Incorporation of the Short-lived Radionuclide ^{36}Cl Into Calcium Aluminum Inclusions in the Solar Wind Implantation Model. G.E. Bricker[1] and M.W. Caffee[2]. [1] Dept. of Physics, Purdue University North Central, Westville, IN. 46391 (gbricker@pnc.edu) [2]Primelab, Dept. of Physics, Purdue University, West Lafayette, IN. 47907 (mcaffee@purdue.edu).

Introduction: Many studies report evidence for the incorporation of the short-lived radionuclide (SLR) ($T_{1/2}$ = 0.3Myr) ^{36}Cl into early solar system materials, including calcium aluminum inclusions (CAIs). Lin et al. [1] infer an initial ^{36}Cl/^{35}Cl ratio of $\geq 1.6\times10^{-4}$ in sodalite from the carbonaceous chodrite Ningqiang based on Al-Mg systematics. Also relying upon Al-Mg systematics, Jacobsen et al. [2] report that initial ratio of ^{36}Cl/^{35}Cl in wadalite from Allende would have been $>8.7\times10^{-3}$ had the initial ^{26}Al/^{27}Al ratio been the canonical value of $\sim5\times10^{-5}$. With an initial ^{36}Cl/^{35}Cl of $\sim2\times10^{-4}$, the source of ^{36}Cl most likely would not be from a nearby super nova, or AGB star [3], leaving solar energetic particle (SEP) irradiation as the likely source of this radionuclide.

Bricker & Caffee [4] proposed a solar wind implantation model for incorporation of ^{10}Be in CAI precursor materials. In this model ^{10}Be and possibly other SLRs are produced by SEP reactions in the proto-solar atmosphere of a more energetic T-Tauri Sun, characterized by SEP fluxes many orders of magnitude greater 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 [5] and ^{14}C [6], in lunar material. Here we consider ^{36}Cl in CAIs in primitive carbonaceous meteorites in accordance with a solar wind implantation model.

Solar Wind ImplantationModel: In the solar wind implantation model, SLRs are 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 are incorporated into inflowing material which has fallen from the main accretion flow from the proto-planetary accretion disk. 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. [7, 8, & 9] 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 [10]. For $\dot{M}_D$, we adopt $1\text{x}10^{-7}$ solar masses year^{-1}. Following Lee et al. [10] we adopt a cosmic mass fraction, X_r, and fraction of refractory material fraction F, of $4\text{x}10^{-3}$ 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 $2.5\text{x}10^{14}$ g s^{-1}.

The effective ancient ^{36}Cl 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 ^{36}Cl that captured into the CAI-forming region; f=0.1. We calculate the ^{36}Cl 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 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. We assume an increase over the current particle flux of ~$4\text{x}10^5$, yielding a particle flux of $3.7\text{x}10^{12}$ protons cm^{-2}s^{-1} for E > 10MeV at the surface of the proto-Sun.

The production rates for cosmogenic nuclides can be calculated via:

$$p = \sum_i N_i \int \sigma_{ij} \frac{dF(E)}{dE_j} dE \qquad (1)$$

where i represents the target elements for the production of the considered nuclide, N_i is the abundance of the target element (g g^{-1}) , j indicates the energetic particles that cause the reaction, $\sigma_{ij}(E)$ is the cross section for the production of the nuclide from the interaction of particle j with energy E from target i for the considered reaction (cm^2) , and $\frac{dF(E)}{dE_j}$ is the differential energetic particle flux of particle j at energy E(cm^{-2}s^{-1}) [11]. We assume gaseous targets, Cl, K, S, of solar composition [12].

The concentration of ^{36}Cl found in refractory rock predicted by our model is given by:

$$N^{^{36}Cl} = \frac{P}{S} = \frac{p \cdot f}{\dot{M}_D \cdot X_r \cdot F} \qquad (2)$$

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

Results: From the value of S given above, and calculations of p from (1), we calculate the concentration of ^{36}Cl in CAIs from (2), and find the associated isotopic ratio for different flare parameters given in the table below.

Table 1 Predicted ^{36}Cl content in CAIs.

Flare Parameter	atoms g^{-1} (in CAIs)	Isotopic ratio
p=2.7, ^{3}He/H=0	3.35x10^{13}	1.14x10^{-5}
p=4, ^{3}He/H=0.1	5.26x10^{13}	1.79x10^{-5}
p=4, ^{3}He/H=0.3	1.54x10^{14}	5.25x10^{-5}

Discussion: From the results above, the isotopic ratio predicted by the solar wind implantation model is from a factor of 4 to a factor of 10 below the inferred initial ^{36}Cl/^{35}Cl ratio of ~ 2x10^{-4}. Given the uncertainty in the parameters, i.e $\dot{M}_D$, X_r, F, and f, the model is viable for ^{36}Cl/^{35}Cl initial ratio of ~ 2x10^{-4}. Jacobsen et al. [2] report, based on Al-Mg systematics, the initial ^{36}Cl/^{35}Cl ratio may have been $> 8.7 \times 10^{-3}$. The model underproduces this value by several orders of magnitude for the flare parameters given here.

Evidence suggests that the distribution of ^{26}Al was homogenous in the solar system, but this is not always the case [3]. Marhas and Goswami [13] found several CAIs that had the "canonical" ^{10}Be/^{9}Be ratio, but were devoid of ^{26}Al, demonstrating a decoupling of ^{26}Al from ^{10}Be. If ^{36}Cl is also decoupled from ^{26}Al, it is difficult to infer what the initial ^{36}Cl/^{35}Cl ratios was based solely on Al-Mg systems, although Jacobsen et al [2] do report a canonical initial ^{26}Al/^{27}Al ratio for primary minerals in their sample. More studies are needed in this area. It would be beneficial to establish a correlation between ^{10}Be and ^{36}Cl to find if the irradiation that most likely produced ^{10}Be also produced ^{36}Cl.

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