Research Article

Incorporation of ^{36}Cl into Calcium-Aluminum-Rich Inclusions in the Solar Wind Implantation Model

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We consider the short-lived radionuclide (SLR) ^{36}Cl in calcium-aluminum-rich inclusions (CAIs) found in primitive meteorites with the solar wind implantation model. In this model, SLRs are produced via nuclear reaction with solar energetic particles (SEPs) interacting with gaseous targets in the protosolar atmosphere in T-Tauri stars. These SLRs are captured by the solar wind and then implanted in CAI precursor materials, which have dropped from the funnel flow leading onto the protostar. This method of incorporating SLRs into solar system materials is currently active in our solar system and has been measured with SLRs from the solar wind being implanted on the lunar surface. T-Tauri stars are capable of SEP fluxes $\sim 10^5$ greater than contemporary SEP fluxes. Here we scale the production rate of ^{36}Cl to the ancient SEP activity. From the enhanced production rates and the refractory mass inflow rate at 0.06 AU from the protosun, we model the ancient ^{36}Cl content in CAIs. We find the initial isotopic ratio of $^{36}\text{Cl}/^{35}\text{Cl}$ to range from about 1×10^{-5} to 5×10^{-5} and the concentration of ^{36}Cl to range from about 3×10^{13} to 1.5×10^{14} atoms g^{-1} .

1. Introduction

Studies report evidence for the incorporation of the short-lived radionuclide (SLR) ($T_{1/2} = 0.3 \text{ Myr}$) ^{36}Cl into early solar system materials, including calcium-aluminum-rich inclusions (CAIs). Lin et al. [1] infer an initial $^{36}\text{Cl}/^{35}\text{Cl}$ ratio of $\geq 1.6 \times 10^{-4}$ in sodalite from the carbonaceous chondrite Ningqiang based on Al-Mg systematics. Also, relying upon Al-Mg systematics, Jacobsen et al. [2] report that initial ratio of $^{36}\text{Cl}/^{35}\text{Cl}$ in wadalite from Allende would have been $> 8.7 \times 10^{-3}$ had the initial $^{26}\text{Al}/^{27}\text{Al}$ ratio been the canonical value of $\sim 5 \times 10^{-5}$.

Clues to the source of the ^{36}Cl can be gleaned from this initial ratio. If the initial $^{36}\text{Cl}/^{35}\text{Cl}$ had been $\sim 2 \times 10^{-4}$, the source of ^{36}Cl most likely would not have been from a nearby super nova or AGB star [3]. A remaining mechanism for the production of this radionuclide is local irradiation from solar energeticparticle (SEP) born in the protosolar atmosphere. The initial SLR ratios can be used to constrain early solar

system evolution and conditions. This is especially true in terms of solar luminosity and flaring characterization.

Bricker and 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 protosolar atmosphere of a more energetic T-Tauri sun, characterized by SEP fluxes many orders of magnitude greater than contemporary particle fluxes. Studies of the Orion Nebulae indicate that premain sequence (PMS) stars exhibit X-ray luminosity and hence SEP fluxes on the order of $\sim 10^5$ over contemporary SEP flux levels [5]. The SLRs are produced through nuclear reactions with these SEPs, and the irradiation produced SLRs are then entrained in the solar wind and subsequently 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 [6] and ^{14}C [7], in lunar material. In this work, we consider ^{36}Cl found in CAIs in primitive carbonaceous meteorites in accordance

with a solar wind implantation model. Table 1 characterizes ^{36}Cl found in CAIs.

2. Solar Wind Implantation Model

2.1. Overview. 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 of these outward flowing SLRs are incorporated into inflowing material which has fallen from the main accretion flow from the protoplanetary 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. [9–11] provides the basic framework for incorporation of SLRs into CAI-precursor materials and the subsequent transportation of these implanted refractory materials to asteroidal distances. Figure 1 is a cartoon of the basic magnetic field geometry, main accretion flow, and SLRs, including ^{36}Cl outflow.

