SUPRA-CANONICAL INITIAL $^{26}Al/^{27}Al$ INDICATE A 10^5 YEAR RESIDENCE TIME FOR CAIs IN THE SOLAR PROTO-PLANETARY DISK.

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Introduction: The first multiple-collector inductively coupled plasma-source mass spectrometry (MC-ICPMS) studies of Mg isotopes in CAIs showed evidence for 25% greater ^{26}Al contents in the early solar system than previously thought. The evidence has come in the form of bulk rock CAI measurements [1, 2] and isochrons obtained by in-situ ultraviolet laser ablation [3]. These first data were few in number. We present new ultraviolet (UV) laser ablation and acid digestion MC-ICPMS analyses of 8 CAIs showing that there was indeed more ^{26}Al in the early solar system than previously thought. We show further that the canonical initial $^{26}Al/^{27}Al$ is a reflection of an ~300,000 yr residence time of CAIs in the protoplanetary disk and cannot be used as a fiducial marker for the beginning of solar system evolution.

Experimental details: Six igneous CAIs from the Allende (M5, USNM 3576-1), Efremovka (E44), Grosnaja (63624-1), and Leoville (144A, MRS3) CV3 meteorites and two fluffy type A CAIs from the Vigarano CV3 meteorite (Vigarano 10 and Vigarano 9) were analyzed by UV laser ablation and MC-ICPMS. In addition, fragments representing substantial portions of three of the objects (Allende 3576-1, Grosnaja 63624-1, and Leoville 144A) were dissolved and analyzed to estimate their bulk Mg isotopic compositions. The laser ablation analyses follow techniques described previously [3]. Laser spot size was typically 50 to 75 μm with pit depths on the order of 20 μm. Corrections (0.04 per mil per Ca/Mg) for the presence of $^{48}Ca^{++}$ were applied. Bulk analyses were acquired using methods described previously [1, 4].

Supra-canonical initial $^{26}Al/^{27}Al$: Laser ablation and bulk data for the CAIs define supra-canonical $(^{26}Al/^{27}Al)_o$ values. Of the 284 laser ablation analyses of the eight CAIs most (79%) lie above the canonical line corresponding to $(^{26}Al/^{27}Al)_o = 4.5\times10^{-5}$ (Fig. 1). The $\delta^{26}Mg^*$ (radiogenic ^{26}Mg) and $^{27}Al/^{24}Mg$ values are correlated and the data for 6 of the 8 objects are consistent with a zero intercept; the laser ablation data include isochrons corresponding to $(^{26}Al/^{27}Al)_o >$ canonical. The precise mass fractionation slope [5] used to compute the excess ^{26}Mg ($^{26}Mg^*$) does not affect the conclusion that $(^{26}Al/^{27}Al)_o$ is greater than canonical in these objects (e.g., Fig. 1); one of our non-igneous CAIs, Vigarano 10, has $\delta^{25}Mg'$ values near 0, meaning that the supra-canonical data for this object can not be a result of the choice of mass fractionation law. Weighted linear regression of the data for 144A defines a $(^{26}Al/^{27}Al)_o$ value of 5.9 (+/– 0.3 2σ) $\times10^{-5}$ with an intercept of 0.0 (+/– 0.07 2σ) and an MSWD of 3.3. The MSWD > 1 indicates real variability in the data beyond analytical uncertainties. The data span up to the $(^{26}Al/^{27}Al)_o = 7\times10^{-5}$ line defined by some bulk CAIs in this study and in previous work [2]. We conclude that inclusion 144A shows evidence for $(^{26}Al/^{27}Al)_o$ of at least 6×10^{-5} and probably higher.

