Incorporation of ^{7}Be, ^{10}Be, ^{14}C, ^{26}Al, ^{36}Cl, ^{41}Ca, and ^{53}Mn Into Early Solar System Materials in the Solar Wind Implantation Model.

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Introduction: Numerous studies have indicated the incorporation of the short-lived radionuclides (SLRs) ($T_{1/2}$<5Myr) ^{7}Be, ^{10}Be, ^{26}Al, ^{36}Cl, ^{41}Ca, ^{53}Mn, and ^{60}Fe into early solar system materials, including calcium aluminum inclusions (CAIs), in amounts above background levels, although the mechanism for this incorporation is a matter of considerable debate (cf.[1]). Bricker & Caffee [2] proposed a solar wind implantation model for incorporation of ^{10}Be in CAI precursor materials. In this model ^{10}Be and possibly other short lived radionuclides (SLRs) are produced by energetic particle reactions in the proto-solar atmosphere of a more active proto-Sun, characterized by proton fluxes higher than contemporary particle fluxes. These SLRs are entrained in the solar wind that is then implanted into CAI precursor material. This production mechanism is operational in the contemporary solar system and is responsible for implantation of solar wind nuclei, including ^{10}Be [3] and ^{14}C [4], in lunar material. We consider the short-lived radionuclides ^{7}Be, ^{10}Be, ^{14}C, ^{26}Al, ^{36}Cl, ^{41}Ca, and ^{53}Mn in calcium-aluminum-inclusions (CAIs) in primitive carbonaceous meteorites in accordance with a solar wind implantation model.

Solar Wind ImplantationModel: We investigate the possibility that ^{7}Be, ^{10}Be, ^{14}C, ^{26}Al, ^{36}Cl, ^{41}Ca, and ^{53}Mn were produced in the solar nebula ~4.6 GYR ago by the bombardment of target material in the solar atmosphere by solar energetic particles. These SLRs escape the solar atmosphere entrained in the solar wind. Some fraction these outward flowing SLRs, referred to as the effective outflow rate, are incorporated into inflowing material from the proto-planetary accretion disk, referred to as the refractory mass inflow rate. In the region in which the inflowing material and outflowing solar wind intersect SLRs may be incorporated into the precursor CAI material.The fluctuating x-wind model of Shu et al. [5, 6, & 7] provides the basic framework for incorporation of SLRs into CAI-precursor materials and the subsequent transportation of these implanted refractory materials to asteroidal distances.

The refractory mass inflow rate, i.e. the mass that falls from the funnel flow onto the star at the X-region is given by

$$S = \dot{M}_D \cdot X_r \cdot F$$

where $\dot{M}_D$ is disk mass accretion rate, X_r is the cosmic mass fraction, and F is the fraction of material that enters the X-region [8]. For $\dot{M}_D$, we adopt 1x10^{-7} solar masses year^{-1} for a starting value. Following Lee et al. [8] we adopt a cosmic mass fraction, X_r, and fraction of refractory material fraction F, of 4x10^{-3} and .01, respectively. We find the rate at which this refractory material is carried into the x-region,called here the refractory mass inflow rate, S, is 2.5x10^{14} g s^{-1}.

The effective ancient SLR outflow rate, P in units of s^{-1}, is given by:

$$P = p \cdot f$$

where p is the ancient production rate and f is the fraction of the solar wind SLRs that captured into the CAI-forming region. We calculate the SLR production rates assuming solar energetic particles are characterized by a power law relationship:

$$\frac{dF}{dE} = kE^{-r}$$

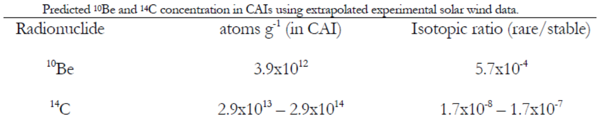
where r ranges from 2.5 to 4. For all spectral indices, we assume α/H= 0.1. For impulsive flares, i.e. r=4, we use ^{3}He/H= 0.1 and ^{3}He/H= 0.3, and for gradual flares, i.e. r=2.5, we use ^{3}He/H=0.

The concentration of SLRs found in refractory rock predicted by our model is given by:

$$N^{SLR} = \frac{P}{S} = \frac{p \cdot f}{\dot{M}_D \cdot X_r \cdot F}$$

where P is given atoms s^{-1} and S is given in g s^{-1}.

Results: We consider experimentally determined ^{10}Be [3] and ^{14}C [4]contemporary spallation production rates scaled to x-ray luminosities scene in T-Tauri stars and ancient enhanced energetic particle fluxes [9] and theoretically determined ^{7}Be, ^{10}Be, ^{14}C, ^{26}Al, ^{36}Cl, ^{41}Ca, and ^{53}Mn production rates.



Predicted ^{10}Be and ^{14}C concentration in CAIs using extrapolated experimental solar wind data.

Radionuclide	atoms g^{-1} (in CAI)	Isotopic ratio (rare/stable)
^{10}Be	3.9x10^{12}	5.7x10^{-4}
^{14}C	2.9x10^{13} – 2.9x10^{14}	1.7x10^{-8} – 1.7x10^{-7}

Figure 1 is a plot of predicted isotopic ratios for various flare compositions normalized to “canonical” ratios.

