

VAPOR-MELT EXCHANGE – CONSTRAINTS ON FORMATION CONDITIONS AND PROCESSES.

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Introduction: There has been a longstanding debate about the extent to which chondrules and H₂-rich nebular gas interacted during and after chondrule formation. Experimental simulations of chondrule textures suggest that they were rapidly heated to near liquidus temperatures of 1500-1700°C for relatively brief periods and then cooled to solidus temperatures (1000-1200°C) at 10-1000°C/hr [1]. This implies formation timescales of hours to days. On these timescales, interactions between chondrules and gas would have been inevitable. Here we review the evidence for such interactions, the constraints that they place on formation conditions and highlight some unanswered questions.

Discussion: For typical nebula pressures, chondrule liquidus temperatures, chondrule formation timescales, experiments and models predict that evaporation from melt would have been inevitable. In environments with low chondrule+dust (solids) densities, there would have been extensive evaporation with relatively little back reaction of the gas. Chondrules forming under these conditions should have the characteristic isotopic and elemental fractionations associated with Rayleigh distillation. However, while chondrules do show elemental fractionations that seem to be related to volatility, they do not show the predicted systematic isotopic fractionations in S, K, Fe, Mg, Si or O [1]. Their absence implies that chondrules were stable melts in equilibrium with the surrounding gas.

Equilibrium and kinetic models indicate that to produce stable chondrule-like melts at inferred chondrule temperatures and formation timescales solids must be enriched by ≥ 1000 relative to solar at a total pressure of $P^{\text{tot}}=10^{-3}$ bars. Higher enrichments are required for lower P^{tot} .

However, other evidence suggests that enrichments in solids may have been much higher during chondrule formation. Even at 1000 times dust enrichments and $P^{\text{tot}}=10^{-3}$ bars, at near liquidus temperatures Na and K will be entirely in the gas, and only recondense into the melt after most olivine and pyroxene has already crystallized. Measurements of Na in olivine phenocrysts from OCs show that Na was present in some chondrule melts throughout their crystallization, requiring orders of magnitude higher enrichment in solids [2,3]. Exactly how high depends on several factors, principally how much Na evaporated at peak temperatures – estimates have ranged from ~10% to ~50%. Nevertheless, the

solids enrichments or absolute densities that the Na requires during OC chondrule formation are much higher than current nebula models can explain.

Similar studies of Na in phenocrysts have not been conducted on CC chondrules. This is primarily because CC chondrules typically have much lower abundances of Na, making the measurements of Na in the phenocrysts much more difficult. Iron is the next most volatile major element. Metallic iron is a common component of chondrules, particularly FeO-poor ones (type I). Iron metal also seems to have been stable during chondrule formation again requiring high solid densities, although not placing as strong constraints on conditions as Na. On the other hand, there are some indications that S was present in chondrule metal melts. While the presence of S in chondrule metal has received less attention than Na, it may require even higher solid densities.

Given this evidence that chondrule melts were stable and that only a fraction of even the most volatile elements were in the gas, it is surprising that there are such small isotopic fractionations amongst chondrules and that there are petrologic features of type I chondrules in OCs and CCs that have been interpreted as the result of SiO₂ metasomatism towards the end of crystallization. Experiments show that condensation of SiO_(gas) into the chondrules is able to explain the observed textures [4].

The small isotopic fractionations could simply be due to incomplete re-equilibration of chondrules with a range of precursor compositions. The evidence for SiO₂ metasomatism is more problematic as perhaps ~3-15 % of the SiO₂ in these chondrules was introduced by this metasomatism [5]. If this much SiO₂ was in the gas phase, then much more of the more volatile Na and Fe should have been in the gas. At present, there is no evidence that this was the case. Resolution of this apparent inconsistency is vital since the geochemical and petrologic evidence provide the most important constraints on chondrule formation models.

References: [1] Chondrites and the Protoplanetary Disk (eds. A.N. Krot, E.R.D. Scott & B. Reipurth). [2] C.M.O'D. Alexander et al. (2008) *Science*, 320, 1617-1619. [3] R. H. Hewins et al. (2012) *Geochim. Cosmochim. Acta*, 78, 1-17. [4] L. Tissandier et al. (2002) *Meteoritics & Planet. Sci.*, 37, 1377-1389. [5] P. Friend et al. (2016) *Geochim. Cosmochim. Acta*, 173, 198-209.