ISOTOPIC COSMOBAROMETRY – A SYNTHESIS OF CONCEPTS AND IMPLICATIONS FOR CHONDRULE AND CAI FORMATION MECHANISMS. E. D. Young[1], [1]Department of Earth & Space Sciences and Institute of Geophysics and Planetary Physics, University of California Los Angeles, 595 Charles E. Young Drive East, 2676 Geology Building, Los Angeles, CA 90095 (eyoung@ess.ulca.edu).

Introduction: Chondrules were once molten spheres in space and the expectation is that they should show evidence for evaporation. However, Mg, K, and Fe isotope data do not follow the trends expected if the molten spheres were present in a near vacuum [1-6]. The lack of isotope fractionation in chondrules contrasts with the large fractionation effects seen in CAIs. The general lack of light-element mass fractionation in chondrules has been a vexing problem because these objects show evidence for volatility-controlled variations in the concentrations of the very same elements lacking isotope fractionation, at odds with the expectations for free evaporation [3]. A synthesis of recent models for volatilization of liquids is used here to constrain the astrophysical environments in which chondrules and CAIs formed. Results suggest that chondrules in general formed within ≤ 1 meter of one another while CAIs were more sparsely distributed during their formation.

Theory: Two theories exist for the lack of isotope fractionation in chondrules. Both rely on the concept of quasi-statical (i.e., near equilibrium) exchange of isotopes between liquid and gas followed by permanent loss of rock-forming elements to the escaping gas phase. One model [7] implies that the chondrules formed in such close proximity to one another that the partial pressures of the rock-forming elements in the surrounding ambient gas approached saturation (see Figure). The other [8] does not rely upon widespread saturation of the gas. Instead it allows that the liquid chondrules exchanged isotopes with the gas evaporating from the object. The local atmosphere of gas is bound to its chondrule by slow diffusion through the ambient gas (Figure). The differences between these two physical situations can be seen with reference to an equation describing the net flux of a component i (e.g., Mg) volatilizing from a molten sphere presented by Richter et al. [8]:

$$J_{i,\text{net}} = \frac{J_{i,\text{evap}}\left(1-\dfrac{P_{i,\infty}}{P_{i,\text{sat}}}\right)}{1+\dfrac{\gamma_i r}{D_{i,\text{gas}}}\sqrt{\dfrac{RT}{2\pi m_i}}}.$$

The equation can be rewritten in convenient form as

$$J_{i,\text{net}} = \frac{J_{i,\text{evap}}\left(1-\dfrac{P_{i,\infty}}{P_{i,\text{sat}}}\right)}{1+\Gamma}$$

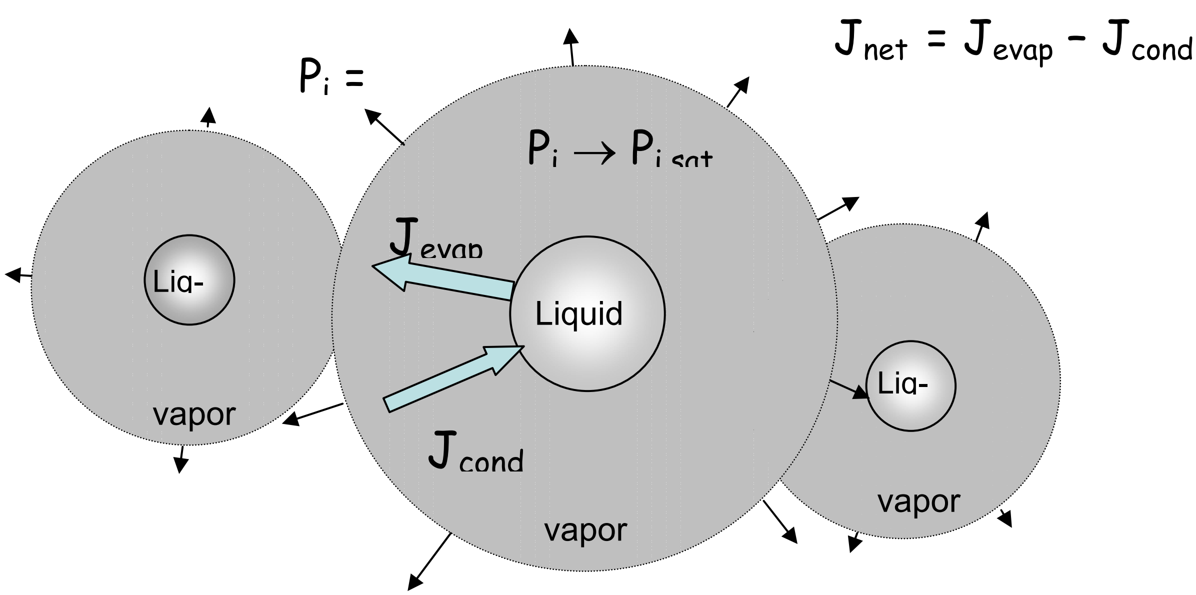
where $J_{i,\text{net}}$ is the net difference between the evaporative and condensation fluxes for species i, $J_{i,\text{evap}}$ is the evaporative flux of i, $P_{i,\infty}$ is the partial pressure of species i far removed from the molten object, $P_{i,\text{sat}}$ is the saturation partial pressure of i, $D_{i,\text{gas}}$ is the diffusion coefficient of i through the gas phase, γ_i is the evaporation factor for i, r is the radius of the molten object, and m_i is the mass of the volatilizing species. In terms of this equation, isotope fractionation will occur when $J_{i,\text{net}}/ J_{i,\text{evap}} \rightarrow 1$ while no fractionation occurs when $J_{i,\text{net}}/ J_{i,\text{evap}} \rightarrow 0$. The latter occurs where the background pressure $P_{i,\infty}$ approaches the saturation pressure $P_{i,\text{sat}}$. This could be the case where a population of volatilizing chondrules contributes to an elevated background of partial pressure of rock-forming elements as envisioned by Alexander [7]. In the other extreme where $P_{i,\text{sat}} >> P_{i,\infty}$, as would be the case where chondrules are not sufficiently close together to cause a pervasive rise in background partial pressures, the only way to prevent fractionation is for Γ to be large, as suggested by Galy et al. [3]. The kinetic theory of gases permits one to compute Γ as a function of pressure. Such calculations show that Γ is large enough to preclude fractionation when total pressures approach 10^5 Pa (1 bar) (e.g., at T = 2000K and γ_i = 0.06, Γ = 0.062 at 100 Pa or 10^{-3} bar and 62 at 10^5 Pa or 1 bar for a chondrule-sized object).