The three bulk (whole-rock) CAI values for Allende 3576-1, Grosnaja 63624-1, and Leoville 144A agree with the laser ablation data for these objects; whole-rock and laser ablation $\delta^{25}Mg'$ and $\delta^{26}Mg'$ values of the objects at comparable $^{27}Al/^{24}Mg$ are consistent. Weighted linear regression [6] of the whole-rock data gives a model $(^{26}Al/^{27}Al)_o$ isochron of 7.0 (+/– 1.32 2σ) $\times10^{-5}$, a $\delta^{26}Mg^*$ intercept of –0.1 (+/– 0.2 2σ), and an MSWD of 0.37. Regression of the whole-rock data using a 0.511 rather than a 0.521 mass-dependent isotope fractionation relationship between $\delta^{26}Mg'$ and $\delta^{25}Mg'$ gives 6.3 (+/– 1.3 2σ) $\times10^{-5}$, –0.2 (+/– 0.2 2σ), and 0.08 for $(^{26}Al/^{27}Al)_o$, $\delta^{26}Mg^*$ intercept, and MSWD, respectively. Bizzarro et al. [7] show ten bulk CAI MC-ICPMS measurements indicating a value for $(^{26}Al/^{27}Al)_o$ of 5.2 (+/-0.1) $\times10^{-5}$. This model isochron is (apparently) based on a "kinetic" fractionation line slope that we assume was 0.511. Our whole-rock CAI data define a $(^{26}Al/^{27}Al)_o$ value of 6.3 (+/-1.3 2σ) $\times10^{-5}$ using this same kinetic fractionation law, indicating that the material studied here has higher $\delta^{26}Mg^*$ than those studied by Bizzarro et al. regardless of the fractionation slope employed. Recalculation of the Bizzarro et al. data using the equilibrium fractionation law (0.521) yields a $(^{26}Al/^{27}Al)_o$ of 6.0×10^{-5}.

Canonical initial $^{26}Al/^{27}Al$: Our study shows that canonical values are prevalent in felspars and melilite exchanged with feldspar. Data for the anorthite-rich inclusion Efremovka E44 define a canonical value for $(^{26}Al/^{27}Al)_o$ (Fig. 2). Melilites from E44 taken by themselves define a line corresponding to $(^{26}Al/^{27}Al)_o =$ 4.3 (+/– 0.5 2σ) $\times10^{-5}$ with an intercept of 0.7 (+/– 0.2 2σ) per mil and an MSWD of 1.0 (Fig. 3). The unit MSWD of the melilites indicates that melilites represent a single population. Addition of anorthite to the melilite regression leaves the latter unchanged; melilite and anorthite are on the same line. The non-zero intercept for E44 melilites is a manifestation of a non-zero initial $\delta^{26}Mg^*$ and indicates Mg isotope exchange between anorthite and melilite.

Time interval: We find that the non-zero initial $\delta^{26}Mg^*$ value for a CAI with canonical $(^{26}Al/^{27}Al)_o$ and the prevalence of the canonical $(^{26}Al/^{27}Al)_o$ value in general are most easily understood if the spread in $(^{26}Al/^{27}Al)_o$ has chronological significance. The time interval Δt before final closure of the ^{26}Al-$^{26}Mg^*$ system, based on $(4.5\times10^{-5})/(6.0\times10^{-5}) = \exp(-\lambda\ \Delta t)$, is 300,000 years. The non-zero initial $\delta^{26}Mg^*$ of 0.7 (+/- 0.2) ‰ for E44 melilite is also explained by continuous exchange of Mg isotopes between melilite and feldspar 300,000 (+/– 100,000) years after initial growth, supporting the Δt of 300,000 years obtained from the spread in $(^{26}Al/^{27}Al)_o$ values.

Residence time: The new evidence that CAIs were subject to Mg isotope exchange early in their history combined with the rate of Mg isotope exchange and consideration of astrophysical settings constrains the residence time of the CAIs in the nebula. We constructed a model for diffusive homogenization of $^{26}Mg^*/^{24}Mg$ between solid anorthite and melilite in E44 (Fig. 2, numbers and arrows) showing that an integrated time of 300 years at near-solidus temperatures of 1600 K is required. These conditions were more than sufficient to reset other smaller Al-rich and Mg-poor minerals.

