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Inheritance of solar short- and long-lived radionuclides from molecular clouds and the unexceptional nature of the solar system

Edward D. Young

Department of Earth, Planetary, and Space Sciences, University of California Los Angeles, 595 Charles E. Young Drive East, Los Angeles, CA 90095, United States

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ABSTRACT

Apparent excesses in early-solar ^{26}Al, ^{36}Cl, ^{41}Ca, and ^{60}Fe disappear if one accounts for ejecta from massive-star winds concentrated into dense phases of the ISM in star-forming regions. The removal of apparent excesses is evident when wind yields from Wolf–Rayet stars are included in the plot of radionuclide abundances vs. mean life. The resulting trend indicates that the solar radionuclides were inherited from parental molecular clouds with a characteristic residence time of 10^8 yr. This residence time is of the same order as the present-day timescale for conversion of molecular cloud material into stars. The concentrations of these extinct isotopes in the early solar system need not signify injection from unusual proximal stellar sources, but instead are well explained by normal concentrations in average star-forming clouds. The results imply that the efficiency of capture is greater for stellar winds than for supernova ejecta proximal to star-forming regions.

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1. Introduction

Correlations between radioactive decay mean lives (τ_R, related to half life by $\tau_R = t_{1/2}/\ln(2)$) and radionuclide abundances (e.g., Wasserburg et al., 1996) provide a test of various scenarios for the provenance of solar-system rock-forming elements. In the simplest case of continuous production and radioactive decay, radionuclides with the shortest τ_R (shortest half lives) should be least abundant when their concentrations are normalized to their stable counterparts. Apparent excesses in ^{26}Al/^{27}Al, ^{41}Ca/^{40}Ca, and ^{60}Fe/^{56}Fe relative to this expectation in particular have been taken as evidence for injection of these short-lived nuclides into the early solar system by a variety of sources, including supernovae proximal to the site of solar system formation (e.g. Ouellette et al., 2007, 2010; Gritschneder et al., 2012). Recent models have underscored the importance of enrichment of short-lived radionuclides in star-forming regions by collapse supernovae (SNe) ejecta (Vasileiadis et al., 2013) and/or by winds from rapidly rotating Wolf–Rayet (WR) or main-sequence WR progenitors (Gaidos et al., 2009; Gounelle and Meynet, 2012).

The atomic ^{60}Fe/^{26}Al (based on measurements of their decay products in meteorites) at the time of formation of the first solids in the solar system was ∼0.002 while the steady-state Galactic value deduced from γ-ray decay activities of these isotopes is ∼0.6 (Diehl et al., 2006, 2010; Tang and Dauphas, 2012; Wang et al., 2007). Supernova debris injection (Vasileiadis et al., 2013) does not offer an obvious explanation for the low ^{60}Fe/^{26}Al. Specific scenarios involving multiple stages of enrichment, first by supernova ejecta in previous generations of star formation followed by subsequent enrichment by winds, can account for the depressed ^{60}Fe/^{26}Al (Gounelle and Meynet, 2012). In most cases, if not all, explanations for the relative abundances of the short-lived radionuclides in the early solar system point to extraordinary sequences of events involving supernovae or combinations of supernovae and WR stars proximal to the site of solar system formation in both space and time. Estimates for the probabilities of these occurrences are often in the single digit percentiles or less (e.g., Gaidos et al., 2009).

Recently, Jura et al. (2013) showed that the initial ^{26}Al/^{27}Al ratio for the solar system of $\sim 5 \times 10^{-5}$ is apparently similar to star-forming regions today in the Galaxy. Their conclusion is based mainly on two observations. Firstly, Jura et al. pointed out that if ^{26}Al is produced locally by winds from massive stars in star-forming regions, the proper calculation for estimating the concentration of ^{26}Al in these regions is to divide the Galactic mass of ^{26}Al (between 1.5 and 2.2 $M_\odot$, Diehl et al., 2006, 2010) by the mass of H_2 in the Galaxy (8.4×10^8 $M_\odot$, Draine, 2011) rather than the mass of total H (4.95×10^9 $M_\odot$) as is commonly done. This is because the former traces molecular clouds, the sites most likely to be enriched by winds. Converting the mass ratio to atomic abundances, and combining with solar abundances of Al (atomic Al/H $= 3.5 \times 10^{-6}$, Lodders, 2003), Jura et al. obtain a ^{26}Al/^{27}Al ratio of 2 to 3×10^{-5} for regions susceptible to star formation today.

E-mail address: eyoung@epss.ucla.edu.