2.2. Refractory Mass Inflow Rate. The refractory mass inflow rate, that is, the mass that falls from the funnel flow onto the star at the X-region, is given by

$$S = \dot{M}_D \cdot X_r \cdot F, \quad (1)$$

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 [12]. For $\dot{M}_D$, we adopt 1×10^{-7} solar masses year^{-1} . The mass accretion rates can vary from $\sim 10^{-7}$ to $\sim 10^{-10}$ solar masses year^{-1} for T-Tauri stars from 1 to 3 Myr [13]. Embedded class 0 and class I PMS stars can have accretion rates from $\sim 10^{-5}$ to $\sim 10^{-6}$ solar masses year^{-1} [14]. The value we adopt corresponds to class II or III PMS stars. Following Lee et al. [12], we adopt a cosmic mass fraction, X_r , and fraction of refractory material fraction F , of 4×10^{-3} and 0.01, respectively. X_r represents the fraction of material that is refractory and F represents the fraction of mass that does not accrete onto the protosun. The choice 0.01 is a maximum for F and corresponds to all the mass which comprises the planets falling from the accretion flow. If some of the rocky material accreting towards the proto-Sun never reached the edge of the accretion disk, F would be smaller by a factor of 20 at most, but this scenario is unlikely. The choice of $F = 0.01$ is the preferred value of Lee et al. [12] in their model. (See Lee et al. [12] for a detailed discussion of X_r and F .) From (1) and the values described above, we find the rate at which this refractory material is carried into the x -region, called here the refractory mass inflow rate, S , is $2.5 \times 10^{14} \text{ g s}^{-1}$. On the extremes, S could be two orders of magnitude greater if the PMS star was classes 0 or 1; S could also be four orders of magnitude less if the mass accretion rate was $\sim 10^{-8}$ to 10^{-10} solar masses year^{-1} and $F \sim 0.0001$.

FIGURE 1: Solar wind implantation model of magnetic field geometry for SLRs production via nuclear reactions. The gray area represents accretion flow onto “hot spots” on the PMS star. SLRs produced close to the protosolar surface are implanted into CAI material which has fallen from the accretion flow (figure after Shu et al. [10]).

2.3. Ancient Effective Production Rate. The effective ancient ^{36}Cl outflow rate, P in units of s^{-1} , is given by

$$P = p \cdot f, \quad (2)$$

where p is the ancient production rate and f is the fraction of the solar wind ^{36}Cl that was captured into the CAI-forming region; $f = 0.1$. (See Bricker and Caffee [4] for a discussion of factor f .) We calculate the ^{36}Cl production rates assuming that solar energetic particles are characterized by a power law relationship:

$$\frac{dF}{dE} = kE^{-r}, \quad (3)$$

where r ranges from 2.5 to 4. For impulsive flares, that is, $r = 4$, we use $^3\text{He}/\text{H} = 0.1$ and $^3\text{He}/\text{H} = 0.3$, and for gradual flares, that is, $r = 2.5$, we use $^3\text{He}/\text{H} = 0$. Contemporary SEP fluxes at 1 AU are ~ 100 protons $\text{cm}^{-2} \text{s}^{-1}$ for $E > 10$ MeV [15]. We assume an increase in ancient particle fluxes over the current particle flux of $\sim 4 \times 10^5$, yielding an energetic particle flux of 3.7×10^{12} protons $\text{cm}^{-2} \text{s}^{-1}$ for $E > 10$ MeV at the surface of the protosun.

The production rates for cosmogenic nuclides can be calculated via

$$p = \sum_i N_i \int \sigma_{ij} \frac{dF(E)}{dE_j} dE, \quad (4)$$

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 $dF(E)/dE_j$ is the differential energetic particle flux of particle j at energy E ($\text{cm}^{-2} \text{s}^{-1}$) [15]. We assume gaseous targets, Cl, K, S, and Ca, of solar composition [16].

TABLE 1: Characteristics of ^{36}Cl found in CAIs.

Stable nuclide	Half-life	Initial isotopic ratio	Stable nuclide (ppm)	Radionuclide (g^{-1})
^{35}Cl	0.3 Myr	1.6×10^{-4}	228	1.1×10^{15}

References Lin et al. [1] and Leya et al. [8].

TABLE 2: Nuclear reactions considered in this paper.

