



Supporting Online Material for

The Formation Conditions of Chondrules and Chondrites

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Fig. S1

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Analytical methods

Tables A1-A4 list the bulk, glass, core olivine and rim olivine compositions used in calculating the K_{DS} listed in Table 1 of the paper. All were measured by electron microprobe using Carnegie's JEOL JXA-8800L electron microprobe and the USGS's JEOL JXA-8900 microprobe. Both are equipped with five wavelength dispersive spectrometers (WDS). For all data reduction, the ZAF correction was used.

Olivine analyses were conducted with a 15 kV, 100 nA beam either as a focused spot or rastered over a 5x5 μm area. All elements were measured by WDS. To minimize the possibility of interferences affecting the Na analyses, a narrow pulse height analyzer energy window of 2 V centered on the Na peak was used and the background measurement positions, 2.1 mm on either side of the Na peak, were carefully chosen for regions where there should be no peaks from other elements in the olivine. In the absence of a suitable olivine standard, an augite standard was used for the Na calibration. Under these conditions and a total analysis time of 1600 s (800 s on the Na peak), a 3σ detection limit for Na in the olivine of ~ 26 ppm was achieved. Repeated analyses showed that olivine is stable against Na loss under these conditions. When possible, profiles across phenocrysts and the cores of olivine microphenocrysts (~ 10 μm) were measured, along with the compositions of the glass and clinopyroxene.

Clinopyroxene analyses were done using 15 kV and 20 nA beam current, with a focused beam. Analysis times were varied, from 60 s on the Na peak in clinopyroxene grains in type II chondrules to 1800 s for those in some type I chondrules. Five to ten areas of glass were measured in each chondrule, chosen to be as free of clinopyroxene crystallites as possible, and covering both the inner and outer parts of the chondrule. Glass analyses followed the procedure of Grossman and Brearley (1). This included a correction made for Na loss during analysis of glass in type II chondrules, which, for the conditions used, was $\sim 11\%$. Although this correction accounts for Na loss during our own analyses, we could not fully assess or correct for Na loss suffered during previous

analyses of our sections by other workers. Previous spot analyses of mesostasis would have depleted the area by at least a factor of 2 in Na, which would be revealed by a statistically low Na measurement relative to other points in the same chondrule. Several of these were encountered, and discarded. Previous x-ray mapping or other prolonged exposure to a scanning electron beam presents more of a problem, as this has the potential to deplete Na in mesostasis over a wide area; experience shows that typical x-ray mapping conditions (100 nA beam current and 20-30 ms dwell time per pixel) can deplete Na by at least 10%. Such artificial depletions would be difficult to detect.

Bulk compositions were measured by superimposing a 10×10 grid of analytical points over each chondrule. Each point was analyzed using a 10 μm wide rastered beam, at 15 kV accelerating voltage and 20 nA beam current. For these measurements, WDS was used for Na, Ti, Al, Mg, Mn, and K, and energy dispersive analysis was used for Si, Ca, Cr, Fe, P, Ni and S. The method had a total analytical time of 70 s for each spot. After analysis, each point was located using backscattered electron imagery, and those falling outside the chondrule border and on cracks or holes were discarded. Analyses with totals below 80% were also discarded, as were analyses that showed evidence for contamination with polishing compound ($\text{Al}_2\text{O}_3 > 3 \text{ wt}\%$, CaO and $\text{Na}_2\text{O} < 1 \text{ wt}\%$; a problem in one of our thin sections). FeO was recalculated by subtracting Fe to form FeS with any measured S. A correction was also made for Fe present as Fe-Ni metal. To do this, spot analyses of metal grains in each chondrule were done for Fe and Ni. FeO was again corrected by removing enough Fe to combine with measured Ni to form Fe-Ni of the appropriate composition. The resulting compositions, including FeO, FeS, and Fe-Ni were normalized to 100% to correct for small cracks, and an average was calculated for the entire chondrule.

Because the average compositions calculated for each chondrule are essentially a modal reconstruction, the data was corrected for the densities of glass, metal, troilite, olivine, and pyroxene contributing to the uncorrected bulk composition. The volume percent of modal glass was calculated by subtracting the average composition measured for mesostasis in each chondrule (Table A2) from the uncorrected bulk composition until either Na or Al, or in a few type I chondrules, Ca, was used up; usually Na and Al approached zero at nearly the same time during the calculation. The volume percent of

metal and troilite were taken to be their concentrations in the uncorrected bulk composition. The residuum after subtracting mesostasis, metal, and troilite was mainly the modal olivine plus pyroxene, and the olivine/pyroxene ratio could be calculated from the (MgO+FeO)/SiO₂ molar ratio. The volume percentages of all four phases were then converted to weight percentages on the basis of their densities. The density-corrected bulk composition was then calculated by multiplying the composition of each component by its weight fraction and summing. Because of larger uncertainties, occasionally low abundance elements concentrated in the glass, like K, would be negative in the residuum. In these case, the bulk K/Na ratios, for instance, were taken to be those of the glass. For P, in type IIs its bulk abundance was determined from its abundance in glass and in type Is from its abundance in metal.