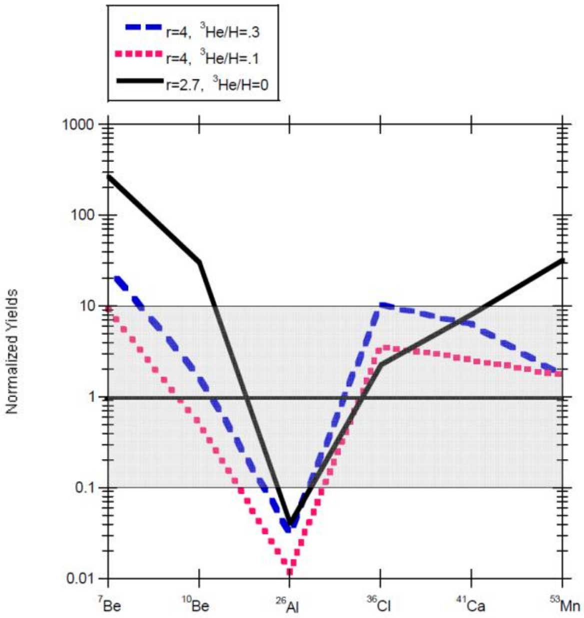


Figure 1 Predicted isotopic ratio of SLR normalized to the "canonical" isotopic ratio for various flare characteristics. The shaded area represents model uncertainties.

Figure 2 is similar to figure 1, but allows for 100 days from the time of ^{7}Be production to implantation in CAI precursors.

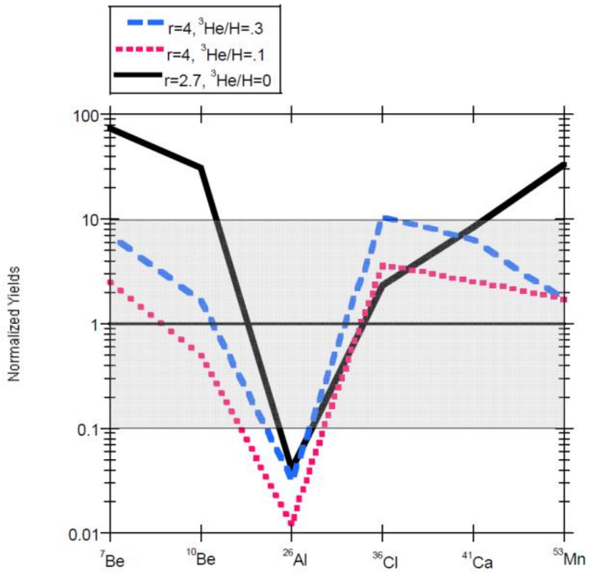


Figure 2 Predicted SLR isotopic ratio normalized to "canonical" isotopic ratio for various flare characteristics. Included here is 100 days of temporal evolution for ^{7}Be from time of production to implantation in CAI precursors.

Conclusion: The implantation model can account for the prevalence of the SLRs ^{7}Be, ^{10}Be, ^{36}Cl, ^{41}Ca, and ^{53}Mn to within a factor of 3 for flare parameters r=4 and ^{3}He/^{4}He=0.1, taking into account the 4x10^5 enhancement in energetic particles. ^{26}Al stands alone from the other nuclides considered here in that we find no viable way to produce ^{26}Al in the amounts found in CAIs without overproducing the other radionuclides. There is little doubt that ^{7}Be and ^{10}Be are produced in local irradiation scenarios. The isotopic ratio of ^{7}Be/^{9}Be in CAIs is 6.1x10^{-3} [10] and the isotopic ratio of ^{10}Be/^{9}Be in CAIs is 9.5x10^{-4} [11], yielding a ratio of ^{7}Be/^{10}Be of ~ 6. The production rate ratio of ^{7}Be/^{10}Be in the early solar system from MeV energetic protons is estimated to be about 70 [12]. Taking into account 100 days from the time of production to implantation, we find ^{7}Be/^{10}Be of ~ 15, well within experimental error. This corresponds to two half-lives from the time of production of ^{7}Be to incorporation into CAI. If the irradiation had taken place in-situ, the expected ratio of ^{7}Be/^{10}Be would be closer to the production rate of ~70 assuming To produce ^{26}Al at levels measured in CAIs through local spallation alone would lead to overproduction in ^{7}Be and ^{10}Be by factors of ~ 50-100.

References: [1] Gounelle, M., Chaussidon, M., & Montmerle, T. 2007, *C.R. Geoscience*, 339, 885. [2] Bricker, G. E., & Caffee, M. W. 2010, *ApJ*, 725, 443. [3] Nishiizumi, K. & Caffee, M.W. 2001, *Science*, 294, 352. [4] Jull, A.J.T., Lal, D., McHargue, L.R., Burr, G.S., & Donahue, D.J. 2000, *Nucl. Instrum. Methods Phys. Res. B*, 172, 867 [5] Shu, F.H, Shang, H., & Lee, T. 1996, *Science*, 271, 1545 [6] Shu, F.H., Shang, H., Glassgold, A.E., & Lee, T. 1997, *Science*, 277, 1475 [7] Shu, F.H., Shang, H., Gounelle, M., Glassgold, A. & Lee, T. 2001, *ApJ*, 548, 1029 [8] Lee, T. et al.1998, *ApJ*, 506, 8. [9] Feigelson, E.D., Garmire, G.P., & Pravdo, S.H. 2002, *ApJ*, 572, 335 [10] Chaussidon M., Robert F., & McKeegan K.D. 2006, *Geochim. Cosmochim. Acta*, 70, 224 [11] McKeegan, K.D. et al. 2000, *Science*, 289,1334. [12] Leya, I., Wieler, R., & Halliday, A.N. 2003, *ApJ*, 594, 605