Mg-Al Isochrons in Presolar Grains: $^{26}Al/^{27}Al$ Ratios are Higher than Previously Estimated

Evan Groopman[1], E. Zinner[1], F. Gyngard[1], S. Amari[1], P. Hoppe[2], M. Jadhav[3], Y. Lin[4], K. Marhas[5], L. R. Nittler[6], Y. Xu[4]

[1]Laboratory for Space Sciences, Washington University in St. Louis, MO, USA [2]Max Planck Institute for Chemistry, Particle Chemistry Department, Mainz, Germany [3]Deptartment of the Geophysical Sciences, University of Chicago, IL, USA [4]Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China [5]Planetary Sciences Division, Physical Research Laboratory, Ahmedabad, Gujarat, India [6]Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, DC, USA

Introduction:

Radioisotopes have played an important role for astrophysics, cosmochemistry, and geochemistry [1], having provided evidence for stellar nucleosynthesis and served as chronometers for dating of geological and biological objects. The initial presence of short-lived radioisotopes in the early Solar System and in presolar stardust grains has been inferred from their daughter products.

The first direct evidence for the initial presence of a radioisotope in presolar grains was obtained for ^{26}Al in SiC in the form of large ^{26}Mg excesses [2]. Zinner & Jadhav [3] constructed isochron-like correlation plots for the Al-Mg, Ca-K, and Ti-Ca systems from depth profiles of presolar graphite grains from the Orgueil (CI1) carbonaceous chondrite. Many of these isochrons show near-perfect correlations among $\delta^{26}Mg/^{24}Mg$ and $^{27}Al/^{24}Mg$, $\delta^{41}K/^{39}K$ and $^{40}Ca/^{39}K$, and $^{44}Ca/^{40}Ca$ and $\delta^{48}Ti/^{40}Ca$, indicating the retention of radiogenic ^{26}Mg, ^{41}K, and ^{44}Ca from the decays of ^{26}Al, ^{41}Ca, and ^{44}Ti, respectively. These are not true isochrons as they do not contain temporal information, however they resemble true isochrons. We focus on the Al-Mg system for its simplicity regarding contamination as there is only one stable isotope of Al.

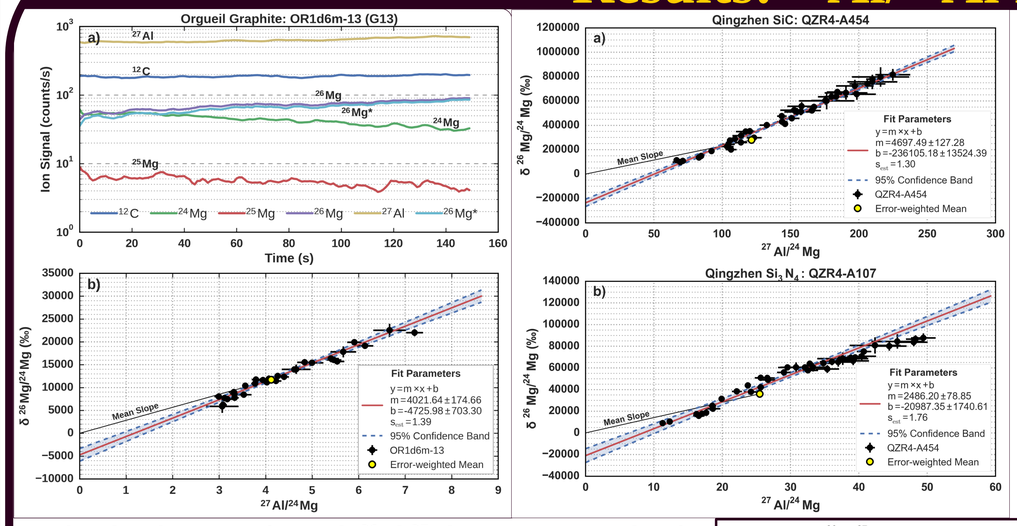
Methods:

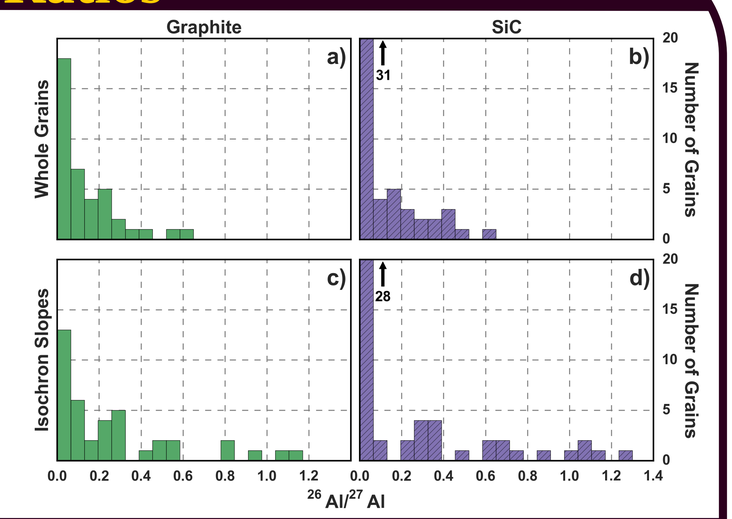
Isochrons were derived from depth profiles of samples whose data were published in previous studies (see table). More than 450 presolar grain depth profiles were processed yielding 92 grains with well-correlated $\delta^{26}Mg/^{24}Mg$ and $^{27}Al/^{24}Mg$ values.

Meteorite	Size/Density Fraction	Grain Type	Size Range (µm)	Mean Size (µm)	Number of Grains	Reference
Indarch	IH6	SiC	0.25–0.45	…	13	13
Murchison	KJB	SiC	0.1–0.2	…	7	9
Murchison	KJE	SiC	0.5–0.8	…	11	7
Murchison	LS	SiC	2–10	3.7	4	11,12
Murchison	LU	SiC	> 10	11.6	4	11,12
Qingzhen	QZR4	SiC	0.4–0.8	0.6	6	14,15
Qingzhen	QZR5	SiC	0.8–2	1.4	4	14,15
Murchison	KJE	Si_3N_4	0.5–0.8	…	1	7
Qingzhen	QZR4	Si_3N_4	0.8–2	…	2	14,15
Murchison	KFA1	LD Graphite	> 1	3.3 (4 grains)	6	8,10
Murchison	KFB1	HD Graphite	> 3	…	2	10
Orgueil	OR1d	LD Graphite	> 1	4.4	31	4,5,6
Orgueil	OR1f	HD Graphite	> 1	3.0	1	4,6
Total					**92**	

