Solar wind implantation model for Be-10 in calcium-aluminum inclusions

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SOLAR WIND IMPLANTATION MODEL FOR ^{10}Be IN CALCIUM–ALUMINUM INCLUSIONS

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ABSTRACT

We propose a model for the incorporation of ^{10}Be within calcium–aluminum inclusions (CAIs) in primitive carbonaceous meteorites. In this model, ^{10}Be is produced by energetic particle reactions in the proto-solar atmosphere of a more active proto-Sun characterized by energetic particle fluxes higher than contemporary particle fluxes. This ^{10}Be is incorporated into the solar wind that is then implanted into CAI precursor material. This production mechanism is operational in the contemporary solar system implanting ^{10}Be in lunar materials. The contemporary production rate of ^{10}Be at the surface of the Sun is $\sim$0.1 ^{10}Be cm^{-2} s^{-1}. Scaling up the contemporary ^{10}Be production in the proto-Sun by a factor of 10^5 would increase the production rate to 10^4 ^{10}Be cm^{-2} s^{-1}. Using this enhanced production value in conjunction with refractory mass inflow rates at 0.06 AU from the proto-Sun we model ^{10}Be concentrations in CAI precursors. We calculate the content of solar-wind-implanted ^{10}Be would have been of the order of 10^{12} ^{10}Be g^{-1} in CAIs, consistent with initial ^{10}Be content found from boron–beryllium isotopic systematics in CAIs.

Key words: meteorites, meteors, meteoroids – protoplanetary disks – solar wind – stars: early-type

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1. INTRODUCTION

Measurements of the decay products of now extinct radionuclides indicate that the radionuclides ^{10}Be, ^{26}Al, ^{36}Cl, ^{41}Ca, and ^{60}Fe were incorporated into high-temperature condensates, most notably calcium–aluminum inclusions (CAIs) in carbonaceous meteorites, at the time of their formation (Gounelle et al. 2007). The potential sources for these radionuclides are widely varied and include stellar sources (supernova, asymptotic giant branch stars, and Wolf–Rayet stars) and energetic particle interactions. Especially noteworthy in the bestiary of extinct radioactivities is ^{10}Be, $T_{1/2} = 1.36$ Myr (Nishiizumi et al. 2007), since ^{10}Be is not formed through stellar nucleosynthesis (Marhas & Goswami 2004). Desch et al. (2003) have proposed an extra-solar nebula origin of ^{10}Be based on the trapping of ^{10}Be galactic cosmic ray nuclei in the molecular cloud and irradiation of the molecular cloud by galactic cosmic rays. Gounelle et al. (2006) and McKeegan et al. (2000) have presented evidence that casts doubt on the viability of this model, leaving local production of ^{10}Be from solar energetic particles as the surviving scenario. The possible detection of the decay products of ^{7}Be in CAIs (Chaussidon et al. 2006), $T_{1/2} = 53$ days (Jaeger et al. 1996), further solidifies the hypothesis that some radionuclides, including perhaps ^{10}Be, were produced locally by energetic particle reactions in the early solar system and subsequently incorporated into early solar system materials.

Table 1 summarizes Be isotopic ratios and concentrations in CAIs used in this paper. Section 3 details a range of values of experimentally determined ^{10}Be initial isotopic ratios and initial concentrations found in CAIs.

Gounelle et al. (2006) assume an X-wind model (cf. Shu et al. 1994) as the astrophysical setting for the irradiation of CAI precursor material. In this model, these early high-temperature condensates are exposed to an enhanced flux of solar protons and helium nuclei at the reconnection ring, at $\sim$0.1 AU before their incorporation into the larger parent body. The specific hypothesis of Gounelle et al. (2006) that direct exposure of CAI precursors at the reconnection ring to energetic particles produced many of the extinct radioactivities originally in CAIs is however controversial (Goswami et al. 2001; Marhas et al. 2002; Desch et al. 2003). The production ratios of the radioactivities and the correlations, or lack thereof, between different radioactivities measured in CAIs represent a test of the viability of the local irradiation model. Using existing nuclear reaction data it is possible to predict the production ratios for a given particle flux, energy spectrum, and target composition. Comparisons of these predictions with measured initial isotopic ratios of extinct radionuclides in primitive materials indicate that a single-stage exposure of CAIs or their precursors to solar energetic particles cannot reproduce the abundances of these radionuclides measured in meteorites (Leya et al. 2003).

