MAKING CAIS AND CHONDRULES FROM CI DUST IN A CANONICAL NEBULA. C. M. O'D. Alexander. Dept. Terrestrial Magnetism, 5241 Broad Branch Road NW, Washington, DC 20001 <alexande@dtm.ciw.edu>.

Introduction: Astrophysical models suggest that at 2-3 AU, ambient midplane pressures would have been 10^{-4} bars or less. Transient events, such as the passage of shock waves, may have increased midplane pressures by roughly an order of magnitude [1]. Thus, at 2-3 AU 10^{-3} bars is a likely upper limit for chondrule and CAI formation.

To explain both the elemental and isotopic compositions of chondrules and CAIs, recent studies have suggested that they may have formed at significantly higher pressures than this [2, 3]. If correct, this suggests that chondrules and CAIs must have formed much closer to the Sun (<<1 AU) where midplane pressures would have been higher. This would have profound implications for our understanding of nebular evolution. In addition, CAIs may have formed from high temperature equilibrium condensates rather than solar composition material [3, 4].

However, neither study considered the effect of gas-melt exchange during formation. Upon heating, chondrules and CAIs would have experienced some evaporation. Unless the vapor generated by this evaporation was immediately removed from the system, it will have interacted with the chondrules/CAIs, possibly significantly modifying the isotopic fractionations that develop.

Here, a kinetic code for modeling silicate-metal evaporation-condensation is used to explore whether, when gas-melt exchange is taken into account, chondrules and CAIs could have formed under more canonical nebular conditions from solar composition material.

Summary of Model: Details of the evaporation-condensation model are given in [5]. Heating and cooling of the dust and gas assemblage is assumed to occur in a closed system at constant pressure. The evaporation-condensation model used here is the diffusionless PCR Case 1 model. It best reproduces the O, Mg and Si mass fractionations in evaporation experiments.

The aim of this paper is to follow the elemental and isotopic evolution of solar composition material upon heating. If temperatures rapidly rise above the solidus of the precursor material, it will partially or completely melt. Melting and crystallization are not included to avoid introducing numerous additional free parameters and uncertainties (rates of nucleation, growth-dissolution and diffusion, initial compositions, sizes and abundances of minerals, etc.). Many chondrules (e.g. barred olivine chondrules) and CAIs were largely or wholly molten near their peak formation temperatures, when most evaporation would have taken place. Thus, for these first order calculations ignoring crystallization is justifiable. Past studies have assumed thermodynamic equilibrium was always maintained [6], although numerous features of chondrules and CAIs indicate that they are not equilibrium assemblages. Despite being entirely molten, bulk 'equilibrium' compositions calculated here are not very different from previous studies [6].

An initially CI-like bulk solid composition is used, but the silicate-metal is assumed to be anhydrous with all S is present as FeS and all remaining Fe as FeO. The excess O (in H_2O/OH, sulfate, magnetite and carbonate) and all C, perhaps associated with ices, are assumed to evaporate instantaneously on heating.

The range of conditions explored were: $P_{tot}=10^{-4}$-10^{-3} bars, constant temperatures of 1400-1700°C, and solid/gas/solar enrichments of 10-40,000.

Results: Figure 1 shows the 'equilibrium' compositions for one set of conditions. Also marked is the region where CAI-like compositions would form, and the Mg# (100*Mg/Mg+Fe) of the melts. CAIs form under a very restricted range of conditions solid/gas/solar=60-80. At 1400°C the range is 20-30 To estimate 'equilibrium' compositions at lower pressures, simply divide the solid/gas/solar ratios by $\sqrt{P_{tot} * 1000}$. Chondrule-like compositions form over a much broader and higher range of solid/gas/solar ratios. Perhaps this broader range explains the greater abundance of chondrules.

In evolving to these equilibrium compositions, isotopic fractionations that develop are much less than would be expected from Rayleigh fractionation. Using Rayleigh fractionation to infer the amount of an element that has been lost is potentially very misleading. To illustrate the effects of gas-melt exchange, Figure 2 compares the Allende chondrule compositions from [2] with simulation results for chondrules heated to 1500°C with $P_{tot}=10^{-3}$ bars and solid/gas/solar≥60 for 290 minutes. As can be seen, the Allende chondrule compositions are reproduced very well. Also shown are the maximum isotopic compositions that develop in these chondrules as they evolve.

Figure 3 compares the isotopic evolutionary paths of objects that develop CAI-like elemental compositions with the CAI data [7, 8]. The starred points are FUN or FUN-like inclusions. The simulations reproduce most of the CAI data very well if: they partially re-equilibrated with the gas, that T≤1500°C and the solid/gas/solar ratios are in the range for producing CAI-like elemental compositions. At 1600°C the paths lie entirely to the left of the data. Slightly lower solid/gas/solar ratios are needed to produce the most fractionated FUN inclusions. All the FUN inclusions are best explained if they have experienced relatively little re-equilibration with the gas, perhaps explaining why they still preserve UN anomalies.

Conclusions: Kinetic modeling shows that when gas-melt exchange is taken into account, chondrule and CAI compositions can be explained by formation from CI dust compositions under canonical nebula conditions at 2-3 AU.

References: [1] Desch, S. J. and Connolly, H. C., Jr. (2002) *Meteoritics Planet. Sci.I 37*, 183-208. [2] Galy, A., et al. (2000) *ScienceI 290*, 1751-1754. [3] Richter, F. M., et al. (2002) *Geochim. Cosmochim. ActaI 66*, 521-540. [4] Grossman, L., et al. (2000) *Geochim. Cosmochim. ActaI 64*, 2879-2894. [5] Alexander, C. M. O'D. (2003) *Geochim. Cosmochim. ActaI*, Submitted. [6] Ebel, D. S. and Grossman, L. (2000) *Geochem. Cosmochim. ActaI 64*, 339-366. [7] Clayton, R. N., et al. (1988) *Phil. Trans. Roy. Soc. Lond. AI 325*, 483-501. [8] Clayton, R. N., et al. (1987) *Lunar Planet. Sci. XVIII,I*, 185-186.

