SOLVING THE CHONDRULE MYSTERY: NOT THERE YET. C.M.O'D. Alexander[1] and J. Cuzzi[2], [1]DTM, Carnegie Institution of Washington, 5241 Broad Branch Road NW, Washington, DC 20015 (alexander@dtm.ciw.edu). [2]NASA Ames Research Center, MS 245-3 Moffett Field, CA 94035.

Introduction: In principle, the physical, mineralogical and chemical properties of chondrules can be used to place limits on their formation conditions. The constraints and their implications are reviewed below.

Thermal histories: The survival of demonstrably relict grains suggests that heating and cooling must have been relatively rapid. Relict grains also indicate that there was recycling of chondrule material through multiple formation events. It is hard to place more quantitative constraints on thermal histories using relict grains as their survival depends on many factors (e.g., initial size and composition, melt composition, thermal history, etc.) [1, 2].

The chondrule textures depend on how many crystal nuclei survived the initial heating. Porphyritic and granular texture indicate the survival of numerous crystal nuclei, while other chondrule types were fully molten. Hence, chondrule textures suggest that peak temperatures approached, but did not necessarily exceed, chondrule liquidii. Taking into account the range of chondrule liquidii and the kinetics of dissolution, peak temperatures would have been of the order of 1700-2100 K [2, 3]. The textures and elemental zoning profiles in phenocrysts also depend on chondrule cooling rates. Modeling and experimental simulation of textures and zoning profiles suggest cooling rates of the order of 1-1000 K/hr [4-6].

Dust/chondrule enrichments relative to gas: Because at low P many elements/oxides become volatile, the elemental and isotopic compositions of chondrules place constraints on the enrichment of chondrules and dust, relative to a solar composition, during chondrule formation. The volatilities of many components are enhanced in the presence of H_2. As a result, these estimates depend on the overall gas pressure, which is hard to estimate independently and must be assumed.

Isotopic constraints: The absence in chondrules of the large, systematic isotopic fractionations associated with free evaporation [7] has been used to infer relatively high lower limits on chondrule+dust (solid) densities prior to heating - solid/gas ratios of 100s to 1000s times solar at $P=10^{-4}$-10^{-3} bars and higher (lower) at lower (higher) total pressures - based on estimated equilibration times. It is not surprising, therefore, that these conditions are the minimum required to produce stable liquids with compositions that resemble those of chondrules [8].

The lack of large, systematic isotopic variations in most chondrules can also place limits on the sizes of chondrule formation regions because there will be diffusive loss of evaporated material from the margins of the regions. Formation regions must be ≥300-12,000 km across for the fraction of chondrules with large isotopic fractionations to be below the observed limits.

Elemental constraints:

Na - Volatile elements (e.g., alkalis) can place some of the most stringent constraints on formation conditions if their abundances at various temperatures can be determined. Na was present in most chondrules at similar levels to the present abundances when cpx crystallization, ~1000-1200°C [8, 9]. Na zoning profiles in olivine phenocrysts suggest that this was the case even at near-liquidus temperatures (~1600°C) [10-14]. Chondrules behaved as roughly closed-systems for Na (≤10 % loss), requiring very high solid/gas ratios – $\sim10^6$ at $PH_2=10^{-4}$ bars and higher (lower) at lower (higher) pressures [11]. A 50% loss of Na, rather than 10%, would decrease the estimated solid enrichments by roughly a factor of 10.

FeO - Major element zoning of Fe, Mn and Cr in chondrule phenocrysts are also consistent with essentially closed system behavior [6, 11]. To achieve essentially closed-system behavior for FeO, requires solid/gas ratios $\sim10^{4-5}$xsolar at $PH_2=10^{-4}$ and higher at lower pressures [15], assuming that the silicate liquid determined the fO_2 of the equilibrium vapor. If metal was in equilibrium with the vapor, the fO_2 would have been lower and the vapor pressure of Fe higher.

Fe – Fe-metal was stable during the formation of many chondrules, particularly type I chondrules that have high liquidus temperatures. If there was ≤10% evaporation of Fe metal, this requires solid/gas ratios that are only slightly lower than those required by Na [15]. If S was retained by some chondrules, even higher solid enrichments would be needed.

