A SEARCH FOR ^{26}AL IN CHONDRITES: CHONDRULE FORMATION TIME SCALES;

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Models of solar nebula accretion and evolution predict rapid coagulation of solids to form meter-size bodies on a time scale of ~0.01 Ma and the growth of asteroid-size planetesimals within 1 Ma [1,2]. No astrophysically viable models yield an extended period of nebular evolution approaching 10 Ma. If this short time scale is representative and if ^{26}Al was uniformly distributed at the canonical initial ^{26}Al/^{27}Al ratio of ~5 x 10^{-5}, observable levels of radiogenic ^{26}Mg* from the decay of ^{26}Al ($\tau_{1/2}$ = 0.72 Ma) should not be confined to CAI but should also be present in Al-rich, Mg-poor phases in chondrules and "old" igneous rocks. Most searches for ^{26}Mg* outside CAI have, however, been unsuccessful. Evidence of ^{26}Mg* in non-refractory objects has been reported in only three ordinary chondrites and the inferred ^{26}Al/^{27}Al ratios fall below the canonical 5x10^{-5} value by factors of between ~7 and 250 [3-5]. Attempts to identify ^{26}Mg* in differentiated meteorites have also been unsuccessful [6-8]. We report here a new search for evidence of ^{26}Mg* in plagioclase-bearing chondrules and igneous rock fragments in seven ordinary chondrites. The absence of ^{26}Mg* in these samples and, more generally, the paucity of ^{26}Al in chondritic material has important implications for an absolute chronology of the early solar system. It appears either (1) ^{26}Al was not uniformly distributed and an initial ^{26}Al/^{27}Al ratio of < 1x10^{-6} is more representative of chondritic material; (2) the predicted evolutionary time scale is too short and the initial formation of solids in the nebula extended over several Ma; or (3) many chondrules and rock fragments are not primary objects but represent material recycled through multiple episodes of evaporation and recondensation, mixing and partial melting, and gas-dust fractionation.

Using PANURGE, we determined the Mg isotope composition of plagioclase in (1) a ~3 mm chondrule in Bovedy (L3) consisting of orthopyroxene laths with interstitial clinopyroxene and plagioclase, (2) a 3x2 mm inclusion in Los Martinez (L6) consisting of a highly zoned, single plagioclase crystal containing abundant, exsolved Cr-rich spinel [9], (3) a 1x1.5 mm barred chondrule in Manych (L3) consisting of olivine laths with interstitial pyroxene and plagioclase, (4) a 1.5x1 mm chondrule in Ragland (LL3) consisting of intergrown pyroxene and olivine with interstitial plagioclase surrounded by pyroxene laths containing poikilitic olivine, (5) a 1.2x1.5 cm basaltic pebble in Barwell (L6) with H-chondrite chemistry [10], consisting of coarse-grained olivine and turbid, brown plagioclase laths, interstitial to the olivine and overgrown by a granular mosaic of clear plagioclase; the inclusion has an ^{40}Ar-^{39}Ar age of 4.44±0.08 Ga and an ^{129}Xe-^{129}I age of -3.7±1.3 Ma relative to Bjurbole, (6) a 0.25 mm spherical chondrule in Ikhrarene (L4) consisting of reversely-zoned plagioclase laths with interstitial olivine, and (7) a 0.5 mm ameboid CAI in Clovis (H3) [11] consisting of irregular patches of anorthite and fassaite with euhedral spinel set in a cryptocrystalline feldspathoid core; a diopside rim surrounds the core. These samples were chosen because they contained plagioclase crystals large enough (> 10 μm) to analyze; no other selection criteria were applied.

