nebular flow [13] and from the need for rapid cooling. Some of the outward transport could be achieved later in the planetary accumulation phase [14], but probably not from well inside 1 AU to ~2.5 AU.

Nonaxisymmetric Nebula: If large-scale nonaxisymmetry (a bar or spiral density wave) occurs in the nebula (e.g., driven by infall), then the nebula temperature field (which is coupled to the gas) is also likely to be nonaxisymmetric. Because solid particles will move on Keplerian orbits whereas the gas will orbit somewhat more slowly (because of radial pressure support), relative motion will occur and the possibility exists for aggregates to orbit in and out of a nonaxisymmetric temperature field [8]. However, the maximum relative orbital velocity of $\sim 10^4$ cm/s occurs only for fairly large (~ 1 m) bodies and falls to very low values for millimeter-sized aggregates [15]. Unless the high-temperature region was exceedingly sharply defined in azimuth, Ch&CAI-sized aggregates would exit the high-temperature region much too slowly to experience rapid cooling.

Clumpy Disk Accretion: Optical observations of strongly time-varying (night to night) phenomena in pre-main-sequence stars suggest the presence of clumps of optically thick matter close to young stars [16,17]. The observations are consistent with the presence of opaque clouds with speeds up to 250 km/s and masses $>10^{22}$ g. The clump lifetime is likely to be very short (years), implying that a mechanism for their continual generation would have to exist, such as the return of disk or infalling matter previously entrained by the stellar outflow. If such clumps exist, and if their high-velocity orbits are inclined to the disk midplane, the clumps will eventually impact and drive shock waves into the nebula. Shock speeds ≥ 5 km/s are required to thermally process chondrule precursor aggregates [18], and this constraint can be used to derive the fraction of the nebula that is shocked to this speed [19]. Assuming that clump-disk impacts occur on a weekly basis over a time period of a million years, essentially every dust grain aggregate in the nebula could be thermally processed once. However, clump masses on the order of 10^{26} g may be needed in order to process aggregates residing in a dust subdisk at the nebula midplane [19].

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CHONDRULE-MATRIX RELATIONSHIPS IN CHONDRITIC METEORITES. A. J. Brearley, Institute of Meteoritics, Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque NM 87131, USA.

The relationship between chondrules and matrix (fine-grained material with a grain size $<5 \mu\text{m}$) in chondritic meteorites has been the subject of considerable controversy and no consensus currently exists [1]. The coexistence of these two components in meteorites with bulk compositions that deviate only slightly from CI abundances suggests that cosmochemically their origins are closely linked. Any consideration of the relationship between chondrules and matrix hinges to a large degree on the origin of matrix. The entire spectrum of models exists from matrix as a nebular product to derivation entirely from chondrules [1]. Early models of solar nebular evolution viewed chondrites as a two-component mixture of high- and low-temperature condensates [2]. However, this model has been challenged by the recognition that the nebula was probably not uniformly vaporized.

Ordinary Chondrites: The matrices and rims of unequilibrated ordinary chondrites (UOCs) have been studied extensively by many workers [e.g., 3–6]. Matrix is in low abundance in UOCs and exhibits significant compositional heterogeneity. In comparison with the bulk composition of UOCs, matrix has fractionated Mg/Si, Na/Si, Al/Si, and Ca/Si ratios and is enriched significantly in FeO relative to chondrule compositions. Unlike chondrules, matrix does not have a solar Ca/Al ratio. Calcium is decoupled from Al and volatile-element abundances are higher in matrices than chondrules. Matrix is dominated by unequilibrated FeO-rich olivines and an amorphous feldspathic component and is the host of C and interstellar materials in OCs [7]. SIMS analyses of rims and matrix in one OC show depletions in REE and refractory elements relative to CI abundances [8]. Oxygen isotopic data for matrix materials suggests, in one case, a close similarity to chondrules [9] and in the other, very- ^{16}O -enriched compositions [10].

Carbonaceous Chondrites: Matrix is most abundant in the carbonaceous chondrite groups but is only anhydrous in the CV and CO groups. The matrices of CO and CV are enriched in FeO and fractionated relative to the bulk [11]. Calcium is also decoupled from Al in CO3 matrix material. Mineralogically, the matrix of the

least-equilibrated CO₃ chondrite (Allan Hills 77307) consists of a disequilibrium assemblage of silicates and amorphous material, which occur in distinct aggregates (10 μm), with diverse compositional characteristics and thermal histories [12]. The matrix materials may represent disequilibrium condensates produced within the nebular or in a circumstellar environment, by analogy with astrophysical data [12]. Trace-element analyses of moderately volatile elements in CO₃ chondrites [13] show complex fractionated enrichment patterns, which are not a simple function of volatility. This argues against a simple condensation model for CO₃ matrix material. CV₃ matrices, which mineralogically appear to be more evolved than CO₃ chondrites, have been viewed both as disequilibrium and equilibrium condensates as well as the products of solid-state reactions on a parent body [1].

Relationships to Chondrules: Any model that relates chondrules to matrix directly, either as a precursor or a product, is problematical because of their disparate refractory element ratios and enhanced refractory element abundances in chondrules. In addition, the presence of mineralogical components in matrices that do not occur in chondrules argues strongly against such an origin for matrix in CO₃ chondrites, although it cannot be ruled out for the UOCs. The only meteorite that plausibly shows a direct link between chondrules and matrix is the unusual chondrite Kakangari, which has chondrules and matrix with essentially identical compositions [14]. Matrix is ¹⁶O-enriched and chondrules ¹⁶O-depleted consistent with heating of matrix to form chondrules in high-temperature events, which caused equilibration of chondrules with an O reservoir close to the terrestrial fractionation line [15]. The presence of fine-grained rims on chondrules as well as matrix inclusions within chondrules [5] indicates that matrix materials were closely associated with chondrules within the chondrule-forming region. A close spatial relationship is also indicated by the volatile enrichments observed in matrices, which may have been the result of volatiles released during chondrule formation recondensing onto matrix grains [16]. Repeated volatilization and recondensation events may be indicated by the complex fractionation patterns of moderately volatile elements in matrices [13]. Compositionally, it is difficult to view matrix as a simple residue left over from chondrule formation or a low-temperature condensate. The depletion of refractory elements in matrix materials and the decoupling of Ca from Al argue against such origins. If matrix was present in the nebula during the rapid thermal excursions, which produced chondrules, some components of fine-grained dust may have experienced periods of volatilization and recondensation. During such events, amorphous or partially crystalline smokes could have formed. It is possible that the more refractory component of dust would not undergo evaporation and melted to form chondrules. Thorough mixing of unprocessed interstellar dust with condensate material with diverse thermal histories may have occurred continuously through the chondrule-forming period. Such material was clearly never heated uniformly to high temperatures, because of the presence of surviving interstellar materials and the highly unequilibrated nature of matrix silicates. Consequently, matrix is probably best viewed as a complex mixture of interstellar material, solar nebular condensates, and fragments that may have been derived from chondrules.

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OVERVIEW OF NEBULA MODELS: POTENTIAL CHONDRULE-FORMING ENVIRONMENTS. P. Cassen, Mail Stop 245-3, NASA Ames Research Center, Moffett Field CA 94035, USA.

Even though many fundamental aspects of nebula evolution have yet to be resolved, observations of T Tauri stars and their circumstellar disks, combined with broadly applied theoretical principles, permit the construction of solar nebula models that are potentially useful for the interpretation of meteoritic data. For instance, quantitative comparisons of model results with meteoritic (and planetary) data can be used to test the following propositions regarding the bulk properties of chondrites and chondrule precursor material: (1) The nebula was hot enough, early in its history, to vaporize all rock-forming material at the midplane of the terrestrial planet region; (2) coagulation from fine dust to pebble-sized objects promoted cooling of the nebula, and concurrently a gas-phase fractionation resulting in an enrichment of rock-forming elements in the hot gas phase; (3) the modulating effect on radiative transport of the evaporation of the bulk of the opacity-producing dust sustained an environment in which refractory material was preferentially accumulated; (4) the growth of rocky objects during the nebula cooling period produced the fractionation of moderately volatile elements observed for bulk chondritic material; (5) time-variable thermal structure, with relatively steep gradients through the terrestrial planet region, produced the compositional differences observed in primitive meteorites.

Whatever the history of precursor material, chondrule formation apparently occurred on timescales of hours, too short to be accommodated by the nebula timescales of years and longer. Therefore, local events are implied. At present, physical models of chondrule formation are quantitatively constrained by four parameters: chondrule size, melting temperature, energy required to melt, and cooling time. If the energy to form chondrules was derived from kinetic energy (e.g., gas-dynamic braking, collisions, ablation), velocities of a few km/s were required to heat the precursor material to melting. In support of models in which the energy is derived from gas-dynamic interaction, the nebular densities that are derived from the conditions that (1) radiative losses from isolated melted chondrules are not excessive and (2) surface tension is sufficient to hold the melted chondrule together are both within a range of plausible values (10⁻⁹ to 10⁻¹¹ g/cm³). Postulated chondrule-forming shocks include the nebula accretion shock, density waves of unspecified origin, shocks due to dense clumps falling into the nebula, planetesi-

mal bow shocks, and explosion-produced shocks (which, for present purposes, includes those made by lightning, flares, or collisions among massive bodies). Some of the same quantitative arguments would apply to chondrule formation by planetesimal ablation.

If the cooling time was set by transport (either mixing with cooler material or adiabatic expansion of associated nebular gas), then the characteristic length scale L of the event is set by $C_s \tau$, where C_s is the sound speed at the chondrule formation temperature (e.g., 1500 K) and τ is the cooling time (e.g., 10^3 s), so $L \approx 3 \times 10^3$ km. If the cooling time was set solely by radiative loss, then one can estimate that surface densities of solid material of about 0.01 to a few g/cm² were involved, depending on what the ratio of fine dust to chondrules was (with the higher values applicable if dust was absent). It has also been suggested that the experimentally determined cooling time is really a reflection of a gradually diminishing heating rate in an optically thin environment (e.g., flare illumination of a midplane layer in an otherwise dust-cleared nebula, or illumination by energetic particles or radiation in a region with little or no nebular gas). In general, requirements derived from the evidence regarding steep spatial and temporal gradients, gas phase composition, a dusty environment, and rapid accumulation all implicate the dusty nebular midplane or, conceivably, a localized transient atmosphere.

CONSTRAINTS PLACED ON THE NATURE OF CHONDRULE PRECURSORS. H. C. Connolly Jr. and R. H. Hewins, Department of Geological Sciences, Rutgers University, New Brunswick NJ 08901, USA.

The melting conditions and cooling rates experienced by chondrules have been experimentally investigated and are reviewed by [1,2]. Presented below is a discussion of experiments [3–7] that have studied the nature of chondrule precursors and what constraints these experiments have placed on chondrule precursors.

Physical Characteristics of Starting Compositions: Experimental studies [3–6] that use a nonisothermal, superliquidus, rapid-melting event (simulating a type of flash melting) and cool with linear and nonlinear rates have investigated how the grain size of the starting composition affects the reproduction of chondrule textures. These experiments show that the type of chondrule texture produced is a function of the degree of melting and the grain size of the starting material. Type IIA, PO chondrule textures [8] can be produced from any grain size starting material depending on the degree of melting experienced. The finer the grain size, the higher the initial flash melting temperature must be to produce type IIA, PO textures. However, relict olivine grains were only observed in experiments performed with starting compositions that have a grain size >125 μm . Barred textures were produced from all the initial grain sizes and compositions of [3,4] when the initial flash melting temperature was too high. Furthermore, the transition temperature from porphyritic to barred differed for each of the studied compositions, suggesting no common transition temperature.

These same experiments have also shown that the production of microporphyritic olivine (MPO) texture similar to type IA chondrules [9] can be reproduced from starting material that has a grain size <125 μm and initial flash melting temperatures that are only slightly superliquidus. If melting occurs from temperatures too high above the liquidus of the starting material, type IIA, PO chondrule

textures are produced. The exact transition temperature from type IA, MPO to type IIA, PO textures varies with the studied grain sizes and starting compositions, suggesting no common transitional temperature for the studied starting materials.

Chemical Characteristics of Starting Compositions: Most experiments have assumed that the bulk composition of chondrules is representative of their precursor assemblages and that chondrule precursors were composed only of silicates. However, other phases such as C [10] and hydrated minerals [11] are known to have existed within the early solar nebula. Therefore these phases are possible chondrule precursors and need investigation.

The experiments of [6] used a type IA chondrule composition ($T_L = 1706^\circ\text{C}$) with added C that was flash melted and cooled with nonlinear cooling rates. The experiments were performed at 1 atm in a CO and CO₂ gas mixture with an f_{O_2} of IW -1.5. The addition of 1–5 wt% C to the starting material produced increasing more Fe-rich olivines (up to Fo_{99,++}) with increasing C content. Dusty olivines with kamacite of varying Ni content and veins of Fe-metal and Fe-rich olivine was produced. Metal ranging from <1 μm to several hundred micrometers was produced throughout the charges. Large metal grains that were mostly found at or near the surface of charges contained only 1–2 wt% Ni and approximately 0.2 wt% Co with significant amounts of dissolved Cr and Si and SiO₂ inclusions. Smaller metal grains found throughout the charges are taenite with 25–30 wt% Ni, with <1 wt% C and no dissolved Cr and Si nor detectable inclusions. These experiments suggest that chondrule precursors may control the redox conditions of chondrules and nebular gases may have little influence on the redox state of chondrules.

The experiments of [7] added serpentine to a type IIAB starting material. Their results show large vesicles are produced after melting by adding a hydrated phase to the starting composition. Because large vesicles are not observed in chondrules, [7] suggested that chondrule precursors were composed of anhydrous minerals.

Constraints on Chondrule Precursors: *Type IIA chondrule precursors.* A critical factor in placing constraints on chondrule precursor is knowing what type of melting event chondrules experienced. Experiments [1–6] have shown that chondrule textures can be reproduced either by incomplete melting in a dust-free environment or from total melts by collisions with dust particles [12]. Textures such as BO/POP have only been reproduced experimentally from total melts, indicating that at least some chondrules were totally melted. The formation of chondrules from total melts by collisions with dust grains suggests that no definitive constraints can be placed on the physical nature of chondrule precursors. However, PO textures with more than one observable relict grain have only been produced by incomplete melting. Therefore, type IIA chondrules were formed by incomplete melting of precursor clumps that contained at least some grains >125 μm and no hydrated phases. Furthermore, we strongly support the formation of type IIA chondrules by a type of flash-melting mechanism and agree with the conclusions of [14].

Type IA chondrule precursors. Type IA textures provide the only definitive constraints on the melting experienced by chondrules and on the grain size of the chondrule precursors. Type IA microporphyritic textures [9] can only be produced by incomplete melting and are limited to below the MPO/PO transition temperature. If the melting event was some type of superliquidus flash melting, then the grain size of the precursor material must be

<125 μm . The finer the grain size, the higher the initial flash-melting temperature type IA, MPO chondrules may have experienced. The reviewed experiments suggest that type IA chondrule precursors were even less than 23 μm .

Additionally, the production of type IA chondrules requires a solid reducing agent such as elemental C within the precursors assemblages. Therefore, type IA chondrules provide no supportive evidence of nebular gas conditions if their redox conditions were controlled by precursor minerals as suggested by [6]. Furthermore, type IA, MPO chondrules were produced the same type of flash-melting event that produced type IIA chondrules [14].

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TURBULENT DIFFUSION AND CONCENTRATION OF “CHONDRULES” IN THE PROTOPLANETARY NEBULA. J. N. Cuzzi¹, A. R. Dobrovolskis², and R. C. Hogan³. ¹NASA Ames Research Center, Moffett Field CA 94035-1000, USA, ²University of California, Santa Cruz CA, USA, ³Synemet, Inc., USA.

Turbulence is known to possess structure on many scales. The largest or integral scale L is usually taken to be the largest relevant dimension of the system; for the nebula as a whole, it would be on the order of a vertical gas scale height $H \sim 0.1R$, where R is the distance from the Sun. Turbulent kinetic energy cascades toward smaller scales; for fully developed, homogeneous turbulence, the turbulent kinetic energy peaks at the integral scale and is distributed within its “inertial range” according to the Kolmogorov energy spectrum $dE(k) = E_0 (kL)^{-5/3} dk$, where k is the wavenumber or inverse wavelength. The smallest scale in a turbulent regime is the Kolmogorov scale η (sometimes referred to as the inner scale). On this scale, molecular viscosity can dissipate turbulent kinetic energy. Turbulent flows are characterized by their Reynolds number $Re = UL/\nu$, where U is a characteristic velocity scale and ν is molecular viscosity. More energetic (higher Re) flows drive turbulence to smaller Kolmogorov scales: $\eta = LRe^{-3/4}$.

Two different turbulent regimes are likely to be of importance. Early stage convective turbulence in a hot nebula probably extends over the entire nebula scale height, and probably has typical eddy frequency comparable to the orbit frequency. At a later stage, midplane shear layer turbulence can be driven by the presence of a differentially rotating, densely settled particle layer, with different length and timescales.

It has become increasingly difficult to reconcile the properties of the protoplanetary environment with widespread, direct accretion

of chondrule-sized fragments into planetesimals by gravitational instability. Weidenschilling [1] suggested that turbulence driven by a dense midplane particle layer diffused particles away from the midplane, preventing the gravitational instability described by [2]. We have pursued this argument somewhat further [3,4]. The crux of the matter is the assumption of *very strong damping* of particle random velocities by [2]. While this might have been appropriate for the centimeter-sized particles envisioned by [2], damping of random velocities for the (at least) meter-sized objects implied by [3] is very difficult. Thus, while incipient fragments in such a layer may become unstable at or near the critical wavelength, they are unable to shrink and collapse very far, and are dispersed by differential rotation much like the “wakes” in Saturn’s ring system [5,6]. Thus, “primary accretionary texture” [7] must be produced in other ways.

It has long been suspected that aerodynamic sorting has played a role in chondrite constituent size distributions [8]. Recently, even stronger evidence has been presented [9]. Aerodynamic sorting requires some applied force in the presence of gas drag. Prior suggestions have generally focused on the role of the vertical component of solar gravity as the main force, but long timescales result from this weak force. Recently, a new effect has been recognized in numerical modeling experiments by which particles of the right size may be strongly concentrated into clumps by nebula turbulence. In fact, it is simple to show that the vertical component of solar gravity is more than an order of magnitude weaker than this (essentially, centrifugation) process described below. Also for this reason, dust rims on chondrules and fragments can be produced in shorter times than previously believed. Although there are no direct implications of this effect as to the energetic process that melted chondrules, we believe the small spatial and temporal scales it represents are of interest for constraining the environment in, or near, which chondrules are produced and/or accumulated into parent bodies. Because even small levels of global turbulence prevent chondrule-sized particles from settling appreciably toward the midplane, this situation could occur throughout the vertical extent of the nebula.

A critical parameter in this process is the particle Stokes number $St = t_s/t_c$, where t_s is the stopping time of the particle due to gas drag, a function of particle size and density, and t_c is a typical eddy turnover time, varying with the likely nature of the nebula turbulence. Optimally concentrated particles have Stokes number of unity when referred to the eddy turnover time of Kolmogorov scale eddies, and are preferentially concentrated by a factor $C > 30$ relative to the average particle volume density [10–12]. Smaller particles remain trapped firmly to the (incompressible) gas, while large particles are only minimally affected by the gas. Particles are initially distributed uniformly throughout all fluid zones, but rapidly become depleted in the “eddies” and concentrate in the most extreme “convergence zones.” A steady state is reached in a few (large eddy) turnover times in which eddy zones are preferentially depleted and convergence zones augmented. Concentration zones retain their identity several times longer than the residence time of a typical particle. We identified clumps in our numerical results using a threshold technique, and fit triaxial ellipsoids to them; it does seem that the clump dimension is on the order of the Kolmogorov scale [13]. Looked at in more detail, real clumps tend to have a complex and interesting structure. This all strongly indicates that centrifugation of optimally sized particles out of a certain scale of vortices contains the driving physics.

Our scaling relationships, which assume the presence of an

inertial range of scales $l = k^{-1}$, include (1) the Taylor scale

$$\lambda = \sqrt{15/Re} = L(15/Re_\lambda)$$

where the Taylor scale Reynolds number is

$$Re_\lambda = \sqrt{15Re}$$

(2) the Kolmogorov scale

$$\eta = LRe^{-3/4} = L(15^{3/4} Re_\lambda^{-3/2})$$

and (3) the eddy frequency

$$\omega_c(1) = \Omega(1/L)^{-2/3}$$

giving specifically

$$\omega_c(\eta) = \Omega(Re_\lambda/15)$$

where Ω is the large eddy frequency (probably the orbital frequency). With these basic relationships we can predict the range of particle and clump sizes expected to be the most relevant as a function of nebula Reynolds number. Unfortunately, the nebula Reynolds number in this stage may only be estimated based on uncertain energetics arguments. These arguments relate to the duration of the nebula, as constrained by the ages of protostellar disks, through the turbulent viscosity $\nu_T = U_c L_c = \alpha c H$, where α is believed to be in the range 10^{-2} – 10^{-4} [14]. Since $\nu_T = U_c L_c = \nu Re$, where $\nu = 10^5 \text{ cm}^2 \text{ s}^{-1}$ is the nebula molecular viscosity, $Re = \nu_T/\nu = \alpha c H/\nu = 10^8$ – 10^{10} . Then $Re_\lambda = 4 \times 10^4$ – 4×10^5 , and the clump size $\eta = L(Re_\lambda^2/15)^{-3/4} \sim 2 \times 10^{-7} L \sim$ several kilometers in the 1–2-AU region. Also, $\lambda \sim \eta(15^{1/4} Re_\lambda^{1/2}) \sim 600 \eta \sim$ a few 10^3 km. It is a little harder to distinguish from our simulations so far whether the clump formation time is on the large eddy timescale or the Taylor eddy timescale. The timescale for the Taylor scale eddies is $\sim \omega(\lambda)^{-1} \sim \Omega^{-1}(Re_\lambda/15)^{-2/3} \sim$ several days.

For particles smaller than the molecular mean free path, $t_s = r\rho_s/c\rho_g$, where r is particle radius, ρ_s is particle internal density, c is sound speed, and ρ_g is gas mass density. Using our basic scaling relationships for a location at 2 AU, and assuming $H = 3 \times 10^{12}$ cm, $c = 10^5 \text{ cm s}^{-1}$, $\rho_g = 10^{-10} \text{ g cm}^{-3}$, and $\rho_s = 3 \text{ g cm}^{-3}$, we obtain the remarkable result that, for current “guesstimates” of the nebula Reynolds number $Re_\lambda \sim 10^5$, the most strongly concentrated particles are a millimeter in diameter or so, in excellent agreement with the typical sizes of chondrules and fragments in primitive meteorites.

The concentration factor c , and how (or even whether) it depends on Reynolds number, is much less well constrained at present than the typical particle size. Although it might be much larger under nebula conditions, little more can be said with confidence about its magnitude at this time because of the large range of Re_λ over which we need to extrapolate. Further numerical experiments constraining the variation of c over a range of Re_λ are underway.

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HEATING AND COOLING IN THE SOLAR NEBULA: CONSTRAINTS FROM REFRACTORY INCLUSIONS.

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CAI Classification: There are three major types of Ca-Al-rich inclusions (CAIs) in CV chondrites with differing bulk chemical composition: types A, B, and C. Type A CAIs consist of melilite and spinel with minor hibonite and perovskite and appear to be nebular condensates whose textures have sometimes been modified by heating but most of which have apparently not been melted. Type B CAIs consist of melilite, fassaite, spinel, and anorthite and show chemical and textural evidence of melt crystallization. Type C CAIs consist of the same four phases as type B CAIs, but anorthite is more abundant. These also appear to have crystallized from melts. Hibonite-bearing CAIs from CM chondrites represent more refractory bulk compositions. A few of the latter have textures suggestive of melt crystallization but most have textures that are either indeterminate or suggest condensation.

Maximum Temperatures: Type A and B bulk compositions have liquidus temperatures of 1500°–1550°C [1,2]. Comparison of melilite mineral chemistry and textures produced in crystallization experiments on type B bulk compositions with chemistry and textures in natural type B CAIs show that these inclusions were most likely partially melted at ~1400°C [3]. Experimental studies on chondrule formation suggest slightly higher temperatures, ~1600°C [4]. Heating above this temperature dissolves spinel and destroys crystallization nuclei, causing formation of dendritic textures not found in natural CAIs. Some of the smaller, more refractory CAIs from CM chondrites show evidence for substantially higher temperature melting events. A CaAl_4O_7 -bearing spherule from Murchison has an inferred melting temperature of ~2100°C, based on textures and phase relations [5].

Cooling Rates: The crystallization sequence for type B bulk compositions is spinel, melilite, anorthite, fassaite. Type B CAIs often contain melilite that is reversely zoned [6]. In normally zoned melilite, early formed melilite is åkermanite-poor and late melilite is åkermanite-rich. In type B CAIs, early formed melilite is åkermanite-poor, but near the outer boundary of melilite crystals, the åkermanite content drops, then rises again. Crystallization experiments have shown that this zoning reversal is due to changes in liquid composition caused by fassaite crystallizing before anorthite. In these experiments, the reversal of order of crystallization of fassaite and anorthite occurs when the cooling rate is faster than

0.5°C/hr. In order to grow euhedral melilite like that seen in natural type B CAIs, CAIs must have been partially melted (in order to preserve spinel grains for melilite nucleation) and must cool at a rate slower than 50°C/hr [3]. Trace-element partition coefficients have been measured for melilite grown at 2°C/hr from type B bulk composition [7]. Measurement of trace-element concentrations in type B CAI melilite gives incompatible-trace-element concentrations higher than those predicted from the experiment. These excesses are probably due to formation of incompatible-element-rich boundary layers during melilite growth and suggest that the natural type B CAIs grew at rates significantly faster than 2°C/hr [8]. These cooling rates are substantially slower than those expected if type B CAIs had cooled by radiation in a nebular gas, but much faster than the cooling rate of the solar nebula. The CaAl_2O_7 -bearing spherule discussed above must have cooled extremely rapidly, since the temperature range from the liquidus to the solidus is 250°–600°C above the maximum temperature stability field of any major phase in a gas of solar composition at 10^{-3} atm. Evaporation of Mg (leading to enrichment of the residue in the heavy isotopes of Mg) at these temperatures would have been extremely rapid [9,10]. The lack of Mg isotopic mass fractionation in this CAI suggests that it cooled radiatively, taking only 0.25 s to cool from the liquidus (~2100°C) to the solidus (1725°C) and a further 0.6 s to cool to the maximum possible temperature of surrounding gas (~1500°C). Chondrules appear to have cooled somewhat faster than normal type B CAIs, at ~100°–2000°C/hr [4].

Transient Heating Events: CAIs sometimes preserve evidence of flash-heating events that produced local partial melting or evaporation effects. A forsterite-bearing CAI from Vigarano shows evidence for local melting and evaporation that produced a 300- μm mantle that is in petrologic and isotopic disequilibrium with the core [11]. This heating event must have been of short duration, as the mantle appears to have been completely melted and the core completely unmelted. Melilite at the exterior of many CAIs shows a polygonal-granular texture and finer grain size than interior melilite, suggestive of local solid-state recrystallization [e.g., 12]. Flash heating has also been proposed as a cause of some of the layers of the Wark-Lovering rims [13] that usually surround CAIs [14]. Multiple episodes of secondary alteration and partial melting were invoked to explain chemical and isotopic features of a Vigarano type B CAI [12]. Processing of this sort may be relatively common among CAIs in CV chondrites and could explain the evolution in bulk composition from types A to B to C. Evaporation of silicate melts leads to substantial O, Mg, and Si isotopic mass fractionation in residues [10,15]. The absence of significant heavy isotope enrichments in these elements in most CAIs indicates that they cannot have been molten for long.

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CRYSTALLIZATION TRENDS OF PRECURSOR PYROXENE IN ORDINARY CHONDRITES—IMPLICATIONS FOR IGNEOUS ORIGIN OF PRECURSOR. T. Fujita and M. Kitamura, Department of Geology and Mineralogy, Faculty of Sciences, Kyoto University, Sakyo Kyoto 606-01, Japan.

Findings of relict grains in chondrules have shown that chondrule melt did not directly condensate from gas but was formed by reheating of precursor materials. Only a few minerals such as olivine and pyroxene with chemical composition in a limited range have been reported as relicts. This therefore limits the study on the origin of precursor minerals. In the present paper, some fine pyroxene fragments in matrices of unequilibrated ordinary chondrites (UOCs) were interpreted to be fragments of precursors. Based on the chemical trends of the fragments, we suggest that the precursor pyroxene was crystallized by an igneous process.

Olivine and pyroxene occur both as chondrule minerals crystallized during the chondrule formation and as relict minerals. These minerals also occur as fine fragments in the matrix of UOCs. Since the effect of secondary equilibration after the accretion is lower in pyroxene than olivine, chemical compositions and internal textures of pyroxenes were the main focus of this study.

Chemical compositions of fine pyroxene fragments (5–20 μm in size) in the matrix of three samples of UOCs [Allan Hills 764(LL3), Yamato 790448(LL3), and Allan Hills 77015(L3)] were compared with chondrule pyroxenes and relict pyroxenes in the same chondrites. The shapes of pyroxene fragments suggest fragmentation of

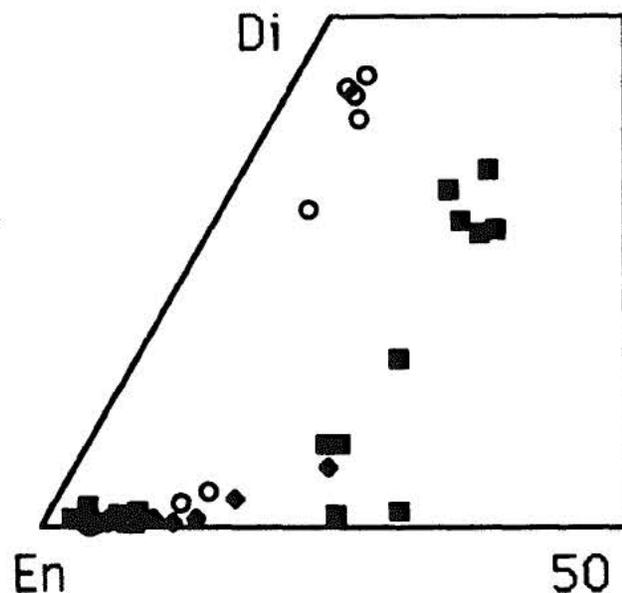


Fig. 1. Compositions of pyroxenes in Allan Hills 77015 plotted in the pyroxene quadrilateral. Open circles, solid squares, and solid diamonds represent compositions of chondrule pyroxenes, fine fragments, and relict pyroxenes respectively.

initially coarser materials. The compositions of the fragments form chemical trends from Mg-rich enstatite to pigeonite and Ca-Fe-rich augite (Fig. 1). The compositions of the relict pyroxene overlaps the trends in the low-Ca range. In contrast, chondrule pyroxenes form different chemical trends, which are more Mg-rich in the Ca-rich region than the trends of the fragments. The different chemical trends cannot be explained by Fe/Mg exchange after the accretion, suggesting distinct origins for the fragments and the chondrule pyroxenes.

Overlapping of compositions of the relict pyroxenes with the chemical trends of the pyroxene fragments in the low-Ca regions suggests a common origin for the fragments and relicts. Examination of the pyroxene fragments under a transmission electron microscope shows for evidence for shock deformation textures, which are essentially the same as those in the relict pyroxene. Therefore, these fragments probably originated from precursors common to the relict of chondrules, although some other enstatite fragments certainly come from the fragmented chondrules as previously reported [1].

