RECONSTRUCTING CHANGING CONDITIONS IN THE SOLAR NEBULA: MODEL CONSTRAINTS AND EVIDENCE FROM MAGNESIUM ISOTOPES IN CAIS. Justin. I. Simon[1], Sara. S. Russel[2], Eric. Tonui[3], and Edward. D. Young[3, 4], [1]Department of Earth & Planetary Sciences, University of California Berkeley, 477 McCone Hall, Berkeley, CA 94720, (simon@eps.berkeley.edu), [2]Department of Mineralogy, Natural History Museum, Cromwell Road London, SW7 7BD, UK, [3]Department of Earth & Space Sciences, University of California Los Angeles, 595 Charles E. Young Drive East, 2676 Geology Building, Los Angeles, CA 90095, [4]Institute of Geophysics and Planetary Physics, University of California Los Angeles, 595 Charles E. Young Drive East, 2676 Geology Building, Los Angeles, CA 90095.

Introduction: Individual calcium-aluminum-rich inclusions (CAIs) preserve distinct isotopic records of early solar system processes. We fit the isotope record obtained by *in situ* measurements of $^{27}Al/^{24}Mg$, $^{25}Mg/^{24}Mg$, and $^{26}Mg/^{24}Mg$ isotope ratios by LA-MC-ICPMS comprising core-to-rim traverses across five CV3 CAIs with models that consider mass dependent isotope fractionation processes. When coupled with the short-lived ^{26}Al chronometer, Mg isotopes can be used to determine when thermal and barometric physiochemical processes occurred in the protoplanetary disk. We obtained numerical solutions to the problem of Mg isotopic fractionation at the moving surface of a shrinking sphere, representing an evaporating igneous CAI, coupled with diffusional transport within the sphere. Solutions to this moving boundary problem were published previously [1]. We took these earlier calculations further and considered the affect of Mg isotope fractionation due to isotope specific transport within the sphere and preferential loss of ^{24}Mg at the surface, as shown previously [2, 3]. Modeling of Mg isotope diffusion and comparisons with data suggests that CAIs pass through regions of relatively high temperature and high Mg partial pressure on 10^2 yr timescales. We suggest that a likely cause of such brief high-T, high-P events is passage of CAIs through shock fronts in the solar protoplanetary disk.

Modeling Approach: For a spherical CAI, diffusion of Mg driven by a change in [Mg] at the surface is described by the equation (e.g., [4]):

$$\frac{\partial[^{x}\mathrm{Mg}]}{\partial t} = D\left(\frac{\partial^2[^{x}\mathrm{Mg}]}{\partial r^2} + \frac{2}{r}\frac{\partial[^{x}\mathrm{Mg}]}{\partial r}\right), 0 < r < s(t)$$

where $[^{x}Mg]$ is the concentration of ^{25}Mg or ^{24}Mg, D is the diffusivity of ^{x}Mg isotope (cm^2sec^{-1}), r is the radial distance from the center of the sphere, and s(t) is the time-dependent radial position of the sphere surface. Mass balance is conserved at the surface of the spherical melt droplet expressed as

$$J_{evap}^{^{x}Mg} = J_{diff}^{^{x}Mg} - J_{ablt}^{^{x}Mg}$$

where $J_{evap}^{^{x}Mg}$ is the evaporative flux of $[^{x}Mg]$ into the surrounding gas, $J_{diff}^{^{x}Mg}$ is the diffusive flux of $[^{x}Mg]$ within the melt, and $J_{ablt}^{^{x}Mg}$ is the ablative flux $[^{x}Mg]$ loss associated with inward motion of the melt-gas interface. An initial condition is set by the relative abundances of ^{25}Mg and ^{24}Mg such that $\delta^{25}Mg'_{DSM3} = 0$ (i.e., the chondrite-like DSM3 magnesium standard [5]). The boundary condition prescribed by mass balance at the surface reflects an Mg flux due to the changing concentration and receding surface. It is described by the equation:

$$D\left.\frac{\partial[^{x}\mathrm{Mg}]}{\partial r}\right|_{r=s(t)} = [^{x}\mathrm{Mg}](K_d - 1)\,\dot{s}$$

where $\dot{s}$ = ds/dt (the rate of ablation). The relative rate of surface migration (i.e., ablation) to the rate of diffusive transport is described by the Peclet number (Pe), a dimensionless parameter, where

$$Pe = -s^{o}\frac{\dot{s}}{D}$$

and where s^{o} signifies the initial value of the time-dependent position of the surface. Models consider ^{25}Mg and ^{24}Mg separately to account for differences in diffusivity. Results are reported as $\delta^{25}Mg'$ values with respect to normalized radial distance.

We obtained a second set of simple numerical solutions to radial diffusive Mg transfer in a solid sphere. These models depict CAIs at subsolidus temperatures considering Mg isotopic exchange with surrounding gas. Wark-Lovering rims are used to define the boundary concentrations in these calculations.

Discussion: Model calculations fit to Mg isotope measurements can be seen in Figures 1 and 2 and support two general episodes of CAI evolution: 1) early evaporation of molten CAIs within an environment of low partial pressure of Mg (P_{Mg}) and low total pressure

(P_{total}) producing high overall δ^{25}Mg and high δ^{25}Mg at the CAI margins, and 2) later reheating at relatively high P_{Mg} approaching saturation resulting in modifications to the original isotopic profile. Modifications to the Mg isotope ratios during reheating apparently occurred in the solid-state.

