

**CONDITIONS FOR MAKING TYPE IIA CHONDRULES IN NEBULAR SHOCKS.** A. V. Fedkin<sup>1</sup> and L. Grossman<sup>1,2</sup>. <sup>1</sup>Dept. of the Geophysical Sciences, Univ. of Chicago, 5734 S. Ellis Ave., Chicago, IL 60637; <sup>2</sup>Enrico Fermi Inst., Univ. of Chicago. (avf@uchicago.edu).

**Introduction:** Chondrules formed by rapid cooling of molten droplets in the solar nebula. Type IIA chondrules are composed predominantly of olivine (mean  $X_{Fa}=0.16$ ) and mesostasis (mean  $SiO_2=62.6$ ,  $Al_2O_3=11.2$ ,  $FeO=7.8$ ,  $MgO=4.5$ ,  $CaO=7.2$ ,  $Na_2O=4.1$ , and  $K_2O=0.6$  wt%), with only ~1% Fe as metal or sulfide [1]. Their bulk compositions are thus strongly depleted in Fe (atomic Fe/Si~0.33xsolar), but only some are depleted in Na and K and some are actually enriched in these elements [2]. The high FeO contents of these objects suggest that they were melted in a gas much more oxygen-rich than one of solar composition, made so perhaps by enrichment in evaporated water ice [3]. At chondrule melting temperatures, elements such as Na, K, Fe, Mg and Si would be expected to volatilize; yet, measured isotopic mass-fractionations of these elements in chondrules are very small [4]. One possible explanation for the suppressed isotopic mass-fractionations is that chondrules were melted and evaporated in a system with high ambient pressures of volatile elements, such as in a region where protochondrule material was enriched relative to the gas by a factor of several hundred relative to solar abundances [5]. Here, we investigate the mineralogical, chemical and isotopic evolution of a C-, S-, H<sub>2</sub>O-free but otherwise CI composition chondrule precursor in a closed system of solar composition, except for being 300x enriched in these precursors and 200x enriched in water relative to solar abundances, along the P-T-time path calculated for passage of a 7 km s<sup>-1</sup> shock wave at an initial  $P^{tot}=1.1 \times 10^{-5}$  bar [6].

**Technique:** We use a kinetic evaporation model based on the MELTS thermodynamic model and described in [7]. The equilibrium proportions of all phases and their compositions are calculated at each evaporation step, and the activities of components in the silicate liquid along with the equilibrium  $f_{O_2}$  of the assemblage are used to compute the vapor pressures of all species. At each step, the vapor pressure and ambient pressure of each species is used to calculate its flux out of or into the droplet using the Hertz-Knudsen equation. The same evaporation coefficients ( $\alpha_i$ ) and their T-dependences are used as in [7], except for that of oxygen,  $\alpha_O$ , which is set at 0.3 at 2000K. An oxygen flux different from that which is stoichiometrically equivalent to the net cation fluxes is driven by the difference between the equilibrium  $f_{O_2}$  of the droplet and the  $f_{O_2}$  of the ambient gas, and causes reduction of

FeO<sub>(l)</sub> and NiO<sub>(l)</sub> (treated as evaporation of oxygen) or oxidation of metallic Fe and Ni (condensation of oxygen). After each evaporation step, the equilibrium assemblage for the new bulk composition is found by iterating on  $f_{O_2}$  until MELTS finds the assemblage with the known oxygen content. Solid silicates were assumed not to evaporate and to preserve the isotopic compositions with which they crystallized. Their surface areal proportions were assumed equal to their volume proportions. Solid and liquid metallic Fe and Ni were allowed to evaporate from spherical alloy grains or drops of 3 μm radius, 2% of which were assumed to be on the surface of the droplet at all times. Solid metallic Fe was assumed to evaporate without isotopic fractionation; liquid metal to do so with an Fe isotopic fractionation factor equal to the inverse root of the mass. Their Fe isotopic compositions were not allowed to equilibrate with that of the silicate liquid, which was assumed to evaporate with the isotopic mass fractionation factors measured for chondritic matter (Fe, Si) and for chondritic and CAI matter (Mg), as summarized in [8]. An inverse root of the mass law was used for K isotopes. During the cooling part of the thermal history, formation of feldspar and ortho- and clinopyroxene were suppressed to simulate subcooling of the silicate liquid and allow its persistence to <1200K, where its interaction with the ambient gas could be studied.

**Results:** The model run begins with a sphere of 0.5 mm radius at 1398K where  $P_H^{tot}$  has reached  $1.1 \times 10^{-4}$  bar and where we assume that 3% of the total Fe is present as FeO, generating an initial equilibrium log  $f_{O_2}$  of IW-3.1 (Fig. 1). The assemblage consists of 31wt% NiFe alloy, 29% olivine (ol) with  $X_{Fa}=0.024$  (Fig. 1), 23% orthopyroxene (opx), 4% clinopyroxene (cpx), 1% spinel (sp), 4% feldspar (fsp) and 8% silicate liquid (liq) containing 9% Na<sub>2</sub>O and 1% K<sub>2</sub>O. Because of the huge water enrichment, the ambient gas begins with log  $f_{O_2}$  of IW-2.1 (Fig.1). As temperature rises, metal is oxidized,  $f_{O_2}$  of the droplet rises toward that of the ambient gas (Fig. 1), the proportion of fsp, opx and cpx decrease as that of liq increases, copious amounts of Na, K and Fe evaporate from liq, and Fe and Ni from solid alloy (Fig. 2), causing  $\delta^{41}K$  and  $\delta^{56}Fe$  (Fig. 3) of liq to rise steeply and  $\delta^{56}Fe$  of the gas first to fall and then to rise. After 57 min,  $X_{Fa}$  of residual olivine and the equilibrium  $f_{O_2}$  of the droplet fall as the total Fe content of the droplet falls by a factor of 2. Significant