Since the chemical trends of the pyroxene fragments from Ca-Fe-poor to Ca-Fe-rich pyroxenes are continuous and smooth, they have been interpreted as forming by crystallization. Crystallization trends similar to the present case have not been reported in condensation experiments and pigeonite is likely to be unstable at condensation temperatures from gas phase. It is therefore suggested that crystallization did not take place from a gas phase but from a liquid phase. This is supported by the observation that the trends are similar to those formed by crystallization from liquids such as in slowly cooled chondrules [2] and in lunar basalts. Furthermore, a chemical trend consisting of pyroxene in igneous fragments and relict pyroxene in the Yamato 790448 is similar to the trends of the fine fragments [3].

The above observations suggest that the precursor of the fine fragments and the relict pyroxene was formed by an igneous process in a grandparent body of the chondrite. Furthermore, the fact that the precursors appear as fragments in the matrix as well as relicts in the chondrule suggests a shock origin for the chondrite by collision of two or more bodies, which had already to some extent undergone igneous differentiation.

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ON THE POSSIBILITY OF PRECIPITATION-INDUCED VERTICAL LIGHTNING IN THE PROTOPLANETARY NEBULA. S. G. Gibbard and E. H. Levy, University of Arizona, Tucson AZ 85721, USA.

Many primitive meteorites contain high concentrations of chondrules—millimeter-sized beads of glassy silicate—in a matrix of essentially unprocessed material. These chondrules were apparently melted by some transient high-energy event, then cooled rapidly on timescales of minutes to hours. Among the phenomena that have been suggested as driving mechanisms for the heating event are high-velocity impacts [1], magnetic flares [2], aerodynamic drag heating [3], or lightning [4,5]. Although nebular lightning has been mentioned as a possibility by several authors [4,6,7], and calculations have been made of the efficiency of such lightning

in melting chondrule precursors [8], a quantitative treatment of processes that might produce nebular lightning has not been attempted.

Terrestrial lightning is believed to be the result of charge-separating collisions between ice particles, followed by gravitational separation of oppositely charged light and heavy particles. Ice-collision experiments have verified that collisional charging does occur, although the mechanism for the charge transfer is still unknown [9]. Inasmuch as water is the most abundant condensable species in the protoplanetary nebula, and because the presumed region of chondrule formation is located near the ice condensation boundary, we have considered the possibility that chondrules were formed by lightning discharges during repeated precipitation cycles (storms).

We have developed a one-dimensional nebular lightning model that utilizes a spectrum of particle sizes. This model has also been applied to the Earth as a test of its predictive ability. Particles grow to an initial size distribution, then undergo elastic charge-separating collisions. Charge separation is opposed by the mobile free charge in the nebula, which can either accumulate on and neutralize the charged ice particles or move to cancel the large-scale electric field. Since the free charge density depends on the grain size distribution, it is determined self-consistently as the particle distribution changes.

Particle charging is assumed to be due to either an inductive or a noninductive process. The inductive process gives a charge transfer that is proportional to the electric field

$$dQ_i = \frac{\pi^2}{2} r_s^2 \cos\theta E (1 - e^{-t_c/t_r}) \quad (1)$$

where r_s is the radius of the smaller particle, θ is the angle between the line of centers of the two particles, t_c is the time the particles are in contact, and t_r is the electric relaxation time of ice. In this work, the physics of ice-ice collisions (duration and area of contact) are determined from a quantitative collision model. Noninductive charge transfer can be modeled by a semiempirical formula [10]

$$dQ_i = F r_i^{1.3} r_s^{1.7} \quad (2)$$

where F is an experimentally determined constant.

The charge on a particle changes with time according to

$$\frac{dQ_i}{dt} = \sum_j \frac{dQ_j}{\tau_j} + \sum_k q_k n_k v_k \sigma_k \quad (3)$$

where the sum j is over particles in other bins, τ is collision time, and the sum k is over free ions.

The number density of each ion, n_k , is determined by a balance between production (assumed to be due to the decay of ^{40}K) and loss to grain surfaces, which gives

$$n_k = \frac{2.98 \times 10^{-8}}{v_k \sum_{\text{grain}} \sigma_{\text{grain}}} \quad (4)$$

where v_k is the ion velocity and σ is the grain cross section for the ion k , which depends on the grain charge.

Applied to Earth's atmosphere, these model calculations confirm that inductive charging (equation (1)) in ice-ice collisions does

not lead to charge transfer sufficiently effective to produce lightning storms. This is a result of the combined short duration of contact and much longer electric relaxation time (owing to the low electrical conductivity of the material). An equilibrium inductive model (where it is assumed that particles remain in contact long enough for charge to flow to a state electrical equilibrium between the two particles) provides enough charge transfer to reach the breakdown field (about 3–500,000 V/m for Earth's atmosphere) in about half an hour, comparable to the observed time for an electrical storm to develop. A model incorporating noninductive charging also produces that result with a value of F (see equation (2)) of about -2000 .

In the protoplanetary nebula, the breakdown field is only 100 V/m. However, our calculations indicate that the conductivity is high enough to short out any developing electric field for any reasonable inductive (physical or assumed equilibrium) or noninductive charging mechanism. It thus seems unlikely that large-scale vertical lightning occurred in the protoplanetary nebula. On the other hand, increasing the dust density (but not the gas density) might provide a better climate for lightning production. We are currently investigating the possibility of smaller-scale radial lightning in a dusty subdisk or near meteorite parent bodies.

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THE ROLE OF CHONDRULES IN NEBULAR FRACTIONATIONS OF VOLATILES AND OTHER ELEMENTS.

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For at least 30 years, cosmochemists have been grappling with the question of how and why groups of geochemically and volatility related elements became fractionated in the major chondrite groups. At least five relatively independent fractionations are known: refractory lithophiles from Si, moderately volatile lithophiles from Si, highly volatile elements from all other elements, siderophiles from lithophiles, and refractory siderophiles from nonrefractory siderophiles. It has always been obvious that there were gross petrographic differences between these same chondrite groups, with high-temperature components (chondrules, CAIs), low-temperature components (especially matrix), and metal-, sulfide-rich components varying widely in abundance, texture, and composition. Virtually everyone who has thought about these facts has been tempted to attribute at least some of the fractionations to the physical separation or mixing of the visible components. By far the most abundant of these components in meteorites is chondrules, and indeed chondrules have long been suspected of playing a direct role

in the fractionation of volatile elements. Clearly, the question of whether chondrules formed before or after chemical components became separated is of fundamental importance to our understanding of the early solar system, as the answer constrains how, when, where, and from what chondrules formed, and tells us about how materials were processed in the nebula. But after three decades of research, and despite renewed enthusiasm in the last few years, the case for the involvement of chondrules in any chemical fractionation process involving bulk meteorites is still extremely weak and mostly circumstantial.

Chondrules were once thought to be poor in moderately to highly volatile elements, resulting in the famous “two-component model” for chondrites [1], in which simple mixing of volatile-poor chondrules and unfractionated (CI-like) matrix explains the elemental abundance patterns of refractory to moderately volatile elements in chondrites. Later work showed chondrules to have far higher volatile contents than could be compatible with such a model [2–4]. Recently, however, the Sears group, in rediscovering a long-recognized group of volatile-poor chondrules (their “group A” chondrules), have attempted to resuscitate a variety of the old two-component model and to begin building a case for a prominent role of chondrules in other nebular fractionations as well [5–8]. They imply that the abundance of such chondrules has been grossly underestimated (in biased studies of separated chondrules), and that there may be enough of them to seriously affect the mass balance of chondrites. However, given the fact that group A chondrules tend to be tiny in ordinary chondrites [9], their numerical abundance of ~35% [7] is misleading: Only ~5% of the mass of chondrules is composed of volatile-poor individuals. So, at least in the case of ordinary chondrites, the arguments summarized in [2–4] against the role of chondrules in the fractionation of volatiles remain intact.

There is other evidence against the supposition that volatile loss was a widespread phenomenon among chondrules, despite the recently popular speculation that recondensation may have replaced lost volatiles in the chondrule population [6,10–12].

1. It seems inescapable that the fine-grained dust that forms rims around chondrules would be the perfect substrate on which volatiles would recondense, yet volatile enrichments on chondrule rims and surfaces are small at best [4].

2. Virtually no chondrules have the peralkaline compositions expected if recondensation were allowed to introduce volatiles back into chondrules, especially low-Al chondrules.

3. Potassium/sodium ratios are modestly fractionated in Semarkona chondrules, but not in a way that is consistent with evaporation/recondensation from a single population of chondrules: Chondrules that are low in alkalis rarely have the high K/Na ratios that would be scavenged from the alkali-rich vapor liberated during evaporation. For this to be true, it follows that chondrules that experienced volatile loss must have been quickly removed from the region of heating, and multiple heating events would not occur. In light of abundant evidence favoring recycling of chondrules through several episodes of melting, it is much more likely that most chondrules formed from material that had already experienced volatile-element fractionation in the nebula.

Grossman and Wasson [13] concluded that chondrules formed from the same components that were involved in the nebularwide fractionation of refractory lithophiles, but *after* that fractionation was already accomplished. Recent work [7,12] reopens the question of whether mixing different types of chondrules in different propor-

tions might be the actual cause of such fractionations. This seems most unlikely. Type I (basically the same as group A) chondrules have high refractory-lithophile/Si and Mg/Si ratios and very low FeO/Si and Na/Si ratios relative to CI chondrites, while other chondrules tend to be much less fractionated. It is clearly not possible to produce the uncorrelated refractory-lithophile/Si and Na/Si ratios in different chondrite groups by varying the amounts of these two types of chondrules, as this would result in a strong anticorrelation of the ratios. There are also far too few type I chondrules in CM chondrites to account for their refractory element enrichments, and too many type I chondrules in "CR" chondrites to be consistent with their lack of refractory enrichment.

The metal-silicate fractionation experienced by chondrites also probably predated chondrule formation. Sulfur was not fractionated along with siderophiles, so the separation of metal and silicate must have occurred at high temperature [14]. Because chondrules contain abundant primary FeS, they must have formed after the fractionation was already accomplished. Thus, the separation of chondrules from other components, and of different types of chondrules from each other, seem to be poor ways of explaining the major nebular chemical fractionations. Although a small percentage of chondrules did experience fractionation during melting, their effect on bulk compositions may have been minor. Chondrules probably reflect the host meteorite (i.e., local nebular) composition, rather than vice versa.

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ASTRONOMICAL OBSERVATIONS OF PHENOMENA IN DISKS. L. Hartmann, Mail Stop 15, Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge MA 02138, USA.

Astronomical constraints on disks around young stellar objects are reviewed. Since disks around the youngest stars cannot generally be resolved spatially, most results are based on analyses of the infrared and radio emission from circumstellar dust and gas. At least half of all young stars seem to have substantial circumstellar disks at an age of $\sim 10^6$ yr. The young objects without disks tend to be binary stellar systems, though not exclusively, and some close binaries may have outer disks that are not tidally disrupted. Probably most, if not all, stars formed originally with circumstellar disks, but evolutionary timescales may differ dramatically. The best current estimates suggest that disks with substantial amounts of gas and distributed small dust particles generally "disappear" on a timescale of $\leq 10^7$ yr. The masses of circumstellar disks around young stars are thought to range from values close to the minimum mass solar nebula $\sim 10^{-2} M_{\odot}$ up to appreciable fractions of a solar mass. These estimates are sensitive to the adopted long-wavelength dust opacities;

the results are probably uncertain within by factor of at least 5 for this reason. Disk sizes are typically estimated to be about 100 AU. All these results are subject to the additional uncertainty of the effects of infalling dusty envelopes, which produce the disks in the first place. It now appears that many of the large dusty structures originally interpreted as disks are actually flattened envelopes falling in to a much smaller (unresolved) disk. The interaction of the infall with the disk is a current topic of active research. The collapse of the protostellar cloud with even modest amounts of angular momentum is thought to result in initially massive disks, and gravitational instabilities rapidly drive material from the disk into the central core. During this period the disk, being fed at infall rates of 10^{-6} – $10^{-5} M_{\odot} \text{ yr}^{-1}$, may dump its material into the central star in FU Orionis outbursts, with disk accretion rates reaching $10^{-4} M_{\odot} \text{ yr}^{-1}$. This instability may be limited to the inner disk (inside 1 AU); the observational evidence is not clear yet. As infall to the disk ceases, disk accretion slows down, with typical rates of $10^{-7} M_{\odot} \text{ yr}^{-1}$ during the T Tauri star phase, which lasts for a few million years. There is not much information on later stages of disk evolution.

EXPERIMENTAL CONSTRAINTS ON MODELS FOR ORIGINS OF CHONDRULES: PEAK TEMPERATURES. R. H. Hewins and H. C. Connolly Jr., Department of Geological Sciences, Rutgers University, P.O. Box 1179, Piscataway NJ 08855-1179, USA.

Introduction: The peak temperatures experienced by chondrules provide a parameter that may allow discrimination between alternative heating mechanisms: Successful mechanisms must provide just enough energy to reach such temperatures and not overshoot them. In principle, determination of peak temperatures from chondrule textures and experiments that duplicate them should be very easy [1]. However, this approach is complicated by the fact that there are several different experimental paths that reproduce chondrule properties: The key property texture depends not only on the peak temperature but also on the heating time [2,3] and, in the case of totally molten droplets, on interactions with other particles [4].

Near-Liquidus Melting: Many experimental studies have demonstrated that chondrule textures depend on the number of nuclei present when cooling began, i.e., the degree of melting [e.g., 5,6]. The increasing nucleation densities in the chondrule textural sequence glass barred/radial porphyritic granular can then be interpreted as superliquidus, near-liquidus, subliquidus, and very subliquidus respectively. Based on this logic the distribution of chondrule textural types and calculated liquidus temperatures yield the range 1400°–1750°C for most chondrules. However, the experimental basis for this involved long heating times (≥ 30 min), whereas chondrule heating was probably much more rapid. The appropriate reference temperatures then are the olivine disappearance temperatures that are some unknown amount above the equilibrium liquidus temperatures.

Flash Melting: Heat transfer to raise temperature and then melt a chondrule takes time and involves an initial steep temperature gradient across the particle. The ambient furnace temperature required to produce a total melt increases as heating time is reduced. This temperature can be as much as 100°C above the liquidus for 5-min heating times with relatively coarse-grained starting material

(125–250 μm) or less with finer precursors. Dynamic crystallization of melts heated at such temperatures for ~ 1 min [2] shows that nucleation of barred olivine can occur with peak temperatures as much as 400°C above the liquidus (for the coarsest-grained precursors). Definition of the peak temperatures is therefore very difficult, especially as the surface layers of chondrules might be strongly superheated for a very brief period. However, as most type I chondrules were incompletely melted, we can define the range in which these particles reached internal thermal equilibrium as 1600°–1800°C or lower for the less melted objects, including dark-zoned chondrules.

Dust Seeding: If type IA chondrules reached 1600°–1800°C in their interiors, accompanying chondrules with less refractory compositions (e.g., type II and type III/IB) might have been totally melted, i.e., glassy. Totally glassy chondrules are rare relative to type III chondrules with excentroradial pyroxene nucleated on the spherule surface and to type II porphyritic chondrules. Totally melted droplets can be induced to nucleate chondrule textures if they are seeded by collisions with dust grains [4]. Thus it is possible that type II porphyries as well as the obvious case of excentroradial pyroxene chondrules were totally melted provided that dust grains could survive in the heated volume or be rapidly reintroduced. The time of superheating would have to be extremely brief as type II chondrules maintain high levels of moderately volatile elements such as Na and S [7–9]. The requirement for total melting and seeding could be dispensed with if type II chondrules were formed separately from type I; e.g., if their more oxidized nature required an environment (e.g., with higher ambient pressure) that somehow damped the heating process, leading to chondrule internal temperatures lower by at least 100°C.

Volatile Element Constraints: At peak temperatures and canonical nebular pressures chondrule melts are unstable relative to vapor. There are, however, surprisingly high concentrations of moderately volatile elements in some chondrules; e.g., Na is essentially totally retained in type II chondrules [7,8] and some S survives melting in the least melted type I chondrules [9]. Conditions for loss vs. retention of such elements therefore potentially provide information on peak temperatures, but volatile loss continues during cooling. As volatile loss rates are extremely sensitive to cooling rates, especially initial cooling rates [9,10], peak temperatures cannot be constrained from chondrule volatile concentrations unless cooling paths are very well known, especially for the highest temperature range.

Barred Olivine Chondrules (BO): The history of estimates of BO peak temperatures well illustrates the problems in estimating the heating conditions of chondrules. The very low nucleation density of BO would require that they were melted essentially at their liquidus temperatures (1400°–1750°C) if the melting times were long [1]. However, a range of 100°C above the liquidus for each composition is possible considering the effect of varying sample size precursor grain size and heating time [11]. Using the flash heating approach [3] produced BO with initial temperatures up to 400°C above the liquidus. In seeding experiments [4] melts can be superheated any amount (subject to limits by volatile loss) and then be caused to nucleate BO textures by collision with dust grains during cooling. Temperature estimation is not as hopeless as the BO case suggests; however, the microporphyritic and granular textures of type I chondrules (with high nucleation densities) can be reproduced by partial melting but not by dust seeding. Therefore we have

a firm estimate of 1600°–1800°C for type I chondrule interiors, and it is unlikely that BO chondrules were much superheated beyond this range.

Conclusions: Type I chondrules, though no doubt briefly superheated surficially, reached internal temperatures of 1600°–1800°C. The situation is less clear for type II chondrules, which were heated to similar temperatures and then dust seeded or were heated in a different environment responsible for their more oxidized nature, which somehow attenuated the heating process.

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MODELS FOR MULTIPLE HEATING MECHANISMS.

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Meteoritic Constraints: From the bulk compositions of undifferentiated (chondritic) meteorites, it has been inferred that temperatures of 1200–1400 K existed in the inner solar system, including the asteroid belt, for time periods of at least tens of years, and that some Ca,Al-rich inclusions (CAIs) in carbonaceous chondrites require formation temperatures as high as 1600 K [1]. After temperatures had decreased to <650 K, the nebular environment was apparently punctuated with relatively brief and repetitious heating events that were sufficiently energetic to melt chondrules and form rim sequences on CAIs. In the case of chondrules, this requires temperatures that peak above 1873 K and remain in excess of ~ 1423 K for a period of ~ 1 hr [2]. In the case of CAI rims, this requires temperatures of at least 1825 K for an even shorter interval of time (\sim seconds) [1,3]. For several reasons, it can be inferred that these transient heating events occurred well within the nebula, probably near the midplane. First, the high contents of alkali elements in Allende chondrules [1] and interelement correlations [e.g., 4] indicate that the precursors of most chondrules were probably condensed solids in the nebula rather than interstellar grains. Condensed solids were probably most numerous near the midplane. Second, evidence exists that chondrules have been processed repeatedly and thus contain recycled fragments of previous generations of chondrules [e.g., 5]. Among this evidence are the textures and chemical compositions of relic grains [6] and the juxtaposition of high-temperature rims around chondrule cores [7]. Thus, at least in the case of chondrules, multiple transient heating events occurring within the nebula after solid material had condensed are strongly suggested.

Astrophysical Considerations: There is abundant evidence that protostellar accretion disks (and, by inference, our protoplanetary

nebula) are not (was not) quiescent [7]. Inferred disk properties suggest deviations from axial symmetry and/or time-dependence of disk accretion rate rather than a classical stable nebula [8]. Direct observations indicate episodic bipolar mass ejections [9] and relatively short-term irregular brightness variations attributed to obscuration by circumstellar cloud clumps [10]. The source of this variability appears to be changes in mass accretion rate perhaps resulting from inhomogeneities in the surrounding molecular cloud core. The most intense variation occurs during FU Orionis outbursts, when the rate of disk accretion can increase by several orders of magnitude within a year, leading to high disk temperatures persisting for decades or more [7]. Statistics lead to the inference that most protostars probably experience multiple (~ 10) FU Orionis outbursts. The repetition timescale is of the order of 10^4 – 10^5 yr, perhaps increasing with time during the evolution of a young star.

Multiple Heating Mechanisms: For the midterm (tens of years) nebular heating events indicated by meteoritic data, FU Orionis episodes represent a likely candidate mechanism. Although these episodes may be too large in spatial and temporal scale to be appropriate for chondrule formation, their occurrence suggests that smaller inhomogeneities in disk accretion rate could have produced smaller-scale transient heating events. In particular, the boundaries between accreting mass elements would have been marked by gas-dynamic shock waves. The latter have previously been shown to be quantitatively plausible chondrule heat sources [11,12].

The most well-known example of a shock wave produced in disk formation is the “accretion shock” formed when infalling gas collides supersonically with preexisting nebular gas. Heating of interstellar grains at the accretion shock was originally considered by Wood [13], who provided an important initial exploration of the physics of gas-grain interactions relevant to chondrule formation. A recent study has shown that postshock cooling enhances gas densities, leading to more efficient heating of infalling interstellar grains at the accretion shock [14]. However, because chondrules seem to represent melted nebular material and have been reprocessed by multiple thermal events, this one-time-only mechanism that melts interstellar material seems inadequate.

Shock waves in the nebular midplane appear to be better candidates for supplying chondrule heating events. Mechanisms for producing shocks in the nebular midplane fall into at least two categories. The first involves accretion of the nebular disk from interstellar material and the transport of that material to a growing protostar. For example, propagating large-scale shocks that penetrate the nebula may have been produced by multiple infalling molecular cloud core clumps [10]. Alternatively, larger inhomogeneities in the molecular cloud core could have produced time-dependent and axially asymmetric phenomena in the evolving disk as suggested by the FU Orionis phenomenon. Initial models of shock waves in the nebular environment [11,12] indicate that these types of phenomena can produce temperatures over periods of time appropriate for chondrule formation. However, these model calculations need to be expanded to account for a more realistic distribution of grain sizes and the negative feedback produced by the partial vaporization of these grains during the high-temperature event. In addition, specific tests of these possible multiple heating mechanisms still need to be made by integrating them with numerical models of disk accretion.

The second category of multiple shock processes in the nebular midplane involves the accretion of nebular material into a planetary

system. For example, small-scale bow shocks upstream of planetesimals in eccentric orbits represents one possible source for the brief high-temperature events that produced CAI rims and should be quantitatively examined in the same way that aerodynamic heating in parent body atmospheres has recently been studied [15].

Finally, included among alternate possible multiple transient heat sources are electromagnetic events such as lightning and magnetic reconnection flares; these possible heat sources will be examined in separate papers at this conference. As mentioned above, aerodynamic heating of CAI rims in transient protoplanet atmospheres has been quantitatively studied [15] but does not represent a plausible mechanism for repetitive melting of chondrules.

Conclusion: Current meteoritic and astrophysical evidence (especially FU Orionis events) suggests that large-scale gas-dynamic shocks penetrating to the nebular midplane represent a promising class of multiple heating mechanisms for the formation of chondrules. Initial numerical models [11,12] have shown that shock heating of chondrule precursor grains in optically thick clouds of grains is especially efficient. Shocks generated by infalling molecular cloud clumps and shocks separating different mass elements in a time dependently and axially asymmetrically evolving disk are possibilities deserving further attention.

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CHONDRULE FORMATION IN LIGHTNING DISCHARGES. M. Horanyi, Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder CO 80309, USA.

Chondrules represent a significant mass fraction of primitive meteorites. These millimeter-sized glassy droplets appear to be the products of intensive transient heating events. Their size distribution, chemical and mineral composition, texture, and isotope composition suggest that chondrules were produced as a result of short-duration melting followed by rapid cooling of solid precursor particles. Gas-dynamic heating, magnetic reconnection, and electrostatic discharges are thought to be the leading candidates to explain chondrule formation. In this paper we summarize our recent theoretical progress on the effects of “lightning” in the early solar

system [1] and also report on preliminary results from our laboratory experiments. Differential settling of various sized dust particles toward the midplane of the nebula is suspected to build large-scale charge separations that episodically relax via the electric breakdown of the nebular gas. The electrostatic discharge is analogous to lightning in the Earth's atmosphere.

In this paper we do not discuss the complex physical processes that may lead to electric field generation. Instead, assuming that this may occur due to a number of inductive and noninductive processes, we use the expected initial conditions in such a discharge. We then follow the expansion of the initially energetic plasma column as it expands, cools, and recombines. We calculate the energy flux reaching the surface of an embedded dust grain and also its subsequent heating. We show that, within the range of expected initial plasma conditions, lightning is a viable mechanism for chondrule formation. We have also modified an existing research facility to allow us to introduce chondrule precursor solid grains into a plasma discharge. These first experiments were designed only to test our dust dropper, the timing device, and ultimately the presence of dust in the plasma. We have observed intense UV light that is produced from the evaporated and sputtered atoms and molecules and also other impurities in the plasma. The presence of dust in the plasma is clearly verified by the greatly enhanced light emission. We are now replacing the broadband UV detector with an existing spectrometer in the near UV to monitor specific lines. We will report on the status of these experiments and also discuss our future experimental plans. We will conclude that lightning remains a leading candidate to explain chondrule formation worthy of more complex theoretical and also laboratory investigations.

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THE EARLY SUN AND THE FORMATION OF CHONDRULES. G. R. Huss, Lunatic Asylum, Division of Geology and Planetary Science, Mail Stop 170-25, California Institute of Technology, Pasadena CA 91125, USA.

Energetics of melting and temperature histories inferred from laboratory experiments are just two of many factors to consider in a model of chondrule formation. Chondrules make up 50–85% of chondrites, which in turn constitute >95% of all meteorites. Thus chondrule formation was both widespread and efficient. Chondrules within chondrites and coarse-grained rims indicate that some were processed more than once. Differences in compositions between UOC, E, and CV chondrites [1,2] indicate that chemical fractionations recorded in chondrites took place before chondrule formation. The narrow size range within a meteorite suggests that chondrules have been size sorted [3]. A systematic decrease in mean chondrule size correlates with increasing Fe, metal, and ^{16}O in LL, L, H, and EH chondrites, suggesting that chondrule formation and chemical fractionations are related [4]. Accretion must have been rapid to preserve the differences between chondrite classes [5].

Mechanisms of chondrule formation should either address the above observations or fit within a broader theory that does. Two sources of energy for chondrule formation, lightning and magnetic reconnections, are currently popular because both release considerable energy in a short period of time and both probably occurred in the early solar system [6]. However, neither mechanism seriously

addresses the efficiency question, and both mechanisms would seem to predict *no correlation* between physical and chemical characteristics of chondrules since neither mechanism depends strongly on the composition of dust.

The early Sun is an energy source that potentially provides a mechanism for chondrule formation and an explanation for the systematics of chondrule populations. Earlier workers have shown that a T Tauri sun would not supply enough energy to melt dust at the radius of the asteroids. However, recent observations indicate that the T Tauri phase is actually the *waning* stage of pre-main-sequence activity [7]. Pre-main-sequence stars are surrounded by accretion disks and are powered by accretional energy. While still embedded in a molecular-cloud core, these stars often drive massive bipolar outflows of molecular gas that has been swept up and accelerated to tens of km s^{-1} by a high-velocity stellar wind (hundreds of km s^{-1}) [8]. The high-velocity wind is more easily observed in the later T Tauri stage when the enveloping gas has dispersed. The wind intensity and luminosity of a young stellar object correlate with the rate of accretion onto the star and can be highly variable [7,8]. Several T Tauri stars have been observed to brighten by factors of up to ~200 in less than a year during FU Orionis eruptions [7]. These luminosity increases are believed to be powered by a rapid increase in the accretion rate onto the star and are accompanied by very powerful winds. The number of observed FUOR eruptions indicates that a pre-main-sequence star undergoes >10 such outbursts and spends ~5% of its time in eruption [9]. There is enough energy in the eruptive FUOR winds to heat micrometer-sized dust to 600–1600 K and the radiant energy could heat solids to 1000–2800 K at 2.5 AU [10].

Figure 1 shows schematically how chondrules might form. A massive transfer of accretion-disk material onto the proto-Sun generates a FUOR eruption that terminates accretion. Material at the inner edge of the now-depleted accretion disk is rapidly heated by intense radiation. The disk is eroded as hot gas moves vertically, down the pressure gradient, and either leaves the disk as a wind or is transferred to the outer disk (Fig. 1). A series of disk shocks raises the temperature ahead of the erosion front, initiating thermal processing of the dust. As centimeter-sized dust balls are incorporated

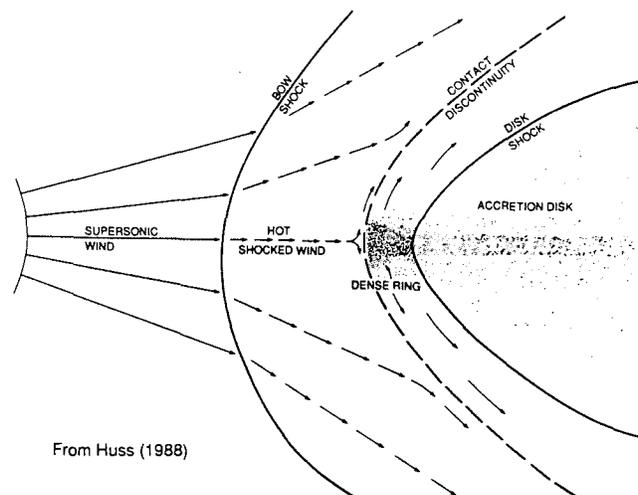


Fig. 1.

into the dense ring behind the contact discontinuity (Fig. 1), they are exposed to the highly luminous Sun and heated. The dust balls eventually melt while becoming entrained in the outflowing gas behind the contact discontinuity. Many evaporate. As the gas velocity decreases away from the disk, some melted droplets fall back into the optically thick accretion disk and cool. These protochondrules could be processed again, though few would survive later cycles. Eventually the fading Sun would no longer be able to erode the disk. Chondrules, the crystallized droplets stranded just beyond the leading edge of the disk, would accrete to form a chondrite parent body. Chondrule size and degree of sorting would depend on the rate of gas loss from the disk, while chemical characteristics would reflect preheating by disk shocks. Since both depend on the power of the eruption, correlations between chemical and physical properties would be expected.

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CHONDRULES AND THEIR ASSOCIATES IN ORDINARY CHONDRITES. R. Hutchison, Mineralogy Department, Natural History Museum, London SW7 5BD, UK.

A theory for the origin of the ordinary chondrites (OCs) must account for the origin(s) of their constituents. If the OCs accreted in a protoplanetary disk, their components represent the variety of materials that coexisted in it, which constrains their possible origins. The following discussion excludes gas-rich meteorites that formed after any disk had dissipated.

Chondrules dominate the OCs and are solidified melts that range from silicate through silicate plus metal and/or sulfide to rare metal and/or sulfide end members [1]. Some are quenched molten droplets; most are abraded subspherical fragments (clast chondrules) of porphyritic or poikilitic rocks of unknown size [2]. Rock fragments with igneous textures and fractionated rare earth elements (REE) are rare [3,4]. In addition, some OCs have fine-grained opaque matrix and rims around chondrules and clasts, which may be accompanied by presolar material [5,6] that was introduced as dust or in a carrier.

Properties of the Components of Ordinary Chondrites:
Chondrule sizes. Chondrules are stated to have a "limited range of sizes" [7] from ~0.1–3.8 mm [8]. Microchondrules may be smaller than 10 μm [9], macrochondrules as big as 5 cm [8]. We have found centimeter-sized, chondrule-textured objects in all three chemical groups in most petrographic types.

Textural relationships between chondrules. Where primary textures survive in unequilibrated ordinary chondrites (UOCs) such as Tieschitz or Krymka, many chondrule pairs, triplets, and quadruplets aggregated when at least one member was plastic [1,10]. Optical observation demands that large portions of such UOCs accreted at about 800°C [11]. In contrast, the irregular shapes of many objects testify to their brittleness before or during accretion.

Textures within chondrules. The conditions required to produce the textures of droplet chondrules are known from experiments [12]. Analogous structures occur in metal-sulfide chondrules in Tieschitz [13]. Clast chondrules may be <4 cm in size and porphyritic, with a preferred orientation of the phenocrysts [2]. Some phenocrysts (preexisting grains) were not in equilibrium with their chondrule liquids [7, Fig. 3a,b]. In poikilitic clast chondrules, olivine globules are enclosed in Ca-poor pyroxene with or without Ca-pyroxene and Ca-plagioclase [3,14].

