NEBULAR EQUILIBRATION OF OXYGEN ISOTOPES IN LOW-$^{26}$Al/$^{27}$Al CORUNDUM-HIBONITE INCLUSIONS (LAACHIs)

A. K. Herbst$^1$, S. J. Desch$^1$, E. T. Dunham$^{2,3}$, M. Bose$^1$, $^1$SESE ASU, Tempe, AZ 85287, $^2$EPSS UCLA, Los Angeles, CA, $^3$EPS UCSC, Santa Cruz, CA. akherbst@asu.edu

Introduction: Chondrites contain many Ca-rich, Al-rich inclusions (CAIs) that formed with so little $^{26}$Al (initial ($^{26}$Al/$^{27}$Al)$_0 < 3 \times 10^{-6}$) that they could not have formed from a canonical reservoir (($^{26}$Al/$^{27}$Al)$_{SS} = 5 \times 10^{-5}$). These include PLAty Crystals of hibonite (PLACs) [1–3], single corundum grains [4, 5], and certain hibonite- and/or corundum-dominated Fractionation and Unknown Nuclear effect (FUN) CAIs [6, 7]. They do not include Spinel-HIBonite inclusions (SHIBs) or normal CAIs dominated by mellite and anorthite. Because of the strong association of low $^{26}$Al with mineralogy, we call these inclusions Low-$^{26}$Al/$^{27}$Al Corundum/Hibonite Inclusions (LAACHIs) [8]. These have been interpreted to have formed before $^{26}$Al existed in the solar nebula and as evidence for ‘late injection’ of $^{26}$Al into the Sun’s protoplanetary disk [9], which would be improbable [10]. An alternative hypothesis proposed by [8] is that LAACHIs formed from presolar corundum and hibonite grains with non-extinct $^{26}$Al (i.e., no live $^{26}$Al) within a solar nebula that had uniform $^{26}$Al from the earliest times. The LAACHI-forming region, within 1.18 scale heights $H$ of the midplane, is characterized by temperatures ($T$) $\approx 1350-1425$ K and contains small (<100 nm) presolar grains with live $^{26}$Al from supernovae and Wolf-Rayet stars as well as larger presolar grains from asymptotic giant branch (AGB) stars with extinct $^{26}$Al. Due to electrical charging in this region, LAACHIs would grow or made of spinel or spent in 0.6 AU, and as evidence for ‘late injection’ of $^{26}$Al into the Sun’s protoplanetary disk [9], which would be improbable [10]. The LAACHI-forming region, within 1.18 scale heights $H$ of the midplane, is characterized by temperatures ($T$) $\approx 1350-1425$ K and contains small (<100 nm) presolar grains with live $^{26}$Al from supernovae and Wolf-Rayet stars as well as larger presolar grains from asymptotic giant branch (AGB) stars with extinct $^{26}$Al. Due to electrical charging in this region, LAACHIs would grow or made of spinel.

Methods: We developed a Python code to perform a Monte Carlo simulation of the vertical movements of $\sim \mu$m-sized presolar oxide grains (corundum and spinel) in the earliest solar nebula at $r \approx 0.6$ AU, with turbulence parameter $\alpha \approx 10^{-3}$, as modeled by [12]. $T \approx 1350-1425$ K within 1.18 $H$ of the midplane [8]. We calculate particle motions, including diffusion, advection, and drift, as modeled by [13]. Using the thermal structure of [12], we simulate thermal histories of temperature vs. time, $T(t)$. We derive internal oxygen diffusion coefficients over time, $D(t)$, assuming an Arrhenius relationship $D(T) = D_0 \exp(-Q/RT)$, where $D_0$ is a pre-exponential factor, $Q$ is the activation energy, and $R$ is the gas constant ($8.314$ J mol$^{-1}$ K$^{-1}$). For corundum, $D_0 \approx 2.5 \times 10^9$ m$^2$ s$^{-1}$ and $Q \approx 625$ kJ mol$^{-1}$ [14]. For spinel, $D_0 \approx 2.2 \times 10^8$ m$^2$ s$^{-1}$ and $Q \approx 404$ kJ mol$^{-1}$ [15]. We calculate the degree of isotopic exchange within a CAI, dividing it into radial shells and using Pick’s law $d\delta/dr = D r^2 d/dr$ ($r^2 d/dr$) to calculate $\delta$ in each shell, where $\delta = (\delta^{18}O - \delta^{18}O_{\text{CAI,init}}) / (\delta^{18}O_{\text{Solar}} - \delta^{18}O_{\text{CAI,init}})$, $c_0$ = 0 initially throughout the CAI, and $c_1$ on the CAI outer boundary.

Results: Particle diffusion coefficients are $\alpha$/$\text{Sc}$, Sc $\sim 0.7$, and grains typically spend hundreds of years within 1.18 $H$ of the midplane. Only 10% of grains spend < 20 years in the $T > 1350$ K region, and only 10% would have remained > 3700 yrs [8]. For grains with radii $a$, the typical timescale to exchange oxygen by diffusion is $t_{\text{diff}} = a^2/D(T)$. For grains with radius 1 $\mu$m at 1425 K, $D(T) \approx 3.1 \times 10^{-23}$ m$^2$ s$^{-1}$ and $t_{\text{diff}} \approx 1030$ yr. Such grains will exchange half their oxygen atoms in only 32 years, 90% in 188 years, and exchange 99.9% of their oxygen atoms with the gas in 0.65 $t_{\text{diff}} \approx 670$ yr [16]. After hundreds of years, some micron-sized presolar grains with initial variations $\delta^{17}$O, $\delta^{18}$O > 10‰ would be indistinguishable from solar. But, grains that were larger, or made of spinel, or spent less time in the region, or more time at lower temperatures, might not equilibrate as completely.

Conclusions: Monte Carlo simulations show that $\mu$m-sized presolar corundum grains could exchange oxygen atoms with the solar nebula gas, and potentially lose their signature of presolar origin, before forming LAACHIs. At the meeting, we will present results of the Monte Carlo simulations quantifying what fraction of presolar grains in the LAACHI-forming region are equilibrated and the variation in oxygen isotopes that would be produced.