From the preceding discussion it should be clear that the level of isotopic fractionation for a major rock-forming element like Mg in an object that was once molten in the early Solar System is a barometer of either total pressure (large Γ) or partial pressures relative to saturation (small Γ). In order to use Mg as a "cosmobarometer," high-precision analyses of Mg isotope ratios in both chondrules and CAIs are required.

Implications: From the high-precision Mg isotope data (and other K and Fe isotope data) available to date, it appears that chondrules crystallized under conditions of either high Γ, meaning high total pressure, or in close proximity to one another where $P_{i,\text{sat}} \sim P_{i,\infty}$. At ambient total pressures of 100 Pa (10^{-3} bar), the latter condition obtains if chondrules formed within approximately 1 meter of one another based on consideration of the characteristic length scale for diffusion of Mg in the gas phase (see calculation at bottom of Figure). Any astrophysical model for chondrule formation must account for this minimum concentration of chondrules so that $P_{i,\mathrm{sat}} \sim P_{i,\infty}$. The only alternative that is consistent with the isotope data is for Γ to have been large. Large Γ would require ambient pressures that are considered to be outside the realm of realistic protoplanetary disk environments, lending weight to the chondrule number density constraint.

CAI's evidently formed under conditions where both partial pressures and total pressures were low because they exhibit marked ^{25}Mg isotope enrichments relative to "chondritic" ^{25}Mg/^{24}Mg (implying there are oxygen isotopic effects of evaporation as well). Published models predict that there should be variations in δ^{25}Mg with growth direction and chemical parameters that include Mg/Al and rare earth concentrations. Identification of such trends would verify that the observed enrichments in δ^{25}Mg are due to a single phase of evaporation. New laser ablation MC-ICPMS Mg isotope data obtained for two different CAIs (see abstract by Simon et al., this volume), one from the Allende meteorite and the other from the Leoville meteorite, show that predicted evaporation trends exist in one CAI but not the other. A multi-stage history for at least some CAIs is implied.

References: [1] Alexander C.M.O.D. et al. (2000) Met. Planet. Sci., 35, 859-868. [2] Zhu X.K., et al. (2001) Nature, 412, 311-313. [3] Galy A. et al. (2000) Science 290, 1751-1753. [4] Alexander C.M.O.D. and Wang J. (2001) Met. Planet. Sci., 36, 419-428. [5] Ash R.D. et al. (1998) LPSC XXIX. [6] Young E.D. et al. (2002) GCA 66(4), 683-698. [7] Alexander C.M.O.D. (2003) LPSC XXXIV. [8] Richter F.M. et al. (2002) GCA 66(3), 521-540.



$D_{i,gas}$ = 2/3 $(1/P_{total}\sigma)(k^3T^3/(\mu_{i\text{-}H2}\,\pi))^{1/2}$

$(D*60s)^{1/2}$ ~ 0.9 m at 100 Pa (10-3 bar)
~ 2.7 cm at 1x105 Pa (1 bar)