Chemical composition. Silicate chondrules may be strongly olivine normative or pyroxene normative [15], with normative sodic feldspar. Extremes are highly quartz normative (some contain silica polymorphs) or nepheline normative [11,16]. Quartz normative chondrules often have normative Ca-feldspar and corundum. Most chondrules have Ca/Al near the cosmic value, but pyroxene-rich chondrules tend to have high Ca/Al and olivine-rich chondrules tend to have low Ca/Al, especially if nepheline normative [16]. The REE are not always unfractionated.

Igneous fragments. Rare fragments with igneous textures and/or REE signatures occur in OCs. An unequivocal example is a 2-mm microgabbro in Parnallee (LL3) [4], which has zoned pyroxenes and REE abundances like lunar mare basalt, but has higher Na and Mn. A 1-mm rock in Semarkona (LL3) has a poikilitic texture, FeO-bearing olivine and pyroxene, and rare anorthite. It cooled to Al-Mg closure when ^{26}Al was "live." The Ca-pyroxene has REE contents indicative of crystallization from a liquid with unfractionated REE at about 8 \times chondritic. Pyroxene and anorthite have complementary REE abundances and Eu anomalies [14]. In a few L6s, igneous inclusions retain H-group O isotope ratios [17].

Chondrule rims and interchondrule matrix. Transmission electron microscopy indicates that rims and matrix are the debris of chondrules and clasts; a nebular fraction is <3 vol% [18]. A high D/H ratio in Semarkona and other isotopic evidence indicate that a presolar component is present [5].

Ages of chondrites and inclusions. The ages of U-Pb closure in phosphates [19] are about 10 m.y. older in H4-5 chondrites than in L5-6. This is consistent with the formation, melting, and break-up of an H-group body before the end of accretion and metamorphism of Barwell, L6, which is demanded by the presence of a partly digested olivine cumulate H-group xenolith in this unshocked chondrite [17].

Conclusion: The formation of the OCs and OC chondrules in a protoplanetary disk requires the OC region to have (1) presolar grains (in a pristine carrier?); (2) differing O isotopic ratios (on a small scale?); (3) rocks >5 cm in diameter; (4) coexisting fractionated chondrule precursors; (5) rocks with igneous textures and REE abundances, one of which formed when ^{26}Al was "live;" (6) existed for about 10 m.y. (duration of accretion?); (7) a high enough density for chondrules to collide before cooling and for most chondrules to hold alkalis; and (8) a composition in equilibrium with FeS above 1000°C. Can these requirements be fulfilled by a protoplanetary disk without planets?

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RELICT GRAINS IN CHONDRULES: EVIDENCE FOR CHONDRULE RECYCLING. R. H. Jones, Institute of Meteoritics, Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque NM 87131, USA.

The presence of relict grains in chondrules offers some insight into the degree to which chondrule material was recycled in the chondrule-forming region. Relics are grains that clearly did not crystallize *in situ* in the host chondrule. They represent coarse-grained precursor material that did not melt during chondrule formation, and provide the only tangible record of chondrule precursor grains. Several different kinds of relics have been identified, and different sources for these grains have been suggested. The compositions of certain relics are very similar to comparable grains in chondrules. These grains provide evidence for recycling of chondrule material, which places important constraints on chondrule formation models.

Relics are commonly identified by a large difference in size, textural differences, and/or significant compositional differences compared with normal grains in the host chondrule. Two important types of relics are (1) “dusty,” metal-bearing grains of olivine and pyroxene [1,2]; and (2) forsterite (Mg-rich olivine) grains present in FeO-rich chondrules [3–6].

“Dusty” olivine and pyroxene grains are common in all types of chondrites [1–3,7,8]. The dusty appearance in transmitted light results from the presence of numerous small (micrometer-sized) blebs of low-Ni, Fe metal distributed throughout the grain. This texture is the result of solid-state reduction of a more FeO-rich olivine or pyroxene grain. Dusty grains are observed in reduced, low-FeO (type I) chondrules and commonly have a clear, metal-free overgrowth of FeO-poor olivine that probably grew during chondrule formation. Reduction of the relic may have taken place either before or during chondrule formation. Rare, FeO-rich grains in reduced chondrules have not undergone reduction [3]. For some dusty grains, the high density of metal suggests that original compositions were above 30 mol% Fa or Fs (Fa = fayalite, Fe-rich

olivine; Fs = ferrosilite, Fe-rich pyroxene) [7,9]. However, detailed studies and estimates of the range of precursor compositions are not generally available at present. In ordinary chondrites, the origin of precursor grains with such high FeO contents is problematical: The most Fe-rich chondrule olivine in unequilibrated chondrites is about Fa₂₅ [10]. No chondrule candidates for the precursors of these grains are evident within the same chondrite. However, in unequilibrated CO carbonaceous chondrites, olivine in FeO-rich (type II) chondrules has compositions around Fa₃₀ [11,12], and this is a likely potential precursor for the most metal-rich dusty olivine. For enstatite chondrites, most of the FeO-rich chondrules that have been described are also reduced, but provide a potential source for dusty relict grains in low-FeO chondrules [8].

Forsterite relics in FeO-rich chondrules occur as cores of composition Fa_{0.5–8} within FeO-rich (Fa_{15–20}) olivine grains [3–6]. The FeO-rich olivine is an overgrowth that grew during chondrule formation. Textures of relict forsterites show that they were partially resorbed into the chondrule melt during the melting episode. The FeO and minor element contents of the forsterites are consistent with their derivation from FeO-poor, type I chondrules. This type of relic is rare in ordinary chondrites, and more common in CO3 chondrites. In one ordinary chondrite (Semarkona), four small relict forsterites, <40 μm across, were observed in three chondrules out of 11 studied [5]. In CO3 chondrites, larger relics, up to 100 μm across, are present in 3 out of 4 chondrules [6]. Olivine dissolution experiments indicate that a 40-μm forsterite grain, typical of type I chondrules in ordinary chondrites, will dissolve in a molten chondrule in a matter of minutes [13]. This suggests that the survival rate of forsterite relics is low, and that forsterite grains were probably more common in chondrule precursors than the observed proportion of relics indicates.

In type 3 ordinary chondrites, approximately 10% of all chondrules contain dusty relict grains, and approximately 5% of all chondrules contain relict forsterite. These grains underwent at least two episodes of chondrule formation. This evidence has important implications for chondrule formation models. Both these types of relics represent major differences in redox conditions between relics and host chondrules, and show that there was intimate mixing between different chondrule types. Two scenarios accounting for this are possible: (1) The O fugacity of each chondrule is defined by the intrinsic O fugacity of the precursor dustball, and chondrules with a range of O fugacities may form in one region; or (2) chondrules with different O fugacities formed in different regions, but close enough in time and space that there was mixing between these regions. The second model is probably more realistic. The presence of relics derived from chondrules also indicates that there were numerous disruptive collisions among chondrules between chondrule-forming events, and this places constraints on the density of material in the chondrule-forming region [14]. The frequency of recycling estimated from relict grains is consistent with estimates made from studies of compound chondrules and coarse-grained chondrule rims [15].

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COLLISION OF COMETLIKE AND SLIGHTLY DIFFERENTIATED BODIES AS AN ORIGIN FOR ORDINARY CHONDRITES. M. Kitamura¹ and A. Tsuchiyama², ¹Department of Geology and Mineralogy, Kyoto University, Kyoto 606-01, Japan, ²Department of Earth and Space Science, Osaka University, Toyonaka 560, Japan.

The origin of ordinary chondrites has been extensively studied. One of the keys to understanding the origin of chondrites is given by the characteristics of relict minerals in chondrules that survived chondrule formation. Some of the relict minerals show shock deformation textures, such as high dislocation densities in relict olivine [1] and stacking faults in relict pyroxene [2]. These textures suggest that shock deformation was the cause of melting of the chondrules. Shock recovery experiments on chondrite and porous chondritic materials [3] showed that the porosity is essential to the formation of large amounts of shock melt. These experiments showed a close resemblance between the bulk composition of the shock melt and the natural chondrules and also strong similarities in the textures of experimentally shocked aggregates of fine fragments and natural fine-grained aggregates. These results suggest a shock-melting origin for chondrules.

Some of the olivine and pyroxene fragments in the matrix of the chondrites have been shown to have a composition closer to the relict minerals than minerals crystallized during the chondrule formation [4]. This suggests that some of the fragments originated from the precursor materials of the chondrules. The chemical trends of the pyroxene fragments, which include that of the relict pyroxene, can be interpreted to have been formed by crystallization not from a gas but from a liquid, suggesting an igneous origin for some of the precursor materials. The relict minerals commonly have inclusions precipitated during the chondrule formation, suggesting different redox conditions during the formation of the precursor and the chondrule/matrix.

Any proposed origin for chondrites, therefore, has to account for the following observations and conclusions: (1) Relict minerals show shock deformation textures, (2) some of the relict minerals are formed by an igneous process, (3) porous material is required to form significant amounts of shock melt, and (4) different redox conditions existed between the precursor and chondrule/matrix formation processes. In order to explain these features, we proposed the collision of a "cometlike" body [5] with a second body that was slightly differentiated by igneous processes as the mechanism of chondrite formation. This suggestion differs from previous shock origin models [6] in that one of the bodies is cometlike. The cometlike body is assumed to consist of silicates, metal, metal sulfides, and grains of highly volatile elements (ice). The ice can provide large amounts of volatiles, which can change redox conditions, and can be

considered to act as pores in shock deformation. According to the present model, minerals in the matrix must be fragments of the precursors and condensates from vapor generated by the shock event. Redox conditions during the shock events are controlled mainly by the volatilization of ice and will be discussed in another paper [7].

A model calculation based on a mechanism of chondrule formation through condensation of vapor resulting from collisions of planetesimals [8] suggests that grains formed by such a collision will not escape but accrete onto the planetesimal, provided the target planetesimal mass is larger than 10^{24} g. Our proposed collision model is also compatible with the conclusions of this calculation. Furthermore, the undepleted nature of moderately volatile elements in chondrules, such as Na can be explained if the evaporation of these elements occurred in a nearly closed system of a cloud consisting of hot vapor, melt droplets, and dust particles. The latent heat production by recondensation of solid dust is also likely to affect strongly the cooling rates of the vapor-melt-dust cloud.

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MICROCHONDRULES IN ORDINARY CHONDRITES: IMPLICATIONS FOR CHONDRULE FORMATION. A. N. Krot^{1,2} and A. E. Rubin¹, ¹Institute of Geophysics and Planetary Physics, University of California, Los Angeles CA 90024, USA, ²Planetary Geosciences, Department of Geology and Geophysics, School of Ocean and Earth Science and Technology, University of Hawaii at Manoa, Honolulu HI 96822, USA.

The occurrence of numerous microchondrules in several matrix-rich clasts and chondrule rims as described below has important implications for the origin of chondrules. It implies that fine-grained material existed in the immediate vicinity of the microchondrules when they formed and that the chondrule-formation mechanism must have been highly localized.

Chondrules in different chondrite groups have distinct average diameters ranging from ~200 to 1000 μm [1]; in addition to these "normal-sized" chondrules there are macrochondrules ranging up to 5 cm in diameter [2] and microchondrules (arbitrarily defined as chondrules <40 μm in diameter) ranging down to submicrometer sizes [3]. Aerodynamic sorting in the nebula has been invoked to account for the size variations of chondrules in different groups [4–6]. Reported size-frequency distributions of ordinary chondrite (OC) chondrules include very few chondrules with diameters <100 μm [7–10]; such chondrules constitute <0.03 vol% of H and <0.006 vol% of L and LL chondrites [3].

Microchondrules in OC have been reported in two principal settings: (1) as rare individuals in the fine-grained matrices of many type-3 chondrites [3,11] and in the clastic matrix of the Dimmitt H regolith breccia [3]; and (2) as the predominant or exclusive chondrule size in a few unequilibrated clasts in LL3.4 Piancaldoli [3], the Rio Negro L regolith breccia [3], L3.7 Mezö-Madaras [12], and LL3.1 Krymka [13].

The $150 \times 200\text{-}\mu\text{m}$ Krymka clast contains ~ 30 olivine microchondrules (Fa_{22-46}), $3\text{--}31\ \mu\text{m}$ in apparent diameter, embedded in fine-grained matrix material. The 5-mm Rio-Negro clast contains about 30 radial pyroxene (RP) chondrules $5\text{--}74\ \mu\text{m}$ in apparent diameter as well as a few normal-sized chondrules and chondrule fragments embedded in fine-grained silicate matrix. The 1-mm Piancaldoli clast contains ~ 100 RP chondrules ($0.25\text{--}64\ \mu\text{m}$ in apparent diameter) embedded in fine-grained silicate matrix; $\sim 15\%$ of the chondrules are compound. The mean composition of the low-Ca pyroxene grains is $\text{Fs}_{4.0}\text{Wo}_{1.3}$. The $6 \times 8\text{-mm}$ dark clast in Mezö-Madaras contains > 140 chondrules ($2\text{--}150\ \mu\text{m}$ in apparent diameter), lithic fragments, and mineral grains embedded in fine-grained silicate matrix. One microchondrule was also found in a troilite-rich rim around a porphyritic olivine (PO) chondrule in Mezö-Madaras [12].

We report here another major setting for microchondrules, one that sheds new light on their origin and has important implications for the general problem of chondrule formation. We have found that several fine-grained rims of matrixlike material around normal-sized porphyritic chondrules contain numerous microchondrules with apparent diameters of $< 20\ \mu\text{m}$.

A dumbbell-shaped $850 \times 1500\text{-}\mu\text{m}$ type I PO chondrule in L3.4 EET90161 is surrounded by a $50\text{--}80\text{-}\mu\text{m}$ -thick fine-grained rim containing a high abundance (> 100) of microchondrules. The microchondrules are homogeneously distributed in the rim and vary in diameter from $2\text{--}20\ \mu\text{m}$; they have similar textures and compositions.

A $500\text{-}\mu\text{m}$ -diameter porphyritic olivine-pyroxene (POP) chondrule in L3.4 EET90261 is surrounded by a $50\text{--}70\text{-}\mu\text{m}$ -thick fine-grained rim containing $\sim 30\text{--}50$ microchondrules, $2\text{--}10\ \mu\text{m}$ in apparent diameter. The microchondrules have similar textures and compositions.

A $1250 \times 1850\text{-}\mu\text{m}$ chondrule in LL3.1 Bishunpur is a compound object consisting of a PO primary and two POP secondary adhesions. The whole compound chondrule is surrounded by a $100\text{--}150\text{-}\mu\text{m}$ -thick fine-grained rim containing a high abundance (> 100) of homogeneously distributed microchondrules. The microchondrules vary in apparent diameter from $2\ \mu\text{m}$ to $50\ \mu\text{m}$ and have similar textures and compositions.

The occurrence of discrete clasts and chondrule rims consisting of abundant microchondrules of similar textures and compositions within fine-grained matrix material indicates that each set of microchondrules formed as a “cloud” of microdroplets during a single chondrule-forming event; they are analogous to normal-sized “sibling” compound chondrules [14]. The occurrence of compound microchondrules also indicates that they formed at high number densities as independent free-floating objects. The microchondrules either formed by simultaneous melting of dust concentrations within a large dustball or by disruption of a normal-sized chondrule droplet. These observations lead to two principal conclusions:

1. Because a microchondrule “cloud” would dissipate quickly due to random motions, it seems inescapable that the fine-grained

material that now composes the matrixlike clasts and rims was in the immediate vicinity of the microchondrules when they formed. This same material may even have been the immediate precursor of the microchondrules. If the matrix-rich clumps in which the microchondrules are entrained were the same precursors from which they formed, the present ferroan compositions of the clumps (e.g., $34\ \text{wt}\%$ FeO in the matrix of the Piancaldoli clast [3]) relative to the microchondrules (e.g., $2.7\ \text{wt}\%$ FeO in Piancaldoli) implies that matrix material became increasingly oxidized with time.

2. The survival of dusty material during chondrule formation, as indicated by the coexistence of microchondrules and fine-grained matrix material, suggests that chondrule formation in general occurs in small (centimeter-sized) regions. Highly localized heat sources such as lightning seem particularly suitable melting mechanisms.

The very small weight fraction of microchondrules in OC could have resulted from a formational process, which preferentially destroyed microchondrules by efficient recycling into larger chondrules or by nebular size-sorting subsequent to chondrule formation [15]. Collisionally induced collapse of the microchondrule-bearing dust clumps may have led to the formation of the chondrule rims and clasts.

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THE JET MODEL OF CHONDRULE FORMATION. K. Liffman^{1,2}, ¹CSIRO/DBCE, P.O. Box 56, Highett, Victoria 3190, Australia, ²Astrophysics Group, School of Physics, University of Melbourne, Parkville, Victoria 3052, Australia.

We estimate the size range of particles that are ejected from a protostellar accretion disk by a protostellar jet. An n-body code is used to determine the subsequent motion of the ejected particles, where the particles are subject to two forces: the gravitational attraction from the protostar, and the gas drag from the halo gas of the accretion disk.

It is highly probable that a protosolar jet existed at the very beginning of the solar system. Such a jet may have influenced the chemical structure of the solar nebula by recycling heated material back into the nebula. Protostellar jets eject a considerable amount of mass ($10^{-3}\text{--}10^{-1}\ M_{\odot}$) over a long lifetime ($10^6\text{--}10^7\ \text{yr}$) [1,2]. A protosolar jet, if it existed, could have ejected $10^{-5}\text{--}10^{-3}\ M_{\odot}$ of “rocky” material (i.e., all elements excluding H and He) from the solar nebula. If only 10% of this material were to fall back to the solar nebula then we would have $10^{-6}\text{--}10^{-4}\ M_{\odot}$ of rocky (possibly

refractory) material being contributed to the solar nebula over a 10^6 – 10^7 -yr period. Given that the “rock” mass of the planets is of order $10^{-4} M_{\odot}$, a protosolar jet may have made a significant contribution to the chemical structure of the solar nebula. Indeed, it is possible that ejecta from the jet flow may have been incorporated into the best preserved samples of the solar nebula: the chondritic meteorites.

Protostellar jets appear to be formed from the innermost regions (≤ 0.1 AU) of protostellar accretion disks. At such close proximity to the protostar, one would expect any nongaseous disk material to be in a molten or semimolten state. We have undertaken an analytic analysis of the expected droplet size that can be ejected by the jet flow and find that the droplet radius is ≤ 1 cm. The gas densities and speeds required to eject such large objects from the close environs of a protostar have been shown (in previous studies) to be well within theoretically expected and observationally confirmed ranges [1–3]. The subsequent motion of these objects, once they are decoupled from the jet flow, is shown to be a linear path across the face of the accretion disk.

If these ejected particles pass through a sufficiently large section of the accretion disk's upper atmosphere, then their speed will become smaller than the escape velocity, and the particles will settle back to the accretion disk (see Fig. 1). It is shown that the denser and larger a particle is, the further it can travel through the gas halo of an accretion disk, thereby producing density-dependent size sorting of particles. Since chondrules have sizes (≤ 1 cm) that are inversely proportional to their density, it is suggested that chondrules are ablation droplets produced by a protostellar jet.

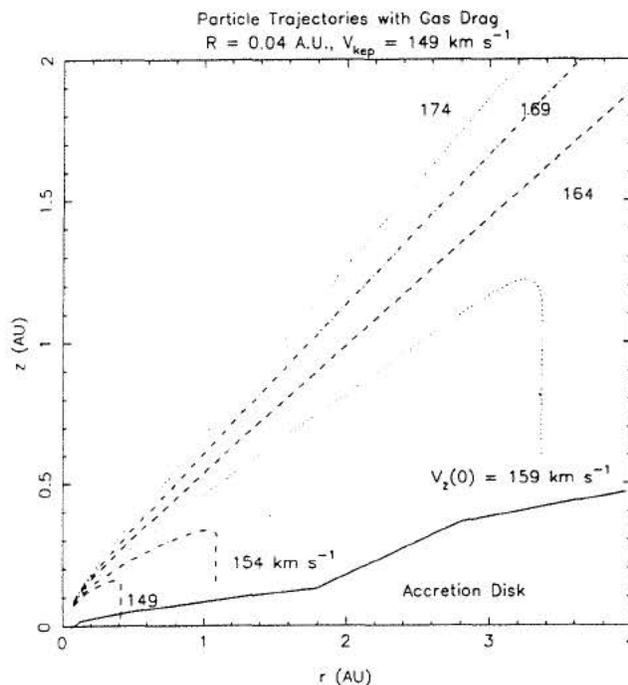


Fig. 1. A solar-mass protostar is located at $r = 0$, $z = 0$. Surrounding the protostar is an accretion disk, the scale height of which is shown in profile. Particles are initially in a circular Keplerian orbit of radius $R = 0.04$ AU. The particles are then given a vertical “boost” velocity, the magnitude of which (in units of km s^{-1}) is shown next to the particles’ trajectories. Particles that are subjected to sufficiently high gas drag are later recaptured by the accretion disk.

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EXPERIMENTAL CONSTRAINTS ON MODELS FOR THE ORIGIN OF CHONDRULES: COOLING RATES. G. E. Lofgren, NASA Johnson Space Center, Houston TX 77058, USA.

There has long been a fascination with chondrules, and one of the first questions is how fast do they cool, or how long was the chondrule-forming event? Stefan-Boltzman calculations for 2-mm molten droplet chondrules suggest they would cool in a few seconds [1]. But most chondrules are porphyritic and such textures require longer to crystallize. Porphyritic textures in fact suggest slow rates, but how slow?

In one of the earliest systematic, dynamic crystallization studies of cooling rate, Tsuchiyama et al. [1] reproduced porphyritic, barred, and radial olivine textures from three different melt compositions. They found the cooling rates to be in the range 3000° – 7200°C/hr , although the best olivine porphyritic textures developed at 1200°C/hr . They attributed the varying textures to compositional differences, with the textures becoming finer grained as silica content increases. Hewins et al. [2] studied a pyroxene-rich chondrule composition and found that cooling from a total melt produced radial pyroxene textures at cooling rates of 50° – 3000°C/hr . Planner and Keil [3] produced microporphyritic chondrules with cooling histories that contained a temperature plateau, which they found necessary to get the more Fa-rich olivine compositions observed in porphyritic chondrules. Lofgren and Russell [4] applied knowledge gained in the study of the nucleation characteristics of terrestrial basalts [5] to a dynamic crystallization study of pyroxene-rich (and later olivine-rich) chondrule melts [6]. While it was clear that porphyritic chondrule textures could be produced at very slow cooling rates ($< 5^{\circ}\text{C/hr}$), it would be more compatible with current models if they could be produced at faster rates. These latter studies combined with [7,8] systematically showed that with nuclei present in the melt, cooling rates up to 1000°C/hr and even higher would still produce porphyritic textures. Barred olivine and pyroxene and radial textures could be produced from an even larger range of cooling rates, 5° – 3000°C/hr .

The Lofgren studies [4–7] help to explain the observation of [1] that the primary variable in producing texture was the composition of the melt. In fact, the primary variable is heterogeneous nucleation. Tsuchiyama et al. [1] used three compositions with increasing silica content ranging from olivine-rich to pyroxene-rich chondrule melts. With increasing silica, the liquidus temperature decreases. They used a constant melting temperature of 1600°C . Their most olivine rich was not totally melted so that nuclei remained in the melt at that temperature and upon cooling a porphyritic texture resulted. The other two compositions were totally melted at 1600°C and nucleation did not occur until significant supercooling had developed and barred and radial textures resulted. The pyroxene-rich composition was superheated so much at 1600°C that only olivine, not pyroxene, nucleated upon cooling, resulting in the radial olivine texture. Hewins et al. [2] were able to get radial pyroxene from a melt of similar composition because they melted their starting material just above the liquidus and pyroxene was able to

nucleate upon cooling. We now understand that the full range of porphyritic to radial textures can be produced in all compositions primarily as a function of the nucleation condition, which is controlled primarily by the melting temperature. The relationship between texture and melt composition, melting temperature, and presence of nuclei remains an important one as summarized by [9]. We also know that if nuclei are present at the initiation of cooling, porphyritic texture can be produced at much faster cooling rates, and that in some compositions can only be produced if nuclei are present. These studies [4–8] in fact provided the framework in which a systematic study of cooling rates could proceed. As a result of our current understanding, the table of cooling rates for given textures presented in [10] is oversimplified, and we know that a given texture can be produced at an even larger range of cooling rates depending primarily on the degree of superheat or subliquidus melting.

How well can the cooling rate be constrained? Not as well as we would like. The finer-grained, radial pyroxene textures are not at all well constrained and can form from 5° to 3000°C/hr. The barred olivine textures are a little more restricted to 500°–2500°C/hr. Porphyritic olivine textures have the most constrained cooling rates because both crystal shape and zoning profiles can be used. Radomsky and Hewins [8] found that the olivine shape was matched best at 100°C/hr, while the zoning patterns matched best at 1000°C/hr. Jones and Lofgren [11] found that both the crystal shape and chemical zoning profiles matched best at 100°C/hr using the experiments of [6] and comparing them with chondrules in Semarkona. These experimentally determined cooling rates are not nearly as fast as those suggested by black-body radiation calculations. The obvious requirement is a locally denser nebula [12] so that mutual radiation of closely spaced particles slows the overall cooling rate in a chondrule forming event.

Why is it difficult to define the cooling rates more closely? The degree of superheat controls the temperature of nucleation and thus the crystal shape more effectively than the cooling rate. For the nonporphyritic textures, chemical zoning is very limited in these very-fine-grained textures and is not very diagnostic of cooling rate. For the porphyritic olivine chondrules that grow from melts with nuclei present there is still a large range of cooling rates from very slow up to 1000°C/hr. It is the chemical zoning profiles that allow us to more accurately determine the cooling rate. The zoning profile is a direct result of the growth rate of the crystal, which is in turn controlled by the cooling rate.

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IMPLICATIONS OF A PHASE-TRANSITION THERMOSTAT FOR CHONDRULE MELTING. S. G. Love, Hawaii Institute of Geophysics and Planetology, School of Ocean and Earth Science and Technology, University of Hawaii at Manoa, 2525 Correa Road, Honolulu HI 96822, USA.

It is widely accepted that chondrules were formed in brief, localized nebular heating episodes. Given the apparent (at least local) high efficiency of chondrule formation [1,2], these thermal events seem to have occurred at a large number of different times and/or azimuthal locations in the solar nebula. It is reasonable to expect that the chondrule-forming events, whatever their underlying cause, were not all identical, but instead occurred with some spread of heating intensities. If this was so, it is puzzling that compositional and textural evidence points to most chondrules having been heated to a very narrow range of peak temperatures: certainly within 1400°–1750°C, and in most cases within 1500°–1550°C [2,3].

A possible explanation for this restricted range of peak temperatures is the chondrules' own heat of fusion (approximately 400 J/g), which acts as a heat sink at melting temperatures. In this picture, chondrule melting acted as its own thermostat, converting a wide spread of thermal energy inputs into a narrow range of peak temperatures. If we assume an initial nebula temperature of less than 400°C [2,4], a peak chondrule temperature of 1500°C, and a heat capacity of ~0.8 J/g-K [5], we find ~900 J/g is necessary to heat the chondrule precursors to melting, and that energy inputs of 900–1300 J/g—a range of reasonable width, which widens further if the heat capacity between the solidus and liquidus is taken into account—will produce the observed majority of incompletely melted chondrules. This idea has different implications for the chondrule formation process, depending on the degree of thermal equilibrium between the chondrules and the surrounding nebula.

Good thermal contact between chondrules and the surrounding gas is suggested in two ways. First, chondrule cooling times inferred from their textures include values much longer than the <1-s cooling time of an isolated chondrule [6,2]; these long timescales imply good thermal contact with the local gas. Second, many proposed chondrule-heating mechanisms (especially those relying on conductive or convective heat transfer) operate with comparable effectiveness on both the solids and the gas. Hydrogen gas, the primary constituent of the nebula, has a heat capacity of ~14 J/g-K; the energy necessary to heat it from 400° to 1500°C is 15,000 J/g, overwhelming compared to the 400-J/g-wide “window” that allows an equal mass of chondrules to be partly melted. For chondrule melting to operate effectively as a thermostat for the chondrules and gas alike under variable heating conditions, the mass of chondrules in a given volume of the nebula must be at least ~10²× that of the H. For a 300-K, 10⁻⁵-atm nebula, this corresponds to at least one millimeter-sized chondrule per cubic meter. This limit is consistent with estimates of the space density of chondrules based on studies of collisional features [4,7], and represents a midplane solid-to-gas enhancement of at least 10⁴ over the “solar” value.

Alternatively, the chondrules may have had poor thermal contact with the gas. This is the case if the evidence for slow cooling (which remains in dispute) is disregarded in favor of a more rapid mechanism, wherein the chondrules are processed too quickly to achieve thermal coupling with the gas. A similar case occurs if an optically thick assemblage of chondrules is heated while the gas remains cool:

Because a chondrule's "sky" would be filled with its hot siblings, it would have to reject its heat via slower, nonradiative processes, which demand a temperature difference between the particles and gas. In these scenarios, the thermal behavior of the chondrules may not be controlled by their surroundings, and nothing can be inferred about the ratio of chondrules to H. To avoid invoking the arguments of the preceding paragraph, however, the heating process must not efficiently deposit energy into the gas in the first place.

In summary, it seems reasonable to guess that the latent heat of fusion of chondrules may have played a part in restricting their peak temperatures to a narrow range. If there was good thermal contact between the chondrules and the surrounding nebula, this idea implies that the mass ratio of chondrules to gas was at least 100:1, consistent with other estimates [7]. This density limit may have further implications for the nebular solid fraction's velocity dispersion, scale height, and prospects for collisional and gravitational coagulation. If, on the other hand, the chondrule formation mechanism operated only on the chondrules themselves, the phase-transition thermostat idea permits no inferences about the solid-to-gas ratio. Nonetheless, requiring thermal isolation between the solids and the gas places constraints on the character of the chondrule heating mechanism.

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FORMATION OF CHONDRULES BY ELECTRICAL DISCHARGE HEATING. S. G. Love, K. Keil, and E. R. D. Scott, Hawaii Institute of Geophysics and Planetology, School of Ocean and Earth Science and Technology, University of Hawaii at Manoa, 2525 Correa Road, Honolulu HI 96822, USA.

A possible mechanism for making chondrules in the solar nebula is electrical discharge ("lightning") heating [1–3], which can create high-temperature (>1600 K), short-duration (~10 s) thermal events as indicated by the chondritic record. Lightning occurs in many diverse terrestrial and planetary settings [4], and may have occurred in the solar nebula; it is thus worthwhile to investigate its implications for chondrule formation.

The character of an electrical discharge depends on its environment. We treat nebula gas pressures between 10^{-7} and 10^{-3} bar, with 10^{-5} bar as a "benchmark" value [5,6]. Gas temperature is chosen as 300 K. Dust:gas mass ratios are 0.01 (the "solar" value) to 10 (a 1000-fold midplane concentration), with 1.0 as a benchmark. We presume 10 m/s turbulent velocities, and two phases of 2 g/cm^3 dust, present in equal masses: 1-mm chondrule precursor particles, and $1\text{-}\mu\text{m}$ prematrix grains. These quantities yield particle-stopping distances and collisional mean free paths. Accumulation of opposite charges on different-sized particles is assumed to occur via a well-

documented [7] thunderstorm electrification mechanism. Neglecting the effect of different materials, we find a (highly uncertain) preferential transfer of ~ 1 electron per chondrule/matrix grain collision.

