REASSESSING THE CONDITIONS OF CHODRULE FORMATION.

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Introduction: Chondrules are likely the product of one of the more energetic processes operating in the asteroid belt and perhaps the inner Solar System. Constraints on formation conditions (e.g., P, T, t, dust density and size of formation region) provide important clues to this enigmatic process.

In principle, the physical, mineralogical and chemical properties of chondrules can be used to place limits on some of these conditions. The survival of relict grains suggests that heating and cooling must have been relatively rapid. Crystal textures suggest that peak temperatures generally approached, but did not necessary exceed, chondrule liquidii, and that chondrules subsequently cooled at rates of the order of 10-1000°C/hr. The absence of isotopic fractionations in chondrules has been used to infer relatively high chondrule+dust (solid) densities prior to heating - solid/gas 100s to 1000s times solar at $P=10^{-4}$-10^{-3} bars, and higher at lower total pressures [1, 2]. Based on frequencies of compound chondrules, the number densities of chondrules during formation have been estimated to be ~0.1-30 m^{-3} [2].

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. The cpx/glass Kds show that during cpx crystallization, estimated to be between 1000-1200°C [3, 4], Na was present in most chondrules at levels similar to observed abundances.

More recently, based on Na zoning profiles in olivine phenocrysts in porphyritic chondrules [5, 6], we have shown that Na was present in chondrules at roughly the present abundances even at near-liquidus temperatures (~1600°C). This implies that chondrules behaved as essentially closed systems. Under even relatively solid-enriched conditions (~100-1000x solar), the alkalis would not have behaved as closed systems [4]. Here we estimate the conditions needed for chondrules to retain their Na even at high temperatures and explore possible implications.

Results: At typical nebular pressures, chondrules will not be closed to Na loss. However, closed system behavior will be approximated if solid densities are high enough that only a small fraction of the Na need evaporate to achieve gas-chondrule equilibrium.

To estimate the densities that are necessary to retain most of the Na, we have calculated the equilibrium vapor pressures over representative type IA and IIA chondrule compositions for constant pH_2 of 10^{-8}, 10^{-6} and 10^{-4} bars. Fig. 1 shows the calculated total pressures as a function of temperature for the type IIA composition. Under most conditions, the total pressure is dominated by the vapor pressure of the chondrule, and monatomic Na is the dominant species in the vapor.

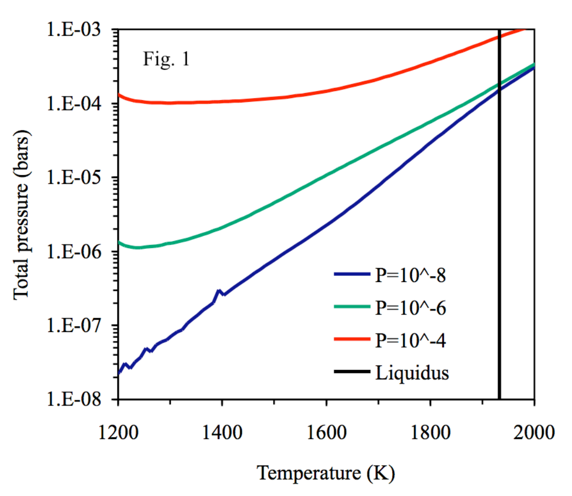

Fig. 1. The total vapor pressures above a type IIA chondrule assuming three constant pressures of H_2.

The solid densities were estimated by calculating, for a given T and pNa, the density of solids required for 90% of the Na to remain condensed. The results are shown in Fig. 2. These solid densities have been converted to chondrule (r=0.05 cm, ρ=3 g/cc) number densities in Fig. 3, and to solid/gas ratios relative to solar in Fig. 4 by summing all H (H_2, H, H_2O, etc.) in the gas and assuming a solar solid/H mass ratio of 0.005.

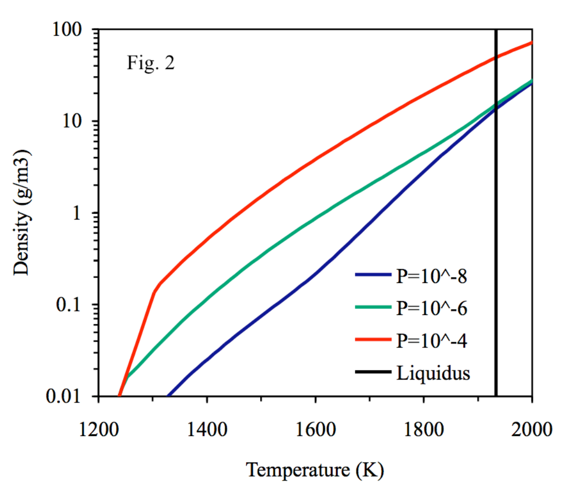

Fig. 2. The type II chondrule densities necessary to keep 90% of the Na condensed. assuming three constant pressures of H_2.

The results in Figs. 1-4 are for type IIA chondrules. Despite their lower Na contents, type IAs require, for a given T and pH_2, somewhat higher dust densities than type IIAs. This probably reflects the lower fO_2 of the type IA equilibrium vapors which will tend to drive the evaporation reaction $Na_2O_{(l)} = 2Na + ½ O_2$ to the right.

