

EXTREME CONDITIONS REQUIRED FOR SUPPRESSION OF ALKALI EVAPORATION DURING CHONDRULE FORMATION. A. V. Fedkin¹, L. Grossman^{1,2} and F. J. Ciesla¹, ¹Dept. of the Geophysical Sciences, The University of Chicago, 5734 South Ellis Ave., Chicago, IL 60637; avf@uchicago.edu, ²Also Enrico Fermi Institute, Univ. of Chicago.

Introduction: The absence of large isotopic mass-fractionations of Fe, Mg and Si in bulk chondrules indicates that chondrule melting occurred without significant net evaporation of these elements [1], and the probable absence of large isotopic variations within individual chondrules indicates that the explanation cannot be that evaporation of these elements was followed by their recondensation into cooling chondrule melts [2]. To suppress evaporation during chondrule formation, conditions of high total pressure (P^t) and/or high dust enrichment have long been regarded as necessary [3], although short heating times have also been stressed [2, 4]. Retention of Na at levels necessary to account for the Na contents of olivine crystal cores in chondrules demands very large dust enrichments [5, 6], computed by [2] to be equivalent to 10^5 - 10^{11} relative to solar composition, depending on P^t . In [2], a closed-system, kinetic evaporation model was developed that tracks chemical and isotopic changes that would occur in chondrule precursor dust clumps surrounded by nebular gas subjected to various shock wave temperature-pressure histories, taking into account effects of non-equilibrium melting and fractional crystallization on liquid composition, and gas-droplet temperature differences. In that work, a highly reduced starting composition was assumed, as it is unlikely that significant FeO formed during primary nebular condensation [7]. All systems investigated in [2] were enriched in water by a factor of 550 relative to solar composition in order to oxidize Fe to levels appropriate for chondrules, at rates assumed to occur on the time-scales of the imposed thermal histories. It was found in [2] that dust enrichments of 600 relative to solar composition at $P^t \sim 4 \times 10^{-2}$ bar during cooling, or dust enrichments of 6×10^4 at $P^t \sim 4 \times 10^{-4}$ bar suppress Fe evaporation sufficiently to produce minimal internal variations of $\delta^{56}\text{Fe}$, but >90% of Na and K were still evaporated. Because these values of dust enrichment, water enrichment and P^t are so much higher than those achieved in dynamic models of solar nebular evolution, it was suggested in [2] that a more favorable environment for chondrule formation may be in plumes of vapor+dust+liquid generated by impacts on icy planetesimals. The purpose of the present work is to investigate quantitatively the conditions of P_H^t and dust enrichment necessary for retention of Na and K during chondrule formation.

Method: The assumed chondrule precursor has chondritic composition, except that Fe/Si, Ni/Si and S/Si are 0.33, 0.33 and 0.01xCI, resp., similar to a Type II chondrule. Its mineralogical composition was assumed to be the equilibrium assemblage at $\log f_{O_2} = \text{IW}-2.6$ and the assumed initial T, yielding an $\text{Fe}^0/\text{Fe}^{2+}$ ratio of ~ 6.6 . The liquidus T for the silicate fraction is ~ 1930 - 1970K , depending on evolution of FeO and alkali contents. The computer program used in [2] was modified for this study to accept different input cooling rates at constant P_H^t , which is the sum of the partial pressures of all hydrogen species, each multiplied by its number of hydrogen atoms per molecule. In this work, a clump of chondrule precursor dust was assumed to have been heated instantaneously, as would be expected in an impact, to a near-liquidus temperature of 1950K where it formed a partially molten droplet with a radius of 0.5 mm . It was allowed to cool at 100K/hr in a closed system in which the gas and condensed phase were not in chemical equilibrium but were in thermal equilibrium due to the large dust concentrations. Evaporation and condensation fluxes were computed from experimentally determined evaporation coefficients using the Hertz-Knudsen equation.

Results: Enormous dust enrichments are needed to suppress alkali evaporation during heating of chondrule precursors at canonical nebular pressures. Because the chondrule precursor is assumed to be a highly reduced nebular condensate assemblage, these huge dust enrichments must be accompanied by huge water enrichments in order that there be sufficient oxygen in the system for oxidation during chondrule formation to yield FeO contents typical of most chondrules.

At a canonical solar nebular P_H^t of $\sim 1 \times 10^{-4}$ bar and a water enrichment of 6×10^3 , a dust enrichment of 6×10^8 is required in order that no more than 7% of the Na and 10% of the K evaporate before they begin to recondense when the droplet cools from 1950K . For the same initial T and water enrichment, the dust enrichment required to prevent evaporation of the same fractions of the Na and K decreases by a factor of ten for every factor of ten increase in P_H^t (Fig. 1). The needed dust enrichments at a given P_H^t are a factor of 2 smaller when the equilibrium f_{O_2} of the droplet is 1.3 log units higher, a factor of 10 smaller when 50% of the Na is the maximum allowed to evaporate [6], a

factor of 3.5 smaller when there is no water enrichment, and a factor of 30 larger when the water enrichment is 2.5×10^5 (Fig. 1). At the maximum dust enrichment factor, 125, found in models of dust coagulation and settling to the nebular midplane [8], total pressures >100 bar would be required. Greater dust enrichments are found in turbulent concentration models but their formation probability drops off dramatically with increasing dust enrichment [9], *e.g.*, the probability of reaching dust enrichments $>10^5$ is only 1 in 10^6 by this mechanism.

When the chondrule precursor is exposed to physico-chemical conditions in the field below the lines in Fig. 1, extensive evaporation occurs. Shown in Fig. 2 are examples of Na recondensation curves for a cooling rate of 100K/hr at $P_H^t = 10^{-1}$ bar, a water enrichment of 600 and dust enrichments of 6×10^4 , 6000 and 600, *i.e.* factors of 2.9 to 290 below the dust enrichment needed to prevent $>7\%$ of the Na from evaporating at the same water enrichment. At dust enrichments of 600 and 6000, $>50\%$ of the Na stays in the gas during 75-200K of cooling, during which a large amount of olivine will have crystallized with lower Na contents than are found in cores of olivine phenocrysts [5, 6]. At a dust enrichment of 6×10^4 , however, $<50\%$ of the Na evaporates and more than half of that recondenses before significant olivine crystallizes.

Conclusions: For thermal histories with peak temperatures near chondrule liquidus temperatures and cooling rates like those of natural chondrules, high-T retention of alkalis by chondrule precursors requires either much larger dust enrichments at canonical nebular pressures than have been predicted in dynamical models of the solar nebula, or much higher pressures than predicted by solar nebular models at less extreme dust enrichments. Furthermore, if the precursor dust consists of reduced nebular condensates, large dust enrichments must be accompanied by much larger water enrichments than have been found in dynamic models of the solar nebula [10] in order to generate the FeO contents of most chondrules. Simultaneous enhancement of all three parameters may occur in solid+liquid+vapor plumes formed by impacts on icy planetesimals. If, on the other hand, the precursor dust is oxidized, the requirement of high water enrichment is relaxed but, since no way is known to generate high FeO in primary nebular condensates, an origin of the precursor dust in an icy planetesimal is still favored [7].

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