We imagine a "gust front" of gas intruding into a well-mixed region of gas and particles. The front quickly accumulates a growing number of small grains with one charge polarity, leaving behind a volume filled with oppositely charged larger particles (Fig. 1). The potential difference between the two charges is equated to the gas breakdown voltage, which depends on the charge separation (d , in cm) and the gas pressure (p , in torr): V (volts) $\approx 25.6 \text{ pd} + 1860$ [8]. Solving yields the discharge gap and voltage ($\sim 2000 \text{ m}$ and 40 kV for the benchmark conditions). At the low pressure of the solar nebula, the discharge will probably resemble a diffuse aurora rather than lightning [9], posing a serious problem for chondrule formation.

The breakdown funnels charge from a region of the gust front with a radius comparable to the discharge gap. The energy released is $\sim 100 \text{ J}$ in the benchmark case. We cautiously assume a discharge channel radius of one molecular collision mean free path. It cannot be less than this distance, and is very likely to be greater (with a corresponding decrease of heat flux onto particles therein). Under the benchmark conditions, a 1-mm particle (with its ion collision cross section increased by charging [3]) in the channel can intercept at most $\sim 1 \text{ J}$, barely sufficient for melting. Results for different conditions are illustrated in Fig. 2. A $1\text{-}\mu\text{m}$ matrix grain in the bolt can be vaporized, possibly explaining the suggested enhanced O fugacity at chondrule formation [10,11], as well as the rarity of micrometer-sized chondrules. Unfortunately, the dust:gas ratios required to significantly increase the O fugacity produce discharges too weak to melt chondrules. Also, this argument predicts a dependence of heating intensity on chondrule size, which has not been found [12].

Two important difficulties arise with the 10–100-s discharge duration for the benchmark nebula [3]. First, a particle in the

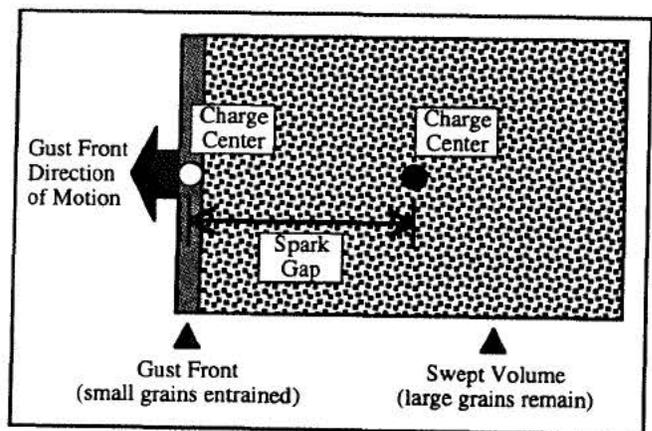


Fig. 1. Assumed electrification geometry.

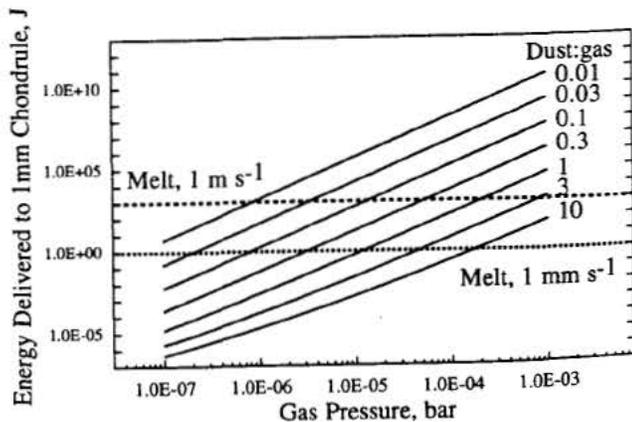


Fig. 2. Maximum energy delivered to a 1-mm chondrule precursor by an electrical discharge under different nebula conditions.

discharge must not reject the energy incident upon it, or the losses (especially radiative) will hold its temperature below melting. Second, a particle must not move faster than ~ 1 mm/s, or it will escape without melting before the discharge ends. Random drift speeds in the nebula were $\sim 10^3 \times$ higher [2,6]. Relaxing the lower-limit estimate of the bolt diameter worsens the problem. Only in the region indicated in the upper portion of Fig. 2 can a chondrule precursor moving at 1 m/s be melted.

Terrestrial lightning completely ionizes its path. We find that, under a wide range of conditions, including the benchmark nebula, a nebular discharge does not release enough energy to ionize its channel. This fact, coupled with the probable diffuse nature of nebular discharges, indicates that they were not analogous to terrestrial lightning.

In summary, we find that nebular discharges do not appear to be a viable source of heat for melting chondrule precursors, regardless of the uncertainty in the details of the model. Nonetheless, we believe nebular lightning worthy of further investigation. Experiments analogous to those currently underway to investigate terrestrial thunderstorm lightning could be fruitful in refining nebular lightning models, and would be doubly interesting in application to nonthunderstorm and planetary lightnings.

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CHRONOLOGY OF CHONDRULE AND CAI FORMATION—Mg-Al ISOTOPIC EVIDENCE. G. J. MacPherson¹ and A. M. Davis², ¹Department of Mineral Sciences, National Museum of Natural History, Smithsonian Institution, Washington DC 20560, USA, ²Enrico Fermi Institute, University of Chicago, Chicago IL 60637.

Details of the timing of chondrule and Ca-Al-rich inclusion (CAI) formation during the earliest history of the solar system are imperfectly known. Because CAIs are more “refractory” than ferromagnesian chondrules and have the lowest recorded initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of any solar system materials, the expectation is that CAIs formed earlier than chondrules. But it is not known, for example, if CAI formation had stopped by the time chondrule formation began. Conventional (absolute) age-dating techniques cannot adequately resolve small age differences ($<10^6$ yr) between objects of such antiquity. One approach has been to look at systematic differences in the daughter products of short-lived radionuclides such as ^{26}Al and ^{129}I .

Unfortunately, neither system appears to be “well-behaved.” One possible reason for this circumstance is that later secondary events have partially reset the isotopic systems, but a viable alternative continues to be large-scale (nebular) heterogeneity in initial isotopic abundances, which would of course render the systems nearly useless as chronometers. In the past two years the nature of this problem has been redefined somewhat. Examination of the Al-Mg isotopic database for all CAIs [1] suggests that the vast majority of inclusions originally had the same initial $^{26}\text{Al}/^{27}\text{Al}$ abundance ratio, and that the ill-behaved isotopic systematics now observed are the results of later partial reequilibration due to thermal processing. Isotopic heterogeneities did exist in the nebula, as demonstrated by the existence of so-called FUN inclusions in CV3 chondrites and isotopically anomalous hibonite grains in CM2 chondrites, which had little or no live ^{26}Al at the time of their formation. But, among the population of CV3 inclusions at least, FUN inclusions appear to have been a relatively minor nebular component.

Evolution Lifetimes of CAIs: The idea that CAIs are simple aggregates of pristine nebular condensates is now recognized to be incorrect for most of these objects. Many have been partially melted from solid precursors [2]. Recent correlated petrologic and Al-Mg isotopic studies of numerous individual inclusions indicate that many CAIs experienced protracted nebular histories, including multiple melting events and possibly multiple alteration events as well, extending over periods as long as several million years [3–5]. Magnesium-aluminum isotopic data are also consistent with an evolutionary scheme [6] that leads from type A inclusions (very refractory; relatively little isotopic disturbance), through type B inclusions (abundant evidence for excess ^{26}Mg , but commonly disturbed and with protracted evolutionary histories), to type C inclusions (little evidence for excess ^{26}Mg).

Relative Chronology of CAIs and Chondrules: In contrast to CAIs, very little evidence for extinct ^{26}Al has been found in primary plagioclase-bearing chondrules [7–11]. If CAIs are representative of most nebular Al at the time of solar system formation, then plagioclase-rich chondrules began forming later than the CAIs or else were much more thoroughly reprocessed at a later time. If CAIs are not representative (i.e., the nebula was isotopically heterogeneous), however, no such chronologic interpretation can be made. Unfortunately, statistical arguments are difficult because

there are far fewer isotopic data from objects other than CAIs. Also, much of the CAI data comes from just two meteorites, Allende and Murchison, whereas data for Al-rich chondrules comes from a variety of carbonaceous and ordinary chondrites. The real test is whether CAI and chondrules from the same meteorite show consistent differences. If, in every case for a variety of meteorites of different types, it can be shown that CAIs have different Mg-Al isotopic compositions than their physically associated chondrules, the chronologic interpretation for those differences becomes compelling. The alternative (heterogeneity) hypothesis would otherwise require that each chondrite systematically drew its chondrules and CAIs from different isotopic (nebular) sources, which seems unreasonable. At the moment this test can be applied only to Allende, because comparable data do not exist for any other meteorite, but the Allende isotopic data are in fact suggestive. Normal (melilite- and/or hibonite-rich) refractory inclusions in Allende show excesses of ^{26}Mg consistent with initial $^{26}\text{Al}/^{27}\text{Al} \sim 5 \times 10^{-5}$, whereas less refractory Allende material such as plagioclase-bearing chondrules, forsterite-bearing inclusions, and type C ("igneous textured") inclusions all show much lower or no ^{26}Mg excesses [8,12,13]. It seems very unlikely that primary nebular heterogeneity can explain this pattern, because of the requirement that different types of materials be selected exclusively from isotopically distinct and separate portions of the nebula, then transported to a common part of the nebula where they were assembled into a single body, the Allende parent body. It remains to be shown if this pattern holds true for other chondrites as well, including ordinary and enstatite chondrites.

Taken together, the available data are consistent with CAIs initially being formed at least 2–3 m.y. prior to the onset of chondrule formation, but the latter may have overlapped in time with the ongoing remelting and alteration of CAIs. Such implied long nebular lifetimes may not be inconsistent with current astrophysical models [14].

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CONSTRAINTS ON CHONDRULE AGGLOMERATION FROM FINE-GRAINED CHONDRULE RIMS. K. Metzler¹ and A. Bischoff², ¹Institut für Mineralogie und Petrographie, Museum für Naturkunde der Humboldt-Universität, Invalidenstrasse 43, 10115 Berlin, Germany, ²Institut für Planetologie, Universität Münster, Wilhelm-Klemm-Strasse 10, 48149 Münster, Germany.

Fine-grained rims around chondrules, Ca,Al-rich inclusions, and other coarse-grained components occur in most types of unequilibrated chondrites, most prominently in carbonaceous chondrites of the CM group [1]. Examples of these structures from the CM chondrite Cold Bokkeveld are shown in Fig. 1. Based on

mineralogical and petrographic investigations, Allen et al. [2] suggested that rim structures in unequilibrated ordinary chondrites could have formed in the solar nebula by accretion of dust on the surfaces of chondrules. Since then, there is a growing acceptance that these structures may represent the result of chondrule/dust interactions in the solar nebula [1,3–11]. Based on the results of the investigation of 14 CM chondrites, the fine-grained rims in CM chondrites have been assigned as "accretionary dust mantles" due to the wealth of arguments for a solar nebula origin and against their origin in a planetary regolith [1]. The main characteristics of CM dust mantles are (1) they are characterized by sedimentary textures, frequently consisting of two or more concentric dust layers of different composition; (2) the grain size of the serpentine- and tochilinite-rich groundmass is in the micrometer range, embedding mineral fragments up to 50 μm ; (3) their outer shape is always very smooth and rounded, in contrast to the angular and irregular shape of the mantled cores (Fig. 1); (4) the contacts between dust mantles and mantled constituents are very sharp; (5) they occur around all types of coarse-grained chondritic components like chondrules, Ca,Al-rich inclusions, PCP-rich objects, mineral fragments, etc.; (6) there is no mineralogical and major-element correlation between the dust mantles and their cores; (7) they are free of solar-wind-implanted noble gases [12,13]; (8) they occur exclusively around components that were never exposed to solar particle irradiation [14]; and (9) there is a distinct positive correlation between the thickness of dust mantles and the diameters of the corresponding cores [1,15], with an average thickness of dust mantles that reaches roughly 19% of the core diameters.

We found the CM chondrite Yamato 791198 to be a key sample in the interpretation of dust mantle structures, since this meteorite is unbrecciated on a centimeter scale and consists nearly exclusively of dust-mantled constituents with only negligible interstitial material [1]. It appears to be a "cosmic sediment" that has preserved its accretionary texture. We interpret this meteorite as a mechanically unaltered sample of the first rock generation of the CM parent body, formed by the agglomeration of dust-mantled components. Relics of

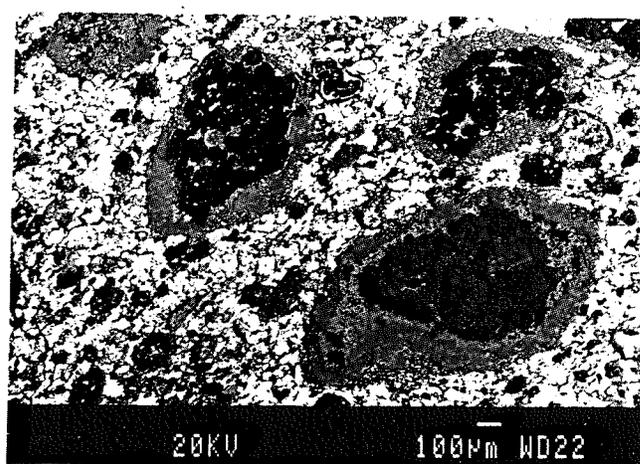


Fig. 1. Relic of accretionary rock in Cold Bokkeveld (CM). This rock type, which can be found in many other CM chondrites, appears to be a "cosmic sediment" consisting nearly exclusively of dust-mantled chondrules and other dust-mantled coarse-grained components.

this "primary accretionary rock" [1] with textures similar to that of Yamato 791198 were found in most other investigated CM chondrites (e.g., Fig. 1), although these meteorites are brecciated to various degrees. Noble gas measurements [see 1] and nuclear track studies [14] revealed that the accretionary rock does not contain solar-wind-implanted noble gases or preirradiated grains. This implies that this rock and its dust-mantled components formed in a nebular region that was shielded from solar and galactic particle radiation. It clearly points against a dust mantle formation in a parent body regolith.

Conclusions: Dust mantles in CM chondrites seem to have formed by accretion of dust on the surfaces of chondrules and other components during their passage through dust-rich regions in the solar nebula. In our view, concentric mantles with compositionally different layers prove the existence of various distinct dust reservoirs in the vicinity of the accreting parent body. Despite mineralogical and chemical differences, fine-grained rims from other chondrite groups principally show striking similarities to dust mantle textures in CM chondrite. This implies that the formation of dust mantles was a cosmically significant event like the chondrule formation itself. As already pointed out by [3], the formation of "fuzzy" balls may have had the effect of promoting the accretion process by increasing the sticking probability between colliding chondrules and dust grains. Dust mantles seem to have formed chronologically between chondrule-producing transient heating events and the agglomeration of chondritic parent bodies. For this reason the investigation of dust mantle structures may help to answer the question of how a dusty solar nebula was transformed into a planetary system.

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THE ORIGIN OF REFRACTORY PRECURSOR COMPONENTS OF CHONDRULES. K. Misawa and N. Nakamura, Kobe University, Kobe 657, Japan.

A percentage of all chondrules from carbonaceous (C) chondrites are intermediate in major-element composition between the rare Ca,Al-rich chondrules [1] and the more abundant ferromagnesian chondrules [2]. Some of them possess fractionated REE and trace-element patterns [3–7] similar to those in CAIs. The abundance patterns are controlled primarily by volatilities expected from a solar composition. On the basis of refractory lithophile fractionations, it is suggested that one of the refractory precursors of C chondrules is a condensate from the nebular gas or an evaporative

residue of primitive dust clumps [5,6].

Several chondrules in C chondrites have a modified group IIREE pattern (CI-normalized La/Sm < 1) with positive Ce and Eu anomalies (Fig. 1), suggesting that their refractory precursors could have formed by the condensation of residual gas after removal of the ultrarefractory component at a relatively low temperature. Similar REE patterns were reported on Murchison, Leoville, Vigarano, Mokoia, and Allan Hills 85085 CAIs [8–12]. Two barred-olivine chondrules from Allende exhibit an enrichment of HREE relative to LREE with the depletion of both Eu and Yb (Fig. 2), which has not been identified in Allende CAIs. This ultrarefractory pattern with fractionated HREE (CI-normalized Gd/Lu ~ 2) may represent a condensate of the most refractory elements at a very early, high-temperature stage. These chemical features suggest that high-temperature processing must have occurred at least once before chondrule formational melting, and that the formation of some high-temperature objects (i.e., CAIs) preceded that of chondrules.

Isotopically fractionated Mg [13] and Ti isotope anomalies [14] were found in refractory-element-rich C chondrules. In addition, on the three-isotope graph, chondrules from C chondrites follow ^{16}O mixing line similar to CAIs [15]. These observations suggest that heterogeneities of isotopes were more common in the precursor dust clumps of C chondrules, and that carrier phases of these isotopic signatures could be primary high-temperature objects (i.e., CAIs). The direct evidence of refractory precursor phases has been found in a ferromagnesian chondrule from Allende [16]. The chondrule preserves a relict fragment of CAIs containing spinel, fassaite, and refractory Pt-group metal nuggets. Although its isotopic signature is unknown, the relict CAI is a possible candidate of a ^{16}O -rich end member of the O-mixing trend.

Chondrules in unequilibrated ordinary (O) and enstatite (E) chondrites rarely exhibit fractionated REE patterns [17,18]. Furthermore, O and E chondrites contain far fewer CAIs and Ca,Al-rich chondrules, implying that high-temperature fractionation did not occur effectively in the nebular locations where O and E chondrites were formed, and that precursor dust clumps of O and E chondrules contained low mass fractions of the high-temperature components.

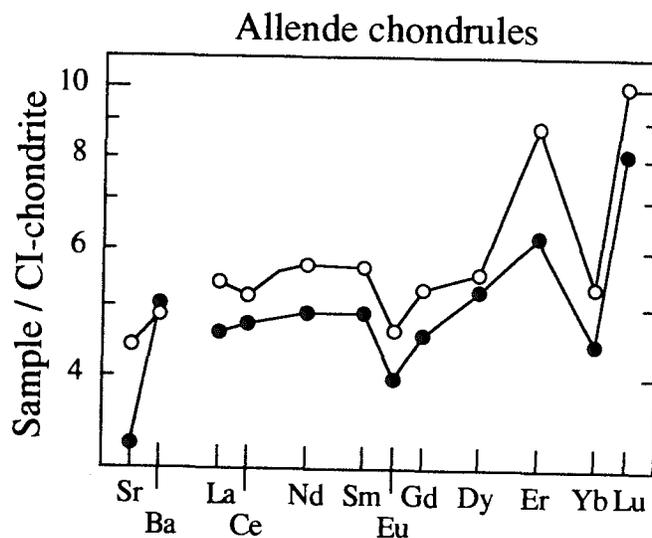


Fig. 1.

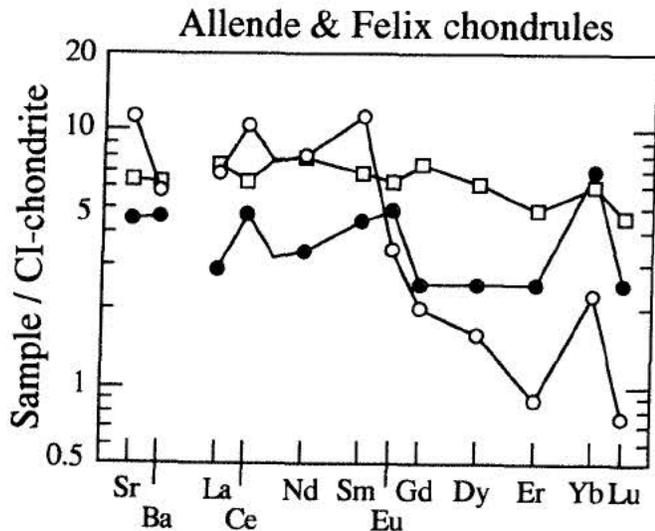


Fig. 2.

Chondrules could have formed by remelting of isotopically and chemically heterogeneous dustballs during flash heating event(s) in different redox nebular conditions. At least some refractory precursor materials may have been coarse-grained, since relict forsterite grains, which have blue cathodoluminescence and contain refractory elements, are more than 100 μm in size [19]. It is not in conflict with the observation that the relict CAI mentioned above is also coarse-grained (>300 μm in size).

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CONSTRAINTS ON CHONDRULE AND CAI ORIGINS FROM VAPOR-LIQUID-SOLID EXPERIMENTS. H. Nagahara, Geological Institute, University of Tokyo, Hongo, Tokyo 113, Japan.

It has been widely accepted that evaporation played an important role in the formation of chondritic constituents and elemental and isotopic fractionation in the solar nebula. Although many workers consider that evaporation is just the opposite of condensation, it is true only when the process is in equilibrium. When the process is not

in equilibrium, e.g., local evaporation, where generated gas moves away from the residual solids, the fractionation path is quite different from the opposite of condensation of the gas with the solar system elemental abundances. The degree of elemental, particularly isotopic, fractionation is strongly dependent on the evaporation rate of the element when evaporation takes place from solid materials. The phase relations and the rate of evaporation of chondrite-forming minerals give constraints on partial pressure of the dust components, total pressure of the nebular gas, and heating rate of the materials.

Partial Pressure of the Dust Components in an Equilibrium Process: Chondrules and probably some CAIs were formed through complete to incomplete melting of preexisting materials. If the process took place in equilibrium with the solar nebula gas, the temperature-pressure conditions were in the stability field of liquid of the bulk composition of each chondrule or CAI. The stability field of chondritic melt has not yet been studied. The phase relation of the olivine systems has been studied in detail [1], where the triple points of forsterite and fayalite are located at 1890°C, 5.2×10^{-5} bar and 1217°C, 6.3×10^{-8} bar, respectively. The minimum pressure required for formation of intermediate olivine melt is between these two values. Since the olivine in chondrule precursors is thought to be Fo > 50, the minimum pressure may be 1×10^{-6} bar. The triple point pressure of enstatite is about 5×10^{-5} bar [2], and that of SiO₂ is between those of enstatite and forsterite. It is worth noting that the triple points of forsterite, enstatite, SiO₂, and fayalite are roughly along a line. Although the triple point of plagioclase has not been experimentally determined, we can roughly estimate it to be 1×10^{-6} bar for anorthite and 1×10^{-8} bar for albite if the triple point of plagioclase is also along the line. Therefore, the triple points of chondrule melts, which are mixtures of olivine, pyroxene, and plagioclase (or rarely SiO₂) components, are estimated to be around 10^{-6} bar partial pressure of silicate components.

The relative abundance of the dust components to H, which roughly corresponds to the (Mg + Si)/H ratio of the solar system elemental abundance, is 2×10^{-6} at the maximum. In order to achieve 10^{-6} bar of the dust component in the nebula requires enrichment of dust components by 4 orders of magnitude when the total pressure is 10^{-4} bar.

Residence Time of Dusts in the Nebular Gas: Nagahara et al. [3,4] showed that the evaporation rate of silicates is strongly dependent on the H pressure. Nagahara and Ozawa [4] determined the vaporization rate of forsterite in a wide range of H pressure and showed that the dependence of forsterite evaporation rate on P_{H_2} is $J_{\text{total}} = J_{\text{evap}} + J_{\text{react}} = 8 \times 10^{-7} + 0.27 P_{\text{H}_2}$. A plausible rate-controlling reaction is thought to be breakdown of a forsterite molecule reacted with a H molecule on the surface of forsterite. The vaporization rate of forsterite in various H pressures is applied to estimate the limit of residence time of forsterite dust with radius of 0.1 μm –1 cm in the solar nebula. Within the plausible range of H pressure of the solar nebula, forsterite vaporizes very quickly. Even a grain with 1-mm radius completely vaporizes in a few days at 1700°C. If the activation energy of the reaction is similar to that of forsterite evaporation in vacuum determined by Hashimoto [5], the grain completely vaporizes in a month at 1600°C. Because the rate experimentally obtained was for continuous evacuation, the estimated vaporization time gives the lower limit of the lifetime of dusts in the solar nebula. In a more plausible model, partial pressure of the forsterite components would increase with the progress of evapora-

tion, which suppresses evaporation, and other O-bearing gas species would also suppress the evaporation, resulting in a longer lifetime of dusts.

Evaporation vs. Isotopic Fractionation: Nagahara et al. [3] showed that O in solid SiO_2 was fractionated by several permil at the evaporation degree of 80% in vacuum but that it was not in H gas. Absence of O isotopic fractionation in H gas is due to rapid vaporization compared to that in vacuum. Some chondrules show little isotopic fractionation [6], which is thought to be formed by evaporation. Most chondrules, however, do not show significant isotopic fractionation. On the contrary, some CAIs show large O isotopic fractionation and also Mg and Si fractionation [6]. The degree of isotopic fractionation can be a good indicator for evaporation.

Evaporation rate of forsterite and diffusion rate of elements are compared assuming that isotopic fractionation of a certain element is effective only when diffusion of the element is rapid enough compared to evaporation rate. Magnesium isotopic fractionation is possible from solid forsterite within melting time of chondrules, but O and Si are not because of the much slower diffusion rate of those elements in solid silicates. Contrary to the solid state, Mg, Si, and O in silicate melt have much larger diffusion rates, and all of them can fractionate. Therefore, if chondrules or CAIs show Mg isotopic fractionation without accompanying O and Si isotopic fractionation, it means that the object has suffered evaporation in H gas of low pressure for fairly short time. If Mg and O (and Si) show isotopic fractionation, they are partial evaporation residue from the liquid state. Absence of isotopic fractionation in many chondrules indicates that they were formed in H gas at considerably high pressure.

Above discussions are based on the evaporation rate at 1700°C, which is higher than the melting temperature for chondrule and CAI formation. Further experimental study, particularly activation energy of vaporization in H gas, would give constraints on chondrule and CAI formation.

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PORPHYRITIC VS. NONPORPHYRITIC CHONDRULES.

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Chondrules can be divided into two broad textural types: porphyritic and nonporphyritic. Porphyritic chondrules are the most common in most chondrites and range texturally from olivine-rich (PO) to intermediate (POP) to pyroxene-rich (PP). Barred olivine (BO) chondrules can be considered a special case of porphyritic. Compositionally they can be divided into type I and II, as originally suggested by McSween [1]. Nonporphyritic are less abundant than porphyritic chondrules in most chondrites—they make up ~15% of the chondrules in ordinary chondrites—and range texturally from glassy (G) to cryptocrystalline (C) to radial pyroxene (RP). Compositionally nonporphyritic differ from porphyritic chondrules and

within this group they are very similar to one another. Here we (1) review and contrast the characteristics of the nonporphyritic and porphyritic chondrules; (2) specify some of the problems associated with the origins of the textural and compositional differences between them; and (3) suggest a possible scenario for their origin, which may have important implications for the evolution of chondrules.

Nonporphyritic chondrules are an integral part of most unequilibrated chondrites. G chondrules are sometimes completely glassy and sometimes exhibit devitrification, have crystallites, and grade imperceptibly into C chondrules. Some have radiating textural domains discernible under cross-polarized light, whereas others exhibit irregular domains. Many are “muddy” or “dirty brown” in color. C chondrules grade into RP, and some may be RP chondrules cut normal to the radiating needles. The radiating needles of pyroxene in RP chondrules have a variable grain size, from very fine to coarse. Many are excentroradial, having nucleated at only one spot on the periphery of the chondrule. Notable features include wavy extinction across fans and interfacing sets of fans, depending on the geometry of the thin-section slice. Some have sharply bounded margins that are compositionally different (more Fe-rich) from the chondrule interior. In broken chondrules, these margins occur only on the original curved chondrule surface and not on the broken portions, indicating that Fe enrichment occurred prior to breakage and incorporation of the chondrule into the host chondrite.

Average sizes of the G, C, and RP chondrules in unequilibrated ordinary chondrites range from 0.45 to 0.93 mm. H chondrites tend to have smaller ones than those in L and LL chondrites, as is the case for porphyritic chondrules. G chondrules are the smallest in each group, with C chondrules intermediate and RP the largest. Chondrule size variations are controlled by the density, viscosity, and surface tension of chondrule-forming melts, and these factors are in turn dependent on the chemical composition, formation temperature, and cooling rate of the melt. RP chondrules formed at somewhat slower cooling rates than C and G chondrules.

The mineralogy of nonporphyritic chondrules is dominated by pyroxene and this contrasts with the porphyritic chondrules, which often have olivine-rich compositions. Bulk compositions reflect the pyroxene-rich mineralogy of the G, C, and RP chondrules; they are similar to one another and differ markedly from the olivine-bearing porphyritic chondrules. Nonporphyritic chondrules have consistently higher SiO_2 and lower FeO and MgO than porphyritic chondrules. There is a striking negative correlation of FeO and SiO_2 for all three textural types, and a complementary positive correlation between mg number and SiO_2 [2]. Bulk SiO_2 controls the normative and modal olivine and pyroxene compositions of the chondrules. Additionally, Si/Al ratios of the nonporphyritic chondrules are generally supersolar, whereas porphyritic chondrules have either solar or near-solar ratios. This suggests that the nonporphyritic chondrules formed from more fractionated nebular materials than the porphyritic chondrules.

The differing characteristics of the nonporphyritic and porphyritic chondrules raise important questions with regard to chondrule formation. Why do they differ compositionally, as well as texturally, from one another? Do nonporphyritic chondrules require a different set of precursors than the porphyritic chondrules, or are the compositional differences between them the result of open-system behavior during chondrule formation? While it is possible to postulate the conditions for the production of quickly cooled melts or quench

products that are quartz-normative, as well as olivine-normative compositions that are crystalline and more slowly cooled, it is more difficult to determine the reasons these differing conditions came about. Is this an evolutionary trend, or is this the result of an unusual set of circumstances? The differences strongly suggest that the nonporphyritic chondrules were derived from a portion of the nebula that differed in time and/or space, and evolved through a process that differed from that of the porphyritic chondrules.

We suggest that the nonporphyritic chondrules formed at a time or location in the nebula in which free SiO₂, or Si-rich gas, was present to a larger extent than that present at the time of porphyritic chondrule formation. The formation of free SiO₂ or Si-rich nebular gas can be achieved through a process of fractional condensation, during which forsterite is removed from the system at an earlier time, at high temperatures [3]. If the nonporphyritic chondrules incorporated SiO₂ as a part of their precursor assemblage, or experienced liquid/gas reactions with a Si-rich gas during chondrule formation, they may represent more fractionated nebular materials than the porphyritic chondrules. These chondrule precursors melted completely, at lower temperatures than that of the porphyritic chondrules, and cooled rapidly. Since nonporphyritic chondrules may have formed at a different time and/or location in the nebula than the porphyritic chondrules, we should expect to find chondrites that are made up largely or entirely of this chondrule type, as well as of other less common chondrule types. Examples of such chondrites include (1) Allan Hills 85085 and similar chondrites, which consist mainly of nonporphyritic chondrules [4]; and (2) microchondrules in chondritic clasts such as those in Piancaldoli and Krymka [5,6]. Bencubbin is an example of a chondritic meteorite that consists of only one type of chondrule, the barred olivine type, and this further indicates that special conditions sometimes exist in portions of the solar nebula, and that aggregational processes sometimes exclude other textural types of chondrules. Thus, there are numerous conditions and aggregational processes that result in the variety of chondrules found in chondrites, and further studies of the rarer chondrule types are needed in order to develop a more complete picture of the events that occurred and their relationship to one another.

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SIDEROPHILE ELEMENTS AND METAL-SILICATE FRACTIONATION IN THE SOLAR NEBULA. H. E. Newsom, Institute of Meteoritics and Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque NM 87131, USA.