Glass densities were estimated using the approach of (2, 3). First the density of a melt with the glass's composition was calculated at an estimate of the limiting fictive temperature using the data of (4). The limiting fictive temperature, T_f , is where melt and glass would have the same density. Then the glass density at room temperature was calculated using an estimate of its coefficient of thermal expansion (α). The values of T_f and α were estimated using the empirical functions $T_f = 1175.5 - 93.93R$ and $\alpha = 10^{-5}(1.877R + 0.5319)$, where R is the ratio of the mole fractions of network modifiers to network formers (e.g., $(X_{MgO} + X_{FeO} + X_{CaO} + 2X_{Na_2O}) / (X_{SiO_2} + X_{Al_2O_3} + X_{P_2O_5})$). This approach is able to reproduce the room temperature glass densities measured by (2) to within 1-2%. The density of olivine was calculated from the atomic Mg/(Mg+Fe) ratio of the calculated olivine and pyroxene component based on the data of (5). The density of pyroxene was estimated by interpolating between 3.2 and 3.95 g/cm³ for end-member enstatite and ferrosilite, respectively. The densities used for troilite and Fe-Ni were 4.61 and 7.95 g/cm³, respectively.

Assessing the bulk chondrule, mineral and glass compositions

Accurate analyses, particularly of Na in olivine, are essential to this study, but the measurements can potentially be compromised in a number of ways. For instance, olivine phenocrysts often contain inclusions, and near the edges of the grains there can be x-ray fluorescence of the adjacent glass or glass just below the surface of the section. These effects will compromise the analyses, especially for elements like Na with low abundances in the olivine and high abundances in the glass. Analyses of clinopyroxene can also be compromised in this way. Consequently, all olivine and clinopyroxene analyses were checked for stoichiometry. In addition, those analyses that differed markedly from the bulk of the analyses were rejected. Generally, in the olivine Na, Mg, Fe, Cr, Mn and Ca are correlated. As a further check, if any phenocryst and microphenocryst analyses fell off the correlation trends in the direction of the glass composition, they were also rejected. Finally, in type II chondrules Al contents are always low. Because even very minor ‘contamination’ of an olivine analysis by glass or inclusions can have a marked effect on Na abundances, only type II olivine analyses with Al₂O₃ contents <0.04 wt% were used. A number of analyses of phenocryst rims and microphenocrysts that were very close to the glass were rejected using this criterion, but it was deemed more important to have reliable Na contents than questionable analyses at the very edges of the grains.

Chondrules, particularly in Semarkona, can have radially zoned mesostasis compositions (6-8). This zonation is secondary, produced by an influx of alkalis, halogen and water after crystallization of clinopyroxene; it probably occurred on the parent body (6, 7). Glass compositions were measured at the edges and cores of the chondrules. If there was a significant difference between edge and core compositions, only the core compositions were used. When evidence for alkali zonation in the mesostasis was found, the Na contents of the bulk compositions were adjusted to give the same Na/Al ratios as those of the core glasses.

A final complication in the analysis of glass in type II chondrules is caused by the segregation of alkalis into two separate phases, albitic feldspar and a more K-rich glass (Grossman and Brearley, 2005). The glass has a Na/K ratio fairly close to chondritic and represents the original mesostasis at the end of crystallization; the albite frequently has Na/K >20×CI, and was likely formed after the solidification of the chondrule. Fifty

percent of the type II chondrules in this study contained albitic regions in the mesostasis. Any analyses of glass that were high in Na and had anomalously high Na/K were discarded.

Clinopyroxene and the initial compositions of chondrule glasses

Even in the chondrules with no alkali radial zonation in their glass, the high mobility of Na means it is possible that they have not remained closed to Na since formation. The Na₂O contents in clinopyroxene and glass in our chondrules resemble those reported in previous studies (6, 9) – for type Is $K_D \approx 0.04$ lines, while the K_D s for most type IIs are significantly higher and more variable. The late crystallizing clinopyroxene in chondrules offers a means to test whether there has been post-crystallization entry of Na into chondrules.

Previously, it was shown that the good correlation between clinopyroxene and glass Na contents in type I chondrules are consistent with clinopyroxene crystallizing from melts with Na contents like that of the current mesostases at temperatures of ≥ 1573 K (6, 9, 10). This temperature is roughly consistent with clinopyroxene crystallization temperatures predicted by MELTS. In type II chondrules, Na in clinopyroxene and glass are not well correlated. This lack of correlation is expected if the clinopyroxene in type IIs typically formed at lower temperatures than in type Is because the Na clinopyroxene-melt K_D becomes more temperature sensitive below ~ 1573 K (6). While we cannot rule out some loss or gain of Na in type II chondrules, the clinopyroxene-glass K_D s suggest that the Na contents of most chondrule glasses (excluding the outer regions of zoned chondrules) were set at the time of the final crystallization of the chondrules.

Assumptions and sources of error in the calculation of K_D s.

A number of assumptions go into estimating the K_D s. For estimating the rim K_D s from the phenocrysts' rims and from microphenocrysts, it is necessary to assume that: (i) the glass has not experienced any change in Na content since solidification, and (ii) the olivines measured were in equilibrium with the glass. The clinopyroxene compositions

suggest that the glasses in most of the chondrules resemble the final melt compositions. However, Na is quite mobile in chondrule glasses, particularly in type IIs, and loss or gain of Na after solidification could account for the distribution of chondrules along the 1:1 line in Figure 2. Some Na loss could even have occurred during analyses of our sections by earlier workers.