This study reveals isotopically normal Mg in all objects examined; no evidence of intrinsic mass-dependent fractionation, $|F_{Mg}|$ < 4 ‰/amu, or radiogenic ^{26}Mg* was found in any plagioclase. We calculate upper limits to the ^{26}Mg*/^{27}Al ratios of between 1.1x10^{-5} and 1.2 x 10^{-7} (Table 1). These data demonstrate that ^{26}Al was much less abundant during crystallization of most plagioclase-bearing objects found in ordinary chondrites than during CAI formation. If this low abundance is due to decay of ^{26}Al from an initial ^{26}Al/^{27}Al ratio of 5 x 10^{-5}, the minimum interval between CAI and chondrule formation is 1.6 - 6.3 Ma. Qualitatively, this scenario appears self-consistent. CAI formed early, at high temperature by partial melting of isotopically anomalous, refractory precursors containing live ^{26}Al. Chondrules most plausibly formed by very similar processes but at a later time, after ^{26}Al decay. The difficulty with this chronological interpretation arises with the need to reconcile the ^{26}Al time scale with the dynamical time scales for condensation, grain aggregation and planetesimal formation; the predicted time scales are one to two orders of magnitude shorter [1,2].

We consider three plausible resolutions of this dilemma. (1) The distribution of ^{26}Al in the solar nebula was not homogeneous and an initial ^{26}Al/^{27}Al ratio of ~5×10^{-5} is characteristic only for CAI. The ^{26}Mg-^{26}Al system then has little chronological significance and the ^{26}Mg*-deficient objects studied here may have formed concurrently with CAI but in a region of the nebula depleted in ^{26}Al. (2) The dynamical time scales for condensation, grain aggregation and planetesimal formation are unrealistically compressed. While there may be little reason *a priori* to question the evolutionary time scale, the formation of kilometer-size planetesimals within 0.1 Ma is very difficult to reconcile with both meteorite chronology and astronomical observations. Differences in initial ^{87}Sr/^{88}Sr ratios and Pb-Pb ages, for example, strongly suggest the eucrite parent body formed > 11 Ma after CAI [8], while astronomical evidence indicates that disk lifetime varies systematically with parent star mass and may be as long as 10 Ma for a one solar mass star [13]. (3) Chondrule formation is a multi-step process involving a repeated sequence of mixing and partial melting, evaporation and recondensation over an extended time scale of several Ma.. Chondrule precursors may have formed contemporaneously with CAI but reprocessing and interaction with a locally dense (gaseous) environment continued until ^{26}Al was no longer extant. Similar reprocessing may have also have affected CAI and may provide an explanation for the low abundance of ^{26}Mg* in some CAI.

With the exception of the Semarkona noritic fragment (^{26}Al/^{27}Al~8×10^{-6}) [3] there is no evidence for high ^{26}Al in chondritic material. It now appears unlikely ^{26}Al was an important heat source for early planetary differentiation and was present only at a very low level during chondrule formation. We suggest chondrule formation was an ongoing process extending over several Ma and the absence of ^{26}Al reflects late formation rather than nebular heterogeneity. Resolution of this question must await high precision Pb-Pb, ^{87}Sr/^{88}Sr and Mg-Al isotope studies on individual chondrules and planetary fragments. Contrib. 5356 (831); NASA NAGW-3297.

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METEORITE		An (mole %)	^{26}Mg*/^{27}Al (x10^6)	ΔT^1 (Ma)
Los Martinez	(L6)	55-18	< 11	>1.6
Ragland	(LL3)	80-77	< 10	>1.7
Manych	(L3)	80	< 1.9	>3.4
Clovis	(H3)	96-84	<1.8	>3.5
Ikhrarene	(L4)	?	< 1.3	>3.8
Barwell	(L6)	74-42	< 0.55	>4.7
Bovedy 1971,1	(L3)	77	< 0.12	>6.3
Parnallee	(LL3)	75-70	< 4, [14]	>2.6
Semarkona	(LL3)	100	7.7±2.1, [3]	1.9±0.2
Bovedy GB-1	(L3)	85	0.25±0.10, [4]	5.5±0.4
Ste. Marguerite	(H4)	?	0.20±0.06, [5]	5.7±0.3

1 Time interval to obtain observed ^{26}Mg*/^{27}Al from $(^{26}Al/^{27}Al)_0 = 5\times10^{-5}$.