HETEROGENEOUS DISTRIBUTION OF ^{26}AL AT THE BIRTH OF THE SOLAR SYSTEM. A. N. Krot[1], K. Makide[1], K. Nagashima[1], G. R. Huss[1], F. J. Ciesla[2], E. Hellebrand[3], E. Gaidos[3], and L. Yang[2]. [1]Hawai‘i Institute of Geophysics & Planetology, University of Hawai‘i at Mānoa, Honolulu, HI 96822, USA. [2]Department of the Geophysical Sciences, University of Chicago, Chicago, IL 60637, USA. [3]Department of Geology & Geophysics, University of Hawai‘i at Mānoa, Honolulu, HI 96822, USA. sasha@higp.hawaii.edu

Introduction: It is believed that ^{26}Al, a short-lived ($t_{1/2}$ ~ 0.7 Ma) and now extinct radionuclide, was uniformly distributed in the nascent Solar System (SS) with the initial ^{26}Al/^{27}Al ratio [(^{26}Al/^{27}Al)$_0$] of ~5.2×10^{-5} [1] suggesting an external, stellar origin rather than local, solar source [2]. However, the stellar source of ^{26}Al and the manner in which it was injected into the SS remain controversial: the ^{26}Al could have been injected either into the protosolar molecular cloud [5], protosolar cloud core [6] or protoplanetary disk [7] by an asymptotic giant branch (AGB) star [3], a supernova (SN) [4], or a wind from a massive star [5,8,9].

Refractory grains (corundum, Al_2O_3 and hibonite, $CaAl_{12}O_{19}$) and inclusions are predicted to be among the first solids formed from a cooling gas of solar composition [10], and, therefore, can potentially constrain the origin and distribution of ^{26}Al in the early SS. Here we show that micron-sized corundum condensates from a gas of ~ solar composition and several types of refractory inclusions, including corundum-bearing CAIs, FUN (fractionation and unidentified nuclear isotope effects) CAIs, platy hibonite crystals (PLACs), spinel-hibonite spherules (SHIBs), and hibonite- and grossite-rich CAIs from several groups of carbonaceous chondrites (CH, CM, CR, CO, CV), apparently recorded a heterogeneous distribution of ^{26}Al at the birth of the SS.

Micron-sized corundum grains from acid-resistant residues of unequilibrated ordinary chondrites and unmetamorphosed carbonaceous chondrites (CI1, CM2, CR2, and CO3.0) were systematically studied for O- and Al-Mg isotope systematics by [11]. Ninety-three out of 96 grains measured have ^{16}O-rich compositions (Δ^{17}O ~ −23±7‰, 2SD) similar to those of the mineralogically pristine and isotopically uniform CR CAIs (Δ^{17}O ~ −23±2‰, 2SD) [12] and solar wind returned by the GENESIS spacecraft (Δ^{17}O ~ −28±2‰, 2SD) [13]. These observations are consistent with a condensation origin of the corundum grains from an ^{16}O-rich gas of ~solar composition. Three corundum grains have highly anomalous O-isotope compositions, and are probably presolar in origin. Seventy nine ^{16}O-rich (solar) corundum grains measured for Al-Mg systematics show large variations of (^{26}Al/^{27}Al)$_0$: 52% of grains have no resolvable excess of radiogenic ^{26}Mg (^{26}Mg*): an upper limit on (^{26}Al/^{27}Al)$_0$ is 2×10^{-6}; 40% of grains have high (^{26}Al/^{27}Al)$_0$, (3.0–6.5)×10^{-5}; 8% of grains have intermediate values of (^{26}Al/^{27}Al)$_0$, (1−2)×10^{-5}. The coexistence of the ^{26}Al-rich and ^{26}Al-poor corundum grains in the same primitive meteorite preclude late-stage (after decay of ^{26}Al) resetting of the ^{26}Al-^{26}Mg systematics of the corundum grains during thermal metamorphism in the host chondrite parent bodies. Late-stage resetting in the solar nebula during thermal processing associated with chondrule formation is also excluded, because chondrule formation occurred in ^{16}O-poor (Δ^{17}O > −10‰) nebular regions [14] when ^{26}Al was still alive [15]. We infer that ^{16}O-rich corundum grains with low (^{26}Al/^{27}Al)$_0$ never contained the canonical abundance of ^{26}Al, i.e., the lack of ^{26}Mg* in 52% of ^{16}O-rich corundum grains is a primary characteristic.

Eight c**orundum-bearing CAIs** from Adelaide (ungr.), Murray and Murchison (CM2) were measured for O- and Al-Mg systematics [16−18]. The CAIs are characterized by ^{16}O-rich compositions (Δ^{17}O range from −17‰ to −25‰) and by a bi-modal distribution of (^{26}Al/^{27}Al)$_0$: two CAIs from Adelaide and two from Murchison lack resolvable ^{26}Mg*. (^{26}Al/^{27}Al)$_0$ in four other CM CAIs are close to the canonical value of ~(4−5)×10^{-5}. We infer that the ^{26}Al-rich and ^{26}Al-poor corundum grains and corundum-bearing CAIs represent different generations of refractory objects that recorded a heterogeneous distribution of ^{26}Al in the early SS.