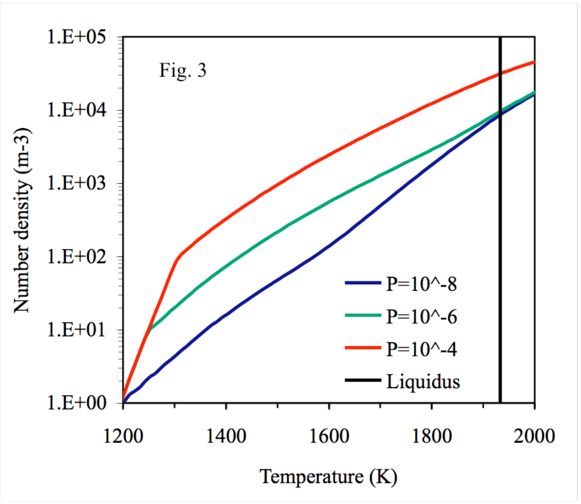

Fig. 3. The number densities of 0.05 cm radius chondrules equivalent to the mass densities in Fig. 2.

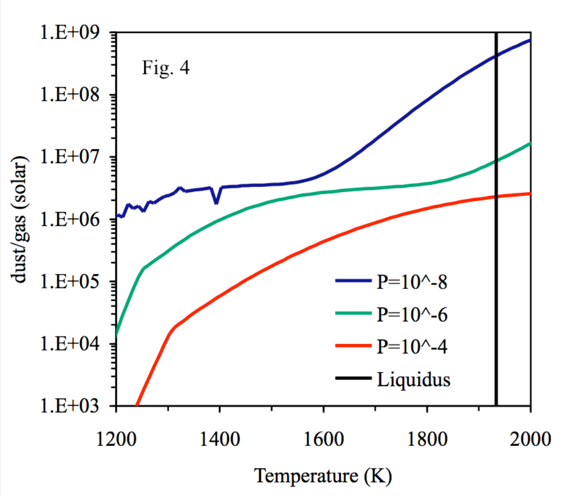

Fig. 4. The solar solid/gas ratios estimated from the results in Figs. 1+2.

Discussion: The densities required for essentially closed system behavior of Na in chondrules are much higher than previously considered for chondrule formation.

In principle, the solid densities could be lower if the fO_2 was enhanced, perhaps by adding large amounts of water ice to the system prior to heating. However, The equilibrium vapor compositions are already highly oxidized, with fO_2 5-10 orders of magnitude higher than for a solar gas and close to IW. The fO_2 cannot have been too much higher or all metal would have been oxidized and minerals such as magnetite would have become stable. Metal is present even in type II chondrules, while magnetite or chromite with significant Fe^{3+} are absent.

If the solid densities cannot reasonably be reduced by increasing the fO_2, the densities near the liquidus temperature in Fig. 2 are lower limits for the densities during chondrule formation. Such high densities can only rarely be achieved on small scales by processes such as turbulent concentration. Intriguingly, these densities exceed those that are thought to be needed to produce planetesimals via gravitational instabilities. This raises the possibility that chondrule and planetesimal formation might be linked. Fig. 5 shows the minimum radii of regions with the estimated densities in Fig. 2 that would be needed to produce a 50 km radius asteroid with a density of 3 g/cc.

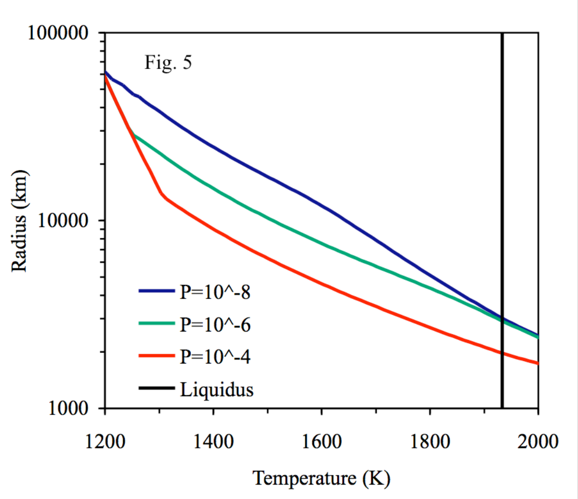

Fig. 5. The minimum radii of regions with the densities in Fig. 2 needed to produce a 50km radius asteroid.

Such high solid densities and solid/gas ratios also have implications for potential heating mechanisms. The densities are much higher than assumed in previous shock models. We have begun to explore the consequences of such high densities, particularly on cooling rates. We are also exploring a general model, perhaps more akin to lightning or impacts, in which a high density region is flash heated, and then expands and cools as a result of the vapor pressure generated by the chondrules. Initial results suggest that to reproduced chondrule cooling rates requires regions that are as large or larger than those in Fig. 5.

References: [1] Alexander C.M.O'D. (2004) *GCA,* **68**, 3943-3969. [2] Cuzzi J.N. and Alexander C.M.O'D. (2006) *Nature,* **441**, 483-485. [3] Alexander C.M.O'D. and Grossman J.N. (2005) *MPS,* **40**, 541-556. [4] Ebel D.S. and Grossman L. (2000) *GCA,* **64**, 339-366. [5] Alexander C.M.O'D. *et al.* (2007) *LPSC,* **38**, #2012. [6] Grossman J.N. and Alexander C.M.O'D. (2008) *LPSC,* **39,** this volume.