There is another mechanism for incorporating ^{10}Be in solar system materials. It is known that ^{10}Be is currently produced in the atmosphere of the Sun by spallation reactions involving oxygen and energetic particles. This spallogenic ^{10}Be is entrained with the solar wind and implanted in solar system materials exposed to the solar wind. Nishiizumi & Caffee (2001) detected solar-wind-implanted ^{10}Be in Apollo 17 trench samples. This ^{10}Be is associated with the outermost layers of the mineral grains, indicating low-energy implantation; solar wind ions have ranges up to 200 nm for typical solar wind speeds of 300–800 km s^{-1} (Grimberg et al. 2006). Based on the ^{10}Be concentration in these grains they calculated the current escape rate of ^{10}Be at the surface of the Sun to be 0.13 ± 0.05 ^{10}Be cm^{-2} s^{-1}, consistent with theoretical estimates that suggest that the current time-averaged solar flare production of ^{10}Be at the surface of the Sun is $\sim$0.1 ^{10}Be cm^{-2} s^{-1} (see the Appendix). This escape rate corresponds to a total production rate of $8.0 \pm 3.0 \times 10^{21}$ ^{10}Be s^{-1} for the contemporary Sun. Jull et al. (1995) have also measured solar-wind-implanted ^{14}C in lunar soils, providing further evidence that radionuclides are produced in the solar atmosphere, entrained into the solar wind, and implanted into material exposed to the solar wind.

Could a similar mechanism be responsible for the presence of ^{10}Be excesses during an earlier epoch?

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Table 1
Be in CAIs

Nuclide	Half-life	Initial Isotopic Ratio	Initial Concentration (g^{-1})
^{10}Be	1.36×10^6 yr (1)	9.5×10^{-4} (2)	5.5×10^{12} (3)
^{7}Be	53 days (4)	6.1×10^{-3} (5)	4.1×10^{13} (6)

References. (1) Nishiizumi et al. 2007; (2) McKeegan et al. 2000; (3) ^{10}Be concentration in g^{-1} calculated from ^{10}Be/^{9}Be and ^{9}Be content in ppb*; (4) Jaeger et al. 1996; (5) Chaussidon et al. 2006; (6) ^{7}Be concentration in g^{-1} calculated from ^{7}Be/^{9}Be and ^{9}Be content in ppb. The ^{9}Be concentration is estimated to be 100 ppb from Duprat & Tatischeff (2008) and Leya et al. (2003).

2. IMPLANTATION MODEL

We propose that ^{10}Be was produced in the solar nebula ∼4.6 Gyr ago by the same mechanism that we observe now, bombardment of O by solar energetic protons and He nuclei. This ^{10}Be escapes the solar atmosphere entrained in the solar wind. Some fraction of this outward flowing ^{10}Be, referred to as the effective ^{10}Be outflow rate and measured in units of ^{10}Be s^{-1}, is incorporated into the inward flowing material from the proto-planetary accretion disk, referred to as the refractory mass inflow rate and measured in units of g s^{-1}. ^{10}Be is incorporated into the refractory CAI pre-cursor material at the intersection of the inflowing material and outflowing solar wind ^{10}Be.

2.1. Ancient Solar Wind ^{10}Be

Like the contemporary solar system, in the early solar system it is known that materials were exposed to the solar wind. Gas-rich meteorites, in particular, archive the ancient solar wind implantation. The presence of surface-correlated light noble gases in meteorites of varying chemical composition attests to the exposure of the regoliths of many meteorite parent bodies to solar wind ions ∼4.6 Gyr ago (cf. Caffee et al. 1987). The presence of solar-wind-implanted noble gases indicates that at the time of regolith formation nebular gas and dust were absent from the part of the solar system in which these regoliths were exposed. Like the contemporary solar wind, the ancient solar wind likely would entrain radioactive species, including ^{10}Be.

There is considerable observational evidence that pre-main sequence (PMS) solar-mass stars experience a period of enhanced flaring activity. For solar-type stars early in their formation, recent measurements of X-rays from young stellar objects in the Orion Nebular Cluster (ONC; Feigelson et al. 2002; Wolk et al. 2006) indicate median luminosities of between ∼10^{30} erg s^{-1} and ∼10^{31} erg s^{-1}. Although there is no chronological link between CAI formation and PMS star evolution, studies suggest the onset of X-ray emissions in the class 0 embedded phase (cf. Hamaguchi et al. 2005; Getman et al. 2007) and the continuation of these emissions through classes I, II, and III phases. Feigelson et al. (2002) and Preibisch & Feigelson (2005) report a temporal variability between stars and a mild decline in X-ray luminosity for solar-mass PMS stars. Getman et al. (2008a, 2008b) report flare morphology to be similar between class II accreting PMS stars and class III non-accreting PMS stars in the ONC, but report that flares from class II stars have less total X-ray energy and are shorter in duration; Prisinzano et al. (2008) also find the X-ray luminosities of accreting PMS stars to be lower than non-accretors in the ONC. Not all PMS stars exhibit enhanced X-ray emissions. From *Chandra* observations Giardino et al. (2007) did not detect X-ray emissions from six class 0 stars in the Serpens star-

forming region and put an upper limit of $L_x \leqslant 0.4 \times 10^{30}$ erg s^{-1} for those class 0 PMS stars. Prisinzano et al. (2008) report results similar to Giardino et al. (2007). Although PMS stars have variable luminosities and their luminosities vary over time, the bulk of the astronomical observations indicate that luminosities, and by association the energetic particle fluxes, of ∼1 Myr ONC young stars are greatly enhanced over contemporary solar levels.