The most important nebular fractionation affecting the siderophile elements is the metal-silicate fractionation. However, the actual nature of the metal-silicate fractionation process and its relationship to the chondrule formation process is poorly understood. Understanding these processes is important in terms of understanding the expected compositional range for planetary building blocks. In a general way the composition of chondrites can be derived from the composition of the CI chondrites by addition or subtraction of a refractory component similar to CAIs (in some cases with a Mg₂SiO₄

component) and by addition or subtraction of Fe metal [1]. Thus normalization to Fe produces the least spread in the normalized abundances of most siderophile elements relative to CI abundances (Fig. 1). Detailed bulk chemical studies of chondrules have shown that their siderophile elements have refractory-element to common siderophile-element signatures (for example, Ir/Ni) that are similar to the bulk meteorites, but distinct among the different chondrite groups [e.g., 2,3]. This data suggests that the chondrules were not supplied to the chondrule groups from a single homogeneous source, and that each chondrite group's characteristic siderophile-element signature was established before chondrule formation. These authors [2,3] make a further inference that all siderophile-lithophile-element fractionation occurred before chondrule formation, but recent discoveries and observations suggest this is not true. The discovery of the metal-rich CH meteorites [e.g., 4], the recognition of the role of aerodynamic forces in the solar nebula [e.g., 5,6], and the possible role of metal-silicate segregation during the chondrule formation process [7] suggests that metal-silicate fractionation occurred before, during, and after chondrule formation.

The behavior of metal during the chondrule formation process is not well understood. Separation of metal droplets from spinning molten chondrules has been discussed [8], and this represents a small-scale metal-silicate fractionation. The existence of metallic droplets that could be called metal "chondrules" has also been discussed [8,9]. Jones [7] proposed that type II chondrules could be derived from type IA chondrules by reduction of FeO and removal of the resulting Fe metal. However, the effects of these processes on siderophile elements cannot be easily evaluated because of our poor understanding of the nature of metal-silicate equilibrium in chondrules and the lack of detailed siderophile-trace-element studies of metal from chondrites. The available data on the siderophile-element chemistry of metal particles in chondrites suggests that the formation processes resulted in a range of compositions [e.g., 10,11].

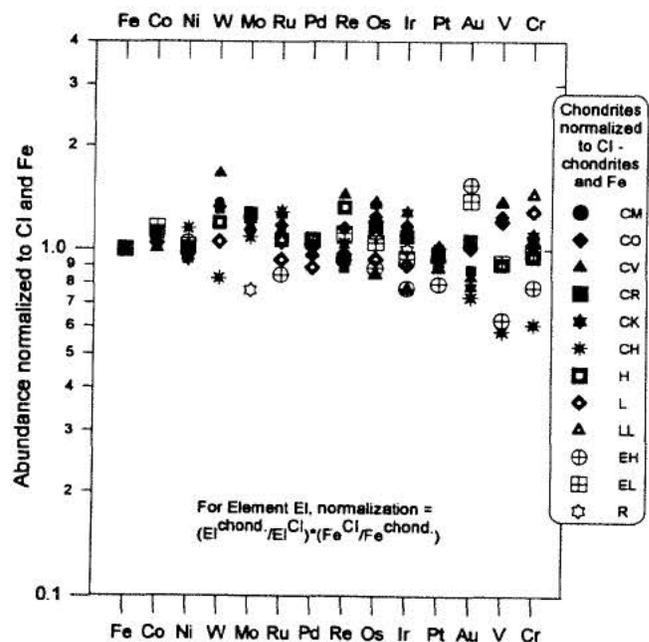


Fig. 1.

The most extreme examples of metallic chondrules may place additional constraints on the formation of these objects. Although originally thought to have achondritic affinities, the metal-rich meteorites Bencubbin and Weatherford are now thought to be chondritic [11,12]. The metallic particles in the Bencubbin and Weatherford meteorites are very large, 0.1–6 mm in diameter. Newsom and Drake [11] discussed the origin of the metal clasts in the Bencubbin meteorite, and showed that they have primitive characteristics, including somewhat variable siderophile-element compositions. Scott and Haack [5] showed that the size distributions of metal and silicate particles in Bencubbin and Weatherford are consistent with sorting by aerodynamic forces. The abundances of volatile siderophile elements in the metal clasts or chondrules are highly depleted as a function of condensation temperature, similar to the volatile lithophile elements in the silicate portion of the meteorites, suggesting a close relationship between the metal and silicate [13]. The large size of the metal clasts may be difficult to reconcile with an origin by separation from spinning molten silicate chondrules. Newsom and Drake [11] discussed a condensation origin for the metal chondrules, but the presence of sulfides in the metal clasts requires later reactions with the nebular gas.

In spite of these complications, several lines of evidence support the close relationship between the silicate portions of the meteorites and the siderophile-element abundances. This evidence includes the correlation between Fe contents and the abundance of siderophile elements (Fig. 1), coupled with the observations [9] that the siderophile elements in chondrules have the same refractory-to-less-refractory-element signature as the bulk meteorites. Another line of evidence is the similar depletion patterns of the volatile siderophile elements and the volatile lithophile elements in virtually every chondritic meteorite. These observations suggest that metal-silicate fractionation, which occurred during and after the chondrule formation process, was a local process. Thus, metallic particles and silicate chondrules were not distributed from a unique source throughout the region of the solar system sampled by the known chondritic meteorites. The chondrite studies lead to several conclusions regarding the determination of initial abundances of siderophile elements in planetary building blocks: The correlation of siderophile elements with Fe, and the consistent relationship between the volatile siderophile and volatile lithophile elements abundances in each chondrite group, allow the initial abundances of siderophile elements to be calculated for planetary objects for which the Fe content is known. The fractionation of refractory to less-refractory siderophile elements cannot be corrected for, based on refractory lithophile contents or Fe content. Fortunately, based on known chondrites (e.g., Fig. 1), this results in an inherent uncertainty of less than plus or minus a factor of 2 for all but the most volatile siderophile elements.

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Mn-Cr ISOTOPIC SYSTEMATICS OF CHAINPUR CHONDRULES AND BULK ORDINARY CHONDRITES.

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We report an ongoing study of the Mn-Cr systematics of individual Chainpur (LL3.4) chondrules [1] and compare the results to those for bulk ordinary chondrites. Twenty-eight chondrules were surveyed for abundances of Mn, Cr, Na, Fe, Sc, Hf, Ir, and Zn by INAA. Twelve were chosen for SEM/EDX and high-precision Cr-isotopic studies on the basis of LL-chondrite-normalized Mn_{LL} , Sc_{LL} , $(Mn/Fe)_{LL}$, and $(Sc/Fe)_{LL}$ (Fig. 1) as well as their Mn/Cr ratios. Classification into textural types follows from SEM/EDX examination of interior surfaces.

The first Cr-isotopic analyses showed the Mn-Cr systematics of Ch-25 to be aberrant compared to those of five other chondrules [1]. Because Ch-25 was enriched in the refractory lithophile elements Sc and Hf, and the refractory siderophile element Ir, by 2.7× and 4.4× LL abundances, respectively, and was depleted in the moderately volatile elements Na and Cr (0.37× LL) and Mn (0.1× LL), we concluded that substantial vaporization may have occurred during chondrule formation. Alternatively, Ch-25 may have formed from refractory-element-rich precursors. Paradoxically, Ch-25 also was enriched in the most volatile element we measured, Zn (1.8× LL), suggesting that it acquired a volatile-rich component as it cooled from a melt. Because of these possible complexities in formation of Ch-25, chondrules with similarly high Sc and, especially, Sc/Fe

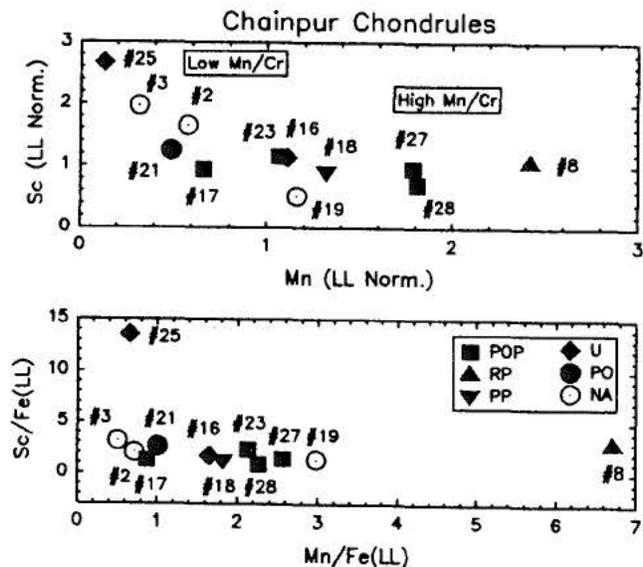


Fig. 1. POP = porphyritic olivine-pyroxene; PP = porphyritic pyroxene; PO = porphyritic olivine; RP = radial pyroxene; U = unclassified; NA = isotopic data not available.

ratios were omitted from the follow-on study. The chondrules chosen covered a wide range of Mn/Cr and Mn/Fe, but a restricted range in Sc/Fe (Fig. 1).

Values of ϵ^{53} (deviations of $^{53}\text{Cr}/^{52}\text{Cr}$ from the terrestrial value in parts in 10^4) for the chondrules and bulk samples of Chainpur, Arapahoe, Colby (Wisconsin), Dhajala, Forest Vale, and Jilin are shown in Fig. 2 plotted vs. $^{55}\text{Mn}/^{52}\text{Cr}$. Corresponding values of ϵ^{54} are plotted vs. ϵ^{53} in Fig. 3. The fitted trend line has the equation $\epsilon^{54} = -0.4 + 1.3\epsilon^{53}$ and a correlation coefficient $r = 0.76$, suggesting the possibility of correlated anomalies. Chromium isotopic heterogeneities might be expected from the observation of excesses at both ^{53}Cr and ^{54}Cr for Allende inclusion EK-1-4-1 [2] and of both positive and negative values of ϵ^{54} in stepwise dissolution of carbonaceous chondrites [3,4]. Oxygen isotopic heterogeneities among Chainpur chondrules relative to a bulk sample were reported by [5].

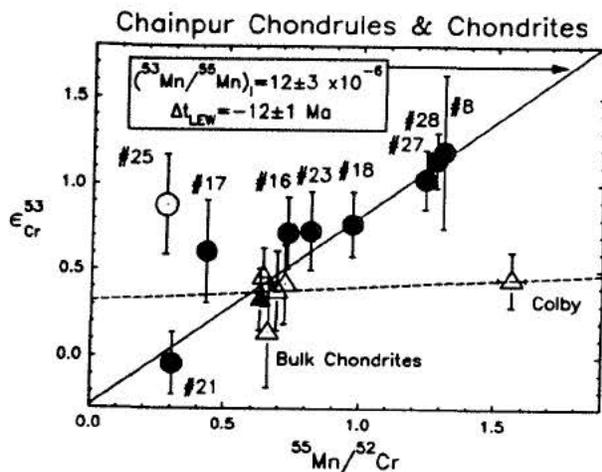


Fig. 2. Mn-Cr data for Chainpur chondrules (circles), bulk Chainpur (filled triangle), and other bulk chondrites (open triangles). Δt_{LEW} is the Mn-Cr formation age relative to the LEW 86010 angrite.

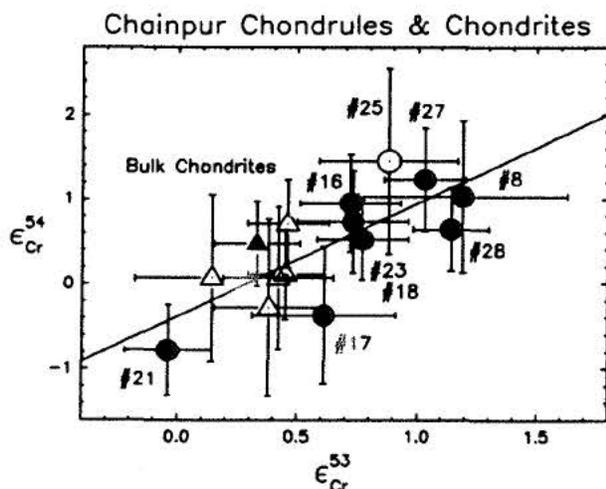


Fig. 3. ϵ^{54} vs. ϵ^{53} for Chainpur chondrules and bulk chondrites. Symbols as for Fig. 2. The trend line may result from mixing different nebular components in chondrule precursors.

Apparent ^{54}Cr heterogeneities among the chondrules are small ($\sim \pm 1$ ϵ -unit), and the slope of the apparent trend line less than expected from $\epsilon^{54}/\epsilon^{53} \sim 3$ found for EK-1-4-1. Earlier work has shown that ϵ^{53} and ϵ^{54} are not in general correlated [2,3,6]. The apparent correlation observed here could be due to averaging during mixing of chondrule precursors. Apparently correlated ^{53}Cr and ^{54}Cr anomalies also could be produced by small interferences at masses 50 or 52, a possibility we continue to evaluate.

If the ^{53}Cr and ^{54}Cr anomalies are correlated, it implies a pre-solar origin, and use of the Mn-Cr systematics of these chondrules for solar system chronometry would be negated or limited. Alternatively, if the variations in ^{53}Cr are due to decay of now-extinct ^{53}Mn ($t_{1/2} = 3.7$ Ma), they provide chronological constraints on formation of the chondrules, or their precursor materials. If the Mn-Cr system remains closed during chondrule formation, the time intervals derived may represent formation of chondrule precursors. Since the chondrule data are not all collinear in the isochron diagram (Fig. 2), they cannot all represent cogenetic systems. We assume that displacement of the Ch-25 datum from the linear correlation is due to late, partial vaporization accompanied by lowered Mn/Cr after decay of ^{53}Mn . We further assume that the bulk chondrites satisfy the same initial Cr-isotopic conditions as the chondrules. Then, a least-squares fit [7] to the chondrule plus bulk chondrite data (Fig. 2) yields an isochron, the slope of which gives initial $(^{53}\text{Mn}/^{55}\text{Mn})_1 = 12 \pm 3 \times 10^{-6}$ for initial $\epsilon^{53}_1 = -0.28 \pm 0.16$. These values correspond to closure of the isotopic systems (= chondrule formation?) at $\Delta t_{\text{LEW}} = -12 \pm 1$ Ma prior to igneous crystallization of the LEW 86010 angrite [8,9], or $\Delta t_{\text{ALL}} = 7$ Ma after Allende CAI, for $(^{53}\text{Mn}/^{55}\text{Mn})_{1,\text{ALL}} \sim 4.4 \times 10^{-5}$ [10]. The latter formation interval is comparable to the shortest I-Xe formation intervals reported for individual Chainpur chondrules [11,12].

The values of $(^{53}\text{Mn}/^{55}\text{Mn})_1$ and ϵ^{53}_1 obtained from the chondrule isochron are compatible within error limits with radiogenic growth in a solar nebula with $(\text{Mn}/\text{Cr})_{\text{solar}} = 0.55$ [13] from initial values $\sim 4.4 \times 10^{-5}$ and ~ -1.7 [10], respectively (Fig. 4). However, the apparent correlated variation of ϵ^{53} and ϵ^{54} (Fig. 3) suggests that much of the variation in ϵ^{53} could be due to "cosmic chemical

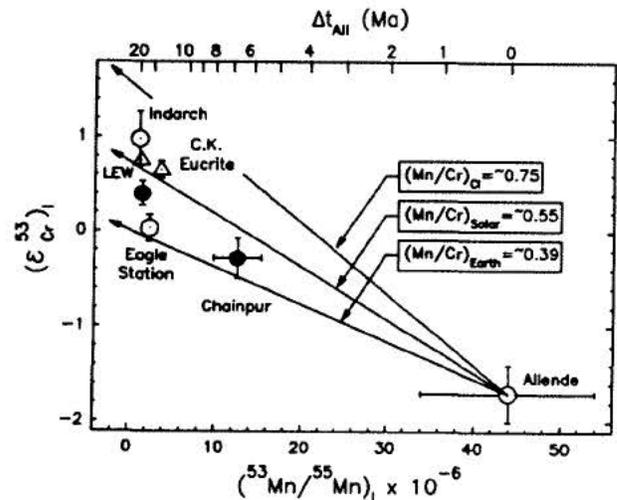


Fig. 4. ϵ^{53} vs. initial $(^{53}\text{Mn}/^{55}\text{Mn})_1$ for the Chainpur whole-chondrule isochron compared to literature values for LEW 86010 [8,9], Chervony Kut [15], Indarch [10], and Eagle Station [10].

memory" [14] and poses a more fundamental problem for chronological interpretations. Additional data for Chainpur and other unequilibrated chondrites should address this ambiguity.

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FORMATION OF CHONDRULES AND CAIs BY NEBULAR PROCESSES. H. Palme, Mineralogisch-Petrographisches Institut, Universität zu Köln, Zùlpicher Strasse 49b, 50674 Köln, Germany.

Chondrules are essential components of most chondritic meteorites. Carbonaceous chondrites, with the exception of CI chondrites, contain 30–50% chondrules, ordinary and enstatite chondrites even more. A better understanding of chondrule formation will therefore lead to an improved understanding of the origin of meteorites. Most studies of chondrules are, however, concerned with their texture and mineralogy. As chondrules, by definition, passed through a molten stage, their present texture and mineralogy can only provide information on conditions of crystallization from a melt and the subsequent solid-state cooling history. Information concerning chondrule formation is contained in their chemical and isotopic composition.

The two most important observations relevant to the chemistry of chondrules are their generally low Fe content and the large compositional variability of chondrules from a single meteorite, reflected in major variations of Mg/Si ratios, of Al and other refractory element abundances, total Fe, metal (Fe,Ni), and sulfide [1]. This large compositional variability is surprising considering the uniform and nearly solar composition of bulk chondrites, which, in some cases, consist of more than 90% of chondrules. The Fe/Si ratio, for example, is nearly the same in the solar photosphere, in CI chondrites, and in CV, H, and E chondrites, despite low Fe contents in chondrules and large differences in the fraction of chondrules among these meteorites. Thus solar Fe/Si ratios in H chondrites are, for example, the result of mixing the proper amounts of metal and chondrules. Apparently, both components must have formed from a single nebular reservoir, implying a close spatial association of chondrule and metal formation.

The compositional variability of chondrules excludes formation from fine-grained dust. Partial melting or fractional crystallization of an initially homogeneous reservoir also cannot account for the compositional diversity, as there is no evidence in chondrules for igneous fractionation. Thus mixtures of coarse-grained nebular components are required to explain the compositional variability of chondrules as concluded by [1]. However, as emphasized before, all components must ultimately have formed from a single well-defined chondritic reservoir, i.e., for each chondrule with a high Si/Mg

ratio there must be one with a low ratio to achieve the chondritic ratio in the bulk.

Carbonaceous chondrites provide even better insight into chondrule formation. The fraction of chondrules in these meteorites is lower than in ordinary and enstatite chondrites, resulting in a higher fraction of matrix. Detailed studies have shown that in carbonaceous chondrites matrix and chondrules are chemically complementary [2,3]. For example, chondrules in Allende are low in FeO, Ni, and Co (but not in Ir), whereas matrix is high in FeO, Ni, and Co. Allende chondrules are high in refractory elements; matrix is low. Surprisingly, even the distribution of Ca and Al between chondrules and matrix is complementary: On the average, Ca/Al ratios are below the cosmic ratio in chondrules and above in matrix of Allende. Again, Allende and other carbonaceous chondrites must have been made from a single nebular reservoir. This reservoir must be capable of producing fine-grained matrix and coarse-grained chondrule precursor components.

The recent observation that in Yamato 86751, a CV chondrite with the same bulk composition as Allende, chondrules have higher than bulk Ca/Al ratios and matrix lower (exactly opposite to Allende), but the bulk meteorite has the cosmic ratio [4,5], implies that each meteorite, even members of the same group, has its own nebular history of chondrule and matrix formation, i.e., chondrules of Allende and of Yamato 86751 are chemically different despite the same bulk composition of both meteorites. There are even hints that average chondrule compositions are different in different parts of Allende, implying also differences in matrix composition to retain the same bulk Allende composition [6].

All these considerations lead to the conclusion that only processing within a very small nebular environment is capable of producing the observed chemical trends. Allende chondrules were not made of Allende matrix and Allende matrix is not the result of processing of chondrules, but instead both components were made from a single nebular reservoir. This does not exclude small fractions of truly exotic material in these meteorites. CAIs in carbonaceous chondrites, for example, may have formed in a different nebular setting as the other parts of the meteorite as the enhancement of refractory elements in CVs compared to the CI standard is the result of addition of CAI material. However, similar refractory-element abundances in Allende and in Yamato 86751 would then be a mere coincidence. It is perhaps more reasonable to assume that the Allende and Yamato 86751 reservoirs were both similar, but that the subsequent condensation history was different for the two reservoirs.

Metamorphic parent body reprocessing as an explanation for some of the observed chemical trends can be excluded, at least in Allende and other CV meteorites. The extremely sharp transition from FeO-rich to FeO-poor olivine in many Allende chondrules constrains the thermal history of the parent body [7]. Major diffusion-controlled elemental redistribution during heating on the Allende parent body cannot have occurred.

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A CERAMIC/SLAG INTERFACE AS AN ANALOG FOR ACCRETION OF HOT REFRACTORY OBJECTS AND RIM FORMATION. J. M. Paque¹ and T. E. Bunch², ¹SETI Institute, Mail Stop 244-11, NASA Ames Research Center, Moffett Field CA 94035-1000, USA, ²Mail Stop 244-11, NASA Ames Research Center, Moffett Field CA 94035-1000, USA.

Introduction: Refractory inclusions or Ca-Al-rich inclusions (CAIs) from carbonaceous chondrites span a wide range of bulk compositions that cannot be explained either by segregation from a gas of solar composition at different points in the condensation sequence or by fractional crystallization from a parent liquid. CAIs are commonly rimmed by Wark-Lovering (W-L) rims, a series of nearly monomineralic layers that have been a source of controversy since the variety of rim sequences occurring on different types of CAIs from Allende were described [1]. The origin of these distinctive features has not yet been resolved, with proponents of accretion, condensation, flash heating, ablation, evaporation, etc. [2]. Rims have generated considerable interest because they potentially contain clues to conditions experienced by CAIs after the formation of the inclusion and prior to incorporation into the parent body.

Ceramic bricks in contact with hot steel slag may produce reaction products in rimlike fashion similar to those found in CAIs. The similarity between the mineralogy of blast furnace slags and CAIs has long been recognized [3,4], with both containing unusual phases not found in terrestrial materials [5]. We provide here a comparison between a ceramic brick/slag multiple-layered interface and a multiple-layered interface between a melilite-perovskite object and a melilite-spinel object in the Allende inclusion USNM 4691-1. These results have implications in interpreting the origin of rims and the textures and compositions of CAIs.

Steel Slag Sample: Sample #2465 from U.S. Steel Research, Monroeville, Pennsylvania, was part of a trough that was used to transfer liquid Fe (with some slag) from an electric arc furnace to other plant components. The trough was made from Al₂O₃ (90%) graphite (10%) brick; the nominal working temperature and time during transfers were ≈1700°C for tens of seconds to <2 min. Constant thermal shocking by repeated liquid Fe contact caused scabbing, and, together with the dissolving action of the slag at high temperature, led to rapid surface failure of the ceramic trough. The solubility of the ceramic in slag determines the elemental gradient in the reacting layer, and hence the diffusion rates of the reaction products [6]. While the temperatures achieved during the steel-making process are below the melting point of the pure ceramics, the interaction between the slag and the ceramic promotes extensive diffusion that is partly dependent on the porosity of the ceramic. The resulting compositional changes enhance partial to complete localized melting of the altered ceramic, and reaction layers develop at the molten Al₂O₃/slag interface. Thus, a series of layers are formed at the contact of the slag with the alumina: (1) quench zone adjacent to the slag (long thin blades of anorthite <10 μm in width) set in a fine-grained matrix consisting mainly of Ti-fassaite; (2) euhedral spinel <100 μm in size, surrounded by pure gehlenitic melilite and interstitial glass; (3) CaAl₄O₇-rich zone; (4) hibonite-rich zone with hibonite laths oriented at high angles to the interface. Two pyroxenes are the dominant phases in the slag: (1) a fassaite rich in Ti, Mn, and Fe; and (2) a fine-grained, Fe-rich pyroxene approaching hedenbergite in composition, with dendritic textures suggestive of quenching or rapid-cooling conditions.

Ca-Al-rich Inclusion: USNM 4691 is irregular in shape, and individual thin sections provide significantly different views of the CAI [7,8]. In section 4691-1 a melilite, perovskite-rich body has interacted with the melilite-spinel main mass of the inclusion and formed a reaction zone. The components of this reaction zone are: (1) normally zoned small crystals of melilite (Åk 1–12; 10–15 μm) with abundant anhedral perovskite (to 10 μm); a very-high-Ti fassaite is associated with the perovskite, with TiO₂ contents exceeding 20 wt%, and spinel is rare; (2) melilite (Åk 3–12), rare perovskite; (3) continuous layer of euhedral spinel + perovskite; (4) narrow rim containing small rounded crystals of CaAl₄O₇ [8] in melilite (Åk 0–5); (5) long (up to 100 μm) laths of Mg,Ti-enriched hibonite oriented perpendicular to the boundary, with melilite (Åk 3–6); (6) spinel-rich CAI with large, clear melilites (to 0.5 mm; Åk 0–10, minor alteration to anorthite, grossular, and nepheline) and minor perovskite.

Discussion: The slag/ceramic interface can be used as an analog for the formation of rims on CAIs and to study the textural effects of the agglomeration of chondritic objects. The sequence of rims observed in the slag sample is a result of the bulk composition of both the ceramic and the slag, the absolute and relative temperatures of both objects, the porosity of the samples, the O fugacity, and the time available for the reaction. If the temperatures of both objects are sufficiently high, homogenization will occur, changing the bulk composition of the original CAI. At lower temperatures partial melting will occur, forming the characteristic W-L rims. If the temperature is not high enough for any melting to occur, the resulting texture could resemble accretionary rims due to fusion of accreted dust particles on the surface of the object. The reaction zone in CAI 4691 is an example of the texture resulting from the merging of larger objects, relatively similar in composition. W-L rims on CAIs probably resulted from the addition of a more Fe-rich “chondritic” dust on the surface of an inclusion followed by a rapid heating event(s) of a temperature sufficiently high to melt or partially melt both components at the interface.

Conclusions: The observation of “monomineralic” layering of minerals at a slag/ceramic interface provides experimental validation that mineral layering, such as that commonly found in rims on CAIs, can result from diffusion of components in a reaction zone formed from dissimilar bulk compositions and temperatures.

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CHONDRULE REMELTING: EVIDENCE FROM COARSE-GRAINED CHONDRULE RIMS AND COMPOUND CHONDRULES. A. E. Rubin¹ and A. N. Krot^{1,2}, ¹Institute of Geophysics and Planetary Physics, University of California, Los Angeles CA 90024, USA, ²Planetary Geosciences Division, University of Hawaii at Manoa, Honolulu HI 96822, USA.

The meteorites that best preserve the nebular record are the type 3 ordinary (OC) and carbonaceous chondrites; their major compo-

nents include chondrules and chondrule fragments, refractory and mafic inclusions, metal-sulfide assemblages, and fine-grained, porous, FeO-rich silicate matrix material. Many chondrules are surrounded by nms; these can be divided into two major types: (1) fine-grained rims, which are composed of matrix material [1]; and (2) igneous or coarse-grained rims, which have igneous textures and larger, less-ferroan mafic silicate grains [2,3].

Fine-grained rims surround most of the chondrules in the least-equilibrated type 3 ordinary and carbonaceous chondrites. They were most likely derived via collapse of clumps of nebular dust that accreted around coarse objects such as chondrules and inclusions.

Coarse-grained or igneous rims surround ~10% of the chondrules in type 3 OC and ~50% of the chondrules in CV3 chondrites as well as some chondrule fragments and isolated mineral grains [2,3]. They probably formed by partly melting finer-grained dust-rich precursors and admixed chondrule fragments. Related to the coarse-grained rims are igneous Fe,Ca-rich rims that consist mainly of Ca-pyroxene, ferroan olivine, and metal-sulfide and occur around some chondrules in CO3 Kainsaz [4]. The coarse-grained rims around type I (small-phenocryst-bearing, FeO-poor) porphyritic chondrules in type 3 OC have pronounced igneous textures (e.g., feldspathic mesostasis, euhedral mafic silicate grains, rounded metal and troilite blebs) indicative of extensive (~80%) melting [5]. Their olivine and low-Ca pyroxene grains have essentially the same compositions as those in the enclosed chondrules. Each of the coarse-grained rims is surrounded by a fine-grained rim of matrix material; the boundary between these rims is sharp. The coarse-grained rims around type II (large-phenocryst-bearing, FeO-rich) porphyritic chondrules are less extensively melted. Most contain relict magnesian olivine and/or low-Ca pyroxene grains; relatively few are surrounded by fine-grained rims. There is probably a continuum between these two rim types, as there is between the chondrule types.

On average, the coarse-grained rims around CV3 chondrules are appreciably more ferroan than the chondrules; this suggests that the precursors of these rims were FeO-rich and compositionally more closely akin to existing fine-grained rims. This is consistent with observations in CV chondrites, which indicate that coarse-grained rims and matrix material have similar bulk compositions and that the finest-grained coarse-grained rims have olivines as ferroan (Fa_{50}) as those in matrix material [2,3]. Although the O-isotopic compositions of coarse-grained rims and matrix material are similar, most rims are poorer in ^{16}O than their enclosed chondrules [6]. The precursors of coarse-grained rims were probably fine-grained ^{16}O -poor dust clumps admixed with ^{16}O -rich mafic silicate grain fragments derived from shattered chondrules.

The occurrence of silicate glass and mobilized metallic Fe-Ni and sulfide in CV coarse-grained chondrule rims [2] and the clearly igneous textures in coarse-grained rims around type I porphyritic olivine chondrules in OC [5] indicate that the rims were heated to temperatures above their solidus. Fine-grained rims probably formed from collapsed clumps of nebular dust; because many coarse-grained rims are themselves surrounded by fine-grained rims [2,5,7], it is almost certain that coarse-grained rims formed in the solar nebula.

The mechanism most likely responsible for heating the coarse-grained rims is the same one responsible for chondrule formation. Chondrules with coarse-grained rims must have been heated at least twice: once during formation and again after having acquired finer-grained, dust-rich mantles. The occurrence of coarse-grained rims around some chondrule fragments and isolated mineral grains indi-

cates that some chondrules suffered fragmentation before acquiring dust mantles and being reheated.

Compound chondrules also reflect multiple melting episodes [8]. For example, enveloping compound chondrules (wherein the secondary forms a shell around the primary) formed in a manner analogous to coarse-grained rims (with which they form a continuum): The primary chondrule became associated with nebular dust that was later largely ($\geq 80\%$) melted to form the secondary chondrule [8]. The high porosity of the fine-grained dusty rim probably promoted melting; the compact nature of the primary chondrule hindered remelting [8]. There is a selection effect: In those cases where the primary chondrule was completely remelted, petrographic evidence of the original compound nature was erased.

Chondrules with "relict grains" [9,10] most likely formed by a process analogous to that of enveloping compound chondrules: entrainment of a liberated chondrule phenocryst in a nebular dust clump, and remelting by the chondrule-formation mechanism.

The evidence for multiple melting of chondrules and chondrule fragments places an important constraint on the nature of the chondrule-formation process: The mechanism must be repeatable. Lightning [11–14] and reconnecting magnetic field lines [15,16] are repeatable heat sources and thus seem to be promising chondrule-formation mechanisms.

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CHONDRULE FORMATION IN THE RADIATIVE ACCRETIONAL SHOCK. T. V. Ruzmaikina¹ and W. Ip², ¹University of Arizona, Tucson AZ 85721, USA, ²Max-Planck-Institut für Aeronomie, D-3411 Katlenburg-Lindau, Germany.

The physical, mineralogical, and isotopic properties of chondrules strongly indicate that they were formed by the rapid melting and resolidification of preexisting solids composed of primitive material [1]. The chondrule precursors were heated to temperatures of about 1800 K in short high-temperature events, followed by cooling with a rate 10^2 – 10^3 K/hr. A heat input of about 1500 J/g is required to heat chondrule precursors to such a temperature and melt them [2].