$^{36}\text{S}(p, n)^{36}\text{Cl}$
$^{37}\text{Cl}(p, pn)^{36}\text{Cl}$
$^{34}\text{S}(^3\text{He}, p)^{36}\text{Cl}$
$^{35}\text{Cl}(^3\text{He}, 2p)^{36}\text{Cl}$
$^{39}\text{K}(^3\text{He}, x)^{36}\text{Cl}$
$^{\text{nat}}\text{Ca}(^3\text{He}, x)^{36}\text{Cl}$

TABLE 3: Predicted ^{36}Cl content in CAIs.

Flare parameter	Atoms g^{-1} (in CAIs)	Isotopic ratio
$p = 2.7, ^3\text{He}/\text{H} = 0$	3.35×10^{13}	1.14×10^{-5}
$p = 4, ^3\text{He}/\text{H} = 0.1$	5.26×10^{13}	1.79×10^{-5}
$p = 4, ^3\text{He}/\text{H} = 0.3$	1.54×10^{14}	5.25×10^{-5}

The cross-sections we use are from Gounelle et al. [17], with the exception of $^{\text{nat}}\text{Ca}(^3\text{He}, x)^{36}\text{Cl}$, which is a new experimental cross-section from Herzog et al. [18]. The Gounelle et al. [17] cross-sections are a combination of experimental data, fragmentation, and Hauser-Feshbach codes. The uncertainty associated with model codes is at best a factor of two. We have used experimental cross-sections, whenever possible, in order to limit uncertainties associated with the calculations. The reactions we have considered here are the primary production pathways. This takes into account both abundance of target material and cross-sections. Any other reaction would add little to the overall ^{36}Cl production rate. Table 2 shows the cross-sections used in the calculations.

3. Results

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

$$N^{36}\text{Cl} = \frac{P}{S} = \frac{p \cdot f}{\dot{M}_D \cdot X_r \cdot F}, \quad (5)$$

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

From the value of S given above from (1) and calculations of p from (4), we calculate the concentration of ^{36}Cl in CAIs using (5) and find the associated isotopic ratio for different flare parameters given in Table 3, and we plot the predicted ^{36}Cl content for spallation production from energetic protons in Figure 2.

4. 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 $^{36}\text{Cl}/^{35}\text{Cl}$ ratio of

FIGURE 2: Predicted ^{36}Cl content in CAIs from energetic protons as a function of solar flare parameter.

$\sim 2 \times 10^{-4}$. Given the uncertainties in the parameters, that is, $\dot{M}_D$, X_r , F , and f , the model is viable for $^{36}\text{Cl}/^{35}\text{Cl}$ initial ratio of $\sim 2 \times 10^{-4}$. Jacobsen et al. [2] report that, based on Al-Mg systematics, the initial $^{36}\text{Cl}/^{35}\text{Cl}$ ratio may have been $> 8.7 \times 10^{-3}$. The model calculations underproduce this value by several orders of magnitude for the flare parameters given here. It is not possible to produce an order of magnitude correct $^{36}\text{Cl}/^{35}\text{Cl}$ ratio of $\sim 1 \times 10^{-2}$ without overproducing $^{10}\text{Be}/^9\text{Be}$, $^{41}\text{Ca}/^{40}\text{Ca}$, and $^{53}\text{Mn}/^{55}\text{Mn}$ by several orders of magnitude.

Clearly, some other mechanism is needed to explain to provenance of ^{36}Cl at the levels described by Jacobsen et al. [2]. A possible scenario is that the irradiation of target material occurred in a volatile rich region away from the protosun. This region would contain much more target materials, that is, Cl, S, and K. Greater target material would lead to greater initial ^{36}Cl content in CAIs. This argument for the enhanced ^{36}Cl found in wadalite samples is also invoked by Jacobsen et al. [2].

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 [19] found several CAIs that had the “canonical” $^{10}\text{Be}/^9\text{Be}$ 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 $^{36}\text{Cl}/^{35}\text{Cl}$ ratios were based solely on Al-Mg systems although Jacobsen et al. [2] do report a canonical initial $^{26}\text{Al}/^{27}\text{Al}$ ratio for primary minerals in their sample.

The irradiation origin of ^{26}Al found in CAIs is a matter of considerable debate. The proposed region where the enhanced ^{36}Cl production may have taken place could have already been seeded with ^{26}Al from some nonirradiation origin, that is, supernova. Conversely, the origin of ^{10}Be is likely from SEP irradiation close to the protosun [4, 17]. 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 . More studies are needed in this area to establish this relationship.

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