evaporation of Si and Mg begins at 70 and 80 min, resp., ultimately causing  $\delta^{29}\text{Si}$  and  $\delta^{25}\text{Mg}$  of the droplet to reach maxima of only 0.79 and 0.26‰, resp. At 92 min, where  $T=1720\text{K}$ , metal melts, causing  $\delta^{56}\text{Fe}$  of liquid metal to begin to rise steeply and that of the ambient gas to fall again.  $\delta^{56}\text{Fe}$  of liq begins to fall at 84 min and then rises sharply just after shock arrival, reflecting the relative rates of evaporative loss of FeO and gain of FeO from dissolution of olivine and/or oxidation of metallic Fe, both phases being sources of relatively low  $\delta^{56}\text{Fe}$ . Upon shock arrival at 96 min ( $T=1859\text{K}$ ), there is 18% alloy, 28% ol ( $X_{\text{Fa}}=.016$ ), <1% sp and 54% liq containing 0.74% FeO and <0.01% of  $\text{Na}_2\text{O}$  and  $\text{K}_2\text{O}$ . Just before shock arrival,  $f_{\text{O}_2}$  of the droplet rises toward that of the ambient gas, and, upon cooling, new ol crystallizes from liq with  $\delta^{56}\text{Fe}$  ranging from 5 to 12‰, and joins residual ol with normal Fe, yielding  $\delta^{56}\text{Fe}\sim 6\text{‰}$  for the bulk ol. K, Mg, Fe, Si, and Na begin to re-condense at 1807, 1716, 1705, 1673 and 1611K, resp. Assuming a greater fraction of the metal grains on the droplet surface significantly delays re-condensation of lithophiles. Preferential re-condensation of light isotopes causes  $\delta^{56}\text{Fe}$  of both liquid metal and liq to become negative.  $\delta^{56}\text{Fe}$  for metal begins to increase after metal freezes, that for liq after >50% of the Fe is condensed. As time passes, relatively high-Fa ol continues to crystallize from liq, causing  $\delta^{56}\text{Fe}$  of the bulk ol to fall. If the droplet were quenched at 1186K (the end of the model run), it would consist of 58 wt% ol ( $X_{\text{Fa}}=.17$ ), 1% sp ( $\text{MgO}=14$ ,  $\text{FeO}=16$ ,  $\text{Cr}_2\text{O}_3=50$ ,  $\text{Al}_2\text{O}_3=19$ ,  $\text{TiO}_2=1$  wt%), 24% metal ( $X_{\text{Ni}}=.068$ ), and 17% glass ( $\text{SiO}_2=65.6$ ,  $\text{Al}_2\text{O}_3=14.2$ ,  $\text{FeO}=1.0$ ,  $\text{MgO}=2.0$ ,  $\text{CaO}=10.4$ ,  $\text{Na}_2\text{O}=5.8$ , and  $\text{K}_2\text{O}=0.4$  wt%).

$X_{\text{Fa}}$  of ol is in good agreement with the average for real Type IIA chondrules. Since some of the earliest ol to crystallize in the model has  $X_{\text{Fa}}<.04$ , the forsteritic cores, interpreted by [1] as relict, would be expected. The alloy content of the droplet is too high, and the FeO content of the glass lower than that of chondrule mesostasis. Re-condensation of some metal separately from the droplet could possibly account for the former, and fractional crystallization of olivine from the liquid possibly for the latter. The very small mass fractionations seen in chondrules were produced here, except for K.  $\delta^{56}\text{Fe}$  of the glass, ol and metal would be -0.17, 0.53 and -0.17‰, resp.  $\delta^{25}\text{Mg}$  for ol, glass and the bulk would be -.01, -.16, and -.01‰, resp.  $\delta^{29}\text{Si}$  for ol, glass and the bulk would be 0.21, -0.82 and -0.13‰, resp. Despite using relatively high values for condensation coefficients of Na and K (.064 and .025, resp., independent of T below 1800K) in this run, these elements did not fully re-condense by 1186K at this chon-

drule enrichment, leaving the droplet with  $\delta^{41}\text{K}$  of -12.2‰. Higher chondrule enrichments and/or lower interaction temperatures could solve this problem.

**References:** [1] Jones R. H. (1990) *GCA*, 54, 1785–1802. [2] Jones R. H. et al. (2005) In *Chondrules and the Protoplanetary Disk*, p. 251. [3] Ciesla F. J. & Cuzzi J. N. (2006) *Icarus*, 181, 178–204. [4] Alexander C. M. O'D. (2004) *GCA*, 68, 3943–3969. [5] Cuzzi J. N. & Alexander C. M. O'D. (2006) *Nature*, 441, 483–485. [6] Desch S. J. & Connolly H. C. Jr. (2002) *MAPS*, 37, 183–207. [7] Fedkin A. V. et al. (2006) *LPS XXXVII*, Abstract #2249. [8] Davis et al. (2005) In *Chondrules and the Protoplanetary Disk*, p. 432.