It is difficult to demonstrate that the olivines that were measured were in equilibrium with the final melt. They are the most extreme compositions we were able to obtain for each chondrule that met the criteria listed above. However, it is not possible to analyze the olivine directly in contact with the glass because fluorescence of the glass will lead to anomalously high Na contents. It is likely that there was some clinopyroxene and olivine growth after the measured olivines crystallized. Therefore, the reported rim K_{DS} should be regarded as lower limits. The pyroxene-bearing chondrules are particularly variable in the ratios of their core/rim K_{DS} (Table 1 and Fig. 2), possibly because olivine ceased crystallizing or was dissolving while the pyroxene was crystallizing, and so the olivine phenocryst rims were not in equilibrium with the observed glass.

For the core K_D estimates, the necessary assumptions are that: (i) the chondrules were full molten when they formed, (ii) that the most extreme core composition in the section of a chondrule reflects the composition of the first material to crystallize, (iii) that there was little re-equilibration during crystallization, (iv) that relict cores can always be recognized and avoided, (v) that the chondrules have remained closed to Na loss or gain since their initial melting, and (vi) that the estimated bulk compositions resemble the true ones (i.e., the sections of the chondrules are representative of the whole, and the grid sampling was unbiased).

All but two of the chondrules analyzed have porphyritic textures. C33 is a barred olivine type II chondrule and was therefore entirely molten. C6 is a type I chondrule that also has olivine bars in its core. Experiments show that to develop porphyritic textures requires that some nuclei survive melting, but these nuclei could be much smaller than the resolution of our instruments. Thus, it is entirely possible that the porphyritic chondrules were essentially completely molten. Nevertheless, it cannot be ruled out that some of the cores are unmelted relicts with similar major element compositions to the surrounding olivine, making them difficult to recognize. Recognizing relict cores is

particularly problematic in type Is. Many of the phenocryst cores in the type Is studied had somewhat higher FeO contents than the rims. This and the high core K_D s in the type Is could be the result of loss of Na and increasingly reducing conditions during cooling. However, it could also mean that most of the cores are relict.

Olivine compositions do not change much in the early stages of crystallization. Consequently, although it is unlikely that any of the sections of the phenocrysts have passed directly through their centers, as long as one or more section in each chondrule passed close to the center, assumption (ii) will be valid.

The preservation of zoning in phenocrysts, particularly those with relict cores, suggests that there was little re-equilibration during crystallization. However, for many chondrules the core compositions are not as Mg-rich as the first predicted by MELTS using the estimated bulk compositions. This could reflect uncertainties in MELTS for these compositions and errors in the assumed fO_2 during crystallization, but it is possible that the measured cores do not represent the very first crystallites, perhaps because near equilibrium was maintained while the crystallites were small.

Calculation of olivine zonation in Figure 1

The two Na zonation curves in Figure 1 of the paper illustrate what would be expected for closed system crystallization and for formation in the nebula with solids densities that until now were considered very high.

The closed system curve was calculated using the bulk composition of chondrule C3 and progressively extracting olivine from it. The Na content of the olivine at each step was calculated using the Na content of the residual melt and a K_D of 0.0075. This K_D is intermediate between the core and rim K_D s measured for chondrule C3 (Table 1). The final mass of olivine was assumed to form 60 μm phenocrysts, allowing for calculation of the radial zonation from the mass fraction of olivine that had crystallized at each step.

To model open system formation in the nebula, we calculated the equilibrium mineral, melt and gas compositions at 10 K intervals from 2000 K, when olivine first appears, to 1140 K. The only silicate phases that were allowed to form were olivine, pyroxene (ortho- and clino-) and silicate melt. The total pressure of the nebula gas was assumed to

be 10^{-3} bars, and the system was enriched 1000 times in CI-composition solids relative to the solar abundance. The predicted radial zonation was calculated as above from the fraction of olivine that had crystallized and the Na content of the melt at every temperature interval. Sodium is confined to the rim of the model phenocryst because it only begins to reside in the melt in significant amounts below 1600 K, while the olivine has already been crystallizing for more than 400 K of cooling. At its center, the predicted phenocryst has what, in terms of Fe/Mg ratio, resembles a relict core. However, this is probably not how relict cores form. While common, relict cores are not ubiquitous in type II chondrules, and the Na zoning around the relict cores is quite different from what is predicted.

Calculation of chondrule equilibrium vapor pressures and solids densities

The equilibrium Na vapor pressure (p_{Na}) over a chondrule is determined by the reaction $\text{Na}_2\text{O}_{(l)} = 2\text{Na}_{(g)} + \frac{1}{2} \text{O}_2$. Hence, the ambient $f\text{O}_2$ largely dictates the Na vapor pressure of a chondrule – the higher the $f\text{O}_2$, the lower the p_{Na} . There is some uncertainty in what controlled the $f\text{O}_2$ during chondrule formation, particularly for the type IIs. Consequently, we calculated the equilibrium vapor pressures in two ways to cover the likely extremes in the $f\text{O}_2$. In the first approach, the equilibrium vapor pressures of the chondrules were calculated using the approach of (11, 12) assuming that only silicates were present (i.e., there was no metal present to buffer the $f\text{O}_2$). Na_2O and P_2O_5 largely dictate the $f\text{O}_2$ under these conditions, and the $f\text{O}_2$ can be orders of magnitude above the iron-wüstite buffer. At such high $f\text{O}_2$ s, one might expect significant Fe^{3+} to be present in chondrules, but primary Fe^{3+} -bearing minerals have not been reported in chondrules. Thus, this approach represents the most oxidizing conditions that could have existed during chondrule formation. If H_2 was present during chondrule formation, as would have been the case if chondrules formed in the nebula, this will depress the $f\text{O}_2$ and increase the p_{Na} .

