WARK-LOVERING RIMS RECORD A SHORT TIMESCALE FOR CHANGING CONDITIONS IN THE EARLY SOLAR NEBULA. J. I. Simon, S. S. Russell, E. Tonui, K. A. Dyl, C. E. Manning, and E. D. Young, 1Department of Earth & Space Sciences and Institute of Geophysics and Planetary Physics, UCLA, 595 Charles E. Young Drive East, 2676 Geology Building, Los Angeles, CA 90095 (jismon@ucla.edu), 2Department of Mineralogy, Natural History Museum, Cromwell Road London, SW7 7BD, UK. A. B.

Introduction: Refractory Ca, Al-rich inclusions (CAIs), the oldest nebular condensates [1], contain a record of the early solar system. Most constituents of the primitive chondrite meteorites, comprising the primary building blocks of the planets [2], formed under conditions characterized by relatively high partial pressures of rock-forming gases (including oxygen) while CAIs formed at low partial pressures in a solar-like gas. The timescale over which this fundamental change in conditions occurred is, potentially, a primary constraint on the timescale over which the early solar nebula itself evolved. Here we present new Mg isotope data that, when coupled with oxygen barometry data (see Dyl et al., this meeting), show that the ubiquitous Wark-Lovering (WL) rims on CAIs formed in places resembling chondrite-forming regions of the solar nebula between 0 and 300,000 years after initial CAI formation. The results suggest that the most primitive solar system objects moved from a reducing solar-like gas to a more oxidizing region of chondritic dust enrichment within 10^3 years or less. Shock waves provide a plausible astrophysical environment for the formation of the CAI rims.

Approach: Magnesium isotope measurements of Allende 3576-1 “b” and Leoville 144A and Leoville MRS3 CAIs were obtained in situ by UV laser ablation multiple-collector inductively coupled plasma-source mass spectrometry (MC-ICPMS) using sample-standard bracketing. All Mg isotope measurements are reported relative to the DSM3 standard, a chondritic value [3]. The external reproducibility of the radiogenic 26Mg excess, expressed as δ26Mg*, and δ25Mg values in our laboratory by laser ablation inferred from repeated analyses of terrestrial minerals and synthetic glasses is better than 0.25‰ (2 s.d.) for both. An equilibrium β value (0.521) is used for calculating δ26Mg* (a lower β value would increase the calculated initial 26Al/27Al for the WL rims because they have δ25Mg values that are depleted relative to bulk chondrite).

Sample Description: Allende 3576-1 “b” is a ~4 mm x 3.5 mm Type B CAI composed of intergrown melilite and Ti, Al-rich diopside surrounded by a mantle dominated by melilite. Spinel is abundant throughout the inclusion. Leoville 144A is a compact, oval ~10 mm x 6 mm Type A CAI composed of fine grained intergrown melilite and lesser Ti, Al-rich diopside that encloses abundant micron-sized perovskite grains. Much like Allende 3576-1 “b”, Mg-rich spinel is distributed throughout Leoville 144A. Leoville MRS3 is an edge fragment of a Type B CAI composed of melilite. All three CAIs have typical WL rims [4].

Discussion: Many CAIs contain thin WL rims composed of bands of single minerals or simple mineral intergrowths made of (from the interior to near the edge of the host matrix): spinel + perovskite ± hibonite, ±melilite, and clinopyroxene that changes in composition outward. These enigmatic features have been studied for decades but their significance has remained elusive. We presented recently new UV laser ablation and acid digestion MC-ICPMS analyses of CAIs [5] (see Young et al., this meeting) showing that the initial 26Al/27Al in the early solar system was at least 6x10^-5. Our Mg isotope data for the WL rims of Allende and Leoville CAIs define an (26Al/27Al)o value of ~5x10^-5 (Figure 1). From the difference between these initial 26Al/27Al values the time interval between initial CAI growth and rim formation can be constrained to be less than ~300 kys.

Heavy Mg isotope enrichment of CAI interiors is common, as in this study (Figure 2), and can be described by an equation that governs the net flux of Mg volatileized from a molten sphere [6], rewritten in the form [7]:

\[ J_{Mg,net} = J_{Mg,net} \left( 1 - \frac{P_{Mg,net}}{P_{Mg,sat}} \right) \]

in which,

\[ \Gamma = \frac{\gamma P_{Mg,net}}{D_{Mg,vol} \sqrt{RT/2\pi m_{Mg}}} \]

where \( J_{Mg,net} \) is the net difference between the evaporative and condensive fluxes for Mg, \( J_{Mg,net} \) is the evaporative flux of Mg, \( P_{Mg,net} \) is the partial pressure of Mg far removed from the object, \( P_{Mg,sat} \) is the saturation partial pressure of Mg, and \( \Gamma \) is largely a function of the pressure-dependant diffusion of Mg in the surrounding gas phase, but also the ambient temperature, radius of the object, the masses of gas species involved, and the evaporation coefficient. In terms of this equation evaporative isotopic fractionation of molten refractory phases towards heavier values will occur when \( J_{Mg,net}/J_{Mg,net} \rightarrow 1 \) (low ambient Mg partial pres-
sure and low total pressure) and no isotopic fractionation will occur when $J_{Mg,net}/J_{Mg, evap} \rightarrow 0$ as a consequence of either high ambient Mg partial pressure or high total pressure [8]. From this equation one may see that the level of isotopic fractionation of Mg in the interior of CAIs, that were once molten in the early Solar System, is a barometer of either total pressure (large $\Gamma$) or Mg partial pressure relative to Mg saturation (small $\Gamma$). In order for isotopic enrichment of their interiors to take place CAIs must exist in low pressure (or low Mg partial pressure) environments when evaporation occurs [6, 8].

The WL rims have near chondritic $\delta^{25}\text{Mg}$ values irrespective of the variably heavy Mg isotope enriched interiors (Figure 2). The ubiquity of WL rims and their similar intrinsic Mg isotopic signatures suggest that they define an important nebular evolutionary process [9]. Condensation likely contributes to the depleted $\delta^{25}\text{Mg}$ composition of the WL rims and therefore their origin. Wark and Lovering originally attributed the rims to late nebular condensation, but after finding enrichments of REE and other refractory trace elements in the rims with respect to the mineralogically distinct interiors, argued that the rims were residues left after intense (>2500 K) brief (<2 seconds) thermal events that evaporated surface material from the CAIs [10]. Why this process would produce concentric monomineralic layers largely made of moderately refractory major elements, like Mg and Si, while fractionating refractory elemental Al/Ca ratios is not obvious. Furthermore, there is little evidence of heavy O isotope enrichment in the rim relative to the interior of Leoville 144A [11]. Likewise the requirements to produce the WL rims by subsolidus diffusion subsequent to flash heating events where CAIs are subjected to, “sudden, powerful injections of energy” that are abruptly quenched is difficult to explain by hydrodynamic modeling arguments [12]. Alternatively, the monomineralic bands typical of WL rims could record progressive reaction driven by large chemical potential gradients, analogous to the monomineralic zones commonly found in terrestrial metasomatic rocks [13].

Collectively, these observations imply a common nebular origin for WL rims by a process that was distinct from those that created the CAI interiors and occurred throughout the region(s) where CAIs formed. The formation of WL rims could be explained by transport of CAIs between distinct nebular regions and are unlikely to have condensed near the hot proto-Sun. These constraints make the x-wind model [14] appealing for evolution of CAIs.