Lightning discharges and flares in the solar nebula [3], and heating of the chondrule precursors by friction with gas decelerated in the accretional shock [4–6] or in a shock (of unspecified origin) within the solar nebula [7], have been discussed as possible mechanisms for chondrule formation.

One advantage of chondrule formation in large-scale shocks is

that a lot of dust material can be processed. An accretional shock, which is produced by infalling gas of the presolar cloud when it collides with the solar nebula, belongs to this type of shock.

In 1984 Wood [4] considered the possibility of chondrule formation in the accretional shock by heating of chondrule precursors by gas drag. He concluded that the density in the accreting material is much lower than needed to melt silicates at the distance of the asteroid belt if the accreting matter had the cosmic ratio of dust to gas, and the mass of the solar nebula did not exceed $2 M_{\odot}$. Melting of chondrule precursors is difficult because of their effective cooling by thermal radiation. Suppression of the radiative cooling of individual grains in dust swarms, which are opaque to thermal emission, was considered to be the only possible means of chondrule formation in solar nebula shocks by [6,7].

Previous models of solid grain melting in solar nebula shocks have neglected gas cooling behind the shock front, i.e., they considered adiabatic shocks. In this paper we show that large dust grains could be heated much stronger than was supposed by these authors, because of effects associated with the gas cooling.

We found that shocked gas is cooled efficiently by dipole molecules and small dust particles, and this results in a sharp increase of gas density in the postshock region.

A stationary distribution of gas temperature, density, and velocity in the postshock region of cooling was obtained for the postshock region, assuming that the velocity of the shock ranged between about 15 and 33 km s^{-1} , equal to the free-fall velocities at distances 8.7 to 1.8 AU for $1 M_{\odot}$. It was assumed that the material has a solar bulk composition (about 2% of mass is situated in elements heavier than He), and that 0.05% of mass is concentrated in small (radius 10^{-5} cm) dust particles, which contribute to the gas cooling.

Submillimeter and larger grains cross the region of cooling before being decelerated, and are heated by the drag (through the cooled and compressed postshock gas) more strongly than in an adiabatic shock. Figures 1 and 2 show the evolution of the grain temperature as a function of time after crossing of the shock front for a grain with the radius 1 mm and density 2.5 g cm^{-3} , and for a fluffy aggregate of the same mass with the density 0.1 g cm^{-3} , respectively.

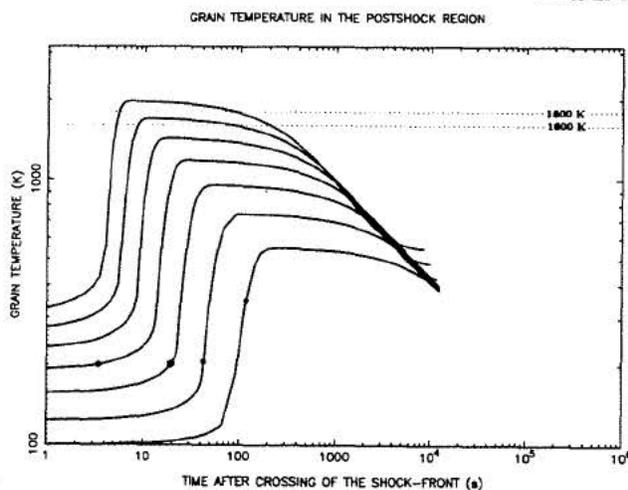


Fig. 1.

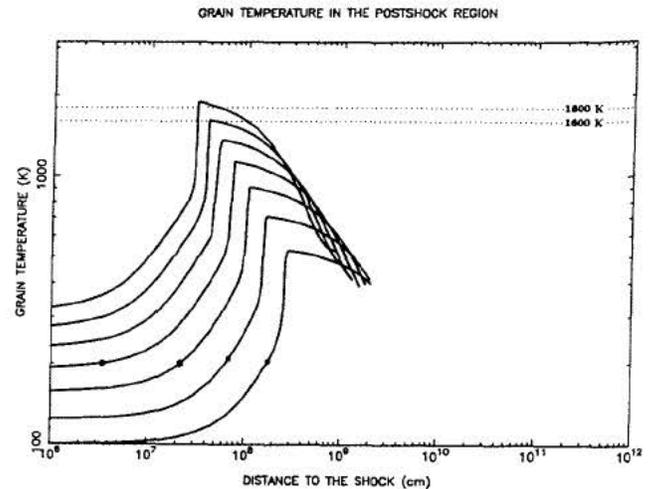


Fig. 2.

The rate of accretion is $3 \times 10^{-5} M \text{ yr}^{-1}$.

These results reveal the possibility of melting of millimeter-sized dust aggregates (chondrule precursors) in the shock produced by infall, even when the matter is transparent for the thermal radiation of the aggregates.

We speculate about the possibility of formation of chondrule precursors in the collapsing presolar cloud and melting of the precursors in the radiative accretional shock during formation of the solar nebula. In such a shock, grains could be melted at heliocentric radii up to the inner part of the asteroidal belt if the density of infalling gas were only few times larger than the average density of infalling gas corresponding to an accretion rate of $10^{-5} M_{\odot} \text{ yr}^{-1}$; the limiting radius for melting increases with density. Clumpy accretion and enhancement of density in the vicinity of the centrifugal radius of infalling gas provide the necessary densities of infalling gas.

Enhancement of drag heating due to fast cooling of postshock gas is also significant for shocks of other origin in the solar nebula. At the central plane of a minimum-mass solar nebula, chondrule precursors could be melted in shocks with velocity $\geq 10 \text{ km s}^{-1}$.

The duration of the molten state and the cooling rate of a grain are determined by the grain's kinetic energy and the rate of its decay (not the timescale of radiational cooling for the grain!). Millimeter-sized compact grains have a temperature $\geq 1600 \text{ K}$ for $\geq 10^3 \text{ s}$, and $\geq 700 \text{ K}$ for $\sim 10^4 \text{ s}$, times that are appropriate for chondrules. These timescales could be larger if grains have larger kinetic energy, e.g., in more fast shocks. Chondrule precursors could be formed as fluffy aggregates before and during the collapse of presolar cloud. Later they must increase their density. We speculate about the possibility of increasing the density of the aggregates by means of mutual collisions or as a result of surface tension when they began to melt.

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THE CIRCUMPLANETARY NEBULAR ENVIRONMENT: A POSSIBLE SOURCE REGION FOR CHONDRULES. I. S. Sanders, Department of Geology, Trinity College, Dublin 2, Ireland.

Hypotheses for the origin of chondrules fall into two broad groups: nebular and planetary [1,2]. Arguments against the latter have prevailed in recent years such that, by default, the less testable nebular setting for chondrule formation is now generally favored. However, the recognition in ordinary chondrites of igneous clasts that probably formed on, or in, small planetoids [3] hints that some parent bodies were still accreting after others had evolved magmatically and lost material to space, presumably by impact. If melting of planetoids can predate accretion, could the same early melting event be related to chondrule production? My affirmative response to this interesting question is expanded below in a chondrule-forming scenario, which incorporates both planetary and nebular features.

The scenario is as follows. The earliest planetary bodies accreted from largely unprocessed, CI-like dust <1 m.y. after the solar system began (i.e., after $^{26}\text{Al}/\text{Al}$ was 5×10^{-5}). During this initial period, even quite small bodies were heated rapidly to melting by the decay of short-lived radioactive isotopes, particularly ^{26}Al . Inevitably many of the bodies collided, releasing enormous clouds of incandescent spray (primary chondrules). The spray itself constituted a powerful, transitory, radiative heat source that sintered, and even melted, dust grains and grain aggregates that became mixed with it in space during the brief aftermath of the collision. In this way various kinds of additional (secondary) chondrules were produced. The cold dust and fragments (chondrule precursors) had two sources. Some of the material was already orbiting each body, as a kind of local, dusty nebular disk, at the time of impact. The rest was ejected from the cooler, and possibly unconsolidated, outer layers of the colliding bodies.

Relative velocity dictated the outcome of any collision. High-velocity impacts disrupted one, or both, of the bodies and scattered chondrules and clasts into space, to be reaccreted on other bodies much later, or to be lost from the solar system altogether. Low-velocity impacts permitted the gravitational reassembly of most of the material, with a net growth in size of the principal (target) planetary body. Rapid fall-back gave rise to hot accretion textures; more gradual fall-back deposited cold chondrules and dust.

Early on, while radioactivity was still powerful, the reassembled bodies underwent “autocannibalization” and melted again internally. Later, when the solar system was about 2 m.y. old and radioactive power was fast waning, energy stored as latent heat of fusion in the molten interiors continued for a while to be available for collision-induced chondrule formation. Molten interiors may also, incidentally, have heated by conduction the blanketing outer layers of initially cold debris to produce the equilibrated chondrites.

The above scenario stems from Zook [4], who advocated the role of molten planetoids in chondrule formation. Although his ideas failed to gain general approval, several more recent observations

appear to reinforce his arguments. Levels of Al-correlated excess ^{26}Mg suggest that short-lived radioactivity was, indeed, sufficiently powerful during the first million years to overheat and melt small planetary bodies [5,6]. Second, experimentally replicated chondrule textures suggest that chondrules cooled relatively slowly, implying that they formed in enormous batches [7], just as the collision model predicts. Third, newly formed chondrules were probably bathed in vapor to account for their retention of volatile elements [8] and for the apparent recondensation of volatiles during cooling [9]. Evaporation of volatile species would be expected during collisional splashing; indeed, passage of chondrules through the vapor may account for their apparent size sorting.

Here Zook’s model is developed further by recognizing that the molten cascade of spray would probably mix and interact with a circumplanetoid disk of cold, orbiting, primitive dust and other debris. Zook’s “planetary” hypothesis for chondrule formation can thus accommodate the kind of textural evidence previously reserved for pro-nebular arguments [1]. Such evidence includes the admixture of chondrules and matrix, dusty chondrule rims (often sintered), and fragments of matrix embedded inside chondrules.

It has been claimed that isotopic and chemical evidence detract from Zook’s model [1]. However, the wide range of O isotopic ratios observed in chondrules can easily be explained, as Grossman [2] admits, if many collisions contributed to the chondrules in a single meteorite. Also, although chondrule compositions lack igneous fractionation trends, and have unfractionated REE patterns, these “nebular” features are not incompatible with the present scenario. They can be explained, respectively, by complete internal melting and the insignificant effect of olivine removal on REE slopes. A well-known chemical feature in L and LL group chondrites is the depletion of Fe, Ni, and Co. The collision scenario would easily explain this fractionation by the incomplete dispersal of the molten metal core of a large body when struck by a smaller body.

Finally, some chondrules indent one another, and appear to have been hot and plastic during accretion [10,11]. Their deformed shapes might be due to shock [12], but in many cases the shapes seem too complex to be explained easily in this way. If hot accretion is accepted, the implied proximity of the chondrule source to the site of accretion would lend yet further support to the scenario envisaged here.

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HEATING DURING SOLAR NEBULA FORMATION AND Mg ISOTOPIC FRACTIONATION IN PRECURSOR GRAINS OF CAIs AND CHONDRULES. S. Sasaki¹, H. Nagahara¹, K. Kitagami^{2,3}, and Y. Nakagawa^{2,4}, ¹Geological Institute, University of Tokyo, Tokyo 113, Japan, ²Department of Earth and Planetary Physics, University of Tokyo, Tokyo 113, Japan, ³Present address: Department of Earth and Planetary Sciences, Tokyo Institute of Technology, Tokyo 152, Japan, ⁴Present address: Department of Earth and Planetary Sciences, Kobe University, Kobe 657, Japan.

In some CAI grains, mass-dependent isotopic fractionations of Mg, Si, and O are observed and large Mg isotopic fractionation is interpreted to have been produced by cosmochemical processes such as evaporation and condensation [1]. Recently Koga et al. found mass-dependent Mg isotopic fractionation in olivine chondrules of Allende meteorites using SIMS [2]. However, conditions necessary for the isotopic fractionation (e.g., temperature, pressure, and timescale) have not been presented.

Nagahara and coworkers conducted evaporation experiments of forsterite (Mg_2SiO_4) at various P_{H_2} conditions [3,4]. Similar to experiments of SiO_2 evaporation [5], evaporation rate at $P_{H_2} > 10^{-5}$ bar is much larger than that at $P_{H_2} < 10^{-6}$ bar. At a higher P_{H_2} condition, reduction by H should enhance the evaporation. Evaporation rates at $1500^\circ C$ and at various P_{H_2} are shown in Fig. 1 in terms of typical distance d , where evaporation proceeds in time t . Diffusion rates of Mg, Si, and O in forsterite are also shown.

When the diffusion distance is comparable to or slightly higher than the evaporation distance, significant enrichment of heavier isotopes in evaporation residues is expected. The fractionation degree becomes highest when the diffusion distance is about twice as large as the evaporation distance. When ambient gas pressure is low ($P_{H_2} < 10^{-6}$ bar), longer duration (or slower rate of temperature change) is preferable for the isotopic fractionation. At higher pressure ($P_{H_2} > 10^{-5}$ bar), the evaporation rate tends to be higher than Mg diffusion rate; evaporative isotopic fractionation of Mg would not take place. Typical midplane pressure at the asteroidal zone of the solar nebula is higher than 10^{-6} bar when $T = 1000$ K. Evaporative fractionation of Mg isotopes would occur at a less dense environment. Figure 1 shows that typical distance d for Mg isotopic frac-

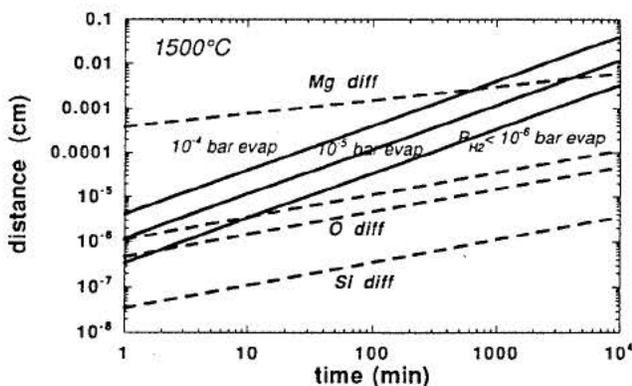


Fig. 1. Comparison between evaporation rates and diffusion rates in forsterite at $1500^\circ C$ in terms of distance d . Evaporation distances $d \propto t^1$ are expressed by solid lines and diffusion distances $d \propto t^{1/2}$ are expressed by dashed lines.

tionation is in the order of 10^{-3} cm = $10 \mu m$, which is much smaller than typical chondrule or CAI size and probably compatible with size of their precursor grains before aggregation.

Heating during solar nebula formation has been presented by a series of works on hydrodynamic calculations by Boss [6–8]. Midplane temperature at the terrestrial zone can be enhanced up to 1500 K in the case of $0.02 M_\odot$ disk. Opacity decrease due to dust evaporation should preclude a much higher temperature. In order to pursue the contraction and heating process in detail, Kitagami [9] numerically simulated vertical gas motion solving radiative transfer precisely with frequency and angle resolutions. Gas contraction toward the disk's midplane should form a shock wave at the off-disk region. Although shock position depends on the initial density distribution, at the asteroidal zone [a (heliocentric distance) = 2.8 AU] the shock is first formed typically around $z = 0.05$ AU, compressed to be about $z = 0.01$ AU, and then rapidly expanded to be about $z = 0.2$ – 0.8 AU.

Heat generated at the shock radiates both inward and outward. When the initial density distribution is spread out and much gas is extant in the off-disk region ($z_0 > a$: z_0 being the position gas density at one-fourth the midplane density; we assume $\rho \propto z^{-2}$ at large z), the inner region between shocks is heated not only by radiation from shocks but also by continuous compression. Under the surface density of a standard model $\Sigma = 1700(a/1 \text{ AU})^{-2.5}$ g/cm² [10], temperature there is enhanced to be higher than 1700 K at $a = 2.8$ AU. When the initial density distribution is concentrated ($z_0 = 0.1$ a), the shock front should rebound and the inner region is heated mainly by radiation from the shocks. The peak temperature around the shock is still as high as 1000 K at 2.8 AU. Outward radiation from the shock also heats the less-dense off-disk region. Gas pressure there is as low as 10^{-8} – 10^{-7} bar, which is much lower than the expected pressure at the asteroidal zone of the solar nebula midplane. As discussed in the above, dust evaporation rate is slower in the relatively low-pressure region, which would be preferable for evaporative isotopic fractionation.

We find an approximate formula for the temperature that depends on heliocentric distance and the initial gas distribution. The equilibrium temperature is approximated by

$$T \approx \left(\frac{GM_\odot \dot{\Sigma}}{a\sigma_{SB}} \frac{3\kappa\Sigma_s}{8} \right)^{1/4} \quad (1)$$

where G is the gravitational constant, σ_{SB} is Stefan-Boltzmann constant, κ is opacity, $\Sigma_s (= 2 \int_z \rho dz)$ is vertical column density, and $\dot{\Sigma}$ denotes mass accretion rate. In the case of the spread initial density distribution, we have larger off-disk mass Σ_s , which hinders outward radiation, and larger mass accretion rate $\dot{\Sigma}$, which releases gravitational energy. Using $\Sigma_s \leq \Sigma \propto a^{-3/2}$ and $\dot{\Sigma} \propto \Sigma/t_K \propto a^{-3}$ (t_K being Keplerian period), we have analytic relations $T \propto a^{-1/8}$, $\rho \propto a^{-37/16}$, and $P \propto a^{-59/16}$. These dependencies on a appear in numerical results. Evaporative isotopic fractionation would not take place in the outer region ($a > 4$ AU), where the temperature is much lower.

Timescale of the peak temperature can be roughly estimated from numerical results. At the shock front of the asteroidal zone, the duration of the peak temperature is about $10^4 \sim 10^5$ min, and the

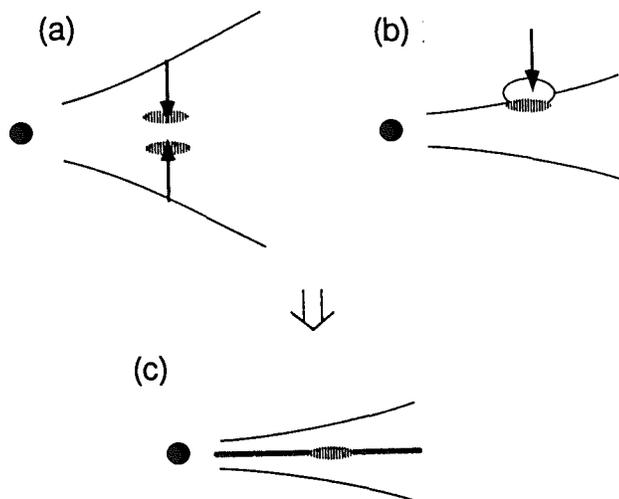


Fig. 2. Heating events during solar nebula evolution. (a) Shock heating during infall of cloud gas onto a protodisk. Evaporative isotopic fractionation would take place at low-pressure environment. (b) Shock heating by a late-accreting gas clump. (c) Heating around disk midplane after solid-gas fractionation and grain growth. Relatively higher pressure is preferable for chondrule formation and melting of some CAIs.

initial cooling rate is 100 K/(20–50 days). This timescale is compatible with the typical time for isotopic fractionation at the vacuum case ($P_{\text{H}_2} < 10^{-6}$ bar), when the temperature is around 1500°C.

Our tentative scenario is shown in Fig. 2. Shock heating during solar nebula formation can cause evaporative fractionation within interstellar grains involved in a gas at the inner zone ($a < 3$ AU) of the disk (Fig. 2a). Alternatively collision of late-accreting gas blobs might cause similar heating if Σ_s and Σ are large enough (Fig. 2b). Since the grain size is small, the solid/gas mass ratio is low and solar (low P_{O_2}), and the ambient gas pressure is low, this heating event could not produce chondrules themselves. We prefer that chondrule formation should proceed around the disk midplane after dust grains would grow and sediment to increase the solid/gas ratio there (Fig. 2c). The heating source there is uncertain, but transient rapid accretion through the disk could release a large amount of heat, which would be observed as FU Orionis events.

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VARIATIONS AMONG CHONDRITE GROUPS—CONSTRAINTS ON NEBULAR PROCESSES. E. R. D. Scott¹, S. G. Love¹, and I. D. Hutcheon², ¹Hawaii Institute of Geophysics and Planetology, University of Hawaii, Honolulu HI 96822, USA, ²Nuclear Chemistry Division, Lawrence Livermore National Laboratory, Livermore CA 94551, USA.

Chondrite Groups and Their Ingredients: Diverse proportions of the four major ingredients are found in the 13 chondrite groups (Table 1). Ca-Al-rich inclusions (CAI) include amoeboid-olivine aggregates, which contain refractory nodules. Matrix material forms aggregates and rims on other constituents and contains micrometer-sized grains and a small, uniform concentration of presolar grains [3]. Fe,Ni grains are mostly derived from hot chondrules. Although bulk nonvolatile chondritic elemental ratios are typically within 30% of solar values, individual CAI and some chondrules show large deviations.

Distinctions Between Chondrite Classes: C chondrites differ from O and E chondrites in having (1) significant abundances of CAI, (2) relatively high bulk refractory abundances, (3) O isotopic compositions that tend to lie on the ¹⁶O-rich side of the terrestrial range, and (4) generally higher abundances of matrix material [2]. E chondrites have uniquely low refractory abundances, little matrix, and highly reduced chondrules. O chondrites have more FeO-rich (type II) chondrules than C and E chondrites. Although the definition of C chondrites has evolved considerably (C is abundant in CI and CM, but not in CK and CO), the term still seems useful as these trends provide constraints (albeit poorly understood) on the nebular origins of groups and components. Among C chondrites, CAI abundance is roughly correlated with bulk refractory abundance, even though a major fraction of the refractories are located in chondrules [4]. CAI were probably accompanied by fine-grained, CAI-like particles that were incorporated into chondrules.

CAI Had Nebula Lifetimes of Several Million Years: CAI with canonical initial ²⁷Al/²⁶Al ratios of 4.5×10^{-5} are found in CV and CM groups: They formed in $< 10^5$ yr [5]. Some CAI were remelted in the nebula 2–4 m.y. later [5,6]. Plagioclase-rich chondrules in O and C chondrites formed > 2 m.y. after CAI formation, assuming ²⁶Al was uniformly distributed [7,8]. The nebula lifetime of several million years inferred from these and other data is consistent with the duration of circumstellar disks of low-mass stars derived from astronomical observations [9]. But theoretical lifetimes for protosolar disks calculated on the basis of turbulent dissipation or drag on solids with Keplerian orbits moving through pressure-supported gas are at least 10× shorter. The formidable complexity of the full disk evolution problem, including radial and convection-driven turbulence, ongoing grain and planetesimal growth, transport, and destruction, and other significant processes [10], suggests that meteoritic and astronomical evidence should prevail.

CAI Formed Before Chondrules: ²⁶Al-based chronometry and textural evidence (CAI inside chondrules, but not vice versa) [11,12] suggest that CAI formed before chondrules and that there was virtually no overlap between their formation periods. Oxygen isotopic data are also consistent with this chronology, as solid-gas reactions during transient heating events caused the O isotopic compositions of solids to evolve toward the gas composition: from CAI to chondrules [13]. FeO concentrations of chondrule olivines, CAI spinels, and chondrule rims also tended to increase because of

TABLE 1. Abundances (vol%) of components in 13 chondrite groups.

Class	C (Carbonaceous)							E (Enstatite)		O (Ordinary)			R
	CK	CO	CV	CH	CR	CM	CI	EH	EL	H	L	LL	
CAI (+ AOA)	4	13	10	0.1	0.5	5	≤0.0001	0.1-1?		0.1-1?		0.0	
Chondrules*	15	40	45	~70	50-60	20	0.001?	60-80		60-80		≥40	
Matrix material	75	30	40	5	30-50	70	99	<2-15?		10-15		35	
Fe, Ni	<0.01	1-5	1-5	20	5-8	0.1	0.00	8-15		10	5	2	0.1
Chondrule size (mm)	0.7	0.15	1.0	≤0.1	0.7	0.3	-	0.2	-	0.3	0.7	0.9	0.4
(Refr./Mg) _{CI}	1.21	1.13	1.35	1.0	1.03	1.15	1.00	0.87	0.83	0.93	0.94	0.90	0.95

From [1-4]. CAI=Ca, Al-rich inclusions; AOA=amoeboid-olivine inclusions.

*Including fragments.

processing, but reduction by internal C or external H caused some decreases.

We infer that (1) earlier transient heating events lasted longer (minutes or more at melting temperatures for CAI [14] rather than seconds for chondrules [15]); (2) since timescales for gravitational collapse of the presolar molecular cloud are 10^5 yr, chondrules did not form during infall into the nebula; and (3) although CAI were rimmed, altered, and sometimes partly melted by later heating events, many CAI were unaffected by chondrule formation.

Timescales for Accretion: To account for the distinct isotopic, chemical, and mineralogical compositions of O, E, and C chondrules, nebular mixing of chondrules over radial distances of 1 AU must have been minimal. Because simple disk models predict fast radial migration of chondrule-sized solids (several AU/m.y. [16]), rapid accretion of chondrules and CAI has been inferred [e.g., 17,18]. However, acceptance of meteoritic and astronomical evidence for long nebular lifetimes relaxes these constraints. Since significant mass resupply to the protosolar disk from infalling interstellar material was unlikely after gravitational collapse of the cloud in 10^5 yr, timescales for significant radial transport could not have been much less than the nebular lifetime of several million years or the entire disk would have vanished into the Sun.

Wood [19] argued for accretion of matrix, chondrules, and CAI within 1 yr of chondrule formation to maintain near-solar chondritic compositions. We infer from Table 1 and other data that proportions of various ingredients were only loosely constrained so that chondrites composed largely of metal, CAI, or FeO-poor (type I) chondrules did not form; accretion periods of $\geq 10^4$ yr cannot be excluded.

Size Sorting of Chondrules and Other Ingredients: Characteristic chondrule sizes (Table 1) imply that chondrules or their precursors were size sorted. In CR chondrites, metal spherules and chondrules have size distributions consistent with aerodynamic sorting of initially unsorted objects (mean size inversely proportional to density) [20]. Although some sorting of chondrule precursors probably occurred, aerodynamic size sorting after chondrule formation may largely account for variations of chondrule sizes, metal abundances, and O isotopic compositions in H, L, and LL chondrites [13,21]. Other chondrite groups do not show similar relationships. Sizes of CAI and chondrules are not closely correlated, presumably because CAI were also size sorted prior to chondrule formation.

However, CV and CH groups respectively have the largest and smallest CAI (1-10 mm and 0.01-0.1 mm) and chondrules (1 mm

and <0.1 mm). Sorting may have occurred during turbulent concentration of articles [22].

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OPEN-SYSTEM BEHAVIOR DURING CHONDRULE FORMATION. D. W. G. Sears, H. Shaoxiong, and P. H. Benoit, Cosmochemistry Group, Department of Chemistry and Biochemistry, University of Arkansas, Fayetteville AR 72701, USA.

The question of whether chondrules behaved as open systems during formation is crucial to our understanding of both chondrule and chondrite formation [1]. The very large range of chondrule types is best summarized by the compositional classification scheme [2,3], wherein the primitive chondrule groups (i.e., those not produced by metamorphic processes) are A1, A2, A5, and B1. In the Semarkona (LL3.0) chondrite, 10.5%, 25.0%, 5.0%, and 56.9% (by number) of the chondrules are groups A1, A2, A5, and B1, respectively [2]. We argue that groups A1 and A2 were produced by reduction and evaporation during chondrule formation of material originally resembling group B1 chondrules. The important but rela-

tively rare group A5 chondrules will not be discussed here [4].

The following observations are relevant to present the question: (1) Group A1 and A2 chondrules contain olivines with low FeO and metal with Ni contents lower than observed in the metal of group B chondrules [5–7]. The coexistence of low-FeO silicates and high-Fe metal *a priori* implies formation of some fraction of the metal by reduction. (2) Group A1 and A2 chondrules show fractionated elemental compositions, while group B1 chondrules show flat elemental abundance patterns [6,8]. In the group A chondrules, Na and K are depleted by factors of 5–100, while Si, Cr, and Mg are depleted by 10–20%. While attention often focuses on Na and K loss during chondrule formation [9], several authors have also discussed Si loss [10]. (3) The ratio of olivine to pyroxene shows the complex variations expected during progressive volatilization of material of initially chondritic composition [11]; loss of Fe by volatilization decreases the olivine FeO (to 2–4 wt%) and causes the px/ol ratio to increase so that many group A2 chondrules are pyroxene-rich. Further evaporation Fe (and reduction of FeO in the olivine to <2 wt%) is associated with significant losses of Si and a decrease of the px/ol ratio to group A1 levels. If the chondrules were random mixtures of precursor grains, there is no reason to expect a relationship between the relative abundance and composition of the olivine and pyroxene. (4) All chondrule groups show a wide range of sizes (Fig. 1 [12]). Figure 1 also shows data for group A3 and B2 chondrules from Krymka, LL3.1. (The slight metamorphism experienced by Krymka is not expected to seriously affect chondrule sizes.) Mean diameters for groups A1, A2, A3, B1, and B2 are 807 ± 398 , 838 ± 392 , 764 ± 299 , 1052 ± 419 , and 970 ± 367 μm , respectively. The student's *t* test indicates that the A groups differ significantly from the B groups at the 0.01 level and that group A chondrules are

significantly smaller, as a group, than group B chondrules. Other authors have made the same conclusion [13]. Huang et al. point out that the size difference is consistent with the compositional differences between group A and group B chondrules [12].

Additional evidence for devolatilization during chondrule formation is the compositional zoning observed in the mesostasis of several Semarkona group A chondrules. The alkali elements are higher in the outer quarter of the chondrule radius, suggesting that alkalis are reentering the chondrule, having once been lost [14]. It is difficult to see how precursor heterogeneities could produce such profiles, or how they could be produced by crystallization or other closed-system processes. Sears and Lipschutz recently argued that abundance patterns of highly mobile trace elements in several chondrules from low type 3 ordinary chondrites reflected a similar kind of process [15].

Group A chondrules clearly formed by major devolatilization and reduction during chondrule formation from material initially resembling group B chondrules. The different chondrite classes seem to contain chondrules with different size distributions, and the chondrite classes show different lithophile-element abundances and degrees of Fe reduction. It will be of great interest to explore the role of the different chondrule groups, and thereby the chondrule formation process, in accounting for these different chondrite properties.

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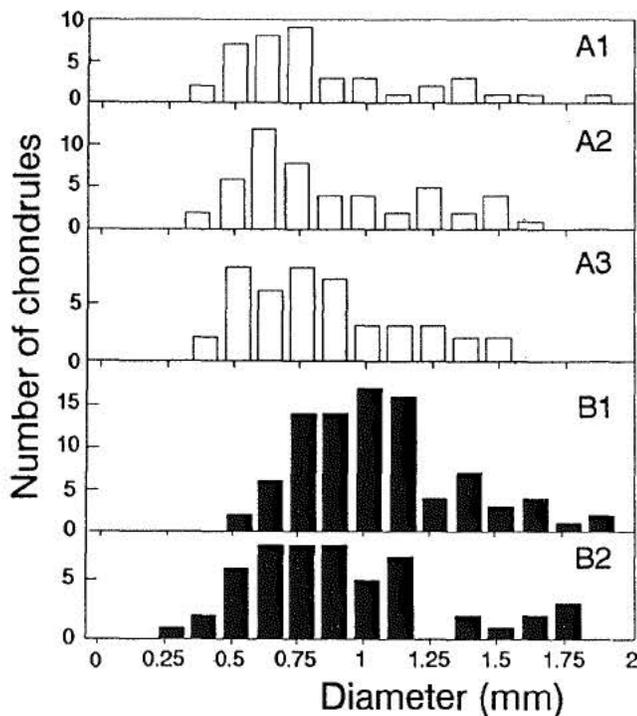


Fig. 1. Chondrule size distribution in chondrules from Semarkona and Krymka.