All local irradiation models, including the one proposed here, absolutely require greatly enhanced energetic particle production in the early solar nebula. Feigelson et al. (2002) report X-ray flares to be $10^{1.5}$ more powerful, $10^{2.5}$ more frequent, and 10^1 more efficient in accelerating particles to MeV energies in ∼1 Myr solar analog stars; the overall effect is a 10^5 increase in energetic particle flux in ∼1 Myr solar analog stars. Radio gyrosychrotron radiation associated with nonthermal MeV electrons in class I protostars (Choi et al. 2008) attests to the production of energetic particles during impulsive X-ray events. Liu & Wang (2009) also report a strong correlation between the acceleration of energetic particles and magnetic reconnection flaring events. (See Feigelson et al. 2002 for a detailed discussion of energetic particles accompanying flares.) Using the *Chandra* X-ray luminosity measurements of ONC objects, such an increase in particle fluxes, and hence production rates, is realistic and perhaps even an underestimate. Based on an X-ray luminosity of 5×10^{30} erg s^{-1} Gounelle et al. (2006) calculated a proton flux ($E \geqslant 10$ MeV) of 1.9×10^{10} cm^{-2}s^{-1} at 0.06 AU from the Sun. This corresponds to a time-averaged increase of 6.8×10^5 in the number of energetic protons produced from young stellar flares relative to contemporary activity, assuming the current flux of energetic protons $E > 10$ MeV at 1 AU is 100 protons cm^{-2} s^{-1} (Reedy & Marti 1991). Using this scaling factor at the Sun's surface, the ^{10}Be production rate would be $5.4 \pm 2.0 \times 10^{27}$ ^{10}Be s^{-1}.

Greatly enhanced flaring activity leads to the acceleration of energetic particles, i.e., protons and He nuclei. These energetic particles interact with the nucleus of target material, primarily oxygen in the case of spallation-produced ^{10}Be, producing a daughter nuclide and secondary particles through spallation reactions. The production rate of daughter nuclei scales with the amount of incident energetic particles. For our calculations, we take a starting value for the ancient ^{10}Be production rate, p, of $3.2 \pm 1.2 \times 10^{27}$ s^{-1}, corresponding to an increase of ∼4×10^5 over contemporary levels.

There are few data that shed light on the spectral shape of the ancient energetic particle flux so we assume for our calculations a shape similar to the contemporary Sun and that ^{10}Be production scales linearly with energetic particle enhancements. In the Appendix, we illustrate the dependence on the energetic particle spectrum of the ^{10}Be production rate.

The distribution of ^{10}B, the decay product of ^{10}Be, in CAIs differs from the distribution of solar wind ions seen in lunar surface materials or gas-rich meteorites. In these materials the solar wind ions are known to be surface correlated, so the formation of the grains, chondrules, etc., pre-dated the exposure of this material to the solar wind (cf. Caffee et al. 1987). The excess ^{10}B found in CAIs is not surface correlated (McKeegan et al. 2000). We hypothesize that ^{10}Be is incorporated into CAI fine-grained precursor material, prior to the final formation of the CAI as it is found in a primitive meteorite. If the ^{10}Be is implanted into precursor materials, the distribution of ^{10}Be would not be surface correlated, but would be distributed throughout the entire CAI.

Estimates of the column density of CAI precursor material at the x-region are of the order 0.1 g cm^{-2} (Lee et al. 1998). This amount of intervening material would prevent solar wind ions from penetrating further into the solar nebula. Consequently, live ^{10}Be would be stopped and effectively mixed with the material in that region of the solar nebula. Lee et al. (1998) adopt a gas column density in the x-region of $\sim 10^{-4}$ g cm^{-2}. This amount of intervening material would not have a notable effect on the solar wind ions.

2.2. Physical Setting and Geometry

The production of ^{10}Be and the efficiency with which ^{10}Be is subsequently incorporated into CAI precursor material are dependent upon the geometries of the proto-Sun–accretion disk system and the associated magnetic fields. Recent models and measurements of PMS stars attempt to characterize magnetic field topology associated with these stars. Zeeman measurement techniques have shown that magnetic field characteristics close to cTTS (classical T Tauri star) are non-dipolar (Johns-Krull 2008). Magnetic field maps made through Zeeman–Doppler imaging of V2129 Oph, a moderately accreting T Tauri star, indicate a dipole field associated with accretion and a much stronger octupole field (Donati et al. 2007). Spectropolarimetric Zeeman signatures on the cTTS BP Tau indicate magnetic topology consisting of a 1.2 kG dipole and a 1.6 kG octupole (Donati et al. 2008). Long et al. (2008) model three-dimensional complex magnetic fields consisting of a dipole with quadrupole and find that the orientation of the magnetic fields plays a key role in the flow of matter onto the star. A review of magnetic structure of T Tauri stars can be found in Jardine et al. (2007).