If metal was present during chondrule formation, as appears to be the case for most chondrules, it will buffer the $f\text{O}_2$ through reaction with FeO in the melt. At least small amounts of metal and sulfide are present in all the chondrules studied (Table A1). However, it is not clear to what extent the metal and sulfide have been affected by

secondary processing. Also, because metal and sulfide will form a single melt at high temperature, it is necessary to accurately determine the metal/ sulfide ratio. This is not always easy to do. Because of these potential ambiguities, rather than use the measured metal/sulfide compositions, in the second approach we assumed that chondrules equilibrated with pure Fe-metal. This results in the lowest f_{O_2S} that were likely to have existed during chondrule formation.

The solids densities required to approximate closed-system behavior were estimated by calculating, for a given temperature and partial pressure of Na, the density of solids required for 90% of the Na to remain condensed. In this case, the solid density, S (g/m^3), is given by

$$S = \frac{P_{Na} M_{Na} f_{Na}}{(1 - f_{Na}) R T X_{Na}}, \quad (1)$$

where P_{Na} is the equilibrium Na vapor pressure of the chondrule (N/m^2), M_{Na} the molar weight (g/mole) of Na, X_{Na} the mass fraction of Na in the chondrules, f_{Na} if the fraction of Na in the system in chondrules, R the gas constant (J/mole/K) and T the temperature (K).

While in the paper we concentrate on the solids densities at liquidus temperatures, the roughly closed system behavior of Na places constraints on solids densities over the entire temperature interval of crystallization. These constraints are important if a chondrule formation model predicts changing solids densities with time and temperature. For instance, in shock models there is significant pre-shock heating of chondrule precursors at much lower solids densities than in the higher temperature post-shock region. Unless there is efficient Na recondensation in the post-shock region prior to the onset of crystallization, the solids densities in the pre-shock region must be high enough to suppress Na evaporation during pre-shock heating.

To illustrate the constraints as a function of temperature, we have calculated the equilibrium vapor pressures in the same way as above for representative type IA and IIA chondrule compositions (Table A5) as they crystallize (Fig. A1). For the silicates-only calculations, we have made additional calculations assuming constant partial pressures of

H_2 (p_{H_2}) of 10^{-8} , 10^{-6} and 10^{-4} bars. At $p_{H_2}=10^{-8}$ bars, the result is essentially that for a H_2 -free system.

How might such high chondrule concentrations be achieved?

Producing the high spatial concentrations of chondrules estimated in this work is a challenge for models of dust dynamics in protoplanetary disks. In a non-turbulent disk small particles are able to settle to the midplane, but once their density approaches that of the gas ($\sim 200\times$ solar), shear between this particle-enriched layer and the gas above it would lead to the development of localized turbulence (15). This turbulence would then loft particles to higher altitudes. This is a self-regulating mechanism that limits the enhancement of solids around the midplane to less than 200. This barrier can be breached if the solids decouple from the gas by growing much larger in size, but such particles would be too large to be chondrule precursors. Obviously, other sources of turbulence will also limit the solid concentrations that settling can achieve.

It is important to note that these studies have largely focused on global increases of solids at the midplane. There are proposed mechanisms that would create much larger enhancements in localized regions of the nebula. One such mechanism, turbulent concentration (16), would allow chondrule-sized particles to concentrate in very dense regions of the nebula if the turbulence parameter ranged between $\alpha=10^{-5}$ to 10^{-3} . The concentrations that would be produced range up to $\square 10^6$ times greater than solar. The small concentrations would be the most common, whereas the very high concentrations would be rare and occupy relatively small volumes of the disk (16). As mass loading at very high concentrations (mass enhancements of $\square 10^5$) develop, the turbulence decays away, resulting in a locally less turbulent region of the disk (17).

It has also been proposed that if the concentration of solids in a particular region of the nebula was high enough, it would be stable against the turbulence that had been predicted to develop as a result of the shear instabilities described above, with (18) arguing that the column density of small solids (chondrule-sized and smaller) must be enhanced by factors of 2 to 10 above the canonical abundance for this effect to occur. This still requires significant settling of the particles to the disk midplane, and thus requires global turbulence to be minor ($\alpha < 10^{-7}$ according to (18)).

Similarly, (19) demonstrated that very large concentrations of particles (enough to form planetesimals the size of Ceres) could develop in disks in which the magnetorotational instability operates as a result of transient pressure gradients that develop within the disk. These studies, however, focused on solids much larger than chondrule-precursors as this produced favorable aerodynamic properties for the particular cases considered. Whether chondrule precursors could similarly be concentrated at lower gas densities (for example) remains to be determined.

Thus, there are ways by which large enhancements of chondrules could be produced at least locally in the solar nebula, though it is important to stress these means must still be studied in more detail before they are universally accepted as plausible. In all cases, it is important to note that concentrations of the type found here would be very rare in the nebula. Thus if there is a causal link between chondrule and planetesimal formation, this could explain how dust (chondrule precursors) was sustained in the nebula over long timescales, whereas most models of planetesimal formation suggest that their formation would take place very rapidly.

Estimating the sizes of self-gravitating regions in a turbulent nebula.

