HETEROGENEOUS DISTRIBUTION OF 26AL IN THE SOLAR PROTOPLANETARY DISK K. K. Larsen[1], A Trinquier[1], C. Paton[1], M. Schiller[1], D. Wielandt[1], M. A. Ivanova[2], J. N. Connelly[1], Å. Nordlund[1,3], A. N. Krot[1,4], and Martin Bizzarro[1], [1]Centre for Star and Planet Formation, Natural History Museum of Denmark, University of Copenhagen, Copenhagen DK-1350, Denmark, [2]Vernadsky Institute of Geochemistry and Analytical Chemistry, Moscow 119991, Russia, [3]Niels Bohr Institute, University of Copenhagen, Copenhagen DK-1350, Denmark, [4]Hawai'i Institute of Geophysics and Planetology, University of Hawai'i at Manoa, HI 96822, USA

Introduction: With a half-life of 0.73 Myr, the ^{26}Al-to-^{26}Mg decay system is the most widely used short-lived chronometer for understanding the formation and earliest evolution of the solar protoplanetary disk. However, the validity of ^{26}Al–^{26}Mg ages of meteorites and their components relies on the critical assumption that the canonical ^{26}Al/^{27}Al ratio of ~5 × 10^{-5} recorded by the oldest dated solids, calcium.aluminium-rich inclusions (CAIs), represents the initial abundance of ^{26}Al for the solar system as a whole. To understand the degree of ^{26}Al homogeneity in the solar protoplanetary disk, we have developed analytical protocols allowing the measurements of the μ^{26}Mg* value and ^{27}Al/^{24}Mg ratios in meteorites by high-resolution multi-collector inductively coupled plasma source mass spectrometry (HR-MC-ICPMS) with an external reproducibility of 2.5 ppm and 0.5%, respectively [1]. Using these techniques, we report bulk Mg-isotope and ^{27}Al/^{24}Mg ratio measurements of a representative suite of inner solar system objects, including CAIs and amoeboid olivine aggregates (AOAs) from the reduced CV (Vigarano type) chondrite Efremovka as well as a number of primitive and differentiated meteorites [2].

Results and discussion: Bulk analyses of four AOAs (E1s, E2s, E3s, E4s) and four CAIs of different types, one fine-grained spinel-rich (22E), two Type Bs (31E, E48), and one Type A (E104), from Efremovka define a line with a slope of (5.252±0.019)×10^{-5} and an initial μ^{26}Mg*$_0$ value of −15.9±1.4 ppm (Fig. 1a). We also analyzed AOAs mantling the E48 and E104 inclusions (i.e. forsterite-rich accretionary rims). The E48 and E104 forsterite-rich accretionary rims plot on the bulk CAI-AOA isochron (Fig. 1b) thereby confirming the contemporaneous formation of AOAs and CAIs and, therefore, the validity of collectively using these objects to define the initial ^{26}Al/27Al ratio and μ^{26}Mg*$_0$ value of the CAI- and AOA-forming region. We interpret the bulk CAI-AOA line as an ^{26}Al-^{26}Mg isochron corresponding to the timing of Al/Mg fractionation prior to and/or during formation of the Efremovka CAIs and AOAs by evaporation, condensation, and evaporative melting. The error on the slope of this isochron corresponds to an age uncertainty of ~4,000 years, suggesting a very short duration of these fractionation events. The intercept of this isochron (μ^{26}Mg*$_0$) represents the initial Mg-isotope composition of the solar system. The slope of the ^{26}Al-^{26}Mg isochron is in excellent agreement with the canonical ^{26}Al/^{27}Al ratio of (5.23±0.13)×10–5 inferred from bulk measurements of CAIs from the oxidized CV chondrite Allende [3]. The initial μ^{26}Mg*$_0$ value of −15.9±1.4 ppm inferred from the Efremovka CAI-AOA isochron is significantly different from the value of −38 ppm predicted for a uniform distribution of ^{26}Al in the solar system (Fig. 1).