Lee et al. (1998) and Gounelle et al. (2001, 2006) assume that flare X-rays are produced and energetic particles are accelerated at the inner surface of the accretion disk from magnetic field line reconnection events occurring at the x-region. In their models, the energetic particles follow a trajectory to the x-region. It is in this region that CAIs are formed and exposed to energetic particles, leading to the in situ spallation production of radionuclides. Evidence suggests that magnetic field lines from dipole fields may indeed extend to the disk regions (cf. Hartmann et al. 1998). Alternatively, Getman et al. (2008b) studied 161 PMS stars with *Chandra X-ray Observatory* and find all X-ray flares in their study to be consistent with magnetic loop solar-like flares occurring close to the surface of the star. Many workers (cf. Getman et al. 2008b; Stelzer et al. 2007) report accreting and non-accreting PMS stars exhibit indistinguishable X-ray flaring structure, indicating that the location of the flaring activity is close to the PMS star and not dependent upon the star–disk interface.

Strictly speaking, the ^{10}Be production rate in our model is independent of geometry. The ^{10}Be production rate enhancement is based on enhanced solar activity, independent of the specific location of the flaring. For the purposes of the calculations, we will assume that the ^{10}Be is produced in flaring events close to the surface of the PMS Sun.

Although there is considerable uncertainty about the physical geometry of the proto-Sun–disk system, the basic magnetic geometry of the model of Shu et al. (1994, 1996, 1997) provides a framework for the production and incorporation of ^{10}Be into refractory rock material. The paradigm of Shu et al. (1994, 1996, 1997) models the solar nebula as a distorted dipole field with magnetocentrifugally driven X-winds. Although our hypothesis for ^{10}Be production is independent of the Shu et al. models, we discuss our model within this framework. Figure 1 illustrates

Figure 1. Magnetic field geometry for ^{10}Be spallation production. The gray area illustrates accretion flow along magnetic field lines onto the proto-Sun, terminating in accretion "hot spots" at high altitudes on the PMS star. ^{10}Be produced close to the surface is implanted in CAI precursor material which has fallen from the accretion flow and subsequently transported to asteroidal distances via the X-wind. (Figure after Shu et al. 1997).

(A color version of this figure is available in the online journal.)

the basic magnetic field geometry, accretion inflow, and ^{10}Be outflow.

Contemporary solar wind ions may originate in expanding $T \sim 10^6$ K coronal loops and associated equatorial streamers (cf. Lang 2001). The work of Getman et al. (2008b) indicates that flaring morphologies in PMS stars are similar to solar magnetic loop flaring events with both footprints anchored on the stellar surface. ^{10}Be, and perhaps other radionuclides, would be produced in these flaring events in the same fashion as contemporary solar wind ions; production rates would scale with flaring intensity.

Feigelson et al. (2002) considered the case of energetic particles produced in X-ray flares in multipolar magnetic fields close to the stellar surface and find that 13% of the X-ray emissions from those flares will impact a flat disk. Irradiation of the disk in accreting PMS stars is the main process for heating the disk; infrared excesses in cTTS over non-accreting wTTS (weak-lined T Tauri stars) attest to the irradiation of the disk from the proto-star (Hartmann 1998). Evidence suggests that disks are flared, leading to exposure of a larger portion of the disk to solar irradiation (cf. Dullemond et al. 2006).

The fraction of energetic particles and solar wind ions that impinge on the disk is modulated by the magnetic field. A magnetic field geometry shown in Figure 1 having field strength ~ 1 kG would effectively trap and divert solar wind ions into the region proposed for the formation of CAIs. Given the complex nature of the magnetic field geometry in the region, it is difficult to ascertain the precise fraction of ^{10}Be solar wind ions that would hit the disk. A lower limit for this fraction is the fraction of the X-ray luminosity impinging on the disk, 0.13 (Feigelson et al. 2002). Magnetic fields are likely to concentrate energetic particles in this region relative to X-rays. Nevertheless, to assess the plausibility of the model we will adopt a value for f, the fraction of energetic particles captured into the CAI-forming region, of 0.1.

The effective ancient ^{10}Be outflow rate, P in units of ^{10}Be s^{-1}, is given by

$$P = p \cdot f. \tag{1}$$

Accordingly, the estimated effective ancient ^{10}Be outflow rate is $P \sim 3 \times 10^{26}$ s^{-1}.