For a region of high chondrule density to become self-gravitating, the escape velocity of chondrules at the surface of the region must be greater than their random velocities. Defining the escape velocity as the typical velocity at which the kinetic energy of a chondrule equals its gravitational potential energy gives

$$\frac{1}{2}m_c v^2 = \frac{GMm_c}{R}, \quad (2)$$

where m_c is the mass of a chondrule, M is the mass of the region, R is the radius of the region, v is the escape velocity at the surface of the region and G is the gravitational constant. The mass of the region with a density, ρ , is given by

$$M = \frac{4}{3}\pi R^3 \rho. \quad (3)$$

Combining equations 2 and 3, the escape velocity is

$$v = R\sqrt{\frac{8}{3}\pi G\rho}. \quad (4)$$

In a turbulent disk, it will be the velocities induced by the random motions of the gas that must be less than the escape velocity. High chondrule densities may damp turbulent motions of the gas. Nevertheless, taking the upper limit for the random chondrule velocity as that of the undamped gas (20) and setting it equal to the escape velocity, we have

$$v = c\sqrt{\alpha} = R\sqrt{\frac{8}{3}\pi G\rho}, \quad (5)$$

where c is the sound speed in the gas and α the dimensionless viscous disk parameter. Rearranging, the critical density for a region becomes

$$\rho_{crit} = \frac{3\alpha c^2}{8\pi GR^2}. \quad (6)$$

Assuming typical values of $\alpha=10^{-4}$ and $c=1000$ m/s, and a chondrule density of 10 g/m³, similar to the lower limit estimates for near liquidus densities in Table 1 and Figure A1, regions >4000 km in radius will be self-gravitating. To be conservative, the value of α assumed here is higher than discussed earlier, but it is typical of the values used to characterize the solar nebula and for matching some aspects of meteorites (16, 17). Of course, if the value of α was lower than this where chondrule/chondrite formed, self-gravitating regions will be smaller for a given density. The sound speed is appropriate for a gas at a few hundred Kelvin, so these sizes apply to when the regions have cooled. If turbulence was much lower, as discussed above, and/or densities much higher, even smaller regions could become self-gravitating.

Estimation of cooling rates and timescales

In estimating the cooling rate of a region with the high chondrule densities calculated here, we adopted two different approaches. In the first, we treated the region as being the equivalent of a uniform (isothermal at temperature T and constant density of ρ) sphere of radius, R . The sphere cools by radiating energy from its surface at a rate of $4\pi R^2 \sigma T^4$, with σ being the Stefan-Boltzmann constant and C_p the heat capacity of the sphere, while its total energy is given by $(4/3) \pi R^3 \rho C_p T$. We assume the density and heat capacity were dominated by the chondrules and ignore the effects of the gas. The cooling rate is thus given by:

$$\frac{dT}{dt} = \frac{3\sigma T^4}{\rho C_p R}. \quad (7)$$

For $\rho = 10 \text{ g/m}^3$, $R = 4000 \text{ km}$ and $C_p = 1000 \text{ J/kg/K}$, the cooling rate at 2000 K would be $\sim 250 \text{ K/hr}$ and at 1500 K would be $\sim 30 \text{ K/hr}$. These rates are consistent with cooling rates inferred for chondrules. Of course, in a natural system cooling rates will vary with radial distance from the center of the region. Nevertheless, the important conclusion of these simplistic estimates are that for the sizes and densities of the regions inferred above, the cooling rates would be of the right order for chondrules.

We can also calculate the thermal adjustment timescale for a spherical region, defined as the time for it to achieve radiative equilibrium with the surrounding medium. This timescale is given by (21):

$$t_{rad} = \frac{\rho^2 \kappa C_p R^2}{64 \sigma T^3}, \quad (8)$$

where κ is the opacity of the medium ($\sim 5 \text{ cm}^2/\text{g}$ for chondrules) and all other terms are defined as above. Using the same parameters as above, the thermal adjustment timescale for a region at 2000 K is $\sim 2.8 \times 10^7$ seconds or ~ 1 year. Even though the exact cooling history will depend on the temperature of the system, the timescale computed here is

much longer than the estimated duration of chondrule formation based on cooling rates. However, the cooling rates only apply to the high temperature epoch (>1500 K). The thermal adjustment timescale is more appropriate to the minimum time that must elapse between chondrule formation and the introduction of low temperature matrix material to the region and final chondrite assembly.

Mixing of matrix, CAIs and chondrules

If the chondrule formation regions were gravitationally bound and could, possibly, directly collapse to form the meteorite parent bodies, we must ask how materials found in chondritic meteorites that were not processed in chondrule forming events (e.g., pre-solar materials, volatile-rich matrix material, and unmelted CAIs) can be intimately mixed in these bodies. Below we outline one plausible scenario.

Once a gravitationally bound clump forms it will tend to contract, but the pressure of the gas in the clump will provide some resistance to inward motions. This significantly increases the timescales for contraction of these bodies as the solids have to settle more slowly to the center of the clump through the gas. The contraction time, dictated by the settling time of the chondrules (17), is estimated to be given by:

$$t = \frac{\rho_g c}{4G\rho_c r \rho_s}, \quad (9)$$

where ρ_g is the local density of the gas, c the local sound speed, r the radius of the particles, ρ_c is the density of the clump and ρ_s the internal density of the particles. Assuming typical parameters of $c = 10^3$ cm/s, $\rho_s = 3$ g/cm³, $r = 0.05$ cm, $\rho_c = 10^{-5}$ g/cm³ as in this work, we find that $t = 8-80$ years for $\rho_g = 10^{-9} - 10^{-8}$ g/cm³ respectively, or $\approx 1-15$ orbits at 3 AU.