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This value is consistent with the solar value when one corrects for the increase in total Al in the Galaxy over the last 4.6 Gyr (e.g., Huss et al., 2009 derive a factor for GCE ^{27}Al growth of 1.62 over this interval). Secondly, Jura et al. noted that white dwarf stars polluted by impacting asteroids show elemental abundances implying rock–metal differentiation; the impactors in these extra-solar planetary systems were once molten. Since these rocks were essentially chondritic in bulk composition and small in size (see Jura et al., 2013 and references therein), making ^{26}Al decay the only viable heat source, the minimum $^{26}\mathrm{Al}/^{27}\mathrm{Al}$ required to produce melting can be calculated and is $\geqslant 3 \times 10^{-5}$ (Jura et al., 2013). It appears that melting of small rocky bodies by the decay of ^{26}Al is common outside of the solar system. The conclusion is that star-forming regions throughout the Galaxy have compliments of ^{26}Al similar to that present in the young solar system.

The proposed concentration of ^{26}Al in star-forming regions offers a natural explanation for the disparity in $^{60}\mathrm{Fe}/^{26}\mathrm{Al}$ between the solar system and the average Galactic value. Where ^{26}Al is produced mainly by WR and pre-WR main-sequence winds, the product ^{26}Al can seed the parental molecular clouds. WR stars are sufficiently massive (e.g., $\gg 25\ M_\odot$, lifetimes of several Myr) that they deposit their ejecta prior to escape from the vicinity of giant molecular clouds where stars are actively forming. By contrast, ^{60}Fe is produced mainly from SNe from a variety of stellar masses with many of the progenitor stars living longer than the lifetimes of parental giant molecular clouds (Murray et al., 2010). Non-detection of γ-decay emission from ^{60}Fe and the presence of resolvable γ emission from ^{26}Al in the Cygnus star-forming region (SFR) where WR stars have been observed suggests the decoupling of these nuclides in at least one SFR (Martin et al., 2009), although the decoupling is uncertain due to the relatively high detection limit for ^{60}Fe γ-decay there.

In this paper the consequences of the apparent heterogeneous distribution of ^{26}Al in the interstellar medium (ISM) are explored for other radionuclides. The production of ^{60}Fe, ^{41}Ca, and ^{36}Cl in particular, relative to ^{26}Al, by stellar winds, and the latest measurements of the daughter products of these nuclides in meteorites, are used to update the plot of relative abundances of the radionuclides versus mean life by decay. The result indicates that the solar abundances of ^{26}Al, ^{36}Cl, ^{41}Ca, ^{53}Mn, ^{60}Fe, ^{107}Pd, ^{129}I, ^{182}Hf, ^{244}Pu, ^{246}Sm, ^{235}U and ^{238}U are *all* consistent with values expected from the average rate and efficiency of star formation in the Milky Way. There appears to be no compelling reason to invoke special circumstances to explain the concentrations of these nuclides. They evidently entered our solar system in concentrations consistent with those expected for molecular clouds in general.

Table 1
Data used to construct Fig. 1.

Species	N_R/N_S	P_R^{SNe}/P_S [a]	Mean life (Myr) [b]
$^{26}\mathrm{Al}/^{27}\mathrm{Al}$	5.2×10^{-5} (1)	1.7×10^{-2} (12)	1.05 (14)
$^{36}\mathrm{Cl}/^{35}\mathrm{Cl}$	5.0×10^{-6} (2)	2.5×10^{-2} (12)	0.43 (12)
$^{41}\mathrm{Ca}/^{40}\mathrm{Ca}$	4.2×10^{-9} (3)	2.3×10^{-3} (12)	0.15 (15)
$^{53}\mathrm{Mn}/^{55}\mathrm{Mn}$	9.1×10^{-6} (4)	0.83 (12)	5.34 (16)
$^{60}\mathrm{Fe}/^{56}\mathrm{Fe}$	1.15×10^{-8} (5)	1.23×10^{-4} (12)	3.78 (17)
$^{107}\mathrm{Pd}/^{108}\mathrm{Pd}$	5.9×10^{-5} (6)	0.84 (12)	9.38 (18)
$^{129}\mathrm{I}/^{127}\mathrm{I}$	1.0×10^{-4} (7)	1.4 (12)	23.0 (19), (13)
$^{146}\mathrm{Sm}/^{144}\mathrm{Sm}$	8.0×10^{-3} (8)	2.7 (12)	98.10 (20)
$^{182}\mathrm{Hf}/^{180}\mathrm{Hf}$	1.0×10^{-4} (9)	0.33 (12)	12.84 (21)
$^{244}\mathrm{Pu}/^{232}\mathrm{Th}$	3.0×10^{-3} (10)	1.14 (12)	115.0 (22), (12)
$^{235}\mathrm{U}/^{232}\mathrm{Th}$	0.133 (11)	1.11 (13)	1015. (23)
$^{238}\mathrm{U}/^{232}\mathrm{Th}$	0.415 (11)	0.84 (13)	6446. (23)

[a] Uncertainties in production ratios taken to be $+2x/-1/2x$ where x is the value for the production ratio. These values are IMF-integrated supernova-dominated production ratios.