2.3. Refractory Mass Inflow Rate

The X-wind model provides a basic framework for incorporating ^{10}Be into CAI precursor materials and subsequently transporting these implanted refractory materials to asteroidal distances (Shu et al. 1994, 1996, 1997). Most inflowing material is accreted onto the star; however, a fraction of this inflowing material may fall out of the flow as solid matter. Alternatively, some material may also drift past the inner region of the disk into the CAI-forming region due to the drag exerted by the more slowly orbiting gas (Shu et al. 1997). Regardless of the specific mechanism, these solids are now located at the inner regions of the disk away from the main funnel flow. It is in this region that solar wind ^{10}Be could be implanted in these solid materials. While the X-wind model provides a conceptual framework for the formation of CAIs, our model only requires the existence of the intersection region between outward flowing solar wind and inward moving CAI precursor materials.

The rate at which this refractory material is carried into this region, called here the refractory mass inflow rate S, is given by

$$S = \dot{M}_{\mathrm{D}} \cdot X_{\mathrm{r}} \cdot F, \qquad (2)$$

where $\dot{M}_{\mathrm{D}}$ is mass accretion rate in solar masses year^{-1}, X_r is the cosmic mass fraction, and F is the fraction of material that enters the x-region (cf. Lee et al. 1998).

Mass accretion rates are not well constrained and likely evolve over time (cf. Calvet et al. 2005; Alexander & Armitage 2006). Calvet et al. (2005) report mass accretion rates ranging from $\sim 10^{-7}$ to $\sim 10^{-10}$ solar masses year^{-1} for young 1–3 Myr T Tauri stars, values similar to those from the models of Alexander & Armitage (2006). Embedded class 0 PMS stars have typical accretion rates of $\sim 10^{-5}$ solar masses and embedded class I PMS stars have typical mass accretion rates of $(1$–$2) \times 10^{-6}$ solar masses year^{-1} (Ward-Thompson 1996). PMS stars may experience a mass accretion of $\sim 10^{-4}$ solar masses year^{-1} during FU Ori outburst (Hartmann 1998). We adopt 1×10^{-7} solar masses year^{-1} for a starting value. This value is at the upper end of the estimates for classes II and III PMS stars and 1–2 orders of magnitude less than that for class I and class II PMS stars, respectively.

Following Lee et al. (1998), we adopt a cosmic mass fraction, X_{r}, and a fraction of refractory material fraction, F, of 4×10^{-3} and 0.01, respectively. The cosmic mass fraction, X_{r}, describes the fraction of the funnel flow comprised of refractory rock and the refractory material fraction, F, describes the fraction of mass that falls out of the accretion flow. $F = 0.01$ is a maximum value and corresponds to all of the refractory mass that comprises the planets dropping out of the accretion funnel flow. Combining these parameters in Equation (2) yields $S = 2.5 \times 10^{14}$ g s^{-1}.

A hallmark of the X-wind model is the outflow of material in the "X-wind" as indicated in Figure 1. After Shu et al. (1997), the location of the x-region may move inward toward the proto-Sun, sweeping up material there and launching this material in the X-wind. The material carried by the X-wind is hypothesized to be sent over the entire solar system with launch distance determined by aerodynamic size sorting; larger bodies fall out of the X-wind and lie relatively close to the x-region and relatively smaller bodies may find their way to comet-forming regions (Shu et al. 1996). Indeed, Brownlee (2008) have discovered apparent CAI material in the comet Wild 2, lending credence to the outflow aspect of the model. Images from the *Hubble Space Telescope* also provide evidence of outflows from PMS stars (cf. www.hubblesite.org). In our model, we assert that the refractory rock material that has been implanted with ^{10}Be is launched via the X-wind.

3. RESULTS

The concentration of ^{10}Be found in refractory rock, in atoms g^{-1}, predicted by our model is given by

$$N^{^{10}\mathrm{Be}} = \frac{P}{S} = \frac{p \cdot f}{\dot{M}_{\mathrm{D}} \cdot X_{\mathrm{r}} \cdot F}, \qquad (3)$$

where P is given atoms s^{-1} and S is given in g s^{-1}. For the stated values of P and S above, we find the concentration of ^{10}Be to be $1.3 \times 10^{12} \pm 0.5 \times 10^{12}$ g^{-1}.