I-Xe STUDIES OF INDIVIDUAL CHONDRULES: WHAT CAN THEY TELL US ABOUT CHONDRULE FORMATION? T. D. Swindle¹ and C. M. Hohenberg², ¹Lunar and Planetary Laboratory, University of Arizona, Tucson AZ 85721, USA, ²Physics Department, Washington University, St. Louis MO 63130, USA.

In the past 14 years, I-Xe studies have been performed on nearly 100 individual chondrules from five different meteorites [1–7]. More than half the studied chondrules come from the unequilibrated ordinary chondrites (UOCs) Chainpur, Semarkona, and Tieschitz. However, “unequilibrated” does not necessarily mean “unaltered” [8–10], and the I-Xe studies of chondrules from UOCs have ultimately been interpreted in terms of postformation alteration. In this abstract, two types of constraints on chondrule formation will be discussed: (1) the duration, location, and timing of postformation alteration (in solids over a 50-m.y. span); and (2) the ages of the

earliest formed chondrules (a few million years after the earliest solids).

I-Xe System: The I-Xe system is based on the decay of ^{129}I , with a half-life of about 17 m.y., to ^{129}Xe . Much of the ^{129}Xe in meteorites is correlated with ^{127}I , indicative of *in situ* decay. Since all ^{129}I present in the early solar system has long since decayed, it is impossible to determine an absolute age with this system. Instead, apparent relative ages are determined, based on comparison of the $^{129}\text{I}/^{127}\text{I}$ ratios. Ages are usually given in comparison to the L4 chondrite Bjurböle, which has a reproducible $^{129}\text{I}/^{127}\text{I}$ ratio of 1.1×10^{-4} [12]. The first attempts to put the I-Xe on an absolute scale have been made recently, and suggest an absolute age of about 4565 Ma for Bjurböle [13,14]. The major host phases for I so far identified are secondary minerals such as sodalite [15] and apatite [13], consistent with an I-Xe system, which is sensitive to postformation alteration.

General Trends: Individual chondrules from Bjurböle [1,7] and Allende [2,5] have been studied, but these provide few constraints on chondrule formation. The Bjurböle chondrules show <2 m.y. variation in age, but may reflect metamorphic events, and the Allende chondrules, like all other objects from Allende, show large variations with individual chondrules, presumably reflecting late low-temperature alteration.

The studies of petrographically characterized individual chondrules from the UOCs Chainpur [3], Semarkona [4], and Tieschitz [6] give very similar results, despite the fact that the meteorites come from at least two different chemical classes, and have petrographic grades ranging from 3.0 for Semarkona to 3.8 for Tieschitz. The most important features are (1) Many of the chondrules do give well-defined apparent ages, and these ages span at least 10 m.y. for each meteorite. (For Chainpur, the span is 50 m.y.) (2) The oldest apparent ages are about 4 m.y. before Bjurböle for Chainpur and Semarkona, but comparable to Bjurböle for the smaller sample (nine chondrules) from Tieschitz. (3) Apparent ages correlate with bulk chemistry (e.g., refractory compositions correspond to older ages) and with petrographic properties. Since bulk composition correlates with textural type, texture and ages might be expected to correlate. But apparent ages also correlate with more subtle petrographic features. For example, in Semarkona, chondrules with sulfides on the chondrule surface, and particularly those with sulfides penetrating between blades of radiating pyroxene chondrules, tend to have younger ages (i.e., to be more easily reset). Since these conditions are similar to those in which evidence of aqueous alteration has been found [9], it has been suggested [4] that the I-Xe ages in these chondrules reflect aqueous alteration. (4) In individual meteorites, initial $^{129}\text{I}/^{127}\text{I}$ ratios are anticorrelated with initial (trapped) $^{129}\text{Xe}/^{132}\text{Xe}$ ratios, consistent with closed-system evolution in a system with a chondritic bulk I/Xe ratio. This observation is a strong argument that the span in ages is not the result of I isotopic inhomogeneity. Furthermore, it means that the material in these chondrules spent the time before their last resetting (as much as 50 m.y.) in a system with chondritic composition rather than solar (i.e., in a solid).

Interpretations: The large range in apparent age, and the evolution of trapped Xe composition, suggest that these chondrules had extended histories as solids before their final resetting. Although this is consistent with chondrule formation in (or on) parent bodies, a variety of lines of evidence suggest that chondrules were nebular creations [11]. Hence, even the chondrules in UOCs must have been altered after formation.

Despite the large number of individual chondrules from UOCs analyzed (45), the oldest are significantly younger than the ages obtained on whole-rock samples of some carbonaceous chondrites. Most notably, the apparent age of the CV3 Vigarano, the oldest apparently well-defined I-Xe age yet determined [16], is more than 8 m.y. before Bjurböle, 4 m.y. before the oldest UOC chondrules. If any of the chondrule ages represent formation ages, then some chondrule formation must have occurred at least a few million years after the formation of the earliest solids (presumably CAIs). It is interesting to note that the rare cases of *in situ* decay of ^{26}Al in UOCs [17,18] correspond to $^{26}\text{Al}/^{27}\text{Al}$ ratios 1 to 2 orders of magnitude lower than the "canonical" ratio in CAIs, again consistent with the lack of material in UOCs that formed in the first 1 or 2 m.y. after the formation of CAIs.

Finally, although several studies have compared chondrules to "matrix," the chronological relationship is still not clear. Early studies [2,19] typically gave matrix ages slightly older than the ages of chondrules, but a more carefully selected sample of matrix from Chainpur [3] gave an apparent age in the middle of the range of ages given by chondrules.

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CHEMICAL PRODUCTION OF CHONDRULE OXYGEN ISOTOPIC COMPOSITION. M. H. Thiemens, Department of Chemistry, 0356, University of California, San Diego, La Jolla CA, 92093-0356, USA.

Defining the source of observed meteoritic O isotopic anomalies remains a fundamental challenge. Generation by nuclear [1] or chemical [2,3] processes have both been suggested as candidates. Recent observations of the extent to which chemically produced mass independent fractionations occur in nature are particularly relevant.

The O isotopic composition of chondrules are particularly striking (see, e.g., a recent review [4]). Chondrules from carbonaceous chondrites define a $\delta^{17}\text{O} = \delta^{18}\text{O}$ line in a three-isotope plot, which is offset from the CAI line. The isotopic composition of whole-rock equilibrated ordinary chondrites and chondrules from ordinary chondrites also define a $\delta^{17}\text{O} = \delta^{18}\text{O}$ trend; however, this line is not colinear with either the $\delta^{17}\text{O} = \delta^{18}\text{O}$ carbonaceous chondrite chondrule or CAI lines. Thus, there are (at least) three distinct $\delta^{17}\text{O} = \delta^{18}\text{O}$ compositional lines observed in meteoritic material. The OC chondrule lines have been suggested as arising from two reservoirs of

solid precursors [5] or solid-gas exchange [6]. For size-separated chondrules in Dhajala, a solid precursor at the ^{16}O -depleted end of the $\delta^{17}\text{O} = \delta^{18}\text{O}$ line exchanging with a gas near the terrestrial intersection was suggested to account for the observed isotopic composition. The opposite trend, however, is observed in Mezö-Madaras and the position of the gas and solid reservoirs would have to be reversed, thus presenting an obstacle to the solid-gas exchange model [4]. Another challenge not addressed is as follows. If the $\delta^{17}\text{O} = \delta^{18}\text{O}$ fractionation lines observed in CC, OC chondrules and CAIs arise from exchange processes, requiring six different reservoirs, how is it that these reservoirs are always situated such that they produce $\delta^{17}\text{O} = \delta^{18}\text{O}$ compositions? This would appear a remarkable coincidence unless the compositions arise as a result of the chemical process producing the chondrules.

The case for production of meteoritic O isotopic components, including chondrules, has been strengthened by a variety of recent observations. The $\delta^{17}\text{O} \cong \delta^{18}\text{O}$ composition has been observed in at least two of the Earth's atmosphere's most important molecules, O_3 [7] and CO_2 [8,9]. Mass-independent compositions have also been observed in tropospheric CO [10] and N_2O [11], thus $\delta^{17}\text{O} \neq 0.5 \delta^{18}\text{O}$ compositions are readily produced in nature. More recently, it was demonstrated that a gas phase reaction may result in production of a SiO_x condensate, which is ^{16}O enriched and mass independently fractionated [12]. Given that such components are readily produced in nature, it must be considered that the source of the $\delta^{17}\text{O} = \delta^{18}\text{O}$ compositions of carbonaceous and ordinary chondritic chondrules are chemical processes and the differences in chondrule $\delta^{18}\text{O}$ along a $m = 1$ trajectory reflect the physical chemistry of the chondrule-forming process.

There are several different types of chemically produced mass-independent fractionation processes. Laboratory experiments have recently shown that the source of the mass-independent O isotopic composition of stratospheric CO_2 is the simple isotope exchange reaction



where CO_3^* is an excited state, with a lifetime of 10^{-11} – 10^{-12} s [13]. The source of the mass-independent fractionation is the short-lived CO_3^* intermediate. As Fig. 1 demonstrates, the final isotopic composition, following exchange, is independent of the O-atom (produced from O_3 dissociation) isotopic composition, even if it is initially mass dependent. Following isotopic exchange, the O isotopic composition of the exchanged O is ^{16}O enriched with a $\delta^{17}\text{O} = \delta^{18}\text{O}$ composition with respect to the bulk (CO_2) reservoir. The striking aspect of these observations is not only the $\delta^{17}\text{O} = \delta^{18}\text{O}$ composition achieved, independent of original isotopic exchange, but the magnitude, which is essentially identical to that observed in CAI spinels (40%). In a chondrule-forming event, if an isotopic exchange occurs, a $\delta^{17}\text{O} = \delta^{18}\text{O}$ composition could be produced, with magnitude dependent upon extent of fractionation, as observed in the experiments of Wen and Thiemens [13].

It is observed in the thermal decomposition of ozone, an anomalous fractionation occurs [14], with the product O_2 enriched in ^{17}O and ^{18}O and $\delta^{17}\text{O} = \delta^{18}\text{O}$, another example of an apparent symmetry dependent fractionation. As discussed in a review [9], the key fractionation parameters are the terminal atoms. Thus, in a flash-heating event with dissociation, e.g., of silicate material, a $\delta^{17}\text{O} = \delta^{18}\text{O}$ fractionation could be produced, provided there is loss of some

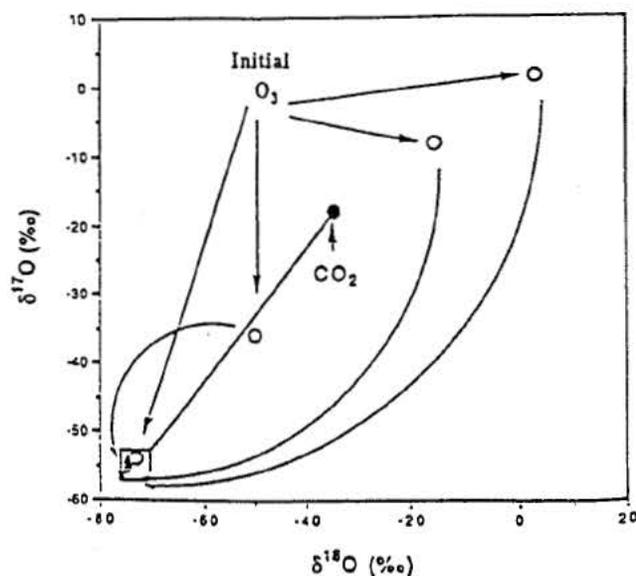


Fig. 1. The effect of initial isotopic composition between atomic O and CO_2 . Atomic O is derived from O_3 . Final isotopic composition of exchanged O is always within the square, which is depleted by $\delta^{17}\text{O} = \delta^{18}\text{O} = -40\text{‰}$ with respect to the bulk CO_2 reservoir [13].

proportion of the initial O. It is important to note that the fractionation arises in a simple gas phase thermal decomposition and requires no excited states.

One of the most significant recent advances with regard to application of chemical fractionation processes to meteoritics was the observation that in the gas phase reaction of $\text{SiH}_4\text{-H}_2\text{-O}_2$ at $\sim 800^\circ\text{C}$, a solid condensate is produced ($\text{SiO}_{1.8}$), which is ^{16}O enriched and mass-independently fractionated [12]. The anomalous fractionation may not arise from O_3 formation and is associated with the solid formation. This is the first demonstration of a solid production with anomalous O isotopes under quasinebulular conditions. It was observed that for the shortest experiments, the solid condensates possess an isotopic composition with $\delta^{17}\text{O} = 0.7 \delta^{18}\text{O}$, precisely the same as observed in enstatite chondrite chondrules.

In conclusion, there are at least three types of chemical processes that produce the isotopic compositions observed in chondrules and CAIs. The processes are rather general, viz, they require no specialized processes and the processes associated with chondrule production are likely to produce the observed compositions. Future experiments, particularly thermal, using controlled gas phase reactions involving SiO_x will be of fundamental importance in further resolving the role of chemical isotopic processes in the early solar system.

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ESTABLISHMENT OF REDOX CONDITIONS DURING PLANETARY COLLISIONS AS AN ORIGIN OF CHONDRITES. A. Tsuchiyama¹ and M. Kitamura², ¹Department of Earth and Space Science, Osaka University, Toyonaka 560, Japan, ²Department of Geology and Mineralogy, Kyoto University, Kyoto 606, Japan.

Collisions between a “cometlike” body (mixtures of chondritic materials and ice) and a slightly differentiated body were proposed for shock origin of ordinary chondrites [1]. In this model, chondrules were formed with shock melting, and matrices were formed both by fracturing of materials and by recondensation of evaporated materials. This model can explain different redox conditions of chondrite formations by ice evaporation. Although this model was originally proposed for ordinary chondrites, we assume here that the model can be extended to chondrite formation in general. In this paper, redox conditions during chondrite formation by collisions will be discussed in the light of phase diagrams for solid-vapor equilibria [2].

It has been known that a variety of oxidation states are exhibited by the chondritic meteorites. Formation of Fe-rich olivines in carbonaceous and ordinary chondrites may have occurred at low temperatures (<500K) in a gas of solar composition or at higher temperatures in a more oxidizing gas [3]. The former model at low temperatures encounters kinetic difficulties. On the other hand, the major constituents in enstatite chondrites could have been formed by condensation of a more reducing nebula gas with C/O = 1 [4]. These different redox conditions can be explained by evaporation of ice with different compositions originated from the “cometlike” bodies. This requires chemical fractionations of the “cometlike” bodies before collisions. Phase diagrams describing solid-gas equilibria at low pressures are useful for analyzing such fractionations, and have been constructed by thermochemical calculations [2]. If H is more abundant than other elements, dominant gas molecule species are simple in a wide range of temperature and pressure, and phase boundaries of vaporous minerals are simple. Such phase diagrams in the system Fe-Mg-Si-O-C-H are shown in Fig. 1. These diagrams are isobaric sections with a constant ratio of heavy elements (Fe, Mg, Si, O, and/or C)/H, and projected from the H-apex. In the diagrams O is taken as the independent component because O changes independently in the vapor phase. It should be noted that thermal barriers run from enstatite-Fe and silica-CO in the diagrams. These thermal barriers are present at high to low temperatures until H₂O ice starts to condense.

When cosmic abundance of the elements is assumed as an initial composition, it is easy to form the oxidizing conditions for carbonaceous and ordinary chondrites by changing the H₂O/H₂ ratios from

the solar composition in the right sides of the thermal barriers in the diagrams. On the other hand, it is seen from Fig. 1a that Si can be formed in the lefthand region (O-poor side) of the thermal barrier. Silicon is solved in metallic Fe in enstatite chondrites. This suggests that such Si-Fe alloys were formed from the O-poor region, such as with C/O = 1. However, it is hard to form such reducing conditions from the solar composition as long as the thermal barriers are present. Such O-poor fractionation can be possible at very low temperatures where the thermal barriers disappear after condensation of C-rich ice, such as CH₄. The above discussions on fractionations are essential even if nebular origins of chondrules are considered.

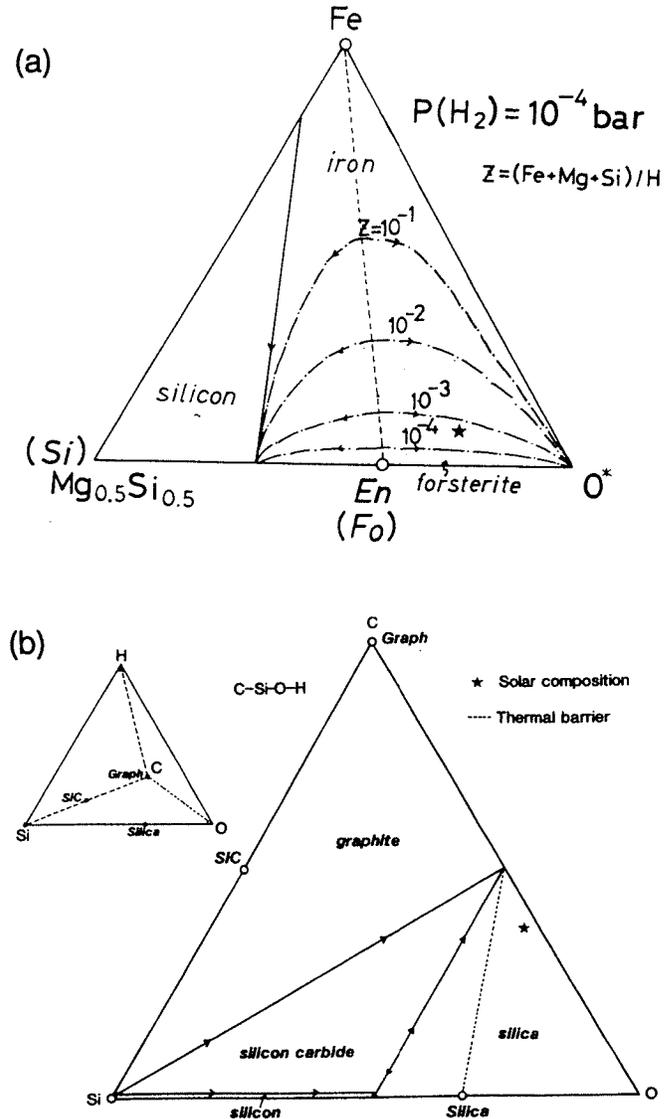


Fig. 1. Phase diagrams under nebula conditions showing vaporous boundaries projected from the H apex. (a) System Fe-Mg_{0.5}Si_{0.5}-O*-H (O* = O-C because of stable CO molecules). Iron-forsterite vaporous boundaries are a function of $z = (\text{Fe} + \text{Mg} + \text{Si})/\text{H}$. (b) System C-Si-O-H. Vaporous boundaries between graphite, silicon carbide, and silica are irrespective of the (C + Si + O) ratio. Dotted lines are thermal barriers, and asterisks show the solar composition.

It has been proposed that CO and CH₄ molecules were dominant, and oxidizing and reducing gas compositions were formed in the solar nebula and jovian subnebula respectively [5]. This can explain oxidizing conditions for carbonaceous and ordinary chondrites by evaporation of H₂O-rich ice formed in the main solar nebula, while reducing conditions for enstatite chondrites by evaporation of CH₄-rich ice formed in the jovian subnebula or under conditions similar to this nebula. It is likely that the ice-rich bodies collided with slightly differentiated bodies as projectiles.

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CHONDRULE ORIGINS: CONSTRAINTS FROM CHONDRULE PROPERTIES AND COSMOCHEMISTRY. J. T. Wasson, Institute of Geophysics and Planetary Physics, University of California, Los Angeles, Los Angeles CA 90024, USA.

The origin of chondrules is a problem for the ages. Yet even though a detailed formation mechanism remains elusive, the constraints on possible mechanisms become more stringent with each systematic examination of chondrules that involves a higher level of resolution.

My constraints are mainly based on studies of chondrules in unequilibrated ordinary chondrites because these have been studied much more than other primitive chondrites. In Table 1, I list these constraints in six categories; the first four are constraints of chondrule origin and the last two reflect the constraints chondrule properties place on the ambient nebula.

Perhaps the most important property of chondrules is that their bulk compositions are closely similar to that of the whole chondrite. Chondritic composition eliminates models calling for the remelting of igneous rocks because these would yield characteristic fractionations of rare earth elements, etc. Siderophile and chalcophile abundances are exceptions; they tend to be lower than chondritic because silicate chondrules are depleted in metallic Fe-Ni and FeS relative to the whole rock. This raises the question of the abundance of metallic chondrules. Spherical metal or metal-troilite particles certainly are rare, but the ragged metal shapes commonly observed probably resulted from extrusion of ductile metal into voids during chondrite compaction. It is possible that most metal particles were melted during the chondrule-forming heating events.

A number of key constraints are based on a combination of equilibrium thermodynamics and kinetics. Many (probably most) chondrules contain relict grains showing that they were incompletely melted. This indicates that the maximum heat fluence was generally not enough to bring temperatures to liquidus levels. This argues against chondrule formation in large, opaque portions of the nebula—having long ($\gg 1000$ s) thermal relaxation times. All chondrules have been $>50\%$ molten, thus their 50%-melting tempera-

TABLE 1. Constraints on chondrule origins.

I. Compositions and origins of precursor materials
<ul style="list-style-type: none"> a. Chondrules have chondritic compositions. b. Chondrules have not formed by melting igneous (differentiated) rocks.
II. The intensity of the heating events that melted the chondrules
<ul style="list-style-type: none"> a. Most chondrules were incompletely melted (indicated by relict grains, etc.), thus the heating events were marginally capable of melting chondrules. b. Most chondrules did not get hot enough (or stay hot long enough) to cause FeS to decompose. c. The fact that the upper limit on chondrule sizes is only $\sim 4\times$ the mean size may reflect the limited nature of the heating events.
III. The rate of heating and cooling
<ul style="list-style-type: none"> a. Volatile loss was minimal, implying brief, flash-heating events. b. Controlled-cooling simulations of chondrule textures imply cooling rates of roughly 0.1 K s^{-1}; these imply thermostating, i.e., hot surroundings.
IV. The number of heating (melting) events experienced by individual chondrules
<ul style="list-style-type: none"> a. Relict grains probably formed in earlier generations of chondrules. b. Independent compound chondrules resulted when a dust aggregate containing a chondrule was melted. c. Many chondrules have igneous rims recording the last flash-heating event. d. Chondrules were not strongly homogenized, thus the number of heating events was limited.
V. The temperature of the nebula at the time of chondrule formation
<ul style="list-style-type: none"> a. Most chondrules contain moderate amounts of FeS implying formation below 680 K. b. Some rare chondrules have low FeO/(FeO + MgO), low FeS, and low alkali contents, implying chondrule formation at $T > 1000 \text{ K}$. c. Some chondrules have FeO/(FeO + MgO) ratios $>30 \text{ mol}\%$, implying formation at $T < 500 \text{ K}$.
VI. The evolution of the solar nebula recorded in chondrules
<ul style="list-style-type: none"> a. As mentioned above, chondrule formation seems to have occurred continuously throughout all nebular epochs and temperature excursions. b. Primary or host chondrules and their secondary chondrules or igneous rims have similar FeO contents implying formation from the same batch of nebular materials, and suggesting that there was a storage region where the chondrule-forming process was not occurring. c. There was appreciable recycling of chondrule materials, as demonstrated by the common presence of relict grains in chondrules and rims; the rarity of microchondrules may reflect recycling.

tures represent the minimum temperatures reached during their formation; calculations using the MELTS program of Ghiorso show these range from about 1700 K to 1950 K. Because, in a canonical nebula having $p\text{H}_2 \leq 10^{-4} \text{ atm}$, all common (e.g., Mg, Si, Fe) and volatile elements are unstable with respect to vaporization at these 50%-melting temperatures, we know that the molten period was relatively brief, probably tens of seconds or less. The rate of cooling

can also be inferred by laboratory simulations of the structures that resulted from chondrule crystallization. Many of these experiments imply relatively slow cooling ($\leq 0.1 \text{ K s}^{-1}$) that seem to require the heating of large ($\geq 10^3$ -km-thick) regions. Slow cooling appears to conflict with observations on relict grains and volatile retention.

Evidence indicating multiple melting events is rapidly accumulating. In addition to the melting of the host chondrule one or more earlier melting events are required to explain relict grains and later events are required to explain independent secondaries of compound chondrules and igneous rims.

Most chondrules contain FeS, which, based on equilibrium relationships in a canonical nebula, is stable at nebular temperatures lower than $< 680 \text{ K}$. Most chondrule mafic minerals have FeO/(FeO + MgO) ratios $> 3 \text{ mol}\%$, indicating nebular temperatures $< 650 \text{ K}$, and many have ratios $> 20 \text{ mol}\%$, indicating temperatures $< 500 \text{ K}$. Nonetheless, some chondrules have olivine Fa $< 1 \text{ mol}\%$ and negligible contents of FeS and alkalis, indicating formation at $T \geq 1000 \text{ K}$, thus chondrule formation appears to have occurred across a wide range of nebular temperatures.

The independent compound chondrules offer information about the evolution of nebular solids. The most common observation is that the FeO/(FeO + MgO) ratio in independent secondaries is the same or slightly higher than those in the primary. This suggests that the two melt-producing heating events occurred within a time short compared to the mean time of nebular evolution (i.e., in a monotonic cooling model, short compared to the temperature relaxation time). Although chondrule materials were recycled through the melting process, the large amount of preserved diversity shows that there were far too few of these cycles to produce homogeneity.

Thus, a successful chondrule-formation model will include a flash-heating process that is repeatable.

THE FINE NEBULA DUST COMPONENT: A KEY TO CHONDRULE FORMATION BY LIGHTNING.

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Chondrule formation by lightning has been proposed several times in the literature [1–5]. Previously the overriding objection to the lightning process of chondrule formation has been that low nebula pressures prevented the buildup of large potential differences. The breakdown potential of a medium is the highest tension per unit length (V/cm) that can be put over the medium without a resulting ionization and avalanche of electrons and ions, i.e., lightning. In the terrestrial atmosphere (at 1 atm) the breakdown potential is $\sim 30,000 \text{ V/cm}$ [6]. The breakdown potential of a gas scale inversely proportional to the pressure [7], and in an H_2 -dominated nebula gas at 10^{-5} atm (corresponding to $\sim 2 \text{ AU}$ from the protosun [8]), is $\sim 0.3 \text{ V/cm}$. In a typical lightning bolt of 1 km this would lead to a potential difference of only 30,000 V, which is only marginally able to heat the chondrule precursor grains by impacting protons and electrons.

The breakdown potential is controlled by “the mean free live distance” of an electron. The mean free live distance is the distance

at which the concentration of primary electrons has been reduced to $1/e$ by recombination. We calculate the mean free live distance in pure H_2 gas at 2 AU to be $\sim 500 \text{ m}$. The mean free live distance can, however, be influenced by factors other than the gas pressure. We propose that part of the nebula’s inventory of dust load was present in the form of fine grains (≈ 25 -nm diameter). If the fine dust constitutes 4 wt% of the dust in the dusty midplane region having a half-thickness of 10^7 cm , the density of fine dust particles was $\sim 7 \times 10^7 \text{ particles cm}^{-3}$ at 2 AU. We estimate that this dust load leads to a reduced mean free live distance of only 7 m, or more than a factor of 65 smaller than that of the pure gas at 2 AU. The breakdown potential is therefore almost solely controlled by the dust. Very conservatively we estimate the breakdown potential to be at least 10, 1.8, and 0.7 V/cm at 1, 2, and 3 AU respectively.

We set the radius of the lightning bolt equal to the kinetic mean free path of the gas. The kinetic mean free path of H_2 at 1 atm is $\sim 80 \text{ nm}$ [9], and scaled to nebular conditions this corresponds to $\sim 1 \text{ cm}$ at 2 AU. We therefore propose bolt radii of 0.12, 1.0, and 3.2 cm at 1, 2, and 3 AU respectively. We assume that the length of the bolts are of the order of 1 km and calculate that the charge released during each strike is 12 mC at 2 AU, leading to an energy release of $63\times$ that necessary to heat and melt a standard chondrule of 10 mg.

Morfill et al. and Love et al. [4,5] claim that the duration of nebular lightning bolts are 10–100 s. Our calculations based on the electron drift velocities in a fully ionized H_2 gas show that first strike durations are 0.96, 3.4, and 7.0 ms at 1, 2, and 3 AU respectively, in much better accordance with the meteoritic evidence than 10–100 s. We cannot exclude that repeated strikes occur once the bolt channel is warmed up (a situation somewhat analogous to the stepped leaders and return strokes in terrestrial lightning), but we do consider it unlikely, primarily because the highly turbulent state of the hot, ionized region intersected by the stroke, which will cause rapid cooling by mechanical mixing.

In conclusion our assessment indicates that chondrule formation by lightning is indeed possible in the solar nebula.

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COOLING RATES OF CHONDRULES: A NEW APPROACH.

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Mineralogy and texture of chondrules have been reproduced experimentally and it was demonstrated that the abundance of heterogeneous nuclei is an important factor controlling chondrule textures [e.g., 1]. Cooling rates of chondrules were estimated from

the zoning patterns of olivine. Low cooling rates ($<100^{\circ}\text{C/h}$) yielded chemically homogeneous olivine crystals, whereas higher cooling rates, between 100° and 2000°C/h , produced olivine compositions similar to those observed in natural chondrules [e.g., 1]. Here, we want to present a new approach to determine cooling rates of chondrules based on the microstructure of chondrule clinopyroxene and plagioclase. All observations were made on Allende chondrules. Details of the transmission electron microscopy data are published elsewhere [2,3].

Pyroxenes in granular olivine pyroxene (GOP) chondrules from the Allende carbonaceous chondrite are Fe-poor and occur as clinoenstatite, orthopyroxene, pigeonite, diopside, and the lamellar intergrowth of pigeonite and diopside. The pigeonite/diopside exsolution lamellae are predominantly intergrown on (001), (100) lamellae are rare. The exsolution lamellae are often slightly wavy and occasionally interconnected indicating a formation by the mechanism of spinodal decomposition and coarsening. An average wavelength of pigeonite/diopside exsolution lamellae on (001) between 25 and 29 nm was observed. Modulated structures in between the (001) lamellae were observed in one grain, indicating the beginning of a second generation of exsolution.

The occurrence of (001) exsolution lamellae in clinopyroxene clearly limits cooling rates. High cooling rates, exceeding a few hundred $^{\circ}\text{C/h}$, would only yield nonperiodic fluctuations or modulated structures and thus can be excluded. Coarsening of exsolution lamellae is slow compared to spinodal decomposition and thus requires lower cooling rates.

The coarsening kinetics of (001) exsolution lamellae in Fe-free clinopyroxene at temperatures between 1300° and 1100°C was studied experimentally by [4]. Cooling rates are usually derived from isothermal time-temperature-transformation (TTT) diagrams [e.g., 5]. Based on experimental data of [4], cooling rates between 10° and 1°C/h in the temperature range of 1350° – 1200°C are obtained from the observed wavelengths of 25–30 nm.

The results of [4] were obtained from isothermal experiments and cannot directly be applied to systems undergoing exsolution during cooling. We therefore tried to model the growth of exsolution lamellae during continuous cooling assuming an initial temperature of 1350°C , which is close to the coherent spinodal [2]. These calculations yield the same order of magnitude ($\approx 10^{\circ}\text{C/h}$) for cooling rates of GOP chondrules in Allende. However, our estimate does only provide an order of magnitude of cooling rates. The major source of uncertainty arises from the fact that the observed wavelengths (25–30 nm) in Allende GOP chondrules are relatively close to the initial wavelengths of the isothermal experiments (5–11 nm). Kinetics of the first stages of coarsening is not well constrained in the experiments of [4], leading to large errors for small wavelengths.