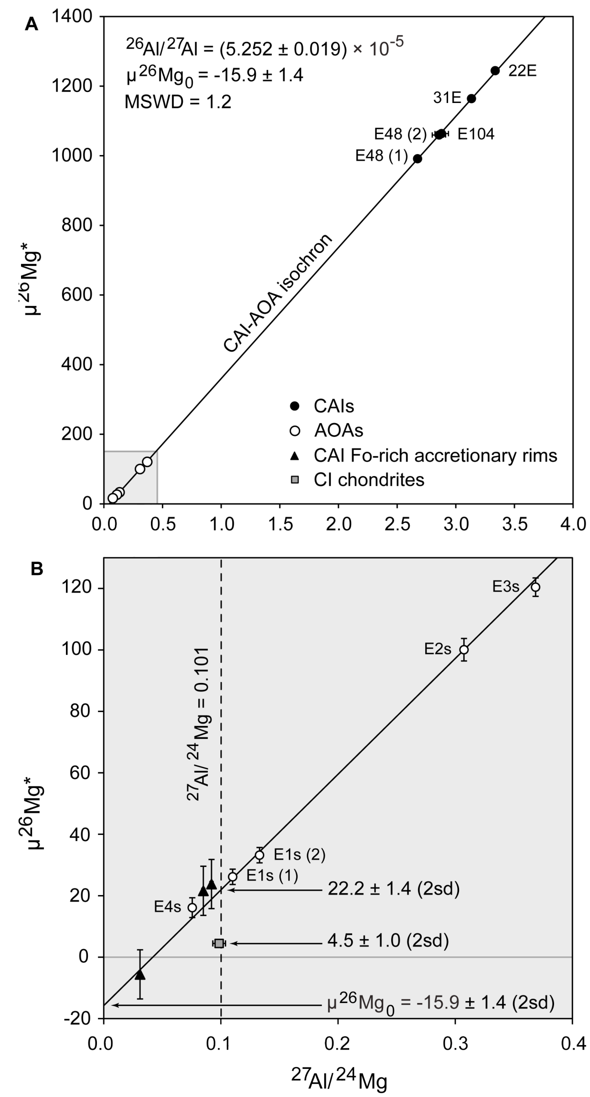

Figure 1: Al-Mg evolution diagrams.

The $\mu^{26}Mg^*$ value of the Efremovka CAI-AOA isochron at a solar $^{27}Al/^{24}Mg$ ratio of 0.101 is 22.2±1.4 ppm. If the $\mu^{26}Mg^*_0$ and $(^{26}Al/^{27}Al)_0$ inferred from the CV CAIs and AOAs are representative of the entire solar system, then solar system materials preserving the solar $^{27}Al/^{24}Mg$ ratio are predicted to have an identical $\mu^{26}Mg^*$ value of ~22 ppm. To test this prediction, we measured bulk Mg-isotope compositions of three CI (Ivuna type) carbonaceous chondrites, which are considered to be the most chemically pristine solar system materials: they have solar abundances of most elements, as well as solar $^{27}Al/^{24}Mg$ ratio. The bulk Mg-isotope compositions of CI chondrites have an average $\mu^{26}Mg^*$ value of 4.5±1.0 ppm, which is significantly lower than the $\mu^{26}Mg^*$ value of 22.2±1.4 ppm defined by the Efremovka CAI-AOA isochron at a solar $^{27}Al/^{24}Mg$ ratio (Fig. 2). We also measured Mg-isotope compositions and $^{27}Al/^{24}Mg$ ratios of one enstatite chondrite, four ordinary chondrites, one R-chondrite, one acapulcoite, two angrites, two ureilites, and one Martian shergottite. None of the whole-rock Mg-isotope analyses of these meteorites approach the $\mu^{26}Mg^*$value of 22 ppm predicted by the CV CAI–AOA isochron and uniform distribution of ^{26}Al.