[b] Uncertainties in mean lives taken to be ±10%.

Data sources: (1) Jacobsen et al. (2008); (2) Lin et al. (2005); (3) Liu et al. (2012); (4) Nyquist et al. (2009); (5) Tang and Dauphas (2012); (6) Schönbächler et al. (2008); (7) Brazzle et al. (1999); (8) Stewart et al. (1994); (9) Kleine et al. (2005); (10) Hudson et al. (1989); (11) Wasserburg et al. (1996); (12) Huss et al. (2009); (13) Jacobsen (2005); (14) Norris et al. (1983); (15) Paul et al. (1991); (16) Honda and Imamura (1971); (17) Rugel et al. (2009); (18) Flynn and Glendenin (1969); (19) Russell (1957); (20) Kinoshita et al. (2012); (21) Vockenhuber et al. (2004); (22) Bemis et al. (1969); (23) Steiger and Jäger (1977).

2. Solar abundances vs. mean lives

Apparent excesses of ^{26}Al, ^{36}Cl, ^{41}Ca, and ^{60}Fe in the solar system have been identified by plotting the ratios of the atomic abundances of the radionuclides to their stable counterparts, N_R/N_S, versus mean lifetimes, τ_R, and comparing the resulting trends with expectations for the ISM (Wasserburg et al., 1996; Lodders and Cameron, 2004; Jacobsen, 2005; Huss et al., 2009). In such plots, the isotope ratios must be normalized to the production ratios for the nuclides, P_R/P_S, because the ratios of nuclides depend on the production ratios as well as on the rates of decay. For example, consider the differential equation for the abundance of a radionuclide in the ISM as a function of time (Jacobsen, 2005):

$$\frac{dN_R}{dt} = \psi(t) P_R - \lambda_R N_R \tag{1}$$

where $\psi(t)$ is the time-dependent rate of nuclide injection into the ISM from stars, P_R is the total production for the radionuclide ($\psi(t) P_R = \text{atoms/yr}$), and λ_R is the decay constant. The analogous expression for dN_S is $dN_S = \psi(t) P_S$. Jacobsen (2005) showed that the solution for the ratio N_R/N_S for extinct nuclides can be written as

$$\log\left(\frac{N_R}{N_S}\right) - \log\left(\frac{P_R}{P_S}\right) \simeq \log \tau_R - \log T^* \tag{2}$$

where T^* is the age of the Galaxy weighted by an evolving production rate such that $T^* = T\langle\psi\rangle/\psi(T)$, $\langle\psi\rangle$ is the average rate of total production and $\psi(T)$ is the rate at Galactic age T. Eq. (2) shows that on a plot of $\log[(N_R/N_S)/(P_R/P_S)]$ vs. $\log(\tau_R)$ one expects the short-lived nuclides to align on a line with slope of unity and an intercept controlled by the age of the Galaxy and the history of star formation.

Eq. (2) is plotted in Fig. 1 for the age of the Galaxy at the time the solar system formed assuming that the rate of nuclide production has been constant ($T^* = T = 12\ \text{Gyr} - 4.6\ \text{Gyr} = 7.4\ \text{Gyr}$). The plotting positions for the various short-lived and longer-lived radionuclides for which we have data from meteoritical materials are shown for comparison in Fig. 1. Isotope ratios, production ratios, and mean life values used in Fig. 1 are listed in Table 1. Here, as is customary, we use ^{232}Th ($\tau_R = 2 \times 10^{10}$ yr) as the pseudo-stable partner for the actinides. Production ratios are taken from Huss et al. (2009). These production ratios are derived from supernova-dominated yields integrated over a Salpeter stellar initial mass function (IMF) that specifies the numbers of stars N_* of mass M_* (i.e., $dN_*/dM_* = \beta M_*^{-2.35}$ and β is a scaling parameter). They are obtained from Eq. (14) in Huss et al. combined with a primary yield of 0.016 (Huss et al., 2009, p. 4928), their k value of unity, and a Galactic age of 7.4 Gyr (time at birth of the solar system). They are generally within a factor of 2 to 3 of earlier supernova-based production ratios (Jacobsen, 2005 and references therein), suggesting uncertainties in $(N_R/N_S)/(P_R/P_S)$ of at least a factor of 2. Short-lived Be isotopes are not included in this analysis for the present as they are generally regarded as being irradiation products. ^{36}Cl may also have an irradiation component and it is noteworthy that the initial solar $^{36}\mathrm{Cl}/^{35}\mathrm{Cl}$ is uncertain to a factor of 2× or more (Lin et al., 2005).

With the exception of the longest-lived nuclides, represented here by ^{238}U and ^{235}U, solar-system radionuclides do not align with relative abundances predicted by Eq. (2). Eq. (2) is inadequate because it fails to incorporate the residence times of material

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