An independent constraint on the cooling rate is obtained from the microstructure of Ca-rich plagioclase. Antiphase domains (APDs) of the type b are frequently observed in plagioclase (An_{90} – An_{80}) from Allende GOP chondrules. Their size varies between 10–30 nm. Type b APDs originate from subsolidus ordering of Al and Si (phase transition $\text{C1} \rightarrow \text{I1}$).

Coarsening of type b APDs in plagioclase was investigated experimentally by [6–8]. TTT diagrams based on the experimental data of [8] yield cooling rates between approximately 10° and 0.5°C/h , if a crystallization temperature for plagioclase of 1350°C is assumed. Lower crystallization temperatures would yield lower cooling rates. According to the ternary phase diagram Mg_2SiO_4 –

$\text{MgCaSi}_2\text{O}_6$ – $\text{CaAl}_2\text{Si}_2\text{O}_8$ [9], crystallization temperatures of Ca-rich plagioclase are between 1317°C and 1270°C . Thus, a crystallization temperature of 1350°C can be regarded as a conservative estimate.

In summary, two independent processes (Ca and Mg diffusion in pyroxene and Al/Si ordering in plagioclase) yield similar cooling rates on the order of 10° – 1°C/h for GOP chondrules in Allende. Our cooling rates are at least 1 order of magnitude lower than those derived from dynamic crystallization experiments.

However, it should be kept in mind that our estimate is only valid in the temperature range of 1350° – 1200°C . No information about cooling rates at higher temperatures can be obtained from the microstructure of clinopyroxene and plagioclase. At lower temperatures cooling rates may have been much faster, as indicated by the fact that we did not observe any orthoenstatite lamellae in clinoenstatite grains. According to experimental data of [10] this would suggest cooling rates on the order of 10^4°C/h at the temperature of the protoenstatite/orthoenstatite transformation ($\approx 1000^{\circ}\text{C}$). It is thus conceivable that a relatively short period of time with slower cooling was followed by a second stage of fast cooling.

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IMPLICATIONS FOR THE EVOLUTION OF CHONDRULES FROM AGGLOMERATIC OLIVINE CHONDRULES. M. K. Weisberg and M. Prinz, Department of Mineral Science, American Museum Natural History, New York NY 10024, USA.

There is considerable evidence that chondrules formed by the melting of solid materials [1–3] and, by default, the early solar nebula is the preferred location for chondrule formation [4]. Agglomeratic olivine (AO) chondrules supply perhaps the most intriguing, direct evidence for chondrule formation from agglomerations of solids. Agglomeratic chondrules have been defined by Van Schmus [5] as “a type of chondrule that has internal textures that suggest that they are mechanical mixtures of individual small crystal fragments of silicates, oxides, sulfides, and metal rather than a crystalline assemblage that is the result of crystallization from a melt.” They appear to be chondrules that were heated to temperatures too low ($\leq 1000^{\circ}\text{C}$) to initiate melting of olivine and pyroxene and as a result do not have the igneous textures commonly associated with chondrules [6]. They therefore may provide insights into the solids that were available in the nebula during chondrule formation. Since all models for chondrule formation must consider the nature of chondrule precursors, it is important to understand the physical, mineralogical, and chemical characteristics of the materials that were melted to form chondrules. Here we review the char-

acteristics of AO chondrules and discuss their implications for understanding chondrule precursors and chondrule evolution.

All AO chondrules are generally similar. They are fine-grained (>50% of grains are <5 μm), olivine-rich (>50% of grains are olivine) objects that are similar in size to coexisting chondrules. Their shapes range from irregular to round and they appear dark to opaque in thin section due to their fine grain size and fine FeS, in some cases. Many AO chondrules contain large (up to 600 μm) euhedral to subhedral transparent olivine crystals. Olivine is, by far, the dominant phase, making up to 94 vol%. Pyroxene, <20%, and plagioclase (glassy to cryptocrystalline), <20%, are much less abundant. Other phases that occur in minor to trace amounts (<5%) include chromite, metal, and sulfide. A few AO chondrules contain microchondrules and spinel-rich refractory inclusions. The dominant fine-grained olivine is Fe-rich (Fa_{28-51}). The larger olivine grains are Fa_{2-6} and all pyroxene is Mg-rich ($\text{En}_{<6}$). Bulk compositionally, AO chondrules have higher Fe and S than most other chondrules. Their refractory lithophile ratios (Si/Al, Mg/Al) are similar to those of most of the common porphyritic chondrules. The nonporphyritic (cryptocrystalline and radial pyroxene) chondrules, however, have higher Si/Al ratios and cannot be derived by closed-system melting of precursors that are compositionally similar to AO chondrules.

Since AO chondrules were heated to lesser degrees than other chondrules, they supply a unique opportunity to study solids that were present in the nebula during chondrule formation. Although mild heating and subsolidus reactions may have altered the compositions of AO chondrules, their mineralogical and compositional characteristics may be representative, for the most part, of the precursor mix of materials that were melted to form chondrules.

Open- vs. Closed-System Formation of Chondrules: There is considerable controversy as to whether the variations in chondrule compositions are mainly controlled by the compositions of the precursors or by open-system behavior during chondrule formation. It is perplexing that AO chondrules have a relatively narrow range of compositions that cannot easily account for the compositions of all chondrules. For example, why are there no agglomeratic chondrules compositionally equivalent to the pyroxene-rich nonporphyritic chondrules? Either we have not yet sampled these pyroxene-rich agglomerates, none survived chondrule formation, or all chondrules formed from a relatively homogeneous mix of precursors that were later modified by open-system behavior during chondrule formation. If the latter is true, then we hypothesize that the pyroxene-rich nonporphyritic chondrules could have been derived from AO chondrulelike materials by later incorporation of free SiO_2 into the precursor mix, or were formed by later liquid/gas exchange with a Si-rich nebular gas. Fractional condensation in a nebular location in which early formed forsterite is removed could result in the formation of free SiO_2 and/or a Si-rich nebular gas [7]. It is also possible that type I and II chondrules formed from the same batch of chondritic materials (i.e., AO chondrulelike objects) and their differences are due to modification by evaporation and/or reduction during chondrule formation.

Chondrule Precursors: The relatively narrow range of AO chondrule compositions suggests that most chondrules formed from a fairly homogeneous mix of precursor materials that were greatly dominated by olivine. Grain sizes of these precursor materials may have been in the 2–5- μm range or smaller; rare larger olivine and/or pyroxene grains were also present. Microchondrules and refrac-

tory inclusions are found in a few AO chondrules. This suggests that in some cases these components may have been melted and incorporated into chondrules melts; however, the scarcity of these materials in AO chondrules indicates that these were generally minor components in the mix of most chondrule precursors.

Formation of Chondrules by Incomplete Melting: The presence of larger olivine crystals in AO chondrules suggests that these crystals may have been present in the early mix of chondrule precursors. We therefore suspect that some of the large phenocrysts in some of the common type I and II porphyritic chondrules may not have crystallized *in situ* from the chondrule melt and may be relicts. Such chondrules may be considered to be agglomerates of large unmelted crystals trapped in a melt.

Heat Sources for Chondrule Formation: Sintered materials, such as AO chondrules and chondrule rims, may have been heated by the same flash-heating event as other chondrules, but were relatively further from the heat source. It is also possible that AO chondrules formed from mixtures of cold dust and hot droplets.

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MAJOR UNRESOLVED ISSUES IN THE FORMATION OF CHONDRULES AND CAIs. J. A. Wood, Harvard-Smithsonian Center for Astrophysics, Cambridge MA 02138, USA.

So much has been learned and published about chondrites, and so many models have been floated (but neither proven nor refuted) that the subject has become extremely diffuse and amorphous. It is impossible to remain simultaneously aware of all the many constraints, from many different subdisciplines, that bear on nebular processes. This paper attempts to impose some structure on the situation and loosen the interpretational logjam by breaking the chondrite problem into a series of well-defined questions (the list is in flux). Most are open questions; those that some might consider closed by now may deserve formal reexamination.

1. Were chondrules formed in the solar nebula (as opposed to planetary environments, or interstellar space near the nebula)? Personally, I don't consider this an open question, but it should be here for the record.

2. If in the nebula, were they formed during the ~0.5-m.y. stage of infall and rapid accretion, or the subsequent ~10-m.y. stage of relative quiescence pictured by astrophysicists [1]?

3. What is the relationship between CAIs (of various types) and chondrules? Were they formed by variants of the same basic process or by different processes altogether? This question is almost never addressed.

4. Over what span of time were the chondrules (and CAIs) created that were ultimately aggregated into any given small volume of chondritic material? Differences in ^{26}Al -initial among coexisting CAIs and chondrules require that they formed over an interval of ~10 m.y., if the Al in all these objects was once isotopically homogeneous. On the other hand, drag-induced radial drift of millimeter-to

centimeter-sized objects in the nebula limits their residence time in the disk to less than this.

5. Did chondrules form by melting of cold, preformed dustballs, or by the accumulation of hot droplets and dust [2]? The former option is universally assumed, but never examined or proven. Either model could incorporate relict grains.

6. Why does each chondrite class have such a sharply defined size distribution of chondrules?

7. Did chondrule/CAI formation always occur in a well-mixed system of cosmic composition, or was the bulk chemistry sometimes changed by physical fractionation of components that condense at different temperatures (involatile minerals, organics, ices, uncondensable gases)?

8. Did chondrules melt as closed or open (to the nebular environment) systems?

9. What were the pervasive impulsive heating events that created chondrules (and CAIs)? (This is the perennial question.)

10. Did these events really pervasively process planetary material in the nebula or was there a relationship between chondrule formation and the onset of chondrite accretion that caused only the processed fraction of planetary material to be preserved in planetesimals?

11. What was the base temperature of the nebula above which transient temperature excursions created chondrules (and presumably CAIs)? This question was reopened by [3] who, citing [4], concluded that the base temperature in the region of chondrite formation was 1200–1400 K.

12. Were the volatile-element depletions displayed by chondrites caused by the thermal processing that created chondrules, or were they already present in the bulk material that chondrule formation operated on?

13. What happened to the volatile elements that were excluded from chondrite formation?

14. Do all representatives of a given chondrite class (e.g., L chondrites) come from a single parent body?

15. Was there an infinite number (i.e., a spectrum) of chondrite types, of which we currently sample only a few, or only a limited number that is reasonably well sampled by the meteorites in our collections? The incorporation of clasts of familiar ordinary chondrite types in polymict breccias early in solar system history suggests the latter.

16. Does the same volatility mechanism that depleted volatile trace elements account for major-element (Si, Mg, Fe) differences between the chondrite classes?

17. Did the various chondrite classes form at different radial distances in the nebula, at different times in the history of the nebula, or both, or were they differentiated in some other way altogether?

The answers to questions 2, 9, 10, 11, and 17 would most strongly constrain astrophysical modeling, but in most or all cases consensus has not been reached among meteoriticists as to what the answers are. The author submits that progress in this area will be accelerated if modelists address these questions separately and explicitly. When the question addressed is linked to other questions, as it usually is, these should be acknowledged and the answers assumed by the writer/speaker should be explicitly stated and, if necessary, defended.

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FLASH HEATING IS REQUIRED TO MINIMIZE SODIUM LOSSES FROM CHONDRULES.

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Introduction: Chondrules were formed by high-temperature melting events, but do not always show Na depletion compared to CI chondrites [1,2], though extensive Na loss has been found in previous isothermal experiments [e.g., 3–5]. While Na loss can be prevented by high partial pressure of Na in the nebula [6], many people favor a flash-heating mechanism to reduce the Na loss from chondrule melts [1]. To examine the validity of the flash-heating hypothesis, we have conducted a series of flash-heating experiments, and observed Na loss rate under different conditions. Our results support the flash heating as a plausible heating mechanism to form chondrules.

Experiments: The experimental procedures are described in [7]. Samples include type IIAB (type II/III), type I, and type IA chondrule analog compositions of [5]. The maximum heating temperatures range from 1300°C to 1620°C. Charges were cooled nonlinearly with an initial (maximum) cooling rate ranging from >5000°C/hr to about 500°C/hr. The f_{O_2} was controlled at IW–0.5, –2, and –4 with a gas mixture of either H_2/CO_2 or CO/CO_2 . Some of the experiments were run in sealed static furnace gas, in which case the f_{O_2} can be maintained at the set value with an error of ± 0.1 log unit in the first 30 min.

Results and Discussions: The major results of our experiments are shown in Fig. 1. We observed much less Na loss from our flash-heating experiments than that from isothermal runs reported in [3,5]. The extent of Na loss is greatly influenced by f_{O_2} , thermal history, and sample composition. The effect of flowing furnace gas on the Na loss rate has also been observed. However, it is significant only under lower f_{O_2} , e.g., with an f_{O_2} of IW–2, the samples run in sealed static gas retain 5–7% more Na than in flowing gas.

Figure 1a shows that to lose <50% of Na, a type IIAB chondrule heated to its liquidus temperature and cooled initially at 2400°C/hr

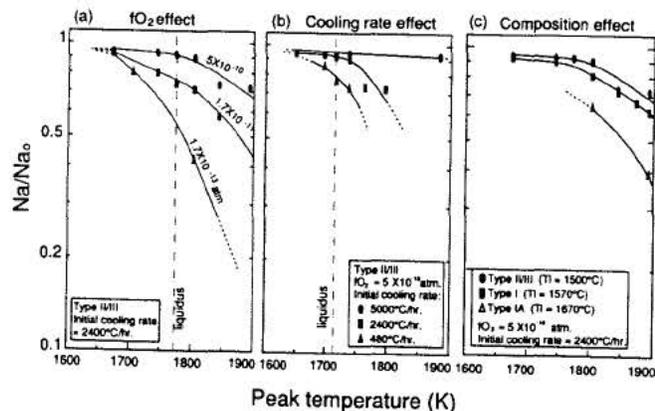


Fig. 1.

requires an f_{O_2} of higher than 10^{-14} – 10^{-13} atm (or slightly lower considering the gas flow effect). These values are about 3 orders of magnitude lower than that calculated by Grossman [1], and are closer to the proposed nebula f_{O_2} of $\sim 10^{-16}$ [1]. Many chondrules (e.g., type II), however, retained far more than 50% of their Na content. Our data indicate that to preserve >80% of the Na content, with an f_{O_2} of between 10^{-10} and 10^{-13} atm, the initial cooling rate has to be >2500°C/hr, or even >5000°C/hr (Fig. 1b). High as they might seem to be, compared to the linear cooling rates of 100°–1000°C/hr determined by [5,8], these are the initial cooling rates for a nonlinear cooling process, which is more realistic considering natural processes, and textures similar to those reported in [5] were observed in our charges. When approaching the solidus temperatures, the cooling rates are in the range of 500°–1000°C/hr. To retain >90–95% of Na, however, even with an initial cooling rate of >5000°C/hr, the f_{O_2} had to be higher than 10^{-11} atm, much higher than the canonical nebula value.

Different starting compositions show similar Na-loss profiles as a function of cooling rate and f_{O_2} , but exhibit noticeable difference in Na-loss rate (Fig. 1c). The Na-loss rates are not inversely correlated with the liquidus temperature of the samples, as speculated in [7], but quite the opposite. A composition effect on the Na vaporization has been found in several studies [e.g., 3,4], but the calculated viscosity and NBO/T for our samples suggest that the reasons might be more than just the difference in the degree of polymerization of the melt [3]. We suspect that the overall Na-loss rate of a charge might be related to the Na vaporization properties of the components of its starting materials. We plan to test this conjecture with more experiments on different compositions. If it proves to be the case, then it can place an important constraint on the chondrule precursor materials.

Flash heating can dramatically reduce Na loss in chondrules. In addition, with this short heating pulse, we not only reproduced the chondrule textures, but also demonstrated that extensive O isotope exchange can take place assuming diffusion controls the exchange process [9], contrary to the argument in [10]. Lewis et al. suggest that chondrules heated for a long time can also preserve their Na content when the partial pressure of Na vapor in the nebula was high enough [6], but the question of the source of the Na vapor has to be answered. Therefore, transient heating as a heating mechanism to form chondrules is plausible. For those chondrules that lost negligible amounts of Na, the f_{O_2} at the time of chondrule formation probably was higher than the canonical nebula value. Higher f_{O_2} in the nebula could be achieved locally by evaporating precursor materials in the dust clump during chondrule formation.

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CHONDRULE PRECURSORS AND COOLING PATHS: THE SULFUREVIDENCE. B. Zanda^{1,2}, Y. Yu³, M. Bourot-Denise^{1,2}, R. H. Hewins³, and H. C. Connolly Jr.³, ¹Museum National d’Histoire Naturelle, 61 rue Buffon, 75005 Paris, France, ²Institut d’Astrophysique Spatiale-91405 Orsay, France, ³Department of Geological Sciences, Rutgers University, P.O. Box 1179, Piscataway NJ 08855-1179, USA.

Introduction: The behavior of moderately volatile elements (Na and S) is controversial [e.g., 1] but critical in understanding chondrule precursors and heating processes. Sulfide appeared to be present in most chondrules [e.g., 2], but S should have been vaporized during chondrule formation. In fact, S is extensively redistributed in the course of metamorphism [3], and its abundance at the end of chondrule formation can only be inferred from the least equilibrated chondrites. Our study of 530 chondrules from Renazzo (CR2) and Semarkona (LL3.0) shows partial volatilization of S during chondrule formation and our melting experiments define conditions for total loss or partially retention of S.

“Primary” Sulfide Distribution in Chondrules from Renazzo and Semarkona: All type I and II chondrules in two sections of Renazzo and one of Semarkona were studied. Their diameters and crystal sizes were determined. The minimum crystal size (MCS) of chondrules is used here as a quantitative indicator of melting, as it is related to the size of the smallest crystals that survived the melting event. Average MCS for type I and type II chondrules of the two meteorites are given in Table 1 (numbers in parentheses refer to the number of chondrules observed). MCS is significantly higher for type IIs than for type Is (indicating more extensive melting of the former), but no difference exists between the two meteorites.

In Table 1, we also distinguish the chondrules that have internal FeS (as opposed to no FeS at all or only peripheral FeS). Type IIs with internal FeS have the same MCS as the whole population of type IIs. Type Is with internal FeS, on the other hand, are strikingly finer grained than the whole type I population, by almost an order of magnitude in MCS. This indicates that those of the type Is that had sulfide in their precursors lost most of it, except for the less-melted ones. Type IIs, on the other hand, were more extensively melted (a logical consequence of their lower liquidus temperatures), but their S retention exhibits no correlation with the melting degree. Differences in S abundances among type IIs could be inherited from the precursors, unless they are related to different cooling histories and/or different f_{O_2} conditions: We tend to favor the latter hypothesis since type IIs seem to have lost part of their S (although to a lesser degree than type Is).

TABLE 1. Minimum crystal sizes in different categories of chondrules (see text).

	Type I		Type II	
	Renazzo	Semarkona	Renazzo	Semarkona
All chondrules	63 μ m (210)	66 μ m (128)	175 μ m (6)	179 μ m (184)
Chondrules with internal FeS	9 μ m (13)	6 μ m (25)	175 μ m (6)	210 μ m (73)

Table 2 gives the S abundance in the chondritic components of Semarkona and shows that, apart from dark-zoned chondrules (less-melted ones, and only a few percent of the chondrule population), chondrules are very depleted in S by comparison with the other components, type Is being, as expected, significantly more depleted than type IIs. Table 2 also shows that the S present in the bulk meteorite is not accounted for in the components reported, since (except for dark-zoned chondrules) all have less S than the bulk. Sulfur in Semarkona is concentrated in the opaque rims that are observed together with isolated troilite grains around approximately three-fourths of both types of chondrules and probably derive from S recondensation at the end of chondrule formation [e.g., 4,5]. Since type IIs exhibit such opaque rims as frequently as type Is and they are depleted in S relative to the bulk, we believe they also lost part of their S as a result of chondrule formation.

Presence of Sulfur in Chondrule Precursors: Although chondrules are melted assemblages, no melt textures between metal and sulfide have been reported before. This stems from metal being rare in type IIs, while S has been lost from most type Is. In the few metal-bearing type IIs and fine-grained type Is we found melted assemblages, including eutectic textures, indicating that S was indeed present in precursors. Sulfide inclusions (Cr sulfide in type Is and troilite in type IIs) are often present in chondritic metal: They most likely derived from a minor amount of S remaining trapped in the metallic melt when most chondrule S was lost. Cr-sulfide inclusions are more abundant in the finer-grained (less-melted) type Is. Abundance of S in dark-zoned chondrules gives a lower estimate of S abundance in chondrule precursors. As noted in [6], for example, the presence of S in chondrule precursors implies these were assembled at temperatures below 650 K.

Experimental Evidence of S Behavior in Chondrule Formation: We conducted experiments to find when and to what degree S could be preserved in chondrules. All the S was lost from isothermal runs, whereas in the case of flash heating, some charges did partially retain their S, depending on initial temperature, heating time, and cooling rate. In those cases, sulfide remains consisted of blebs evenly distributed throughout the charge and, when associated with metal, displayed melt and eutectic textures similar to those observed in natural chondrules.

Conclusion: The comparison of S behavior in chondrule formation with experimental conditions allows us to put constraints on the heating conditions of chondrules as summarized in Fig. 1, where the middle region is where experiments with remaining S were found. In order to preserve some S in chondrules, peak temperatures may have been as high as 1750°C (for about a minute) if initial

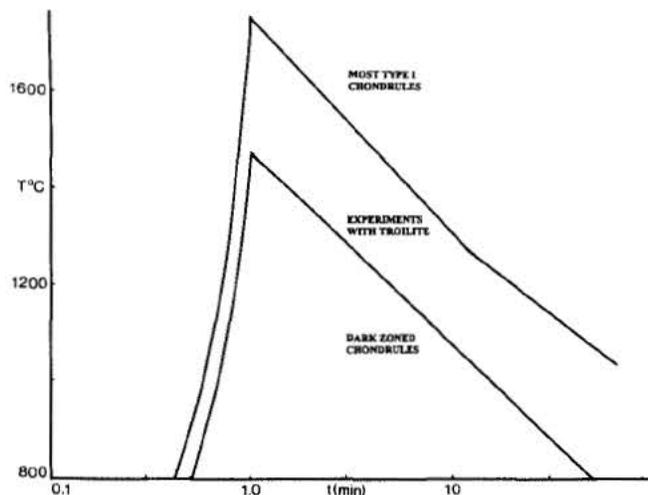


Fig. 1. Sulfur behavior as a function of heating and cooling conditions.

(tangential) cooling rate was at least 5000°C/hr, or as low as 1470°C if initial cooling rate was much lower. These results are consistent with a flash-heating mechanism for chondrule formation.

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TEXTURAL VARIABILITY OF ORDINARY CHONDRITE CHONDRULES: IMPLICATIONS OF THEIR FORMATION. N. G. Zinovieva, O. B. Mitreikina, and L. B. Granovsky, Department of Petrology, Faculty of Geology, Moscow State University, Lenin Gory, Moscow 119899, Russia.

SEM (CamScan 4-DV) and microprobe examination of the Raguli H3-4, Saratov L3, and Fucbin L5-6 ordinary chondrites and the analysis of preexisted data on other meteorites have shown that the variety of textural types of chondrules depends on the chemical composition of the chondrules. The comparison of bulk-rock chemistries of the chondrules by major components demonstrates that they apparently fall, like basic-ultrabasic rock, into groups of dunitic and pyroxenitic composition. This separation is further validated by the character of zoning in chondrules of the intermediate, peridotitic type. The effect is vividly demonstrated by the “chondrule-in-chondrule” structure.

The chondrules of dunitic and pyroxenitic composition of any petrological type always have sharp boundaries with matrix. The peridotitic chondrules of low petrological type chondrites have the

TABLE 2. Sulfur abundance (wt%) in the chondritic components of Semarkona.

Component	Abundance (st.dev.)	Reference
Bulk	1.9	[7]
Type I chondrules	0.07 (0.05)	[8]
Type II chondrules	0.34 (0.44)	[9]
Dark-zoned chondrules	2.5 (2.4)	[10]
Coarse-grained chondrules	1.2 (1.2)	[10]
Matrix	1.6 (1.4)	[10]

sharp boundaries with the matrix as well, while the boundaries of the peridotitic chondrules of high petrological type chondrites are indistinct.

Earlier we presented [1,2] the evidences of liquid immiscibility genesis of low petrological type chondrites: (1) the droplike chondrule structure often slightly extended according to the fluidal structure, (2) the existence of the compound chondrules forming dumbbell-shaped clusters of two or three drops (it is necessary to note that the growth of the olivine and pyroxene crystals of the junction is directed toward both chondrules), and (3) the existence of the sharp boundary chondrule-matrix often accompanied by the monomineral olivine rim in which we could observe the growth of the olivine crystals (directed normally to the boundary) both toward the chondrule and the matrix.

The silicate ground mass surrounding the dunitic and pyroxenitic chondrules of the high petrological type Fucbin L5 chondrite conforms to the chondrule's outlines, and some minerals and their aggregates started to crystallize on the chondrule surface. This process indicates that the chondrule-matrix boundary did exist prior to the ground-mass crystallization.

The comparison of chemical composition chondrules of different chemical group chondrites has shown that the ratio of major petrogenetic elements in every of these groups was responsible for the formation of different chemical types of chondrules (dunitic, peridotitic, and pyroxenitic), while the amount and ratio of minor elements were responsible for variety of textural types of chondrules inside these chemical types of chondrules.

There are three chemical types of chondrules (Fig. 1) depending on the content of major petrogenetic chondrite components: SiO_2

and $\text{FeO} + \text{MgO}$. These three groups are comparable to ultrabasic rocks of dunite, peridotite, and pyroxenite compositions. The increasing of the silica content from dunitic to pyroxenitic group of chondrules increases the variety of textural types of chondrules as the silicity of the respective group becomes higher. Chondrules of the dunite composition form just barred-olivine, porphyritic-olivine, and granular textures, while pyroxenitic chondrules have any textures with different amounts of pyroxene and olivine. Changes in liquidus assemblages are controlled by the ratio $\text{SiO}_2/\text{Al}_2\text{O}_3$ in the chondrule bulk-rock chemistry. Lines 1 and 2 outline fields of chemical compositions of chondrules with porphyritic grains of olivine, olivine + pyroxene, and pyroxene accordingly. Line 3 outlines the field of chondrules poor in alumina. This group of chondrules is characterized by nearly holocrystalline texture. Chondrules more or less enriched in Al_2O_3 (plagioclase component) show a wide range of structural types within every compositional group, and chondrules rich in Al_2O_3 form the glassy textures. So within each of these chemical groups the texture type depends on the amount of Al_2O_3 .

The textural type of chondrules depends (Fig. 2) on the ratios $(\text{Na}_2\text{O} + \text{K}_2\text{O})/\text{CaO}$ and $\text{SiO}_2/\text{Al}_2\text{O}_3$. Regions with constant proportions of minor components correspond uniquely to the modal composition and texture of chondrules. In contrast to previous diagram, different textural types of chondrules form different fields that vary in ratios of minor elements. Even fields of porphyritic and radial chondrule textures can be distinguished by the ratio of minor elements.

The separation of the experimental melted ordinary chondrite melts into silicate and sulfide-metallic melts [3] with further sepa-

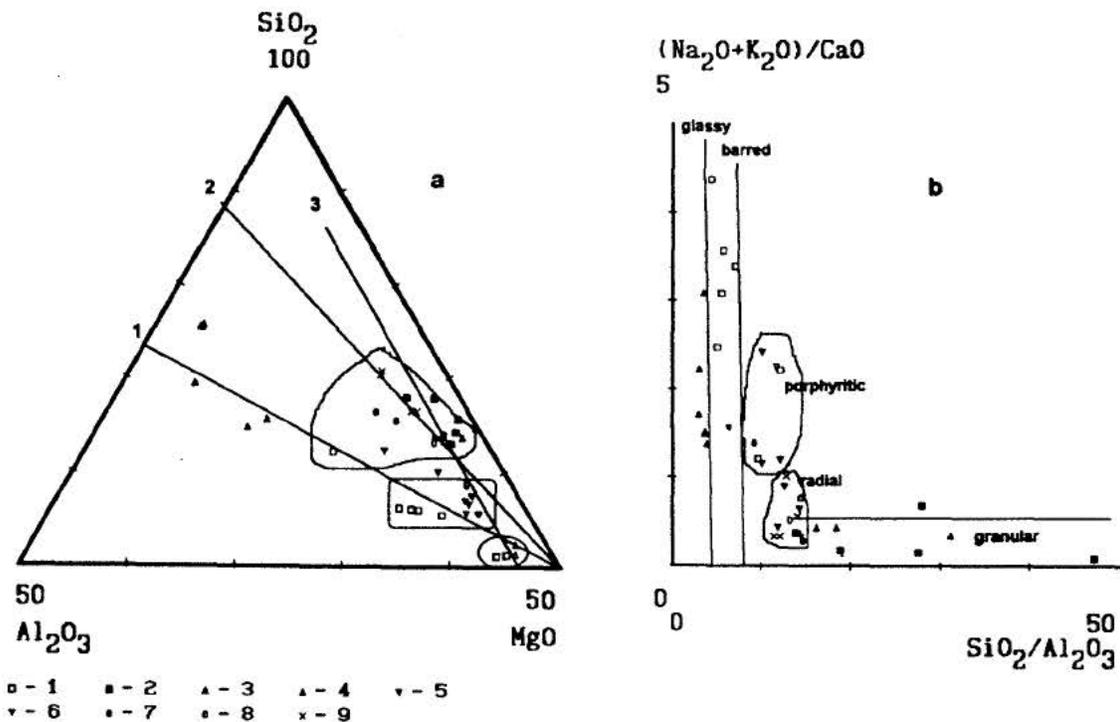


Fig. 1. (a) Chemical chondrule types and (b) texture chondrule types. 1 = barred Ol; 2 = granular Px (fine-grained); 3 = cryptocrystalline (glassy); 4 = granular Px-Ol (coarse-grained); 5 = barred Px-Ol; 6 = porphyritic Ol-Px; 7 = porphyritic Px; 8 = radial Ol-Px; 9 = radial Px.

ration of the sulfide-metallic melt into sulfide and metallic melts [4–6], and further separation of the silicate melt into two coexisting immiscible silicate melts [7] is well known.

The comparison of natural chondrule compositions and experimental melts has shown that there is liquid immiscibility of two scales (macro- and microscale immiscibility). Melts of the strongly different composition (dunitic and pyroxenitic chondrules) have formed as a result of macroscale immiscibility. This type of immiscible splitting or separation can be and have been modeled. Chondrules different in texture but close in their chemical composition (different just in minor elements) have formed by the microscale immiscibility. It is very difficult (maybe impossible) to model such immiscible separation, because the multicomponent system is much too complicated. The same problem has been discussed for the metal-sulfide system [6], where we have described the existence, in contrast to phase diagrams, of the liquid immiscibility in the real Fe-Ni-S system.

We suppose [6,8] that the variability in textural types of chondrules with different silicities as well as their discrete silicity itself and the immiscible separation of chondrite melt into silicate and metal-rich constituents is controlled, within a particular meteorite, by the microheterogeneity of the silicate melt, which is connected with the process of microscale immiscible splitting. This process is controlled by the mechanism of acid-base interaction of chemical components of a single silicate system. This phenomenon is typical of all chondrites, including their high petrological types. The micro-

immiscible splitting characterizes the superliquidus zone of multicomponent system, has a metastable character, and occurs under sharp supercooling.

The constant compositions or the similar zoning of minerals and the similar two-stage character of the chondrule crystallization for every chondrite group show that there was crystallization from a common (for every chondrite group) parental silicate melt with the same temperature of the beginning of the crystallization and with just a single period of intense supercooling. Similar conditions of the melt supercooling in chondrules of different chemical group chondrites let us suppose [8] that their origin is due to catastrophic explosions, which may be responsible for the destruction of planets themselves on the chondrite stage of their formation.

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