A first-order test of the implantation model is whether it accounts for the concentration of ^{10}Be measured in CAIs. McKeegan et al. (2000) report a ratio of ^{10}Be/^{9}Be $= 9.5 \times 10^{-4}$ in CAIs from Allende; Sugiura et al. (2000) report a ratio of ^{10}Be/^{9}Be of 5.2×10^{-4} for Allende and 6.3×10^{-4} and 7.7×10^{-4} for Efremovka CAIs; and Marhas & Goswami (2003) report a ratio of ^{10}Be/^{9}Be of 8.0×10^{-4} for Murchison and 4.4×10^{-4} for Allende FUN inclusion HAL. We use the value of 9.5×10^{-4} as a baseline value to assess our model. The Be concentrations from several spots of the three samples measured by McKeegan et al. (2000) range from 10 to 7500 ppb; Phinney et al. (1979) obtained comparable values. Leya et al. (2003) adopt a bulk value of 237 ppb for a Be concentration in proto-CAI material. Using CI abundances, Duprat & Tatischeff (2008) calculate a ^{10}Be concentration of 1.58×10^{12} g^{-1} for early solar system material. This latter value may underestimate Be in CAIs as Be is a refractory element and its content in CAIs would be significantly greater than its content in CI meteorites (Gounelle et al. 2001). Assuming a concentration of 100 ppb as an order of magnitude estimate for Be and an initial ^{10}Be/^{9}Be ratio of 9.5×10^{-4}, the measured ^{10}Be concentration in CAIs is 5.5×10^{12} g^{-1}.

While our initial predicted value is a factor of 4 less than the measured value it is nevertheless close enough to warrant a closer inspection of the assumptions going into our model. For many of the parameters that impact the predicted ^{10}Be concentration in CAIs the range of plausible values spans several orders of magnitude. For our proof-of-principle calculation, we selected conservative values for these parameters; however only a small change in any of these would produce quantitative agreement between our prediction and the measured value.

4. DISCUSSION

The success of the implantation model hinges on several issues: can implantation explain the correlation between ^{10}Be and ^{9}Be observed by McKeegan et al. (2000) and others, and does the implantation model account for the concentration of ^{10}Be in CAI material?

The measurements of ^{10}Be by McKeegan et al. clearly indicate that the ^{10}Be is not surface correlated and that it is correlated with stable ^{9}Be. Our model prescribes implantation in fine-grained materials prior to their incorporation into the larger CAIs so we expect the ^{10}Be to be distributed throughout the CAI, much like the ^{9}Be. The textural evidence of CAIs indicates multiple stages of heating, and this processing has been used to explain the correlations between isotopes in CAIs (cf. Gounelle et al. 2001, 2006). Likewise, in our model, the multiple stages of melting and evaporation would homogenize the ^{10}Be from the solar wind with the ^{9}Be.

Figure 2. Logarithm of the effective ^{10}Be outflow rate in the x-region vs. logarithm of the refractory material inflow rate. The model point + represents predicted ^{10}Be concentrations in CAIs of 1.3×10^{12} g^{-1} for the stated model parameters and the gray region indicates a range of plausible values for these parameters. We also plot the set of log P and log S which would lead to the fiduciary ^{10}Be content in CAIs of 5.5×10^{12} ^{10}Be g^{-1}, represented by the line, assuming a bulk Be concentration of 100 ppb and ^{10}Be/^{9}Be ratio of 9.5×10^{-4} reported by McKeegan et al. (2000).

In the implantation model, the factors affecting the concentration of ^{10}Be in CAIs are the effective ^{10}Be outflow rate and the refractory mass inflow rate. Greater ^{10}Be production rates, i.e., more intense flaring or more efficient incorporation of flare-produced ^{10}Be into the CAI-forming portion of the nebula, lead to greater effective ^{10}Be outflow rates and consequently higher ^{10}Be concentrations. Likewise from Equation (3), lower refractory mass inflow rates result in higher ^{10}Be concentrations. Figure 2 illustrates the range of effective ancient ^{10}Be outflow rates plotted against the corresponding necessary refractory mass inflow rate which would lead to the canonical content of 5.5×10^{12} ^{10}Be g^{-1} CAIs. As is evident from this plot there is intersection between plausible mass inflow, ^{10}Be outflow, and the line representing measured ^{10}Be concentrations.

4.1. Effective ^{10}Be Outflow Rate

For our baseline calculation, we assumed a solar proton flux a factor of 4×10^5 higher than the present activity. Based on recent luminosity measurements of T Tauri stars this value seems readily achievable and may even underestimate the likely value. The measurements of Feigelson et al. (2002) and Wolk et al. (2005) are of embedded proto-stars, presumably class 0 or class I. Telleschi et al. (2007) found that X-ray emissions in wTTS are a factor of 2 more than in cTTs stars and Prisinzano et al. (2008) found that class II X-ray emissions are a factor of 2 greater than class I X-ray emissions. An increase over the 4×10^5 level would move the model point in Figure 2 up toward the line and a decrease would correspondingly move it down and away from the line.

For our baseline calculations, we have assumed ^{10}Be production from proton irradiation of ^{16}O. Gounelle et al. (2006) discussed the possibility that a fraction of ^{10}Be produced in the solar nebula was produced by impulsive flares. Thse flares have steep energy spectra and higher ^{3}He/^{1}H ratios. Since the ^{10}Be production rate is dependent upon the proton flux, the energy spectra, and the fraction of ^{3}He, these values may significantly impact the ^{10}Be production rate. In particular, the cross section for the reaction ^{16}O(^{3}He, x)^{10}Be (cf. Gounelle et al. 2006) is more favorable for the production of ^{10}Be than for the proton-induced reaction. Substantial production via this pathway would increase ^{10}Be production rates, effectively increasing ^{10}Be concentrations in CAIs.