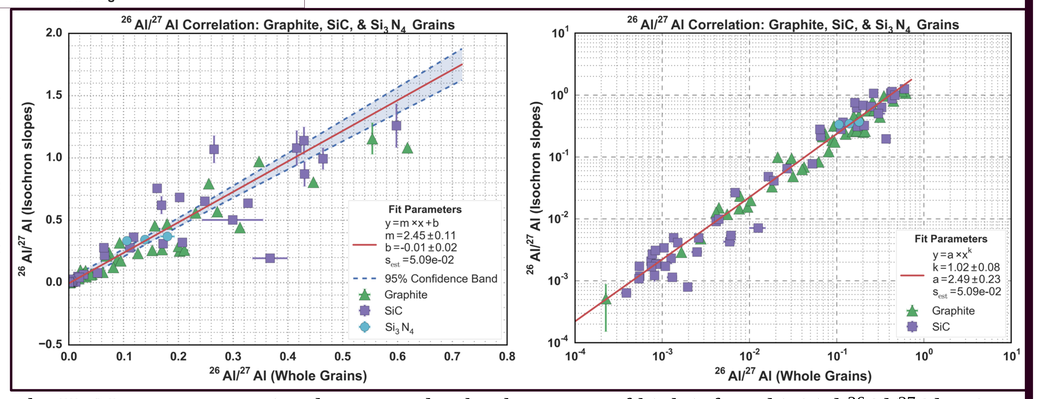
NanoSIMS depth profiles were obtained using an O^- primary beam to measure the positive secondary ions of $^{24,25,26}Mg^+$, $^{27}Al^+$, and either $^{12}C^+$, $^{28}Si^+$, or $^{40}Ca^+$ [4–15]. Following [3], isochrons were generated by dividing NanoSIMS depth profiles into 5-cycle bins, with the bin averages of $\delta^{26}Mg/^{24}Mg$ and $^{27}Al/^{24}Mg$ calculated and plotted on an isochron plot. Error bars indicate the standard error of the mean $\delta^{26}Mg/^{24}Mg$ and $^{27}Al/^{24}Mg$ values in each bin. Isochrons were fitted with Orthogonal Distance Regression (ODR), a total least-squares regression technique that includes both x- and y-error weighting [16], as the $\delta^{26}Mg/^{24}Mg$ and $^{27}Al/^{24}Mg$ errors are correlated.

Results: $^{26}Al/^{27}Al$ Ratios

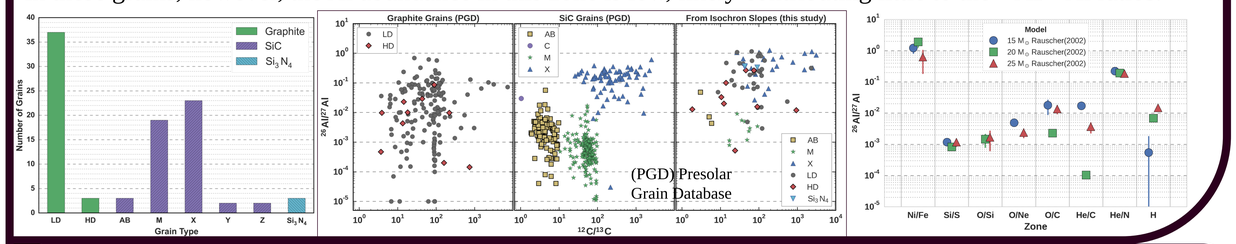




The distributions of initial $^{26}Al/^{27}Al$ ratios are similar for presolar graphite and SiC grains for values derived from either isochron slopes or from conventional whole-grain measurements. **The inferred initial $^{26}Al/^{27}Al$ ratios derived from isochron slopes are larger than those derived from whole-grain measurements by an average factor of 2.45 ± 0.11.** Linear regressions of the SiC and graphite grain populations separately yield factors of 2.52 ± 0.16 and 2.30 ± 0.11, respectively.

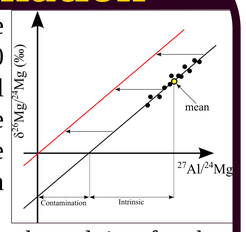


SN Models [17]: The He/N zone was previously assumed to be the source of high inferred initial $^{26}Al/^{27}Al$ ratios in SN grains, although 25 of the 92 presolar grains have initial $^{26}Al/^{27}Al$ ratios inferred from their isochron slopes greater than the range of $^{26}Al/^{27}Al$ ratios in the He/N ($^{26}Al/^{27}Al < 0.34$) and He/C ($^{26}Al/^{27}Al < 0.16$) zones, with 6 grains having $^{26}Al/^{27}Al$ ratios > 1. Only the Ni/Fe zone in these models can reproduce the $^{26}Al/^{27}Al$ ratios in these grains, however, the Al abundance in this zone is low, likely contributing little to the $^{26}Al/^{27}Al$ ratios.