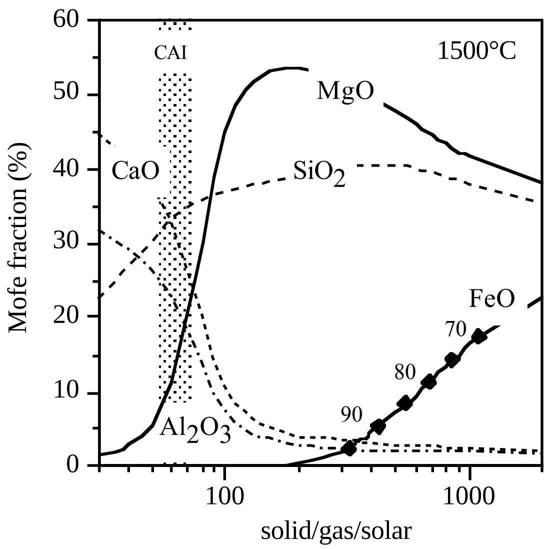

Figure 1. The 'equilibrium' compositions at 1500°C and $P_{tot}=10^{-3}$ bars. Also marked are the Mg# for the melts.

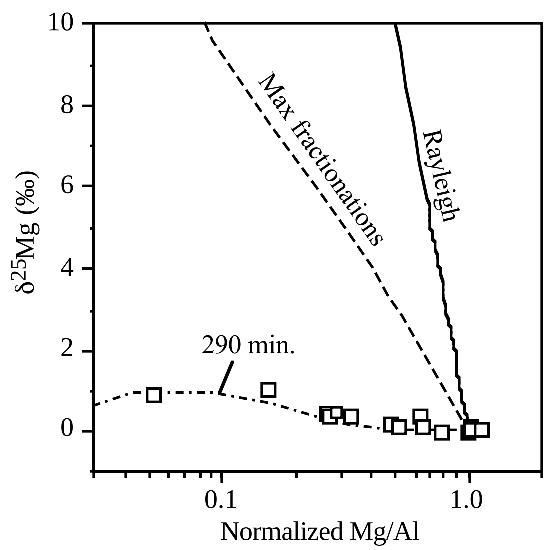

Figure 2. The compositions of Allende chondrules [2] are compared the compositions of model chondrules heated at 1500°C with $P_{tot}=10^{-3}$ bars and solid/gas/solar≥60 for 290 minutes. Also shown are the maximum fractionations that the model chondrules develop as they evolve.

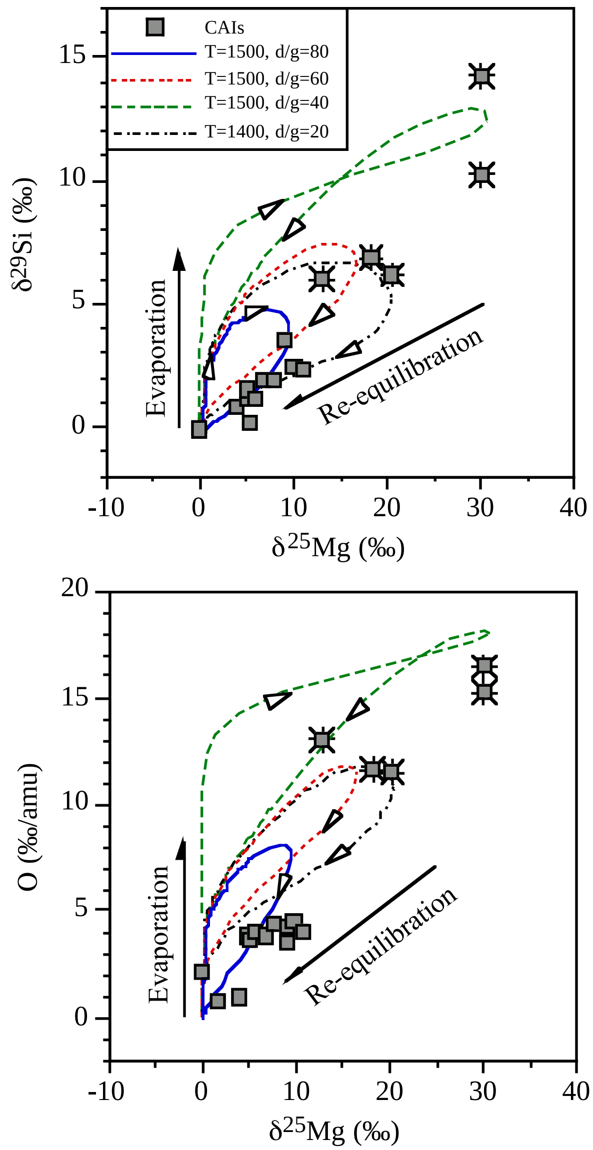

Figure 3. Comparison of CAI isotopic mass fractionations with model evolutionary paths. O mass fractionations were estimated assuming all CAIs started on a slope 1 line that went through the origin in a O 3 isotope diagram. With the exception of the 1500°C, D_g=40 path, the paths are for objects that form under conditions where CAI-like 'equilibrium' compositions are produced. Starred symbols are for FUN or FUN-like inclusions. D/g=solid/gas/solar.