The most difficult parameter to constrain is the fraction of ^{10}Be that impacts the disk, f. Given the complex nature of the magnetic field geometry in the region, it is difficult to ascertain the precise fraction of ^{10}Be solar wind ions that would hit the disk. For our baseline calculation we adopted 0.1, based on Feigelson et al. (2002), likely a lower limit. Increasing this value moves our baseline estimate up in Figure 2 toward the line of canonical ^{10}Be concentration.

Romanova & Lovelace (2006) find that a T Tauri star with an appreciable dipole magnetic component may develop a low-density magnetospheric gap, which allows for the potential survival of planets in that region or the accretion flow may proceed through the equatorial region; each scenario is dependent upon reasonable input parameters. Similarly, Gregory et al. (2006) model mass accretion on T Tauri stars and find that magnetic field geometry has a significant effect on funnel flow hot-spot location. Donati et al. (2007) model the magnetic topography of the cTTS star V2129 Oph and find high-latitude accretion spots. It is plausible that a low-density region free of accretion flow onto the proto-Sun existed. Indeed, this region may be necessary for the survival of planets <5 AU from the Sun. ^{10}Be produced in solar flares close to the Sun would therefore escape the main accretion flows of material onto the Sun and perhaps become implanted in CAI precursor dropping out of the funnel flow onto the star.

4.2. Refractory Mass Inflow Rate

Critical parameters affecting the refractory mass inflow rate are the mass accretion rate of the PMS star and the fraction of mass suitable for CAI formation, as detailed by Equation (2).

For PMS stars, estimates for the mass accretion rate, M_D, span 6 orders of magnitude, ranging from $\sim 10^{-4}$ solar masses year^{-1} for FU Ori outbursts to down to $\sim 10^{-10}$ solar masses year^{-1} for more evolved class III PMS stars. We based our initial estimates on the values of Calvet et al. (2005), who report mass accretion rate ranges from $\sim 10^{-7}$ to $\sim 10^{-10}$ solar masses year^{-1} for young 1–3 Myr T Tauri stars. Our baseline mass accretion rate is 10^{-7} solar masses year^{-1}. A lower mass accretion rate, in the range of 10^{-8} to 10^{-10} solar masses year^{-1}, typical of more evolved PMS stars, would move the ^{10}Be concentration in CAIs as shown in Figure 2 to the left, toward the line representing ^{10}Be measured concentration in CAIs. On the other hand, class 0 and class I PMS stars have mass inflow rates larger than $\sim 10^{-7}$ solar masses year^{-1}, which would move the model point in Figure 2 away from the line representing 5.5×10^{12} ^{10}Be g^{-1}.

Following Lee et al. (1998), we chose $F = 0.01$ for the fraction of mass suitable for CAI. A lower value is physically possible, thereby decreasing the refractory mass inflow rate, moving the model to higher concentrations of ^{10}Be found in CAIs and toward the line in Figure 2. The calculation of F from first principles is not possible, but our selection of $F = 0.01$ is an upper limit to the true value; F could be smaller by a factor of 20. (cf. Lee et al. 1998).

4.3. ^7Be

Chaussidon et al. (2006) have detected ^{7}Be in CAIs from Allende. They report a ^{7}Be/^{9}Be ratio of 6.1×10^{-3}. Spallation-produced ^{7}Be decay has also been detected in the photospheres of stars (Mandzhavidze et al. 1997). This radionuclide could be entrained in the solar wind as well. The production rate ratio of ^{7}Be/^{10}Be in the early solar system from MeV energetic protons is estimated to be about 100 (Leya et al. 2003), yet the measured ratio ^{7}Be/^{10}Be is about 5. A simple in situ irradiation model has difficulty accounting for the difference in production ratio of ^{7}Be/^{10}Be and the measured ^{7}Be/^{10}Be measured ratio, although Gounelle et al. (2006) assert that their model satisfactorily reproduces the correct ratio of ^{7}Be/^{10}Be. Considering the half-life of ^{7}Be, 53 days, a delay of 100 days from the time of production of ^{7}Be to the time of incorporation in CAIs via the implantation model would produce a measured ratio ^{7}Be/^{10}Be of about 5.

Confirmation of the presence of ^{7}Be in CAIs would buttress the hypothesis that these isotopes were produced locally. Given the large difference in half-lives of these two isotopes of Be, variations in the ^{7}Be/^{10}Be ratio in primitive materials may serve as a chronometer for processes occurring in the CAI-forming region of the solar nebula.