In detail, fitting the models for mass-dependent isotope fractionation by evaporation and diffusion in the liquid and solid states to the observed Al-Mg isotope systematics in CAIs imply that:

(1) CAIs exhibit elevated δ^{25}Mg' values in their interiors that require isotope specific diffusion-limited evaporation of molten spheres in low total pressures, and low Mg partial pressure environments.

(2) Low δ^{25}Mg' margins of profiles in igneous CAIs are explained by immersion of the CAIs in a high-P_{Mg} and high-T gas with chondritic δ^{25}Mg' for a total of 100's yrs.

(3) δ^{26}Mg* in WL rims and in the margins of CAIs require that the total time elapsed between evaporation and immersion in the chondritic (high P_{Mg} and δ^{25}Mg' ~0) gas was < $t_{1/2}$ for ^{26}Al.

(4) CAIs experienced a variety of thermal histories as demonstrated by their distinctive Mg isotope profiles and Al-Mg systematics.

Our results suggest two components to CAI evolution. The first resulted in elevated δ^{25}Mg' interiors and margins and preserved supra-canonical initial $^{26}Al/^{27}Al$ (~6 to 7.0x10^{-5}) values (e.g., [6]). The second, subsequent to the first in many CAIs, caused low δ^{25}Mg' margins as a result of reheating. Reheating also caused partial isotopic exchange with a chondritic gas and internal Al-Mg isotopic resetting to canonical ($^{26}Al/^{27}Al)_0$. These disparate histories provide a logical explanation for the existence of CAIs with supra-canonical ($^{26}Al/^{27}Al)_0$ values and the preponderance of CAIs with canonical ($^{26}Al/^{27}Al)_0$ values.

This two-stage evolution explains a great deal about the complexities of the $^{26}Al/^{26}Mg$ system in these objects. It also explains the growth of Wark-Lovering rims on CAIs (cf. [7]). Evaporative enrichment in $^{25}Mg/^{24}Mg$ implies high temperatures (melting) and low pressures (isotope fractionation), like those near the protoSun. Later heating at higher partial pressures of rock-forming elements can be attributed to a fall back into the mid-plane of the disk, turbulent radial transport through the disk, and/ or passage through shock waves. The 10^2 yrs of reheating based on the rate of Mg isotope diffusion in CAIs is consistent with the time required to achieve resetting of the Al-Mg system. This short time spent at high temperatures occurred over a more protracted total elapsed time interval of 10^5 yrs, implying episodic heating.

References: [1] Young, E. D. et al. (1998) *GCA, 62,* 3109-3116. [2] Richter, F.M. et al. (2003) *GCA*, *67,* 3905-3923. [3] Richter, F.M. and A.M. Davis (2004) *LPS XXXIV,* 2047. [4] Crank, J. (1975) Oxford University Press. [5] Galy, A. et al. (2003) *JAAS, 18*, 1352-1356. [6] Young, E.D. et al. (2005). *Science,* 1108140, [7] Simon, J.I. et al. (2005) *EPSL, 238*, 272-283.

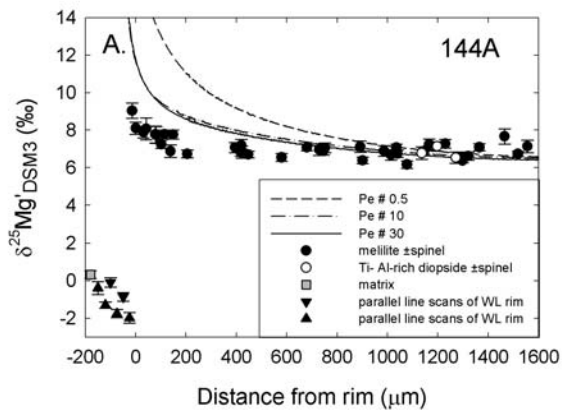

Figure 1. Mg isotopic profile for CAI Leoville 144A compared with our model calculations. Initial model conditions include a bulk chondritic δ^{25}Mg' value (0), r^o = 0.5 to 1.5 cm, 1673 K, Peclet number = 0.5 to 30, $\dot{r}$ = 10^{-6} to 2x10^{-5} cm^{2}s^{-1}, K_d = 50, and Δt ~700 to ~1500 minutes.

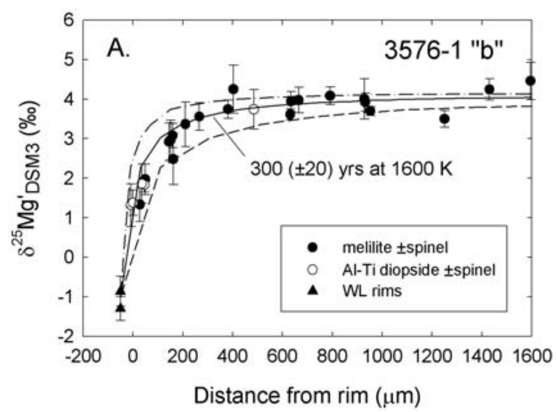

Figure 2. Solid-state Mg diffusion model curves for CAI Allende 3576-1b that represent Mg isotopic exchange with a chondritic gas at 1600 K for 280 yrs (dash-dot), 300 yrs (solid), and 320 yrs (dashed), respectively.