It is possible that the elevated $\mu^{26}Mg^*$ of 22.2±1.4 ppm at the solar $^{27}Al/^{24}Mg$ ratio defined by the CAI–AOA regression reflects a pre-history of elevated $^{27}Al/^{24}Mg$ ratio for the CAI- and AOA-forming reservoir as a whole. However, the mineralogy and bulk chemistry of CAIs and AOAs are consistent with formation from a gas of solar composition [4], and even allowing for a 15% increase in the $^{27}Al/^{24}Mg$ ratio of the CAI-forming region requires timescales in the order of 1.5 Myr to produce the offset of 22.2 ± 1.4 ppm in CAIs and AOAs. Such an extended pre-history is inconsistent with the brief interval of ~4,000 years for the formation of these objects. Likewise, the observed variations in $\mu^{26}Mg^*$ values of chondritic meteorites cannot be uniquely explained by Al/Mg fractionation events in the protoplanetary disk. For example, only 2.6 ppm of the observed 8.6±1.4 ppm difference between the average $\mu^{26}Mg^*$ values of the CI and ordinary chondrites could be attributed to Al/Mg fractionation. Similarly, R- and CI chondrites have nearly identical $^{27}Al/^{24}Mg$ ratios, yet their $\mu^{26}Mg^*$ values are different by 5.9±2.6 ppm. Thus, we conclude that the $\mu^{26}Mg^*$ variability must represents ^{26}Al heterogeneity or, alternatively, Mg-isotope heterogeneity amongst inner solar system reservoirs.

If the totality of the $\mu^{26}Mg^*$ variability is related to ^{26}Al heterogeneity, it is possible to estimate the initial ^{26}Al abundance in the accretion regions of asteroids and planets by comparing their present-day $\mu^{26}Mg^*$ with the initial $\mu^{26}Mg^*_0$ defined by the CAI–AOA isochron and its intercept at the solar $^{27}Al/^{24}Mg$ ratio. If this assumption is valid, then large-scale heterogeneity—up to 80% reduction of the canonical $^{27}Al/^{26}Al$ ratio—existed throughout the inner solar system.

Rigorously testing whether the $\mu^{26}Mg^*$ variability primarily reflects ^{26}Al heterogeneity can be achieved by comparing high-precision U–Pb and ^{26}Al–^{26}Mg ages of pristine solar system materials. We focus our discussion on the age difference between CAIs and the SAH99555 angrite [5, 6]. We measured the U-isotope composition and Pb-Pb ages of two CAIs that were also studied for ^{26}Al-^{26}Mg systematics, namely the 22E and 31E CAIs [7]. Together with the SJ101 CAI [8], the 22E and 31E inclusions define an average U-corrected Pb-Pb age of 4567.21±0.24 Myr, which is our best estimate for the absloute age of the CAI-forming event. Based on the U–Pb system, we calculate an age difference of 3.57±0.54 Myr between the formation of CAIs and crystallization of SAH99555, which is not compatible with the age difference of $5.02^{+0.15}_{-0.13}$ Myr inferred from the ^{26}Al-^{26}Mg system. Given the short duration of the CAI-forming process inferred from our study and the consistency in the Pb–Pb age of the SAH99555 meteorite obtained by different studies, it is unlikely that this age difference reflects selective disturbance of the isotopic chronometers. Rather, it is consistent with our proposal that the CAI-forming reservoir was characterized by an enhanced abundance of ^{26}Al compared to the accretion region of the angrite parent body. To reconcile the mismatch between the U–Pb and ^{26}Al–^{26}Mg ages of CAIs and SAH99555, the initial abundance of ^{26}Al in the accretion region of the angrite parent body is required to be reduced by 57%–85% of the $^{26}Al/^{27}Al$ value present in the CAI-forming reservoir, considering the uncertainties of the U–Pb ages. This is consistent with our independent estimate of 69% based on the Mg isotopes, which corresponds to an initial $^{26}Al/^{27}Al$ of ~$1.6\times10{-}5$ for the angrite parent body and relative ^{26}Al–^{26}Mg age of 3.78±0.23 Myr for SAH99555, and is in excellent agreement with its U–Pb age. We conclude that the bulk of the $\mu^{26}Mg^*$ variability reflects heterogeneity in the abundance of ^{26}Al across the solar protoplanetary disk at the time of CAI formation.

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