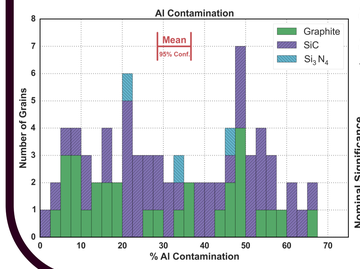


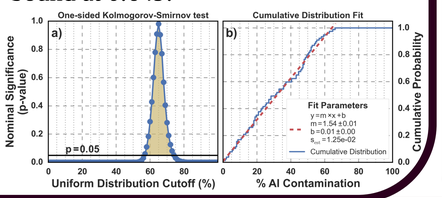
Results: Al contamination

The majority of isochrons have negative $\delta^{26}Mg/^{24}Mg$ intercepts, often less than minus 1000 ‰. The vast majority of grains have minimal scatter about their isochrons, so these may be explained by constant Al contamination on the grains' surfaces (Appendix of [3]), likely from acid etching during the host rock acid dissolution.



We estimated the quantity of Al contamination by solving for the horizontal shift required for the isochron to intercept the origin relative to the error-weighted mean $^{27}Al/^{24}Mg$ values. The resulting distribution of fractional Al contamination is not obviously different for graphite and SiC grains. The total contamination distribution matches a sample drawn from a continuous uniform distribution with bounds at 0% and 65%. A linear fit to the cumulative distribution with a slope of 1.54 corresponds to an uniform distribution with an upper bound at 0.649.





Conclusions:

The majority of isochrons have negative $\delta^{26}Mg/^{24}Mg$ intercepts, often less than minus 1000 ‰ due to Al contamination, making it impossible to infer the initial $^{26}Mg/^{24}Mg$ ratio of the samples. The conventional whole-grain method for inferring initial $^{26}Al/^{27}Al$ ratios, by essentially calculating the slope of the line between the average $\delta^{26}Mg/^{24}Mg$ and $^{27}Al/^{24}Mg$ values and the origin, underestimates the isochron-derived $^{26}Al/^{27}Al$ ratios by a factor of **2.5**. Many presolar grains from SNe have $^{26}Al/^{27}Al$ ratios that far exceed the ratios predicted in the He/C and He/N zones; the Ni/Fe zone is unlikely to contribute enough Al to affect the grains' $^{26}Al/^{27}Al$ ratios.

References: **[1]** Diehl, R., In R. Diehl, D.H. Hartmann, & N. Prantzos (eds.), Astronomy with Radioactivities, vol. 812 of Lecture Notes in Physics (Springer Berlin Heidelberg, (2011), 3–23. **[2]** Zinner, E. et al. (1991) Nature, 349, 51–54. **[3]** Zinner, E. & Jadhav, M., (2013) ApJ, 768, 100–118. **[4]** Jadhav, M. et al. (2006) New Astron. Rev., 50, 591–595. **[5]** Groopman, E. et al. (2012) ApJL, 754, L8–L13. **[6]** Jadhav, M. et al., (2013) GCA, 113, 193–224. **[7]** Xu, Y. C. et al. (2012) 43rd LPSC, Abs. #1094. **[8]** Amari, S. et al. (2014) GCA, 133, 479–522. **[9]** Hoppe, P. et al. (2010) ApJ 719, 1370–1384. **[10]** Xu, Y. et al., (2015) ApJ, 799, 156–178. **[11]** Amari, S. et al. (1994) GCA, 58, 459–470 **[12]** Zinner, E. & Jadhav, M. (unpublished) **[13]** Zinner, E. et al. (2007) GCA, 71, 4786–4813. **[14]** Lin, Y. et al. (2002) ApJ, 575, 257–263. **[15]** Lin, Y. et al. (2010) ApJ, 709, 1157–1173. **[16]** Boggs, P.T. & Rogers, J.E., In P.J. Brown & W.A. Fuller (eds.), Contemporary Mathematics: Statistical Analysis of Measurement Error Models and Applications, vol. 112 (American Mathematical Society, 1990). **[17]** Rauscher, T. et al. (2002) ApJ, 576, 323–348.