
Recently, it has been suggested that recycling of chondrule fragments [1] and volatile loss during chondrule formation [1-3], rather than nebular condensate precursors [4], could have produced the inter-element correlations observed amongst lithophile elements in bulk chondrule INAA data. The exploration of recycling-volatility models has been motivated by several observations. Firstly, there is scant mineralogical evidence that 'traditional' equilibrium condensation occurred, and the presence of presolar grains in all chondrite groups shows that at least some nebular material did not experience nebular-wide heating. In addition, the rims and matrices of chondrites do not contain the equilibrium condensates expected from the deduced chondrule precursor compositions [4]. Nor do the refractory condensates ever survive unmelted in chondrules despite the presence of chondrule derived relict olivine.

Secondly, there is petrologic evidence for recycling of chondrules, these include; most relic grains apparently having come from chondrules [5], compound chondrules with one enclosing the other [6], reheating of chondrules [6,7] and chondrule rims containing chondrule fragments [8].

Relict grains are found in at least 10-15% of OC chondrules [9] and since their survival rate during chondrule formation is likely to have been significantly less than 100%, this must be a lower limit for the number of chondrules that contain recycled material. Ion probe measurements show that the refractory lithophiles, which make up the most important group of intercorrelated elements in the INAA data, are, with the exception of Mg, all highly incompatible in chondrule melts. As a result, the refractory lithophiles are concentrated in chondritic relative abundances in the chondrule glasses [1]. The latter observation, combined with the evidence for recycled material in chondrules, suggests a very simple means of producing the correlations amongst the refractory lithophiles - namely that chondrules formed by randomly sampling fragments of a previous generation and in so doing inherited variable amounts of glass. Almost all the other reported correlations amongst the lithophile elements in the bulk chondrule data can also be reproduced by the random sampling model [1]. However, a more complete model of chondrule formation would probably have to include incorporation of rim/matrix, reduction/oxidation and, as is discussed below, volatile loss.

Both precursor heterogeneity and volatility can, in principle, produce large compositional variations but what are their relative contributions to the range of chondrule compositions? To assess the role of volatility a simple model based on the vacuum evaporation data of [10] has been developed. The model assumes a cooling rate of 1000°C/hr and a range of chondrule masses (100-0.4mg) that is similar to the range analyzed by INAA. The major free parameter is the initial peak temperature a chondrule experienced. Fe, either as metal or FeO, is the most volatile of the major elements and its abundance in chondrules can be used to put limits on the range of peak temperatures. Fig. 1a compares the total Fe content of chondrules from Semarkona (LL3.0) and Chainpur (LL3.4) [11-15] as a function of mass with predictions for chondrules with an initially LL-chondrite-like bulk composition. Fe-metal and FeO were assumed to evaporate at the same rate. Fig. 1a suggests that most chondrules experienced peak temperatures of between 1900K and 2100K, almost exactly the range estimated from liquidus temperatures [17].

At these temperatures some Si and Mg will also be lost, particularly when peak temperatures approach 2100K. Loss of Fe, Mg and Si will result in an increase in the concentrations of the most refractory elements, such as Al. Fig. 1b plots the range of Fe contents against the Al contents calculated on an Fe-free basis. Also plotted in Fig. 1b are the curves predicted if chondrules saw peak temperatures of between 1900K and 2100K (1x). There is considerable scatter in the chondrule Al contents, much of which is probably due to precursor heterogeneity. However, those chondrules with the more extreme Al contents may indicate that Si and Mg were often more volatile, relative to Fe, during chondrule formation than the vacuum experiments would predict. This is not entirely unreasonable since the volatility of MgO and SiO2 can vary by almost two orders of magnitude, depending on the P(H2) [18]. However, it is not known if Fe volatility is also influenced by the ambient gas. Nevertheless, the most Al-rich chondrules can be explained if MgO and SiO2 evaporate at rates that are about 5x faster, relative to Fe, than in the vacuum experiments. Assuming Fe evaporation rates are not influenced by P(H2) this increased rate would require a P(H2) of about 10^-5 atm. [18].

One elemental correlation in the INAA data that poses a significant challenge to the recycling model is the one between Mg and the other refractory lithophiles. Recycling cannot easily produce the Mg-refractory lithophile correlation because most of the Mg is in the olivine and pyroxene while the other refractory lithophiles are in the glass. One means of producing the correlation without recourse to condensate precursors is the volatile loss of Si from some chondrules [1-3]. Fig. 1c compares the predicted variations of Mg and Al, both for 1x and 5x the vacuum evaporation rates, with that of the measured chondrule compositions. As can be seen, the slope of the trend in Fig. 1c is similar to the predicted ones but the scatter in the chondrule compositions is much larger than could

© Lunar and Planetary Institute • Provided by the NASA Astrophysics Data System
be produced by evaporation and/or analytical error. The scatter almost certainly reflects heterogeneity in the chondrule precursors. [1] has demonstrated that most of the chemical trends seen in the chondrules can be simulated by randomly sampling (recycling) phases from a previous generation of chondrules. Fig. 1d shows the results of a model that combines the recycling model of [1] with the volatility model above (peak T=1900K-2100K and evap. rates 1-5 times [10]). As can be seen the combined model produces a distribution of Al and Mg abundances that is very similar to the chondrule INAA data.

Fig. 1. (a) Comparison of Fe contents as a function of mass in LL-chondrite chondrules [11-15] with curves calculated assuming cooling rates of 1000°C/hr and peak temperatures between 1900K and 2100K. (b) Comparison between LL chondrules [11-13] and curves calculated assuming 1x and 5x the vacuum evaporation rates of [10]. (c) Comparison of LL and H chondrules [11-13,16] with curves calculated assuming 1x and 5x the rates of [10]. (d) Simulated LL chondrule compositions combining recycling [1] and volatile loss.