

EVAPORATION DURING CHONDRULE FORMATION, RECONDENSATION AS FINE PARTICLES, AND THE CONDENSATION OF S AND OTHER VOLATILE ELEMENTS. John T. Wasson and Josep M. Trigo-Rodriguez, Institute of Geophysics and Planetary Physics, University of California, Los Angeles, CA 90095-1567, USA. (jtwasson@ucla.edu)

There are two key assumptions in the classic model of nebular condensation: a) that the nebula was initially hot enough for most elements to have been vaporized; and b) that the cooling rate was slow enough to permit equilibrium between solids and gases to be approached, and trace elements to diffuse into the interiors of host phases. Here I examine a very different picture that follows the volatilization associated with the heating of chondrules, and the rapid condensation that occurred immediately following these flash heating events. This condensation occurred rapidly and produced smoke-like solids. This may have been the dominant process that produced the fine ($\leq 1 \mu\text{m}$) nebular solids preserved as matrix in primitive chondrites, and may have provided the mechanism for converting metallic Fe to FeO and FeS.

For a nebula with a solar composition and a partial pressure of H_2 (p_{H_2}) of 10^{-5} atm the equilibrium 50%-condensation temperatures of the three common elements Mg, Si and Fe are around 1300 K [1]. This temperature is about 600 K lower than typical 90%-melting temperatures of common chondrules (e.g., [2]). A number of chondrule-formation processes have been proposed, but the majority involve the melting of preexisting nebular solids, the precursor materials. The majority of chondrules contain FeS in their interiors; thus it is reasonable to assume that the nebula had cooled to ≤ 600 K, i.e., below the 50% condensation temperature of S as FeS by the time most chondrules were formed.

Any process capable of melting chondrule precursors will also vaporize some fraction of these. However, two factors reduced the rate of vaporization: a) the slow rate of heat conduction into grain interiors (a key reason that relict grains are so common in chondrules) and the relatively low vapor pressures (and thus evaporation rates) of chondrule melts.

In contrast, fine nebular materials would have largely vaporized at the high temperatures (probably >2500 K) that were necessary to allow reasonably rapid heat conduction into the interiors of grains. Wasson [3] suggested that a reasonable working assumption is that, during chondrule melting events, the mass of solids vaporized was about the same as the mass that melted to form chondrules.

The matrix/chondrule ratio in unequilibrated chondrites that avoided appreciable aqueous alteration ranges from about 0.2 to 1. Thus it would appear that, if all chondrules experienced one major melting event, all of the matrix would have experienced evaporation and recondensation. A caveat is that, because fine materials were probably less efficiently agglomerated, the matrix/chondrule ratio is a lower limit on the fine/coarse ratio in nebular silicates.

There is increasing evidence that chondrules experienced several and perhaps many melting events. This is documented by the common presence of relict grains, igneous rims and independent compound chondrules [4,5]. During the last years evidence has been found that the amount of

new growth of mafic minerals following the last melting events was only about $5 \mu\text{m}$ [6]. This leads to the view that the large ($>50 \mu\text{m}$) mafic phenocrysts are themselves the products of multiple melting events. Some of these chondrules seem to have experienced heating events that caused remelting of mesostasis with very little resorption of phenocryst surfaces. My working model is that each chondrule experienced 1 or more "major" events that produced extensive melting, but many smaller melting events that deposited less energy.

Although the events that produced little melting were less intense and only caused maximum chondrule temperatures near 1500 K, the small grains that were heated to this temperature would also have experienced extensive vaporization. Thus, during the entire period of chondrule formation envisioned here, all of the fine material in the nebula would have been vaporized and recondensed multiple times.

It is possible that most chondrule matter has also been vaporized at least once by the same process before the process was halted by agglomeration. The possible exceptions are the low-FeO chondrules both because they are more refractory than the high-FeO chondrules and because, at least in some cases [7], they preserve primitive compositions that would have been altered by repeated recycling.

A problem of long standing in cosmochemistry is the formation of FeS and FeO. If equilibrium prevails, FeS condenses around 600 K [8], and FeO is expected to reach a concentration of 20 mol% in olivine at about 500 K. But, as Kerridge [9], Lauretta et al. [10] and others have noted, equilibrium condensation is only possible if there is free Fe metal available in the nebula. If Fe metal is sequestered in chondrules or corroded to FeS then much of it is not available for condensation.

The S/Fe atom ratio in the Sun is estimated to be about 0.5; thus to fully condense S as FeS it is necessary to expose half of the Fe to the nebular gas. In the classic cosmochemical condensation model in which the grain size of the Fe is assumed to be that observed in chondrites such as LL3.0 Semarkona, the exposure of such a large fraction of the Fe seems impossible to achieve.

If, however, Fe evaporation was extensive during chondrule formation (as expected because temperatures were ~ 600 K higher than the condensation temperature), there should have been large amounts of Fe in contact with the gas, and FeS condensation could have occurred.

Of course, condensation following flash evaporation would not have produced equilibrium condensation. Instead, metal would have bonded to O or S to form any bond that was strong enough to withstand immediate breakage at the ambient nebular temperature. Because of the continued heating by the chondrule forming process, metastable products would have gradually converted to the compounds that are the most stable. However, this process probably did not go to completion.

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