Wood [8] proposed that spiral density waves in the nebula could be the shock waves responsible for heating. He described a circumstance in which two waves symmetrically distributed in the nebula travel with orbital periods of ~900 years independent of circumstellar distance R. For material in quasi-Keplerian orbit in the inner solar nebula, these waves would have behaved as if they were effectively stationary. In this situation, the total time required to achieve resetting of the ^{26}Al-$^{26}Mg^*$ system in anorthite and melilite (300 years at 1600 K) by passage of CAIs through the shocks is $\tau = (1/R)\int_0^R \Omega^{-1} dR\ (N/2)$ where Ω is the Keplerian angular velocity ($(R/(1\ AU))^{-3/2}$) and N is the number of one-day shock episodes required to achieve Mg resetting. N must add up to 300 years of heating, requiring that $N = 300 \times 365 = 109{,}500$ if shock heating lasts about 1 day. The residence time τ obtained from this scenario for a CAI drifting inwards from 3 AU is 2.3×10^5 years. The precise value for τ is sensitive to the exact time-integrated temperature but is always 10^5 years.

Conclusion: The estimated τ from diffusion and astrophysical constraints and Δt from isotopic constraints agree; CAIs existed in the protoplanetary disk for ~300,000 (+/- 100,000) years.

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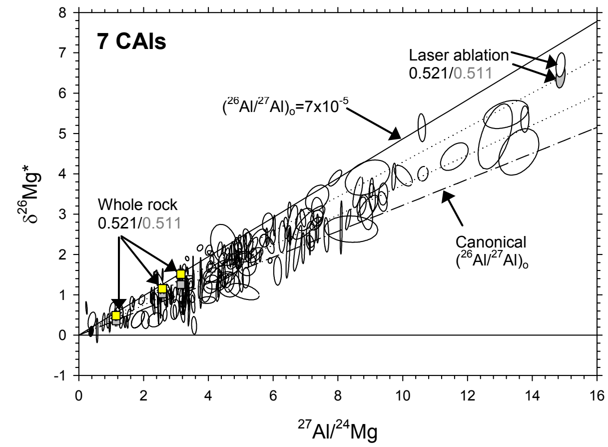

Figure 1. Compilation of 203 analyses for 7 of the 8 CAIs in this study (81 analyses of Grosnaja 63624-1 are omitted for clarity). Error ellipses are 1σ. Whole-rock values in yellow.

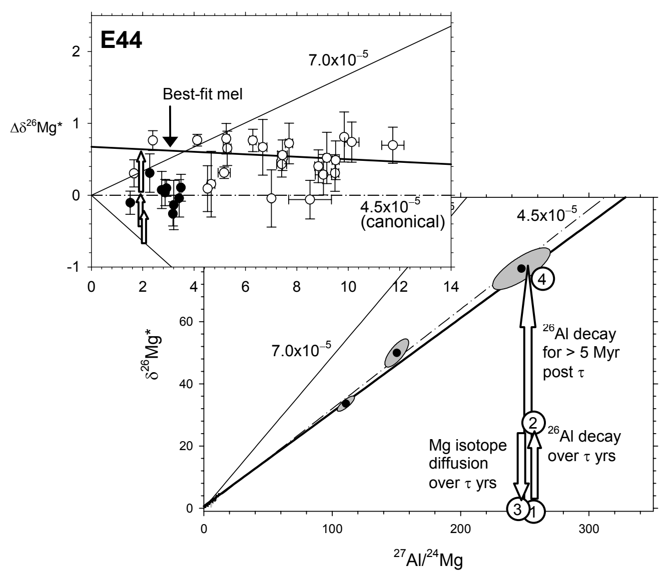

Figure 2. Data for E44. Lower right: feldspars. Upper left: mel + fs (black) as deviations from canonical line.