Assuming the diffusivity of small grains in a turbulent gas (see 20), a particle could travel a distance of

$$x(km) = 9000 \left(\frac{\alpha}{10^{-7}} \right)^{1/2} \left(\frac{t}{1yr} \right)^{1/2}. \quad (10)$$

Even at very low levels of turbulence ($\alpha < 10^{-7}$), a particle could diffuse 25,000 km over an 8 year period (3 times that over an 80 year period). This is greater than the scale of the chondrule formation region estimated by (22).

Thus we arrive at a picture of chondrule formation being restricted to occur in very small regions of the nebula with very high densities of solids. Given the high densities of solids, it is likely that whatever event was responsible for chondrule formation would have processed solids in that region to a different extent than materials further away. For example, as discussed in (23), there is significant feedback on the gas by the solids if chondrules form via shockwaves allowing higher temperatures to be reached at high chondrule concentrations than would be otherwise. Thus a low velocity shock ($\approx 2-3$ km/s) could suffice to melt the chondrules in the very dense clump, but minimally process materials outside the clump, allowing pre-solar grains or CAIs located thousands to ten thousands of kilometers away to show no signs of thermal processing. If the chondrules then become gravitationally bound after their processing (due in part to the increased density that accompanies processing in shock waves) they will contract on timescales of a few orbits. This would allow the unprocessed materials to diffuse into the self-gravitating clump before it completely collapses.

We stress this scenario requires detailed testing, but it is consistent with our current understanding of chondrule formation and mixing in protoplanetary disks. Future work should address the specific details of dust grains diffusing into self-gravitating clumps.

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Fig. A1. The solids densities necessary for 90% of the Na to remain in (a) type IIA and (b) type IA chondrules rather than be lost to the gas. As described in the text, to estimate the range of possible densities required, the densities were calculated using the Na partial pressures in the equilibrium vapor over the chondrules assuming: (i) three constant partial pressures of H₂ (10⁻⁸, 10⁻⁶ and 10⁻⁴ bars), and (ii) that the fO₂ of the vapors were buffered by equilibrium between FeO in the melt and pure Fe-metal.

Table A1. The bulk compositions (wt%) determined for the Semarkona chondrules studied.

	Na ₂ O	MgO	Al ₂ O ₃	SiO ₂	P ₂ O ₅	K ₂ O	CaO	TiO ₂	Cr ₂ O ₃	MnO	FeO	FeS	Ni	Fe	Total
C1	1.16	32.40	2.33	42.11	0.43	0.12	2.13	0.11	0.53	0.39	17.09	0.24	0.33	0.66	100.03
C2	1.44	31.00	3.01	45.21	0.05	0.18	3.24	0.14	0.62	0.43	12.54	0.42	0.49	1.20	99.95
C3	0.94	30.78	2.52	42.10	0.37	0.14	2.19	0.11	0.47	0.39	19.08	0.38	0.47	0.24	100.20
C4	0.65	35.01	1.83	44.23	0.05	0.13	2.13	0.08	0.53	0.42	12.94	0.17	0.36	1.67	100.22
C5	0.87	28.89	2.17	40.30	0.27	0.12	2.12	0.09	0.40	0.40	21.35	1.74	0.51	0.77	99.99
C6	0.18	38.94	6.30	45.70	0.12	0.02	6.14	0.31	0.26	0.09	0.53	0.11	0.52	0.96	100.19
C7	0.65	39.09	6.65	44.53	0.09	0.03	5.36	0.32	0.40	0.14	0.47	0.20	0.56	1.69	100.17
C8	0.17	41.96	4.52	45.52	0.08	0.03	3.43	0.16	0.51	0.16	0.74	0.23	0.32	2.27	100.11
C9	0.08	43.32	2.84	45.53	0.16	0.03	2.32	0.13	0.35	0.07	0.73	0.16	0.67	3.79	100.16
C10	1.32	29.52	3.33	42.08	0.46	0.13	3.00	0.12	0.59	0.38	17.20	0.94	0.32	0.51	99.90
C11	0.05	40.60	4.40	39.78	0.11	0.02	2.82	0.14	0.46	0.09	0.67	0.42	0.92	9.65	100.12
C13	1.96	23.95	3.89	43.92	0.11	0.23	2.80	0.17	0.49	0.46	15.06	2.74	0.54	3.68	100.02
C14	1.38	30.77	2.79	42.83	0.18	0.13	2.66	0.11	0.42	0.37	15.65	1.83	0.43	0.25	99.81
C18	1.54	28.93	2.92	41.35	0.12	0.14	2.01	0.10	0.60	0.45	17.82	2.14	0.80	1.08	100.00
C19	1.34	31.13	4.25	48.93	0.05	0.13	2.41	0.14	0.60	0.56	6.76	0.38	0.56	2.65	99.89
C20	1.05	36.73	2.54	44.39	0.06	0.13	2.42	0.10	0.56	0.44	10.41	0.21	0.31	0.62	99.97
C22	1.36	32.16	3.39	43.11	0.30	0.15	2.46	0.11	0.57	0.42	13.00	1.14	0.61	1.23	100.03
C23	1.51	27.83	3.28	40.49	0.21	0.12	2.55	0.11	0.48	0.41	18.87	2.03	0.63	1.26	99.80
C27	0.85	33.09	2.27	46.91	0.07	0.08	1.94	0.09	0.63	0.48	10.90	0.26	0.41	1.97	99.94
C29	1.81	27.05	2.99	44.76	0.06	0.24	3.27	0.12	0.68	0.54	12.87	3.82	0.50	1.00	99.71
C31	1.09	29.23	2.28	46.10	0.06	0.10	1.83	0.09	0.65	0.51	15.76	0.47	0.44	1.27	99.86
C33	1.65	28.81	3.61	42.60	0.55	0.19	3.65	0.16	0.58	0.55	15.46	1.18	0.40	0.40	99.78
C34	2.16	21.43	3.98	40.33	0.57	0.22	2.88	0.14	0.54	0.42	16.11	4.68	1.23	5.24	99.92
C35	1.79	25.09	3.90	41.74	0.56	0.20	3.01	0.14	0.50	0.39	19.74	1.67	0.72	0.37	99.82
C38	0.99	34.44	2.54	41.04	0.54	0.12	3.02	0.12	0.51	0.45	14.05	0.48	0.50	1.00	99.80
C40 ¹	0.45	29.85	1.90	50.60	0.11	0.08	1.01	0.06	0.61	0.59	13.85	0.53	0.18	0.37	100.18