CAIs in CH chondrites show a bi-modal distribution of (^{26}Al/^{27}Al)$_0$ [19−21]. Most CAIs (~85%) composed of grossite ($CaAl_4O_7$), hibonite, Al-rich pyroxene, perovskite ($CaTiO_3$), and gehlenitic melilite ($Ca_2Al_2SiO_7$–$Ca_2MgSi_2O_7$) show either unresolvable or small ^{26}Mg* corresponding to (^{26}Al/^{27}Al)$_0$ of ~4×10^{-7}. About 15% of CAIs (some of the grossite-rich CAIs and the less refractory inclusions composed of melilite, spinel ($MgAl_2O_4$), Al,Ti-pyroxene and anorthite ($CaAl_2Si_2O_8$)) have ^{26}Mg* corresponding to (^{26}Al/^{27}Al)$_0$ of ~5×10^{-5}. The ^{26}Al-poor and ^{26}Al-rich CAIs have similar ^{16}O-rich (Δ^{17}O < –20‰) compositions. We infer that the ^{26}Al-poor and ^{26}Al-rich CH CAIs represent different generations of refractory objects that recorded a heterogeneous distribution of ^{26}Al in the early SS.

PLACs and SHIBs commonly found in CM chondrites show significant variations in (^{26}Al/^{27}Al)$_0$. Most PLACs have either unresolvable excesses or deficits of ^{26}Mg*. The inferred (^{26}Al/^{27}Al)$_0$ in SHIBs range from 1 to 6×10^{-5} [17,22,23]. It is suggested that these variations reflect early, prior to homogenization of ^{26}Al in the inner SS, formation of PLACs and some of SHIBs [17,22,23].

FUN and FUN-like CAIs from CV, CM, CO, and CR chondrites measured for ^{26}Al-^{26}Mg systematics show either deficits [12,24−28] or small excesses of $\delta^{26}Mg^*$ [29−37]. The inferred $(^{26}Al/^{27}Al)_0$ range from $(5.2\pm1.7)\times10^{-8}$ in HAL [29] to 2.4×10^{-5} in the HAL-like hibonite grain Isna S16 [35]. The observed variations in $(^{26}Al/^{27}Al)_0$ ratio most likely reflect early formation of FUN and FUN-like CAIs, prior to homogenization of ^{26}Al in the inner SS.

Discussion: The heterogeneous distribution of ^{26}Al among refractory grains and inclusions, that appear to have formed at the birth of the SS [38−40], and the lack of correlation of the Al-Mg and O-isotope systematics in these objects provide important constraints on the origin of ^{26}Al in the early SS and the way it was injected into the SS. These observations are inconsistent with inheritance of ^{26}Al from a molecular cloud enriched by a previous generation of stars [5], which should have produced a uniform distribution of ^{26}Al. They are also inconsistent with late-stage injection of ^{26}Al into the protoplanetary disk [7], when the efficiency of CAI formation and outward radial transport were probably low [41]. Instead, they may indicate that injection of ^{26}Al occurred into the protosolar molecular cloud core nearly contemporaneously with its collapse.

The similar O-isotope compositions of the ^{26}Al-rich and ^{26}Al-poor refractory grains and inclusions and the Sun may suggest injection of ^{26}Al by a massive (>20 $M_{\odot}$) Type II SN, by a wind from a massive star, or by a low-mass (1.5 $M_{\odot}$) AGB star [3,42−44]. Injection of ^{26}Al by a less massive supernovae or by a 3–6 $M_{\odot}$ AGB star are unlikely, because it is expected to produce significant change in oxygen-isotope composition of the SS, that has not been observed [42−44].

To distinguish between an explosive SN and a stellar wind origin of ^{26}Al, other isotopes (e.g., ^{60}Fe-^{60}Ni isotope systematics) must be measured. In contrast to SNe, stellar wind from a massive star does not produce ^{60}Fe [e.g., 42]. We note that the initial abundance of ^{60}Fe in the SS remains controversial. The inferred initial $^{60}Fe/^{56}Fe$ ratios range from $(2–5)\times10^{-7}$ [45] to $\leq1\times10^{-8}$ [46,47]. Due to the presence of nucleosynthetic isotopic anomalies in Ni, the detection of radiogenic ^{60}Ni in bulk CAIs [48] is ambiguous.

Conclusions: We conclude micron-sized corundum condensates from a gas of solar compositions and several types of ^{26}Al-poor refractory inclusions from unequilibrated ordinary chondrites and unmetamorphosed carbonaceous chondrites recorded heterogeneous distribution of ^{26}Al in the inner SS during an epoch of CAI formation. The data suggest that ^{26}Al was injected into the collapsing protosolar molecular cloud core just before or during formation of the first refractory solids and was later mixed through the protoplanetary disk. If the inferred low initial abundance of ^{60}Fe in the early SS [46,47] is correct, it would imply that ^{26}Al was delivered by a wind from a neighboring massive star(s) and not by an explosive SN. Considering heterogeneous distribution of ^{26}Al in the CAI-forming region, which may have existed for a short period of time in a localized region of the protoplanetary disk, the canonical $^{26}Al/^{27}Al$ ratio inferred from whole-rock Al-Mg isotope measurements of CV CAIs and AOAs [1,49] and the high-precision internal isochrons of the apparently unmelted fluffy Type A CAIs [50] may not necessarily represent the initial abundance of ^{26}Al in the whole SS [e.g., 49].

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