Compound and irregular chondrules: Based on the frequencies of compound chondrules, the number densities of chondrules during formation have been estimated to be ~0.1-30 m^{-3} [16]. These estimates are orders of magnitude lower than the $\sim10^4$ m^{-3} or more required by the Na data. However, the compound chondrule number densities may have been significantly underestimated [15], and in any case large uncertainties remain in making these estimates, such as the relative velocity that sets the collision rate.

Whence chondrule diversity: Chondrules exhibit considerable compositional and textural diversity. Both chemistries and textures will have depended on the compositions and grain sizes of their precursors, and the formation conditions and timescales. At present, there is no consensus about how this diversity was produced (one event or many, dominated by precursors or formation conditions, etc.). The rarity of obvious chondrule precursors contributes to this uncertainty. The rarity of precursors could be because: (i) there is a direct link between chondrule and chondrite formation, (ii) precursors were not concentrated during planetesimal formation (but were concentrated when making chondrules), (iii) chondrules were largely their own precursors, (iv) multiple formation events and a limited source of primitive precursors meant that chondrules became their own immediate precursors, or (v) chondrules formed by impacts.

It is possible that considerable diversity could have been generated in a single formation event. [16] showed that gas diffusion rates would have limited the sizes of the volumes within which chondrules could have communicated chemically. Consequently, for the sizes of formation regions inferred above, there would have been multiple sub-regions that had different compositions/conditions. It seems possible that a range of textures might still have persisted in a single sub-region if, for instance, the precursors had very different liquidus temperatures and/or initial grain sizes. The extent to which a chemical diversity could have been preserved in a sub-region will have depended on the rates of re-equilibration between chondrules. Chondrules do show small variation in isotopic mass fractionation in Mg, Fe and Si [7], which may be the result of incomplete re-equilibration of a diverse population of chondrule precursors [15].

There has been speculation that chondrule precursors became increasingly FeO-rich and ^{16}O-poor with time. FeO-rich minerals in precursors would be destroyed more readily than Mg-rich ones, but the presence of dusty (reduced) relict olivines in very FeO-poor chondrules clearly shows that they had FeO-bearing minerals in their precursors. Nor is there a simple relationship between the FeO content and O isotope composition of chondrules. Finally, if one takes maximum peak metamorphic temperatures of a chondrite group as a crude proxy for ^{26}Al content and, therefore, accretion time, the order of accretion was roughly EC, (OC,R,CK), CO, CV, (CR,CM,CI). If correct, there is no obvious systematic variation in either oxidation state or O isotopic composition.

Theoretical considerations: The chondrule mass concentrations imposed by the Na and, to a lesser extent, the Fe-metal and FeO constraints, all functions of chondrule number density, size and redox state, are orders of magnitude larger than previously believed. These densities present considerable challenges to nebular models of chondrule formation, both in terms of producing such densities and heating such dense regions sufficiently.

We are exploring whether there are ways of reconciling, within their current uncertainties, the density constraints with known nebula properties and processes. We will explore the uncertainties associated with differences between equilibrium and kinetic, open and closed system models, and the plausible ranges of nebula properties, such as gas density and water abundance, in the chondrule formation region.

Ultimately, any complete chondrule/chondrite model must also account for: the apparent chondrule age ranges, retaining chondrite class differences, particularly in a turbulent nebula, the addition of CAIs, primitive dust, fine-grained accretion rims after chondrule formation, the apparent rarity of chondrule precursors, evidence for multiple chondrule heating events, and the full range of chondrule elemental compositions.

If the nebula is laminar (non-turbulent) in the asteroid formation region, particle growth to plantesimal sizes is rapid in the midplane, which seems incompatible with a number of known properties and a non-optimal heating environment. If the nebula is turbulent, two mechanisms have been suggested for concentrating solids; one operates on chondrule-sized particles and one on m-to-dm-sized particles, which might be thought of as aggregates of chondrules or their precursors [17,18]. We will explore the implications of both scenarios in terms of maximum concentrations, volume fractions, and lifetime of dense clumps, which of them are bound and which will be dispersed back into the nebula, which can survive nebula ram pressure, the implications of these properties for chondrule cooling histories, and the possibility of mixing within bound clumps before they sediment into planetesimals. For instance, to satisfy the Na constraints of [11] by turbulent concentration may require higher than canonical gas densities prior to heating. Shocks can increase densities and pressures post-heating, which will reduce the needed pre-heating densities, but can they adequately heat regions where solids/gas mass ratios may be >100? We are also exploring whether the thermal histories, both heating and cooling, can constrain the densities and length scales of the chondrule formation regions.

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