¹Not density corrected because good mesostasis analyses were not obtained.

Table A2. The average glass compositions (wt%) for the chondrules studied.

	Na ₂ O	MgO	Al ₂ O ₃	SiO ₂	P ₂ O ₅	K ₂ O	CaO	TiO ₂	Cr ₂ O ₃	MnO	FeO	Total
C1	4.88	2.27	12.09	63.77	1.89	0.55	5.96	0.48	0.08	0.20	6.85	99.01
C2	5.94	1.62	13.37	70.41	0.23	0.92	1.47	0.51	0.07	0.24	5.97	100.76
C3	4.52	3.43	12.55	62.66	1.69	0.76	4.93	0.44	0.06	0.16	6.08	97.26
C4	3.91	1.68	11.04	70.93	1.40	0.90	0.57	0.53	0.03	0.18	6.54	97.71
C5	5.65	1.06	14.64	69.12	1.25	0.89	2.88	0.51	0.04	0.07	3.29	99.41
C6	0.57	5.81	19.76	54.66	0.01	0.01	15.66	0.92	0.46	0.14	0.35	98.35
C7	1.43	3.35	14.13	67.88	0.00	0.08	9.87	1.11	0.41	0.33	0.56	99.14
C8	0.81	5.58	18.13	57.73	0.02	0.03	14.49	0.76	0.58	0.24	0.38	98.76
C9	0.44	6.03	18.38	56.39	0.01	0.03	15.16	0.60	0.47	0.10	0.37	98.00
C10	5.87	2.70	12.49	65.58	0.68	0.70	4.50	0.56	0.22	0.17	6.53	99.99
C11	0.25	6.61	23.20	50.47	0.01	0.00	15.74	1.13	0.60	0.10	0.46	98.57
C13	6.82	0.75	14.21	73.57	0.31	1.00	0.57	0.53	0.03	0.09	4.14	102.02
C14	6.64	2.78	13.33	66.41	0.74	0.65	2.56	0.44	0.07	0.19	7.98	101.80
C18	6.72	0.68	14.87	71.78	0.28	1.00	0.62	0.53	0.01	0.11	3.94	100.53
C19	8.45	1.50	16.37	67.26	0.09	0.79	2.11	0.59	0.03	0.32	4.41	101.94
C20	5.92	2.25	12.03	72.37	0.21	0.89	0.81	0.48	0.08	0.22	5.14	100.40
C22	6.54	2.51	11.20	67.23	1.38	0.74	1.53	0.51	0.05	0.32	8.26	100.27
C23	6.93	2.77	14.32	69.03	0.67	0.92	1.94	0.43	0.09	0.12	4.68	101.90
C27	7.77	1.14	16.09	69.79	0.25	0.94	0.80	0.56	0.04	0.17	3.89	101.44
C29	10.18	1.32	15.75	67.80	0.04	0.38	1.19	0.36	0.07	0.12	3.32	100.54
C31	7.47	1.10	14.28	69.99	0.25	0.88	0.81	0.56	0.05	0.22	6.92	102.53
C33	7.33	4.94	9.30	68.49	0.76	0.64	1.11	0.38	0.05	0.41	8.42	101.83
C34	5.88	2.58	13.95	65.57	1.86	0.80	3.05	0.56	0.09	0.16	6.32	100.82
C35	5.05	3.06	11.44	63.95	1.46	0.70	7.50	0.56	0.16	0.16	7.32	101.35
C38	6.07	2.15	10.45	71.66	0.26	0.83	0.55	0.42	0.04	0.34	8.57	101.34

Table A3. The most Na- and Fe- poor core olivine compositions (wt%) for the chondrules studied.

	Na ₂ O	MgO	Al ₂ O ₃	SiO ₂	P ₂ O ₅	CaO	Cr ₂ O ₃	MnO	FeO	Total
C1	0.0090	50.33	0.03	40.64	0.00	0.11	0.28	0.22	10.20	101.83
C2	0.0041	47.26	0.03	39.71	0.02	0.11	0.42	0.26	10.59	98.41
C3	0.0090	48.22	0.03	38.96	0.09	0.12	0.27	0.21	9.72	97.65
C4	0.0050	48.15	0.02	39.40	0.03	0.09	0.30	0.24	9.00	97.25
C5	0.0133	40.50	0.02	37.61	0.03	0.15	0.42	0.32	18.92	98.02
C6	0.0035	55.00	0.16	41.12	0.00	0.40	0.16	0.02	0.55	97.44
C7	0.0007	55.35	0.36	41.21	0.00	0.50	0.11	0.01	0.35	97.96
C8	0.0012	55.01	0.07	40.34	0.00	0.25	0.27	0.05	0.61	96.62
C9	0.0021	54.18	0.08	40.84	0.00	0.25	0.23	0.03	0.66	96.30
C11	0.0039	53.92	0.04	38.68	0.00	0.30	0.23	0.03	0.65	93.89
C13	0.0060	44.97	0.04	39.74	0.01	0.09	0.40	0.34	14.56	100.19
C14	0.0045	49.35	0.04	40.01	0.02	0.10	0.27	0.20	8.77	98.78
C18	0.0050	44.37	0.02	38.84	0.01	0.09	0.47	0.40	15.04	99.23
C19	0.0012	50.98	0.02	40.04	0.00	0.07	0.34	0.25	6.16	97.89
C20	0.0043	50.77	0.04	40.73	0.01	0.09	0.36	0.26	7.56	99.85
C22	0.0080	49.43	0.03	40.06	0.01	0.11	0.34	0.25	8.75	98.98
C23	0.0022	46.57	0.02	39.42	0.05	0.08	0.35	0.21	11.86	98.58
C27	0.0052	47.09	0.02	40.07	0.00	0.10	0.42	0.36	11.96	100.04
C29	0.0017	46.55	0.03	39.43	0.00	0.08	0.46	0.39	12.25	99.21
C31	0.0066	45.43	0.03	39.95	0.03	0.10	0.39	0.34	14.37	100.68
C33	0.0041	45.78	0.02	40.02	0.00	0.09	0.34	0.33	13.92	100.53
C35	0.0105	44.37	0.04	39.23	0.04	0.16	0.45	0.31	15.63	100.26
C38	0.0035	45.96	0.03	37.94	0.01	0.10	0.41	0.34	12.63	97.42
C40	0.0026	45.68	0.02	39.02	0.02	0.06	0.45	0.43	13.50	99.20

Table A4. The most Na- and Fe-rich rim and microphenocryst olivine compositions (wt%) for the chondrules studied.

	Na ₂ O	MgO	Al ₂ O ₃	SiO ₂	P ₂ O ₅	CaO	Cr ₂ O ₃	MnO	FeO	Total
C1	0.0330	36.00	0.03	37.72	0.00	0.38	0.47	0.62	27.65	102.91
C2	0.0167	40.56	0.02	38.08	0.06	0.26	0.67	0.55	18.54	98.78
C3	0.0284	35.51	0.03	36.46	0.20	0.36	0.49	0.50	25.10	98.71
C4	0.0240	38.68	0.01	38.04	0.02	0.21	0.69	0.61	20.46	98.76
C5	0.0298	35.51	0.02	36.26	0.10	0.28	0.52	0.46	24.41	97.62
C6	0.0031	55.35	0.16	41.36	0.00	0.43	0.18	0.02	0.52	98.06
C7	0.0033	55.30	0.17	41.18	0.00	0.38	0.23	0.05	0.55	97.91
C8	0.0020	55.13	0.11	40.62	0.00	0.33	0.25	0.04	0.62	97.15
C9	0.0036	54.53	0.14	41.15	0.00	0.27	0.30	0.04	0.65	97.14
C10	0.0359	41.74	0.04	38.22	0.05	0.24	0.61	0.53	19.63	101.13
C11	0.0016	53.99	0.07	38.77	0.00	0.30	0.34	0.08	0.77	94.37
C13	0.0312	30.93	0.02	36.05	0.03	0.30	0.29	0.72	30.10	98.52
C14	0.0276	32.64	0.03	35.86	0.45	0.24	0.34	0.60	28.06	98.26
C18	0.0132	38.65	0.02	37.85	0.04	0.21	0.50	0.55	21.06	98.91
C19	0.0072	46.48	0.02	39.29	0.00	0.19	0.61	0.62	10.47	97.71
C20	0.0181	39.49	0.03	37.90	0.01	0.24	0.61	0.76	18.11	97.18
C22	0.0353	32.96	0.03	36.32	0.17	0.28	0.39	0.79	26.68	97.68
C23	0.0214	33.77	0.03	35.05	0.09	0.32	0.41	0.60	27.07	97.38
C27	0.0105	39.32	0.03	37.70	0.01	0.23	0.49	0.65	19.78	98.23
C29	0.0035	43.98	0.02	38.67	0.00	0.10	0.52	0.53	14.94	98.78
C31	0.0148	34.55	0.02	37.67	0.01	0.24	0.43	0.77	26.87	100.62
C33	0.0201	40.13	0.02	37.81	0.01	0.21	0.52	0.63	17.28	96.64
C34 ¹	0.0193	37.35	0.07	37.24	0.11	0.30	0.37	0.49	23.63	99.62
C35	0.0239	38.11	0.04	38.12	0.24	0.28	0.51	0.46	23.27	101.08
C38	0.0166	41.40	0.03	38.49	0.03	0.21	0.62	0.55	16.96	98.32

¹The Al₂O₃ content of this is higher than our criteria of 0.04 wt% for type II chondrules, but no better analysis could be obtained.

Table A5. The compositions used to calculate chondrule vapor pressures (From 13, 14).

	Type II A	Type I A
SiO ₂	45.72	46.96
TiO ₂	0.11	0.20
Al ₂ O ₃	2.72	4.09
Cr ₂ O ₃	0.52	0.46
FeO	15.06	1.24
MnO	0.40	0.13
MgO	31.71	42.63
CaO	1.92	3.67
Na ₂ O	1.67	0.54
K ₂ O	0.17	0.07