4.4. Other Radioactivities

It is well known that evidence exists for the inclusion of other short-lived radionuclides in CAIs. This partial list includes ^{26}Al, ^{36}Cl, ^{41}Ca, ^{53}Mn, ^{60}Fe, and ^{7}Be (Chaussidon & Gounelle 2007). It is tempting to ascribe all the radioactivities seen in the early solar system to a single mechanism; however, so far no single mechanism can explain the array of isotopic effects seen in meteorites. Our purpose in this work is to explore the possibility that the mechanism observed by Nishiizumi & Caffee (2001), operable today, may also have produced ^{10}Be excesses in the early solar system. With the exception of ^{60}Fe, the other radionuclides could be produced through solar energetic particle (SEP) reactions in the same manner as ^{10}Be; future work will consider these other radionuclides.

5. SUMMARY

The provenance of ^{10}Be anomalies is one of the most perplexing unresolved questions in the study of primitive meteoritic materials. While several models have been proposed to date there is no consensus on the means by which this radionuclide was incorporated into CAIs. We propose that ^{10}Be was made in the early solar system but that it was not created within the CAIs. We assert that the radionuclides were produced in the ancient solar atmosphere through spallation reactions with SEPs and that these radionuclides flowed outward from the photosphere in the ancient solar wind and were incorporated into inflowing CAI precursor material. One possible setting for such a scenario is the x-region in an X-wind model of solar system evolution. From the rate of production of radionuclides in the ancient solar atmosphere and the inflow rate of precursor CAI material, we calculate the ^{10}Be concentration expected in CAI precursor material. Several parameters are involved in calculating the ^{10}Be content in CAIs with the implantation model. These parameters are themselves difficult to quantify; however we have selected values that are generally conservative in that deviations generally increase ^{10}Be concentrations, and fall within the values found in the literature.

Figure 3. Production rate of ^{10}Be from the spallation reaction of energetic protons on an O target of solar abundance. We assume a differential SEP flux power-law relationship, $\frac{dF}{dE} = KE^{-p}$, where p goes from 2.5 to 4 and the proton flux for $E > 10$ MeV is of order 100 protons cm^{-2} s^{-1} at 1 AU.

A plausible parameter set for the implantation model which produces the ^{10}Be content found in CAIs is $f = 0.1$, ^{10}Be production enhancement over contemporary levels of 4×10^5, $\dot{M}_D = 1 \times 10^{-7}$–$5 \times 10^{-8}$ solar masses year^{-1}, and $f < 0.01$. The mass accretion given here is not typical of classes 0 or I PMS stars, indicating that ^{10}Be implantation occurred during the cTTS phase. A chronology does not exist for CAI formation, but for the implantation model to be viable with this set of parameters, formation must have occurred when the mass inflow rate was that of a cTTS star. It has also been shown by Prisinzano et al. (2008) that class II X-ray emissions are a factor of 2 greater than class I X-ray emissions; taken together with the measurements of Wolk et al. (2005), the choice of 4×10^5 enhancement in SEP over contemporary levels is appropriate.

APPENDIX

CONTEMPORARY PRODUCTION OF ^{10}BE IN THE SOLAR PHOTOSPHERE

The production rate for cosmogenic nuclides (s^{-1}) is given by

$$P = \sum_i N_i \sum_j \int \sigma_{ij}(E) \frac{dF(E)}{dE_j} dE, \qquad (A.1)$$

where i represents the target elements for the production of the nuclide, N_i is the abundance of target element, j indicates the energetic particles that cause the reaction, $\sigma_{ij}(E)$ is the thin cross section for the production of nuclide from the interaction of particle j at energy E from target i for the reaction, and $\frac{dF(E)}{dE_j}$ is the differential energetic particle flux of particle j at energy E (Reedy & Marti 1991). We assume a thin gaseous target of solar composition with an O composition of 1.413×10^7 per 1.00×10^6 Si atoms (Lodders 2003), where the density of the photosphere is 1×10^{-7} g cm^{-3} (Robitaille 2006).

The reaction cross section is taken from the measurements of Sisterson et al. (1997). For the contemporary Sun, we assume an energetic proton flux of $\sim$100 protons cm^{-2} s^{-1} for

E >10 MeV at 1 AU (Reedy & Marti 1991), corresponding to 9.3×10^6 protons cm^{-2} s^{-1} at the surface of the Sun. We ignore any production from secondary neutrons, which may be produced from the primary reaction. We calculate the ^{10}Be production rate assuming that the protons are characterized by a power-law relationship: $\frac{dF}{dE} = KE^{-p}$ where p ranges from 2.5 to 4. From the production rate, we find the flux rate by dividing the production rate by the surface area of the Sun, 6.15×10^{22} cm^2. The production rate flux of ^{10}Be from energetic protons is shown in Figure 3. It is known that the energetic particle flux and spectral index experience both short- and long-term variations (cf. Nishiizumi et al. 2009). A rigorous calculation of the ^{10}Be flux for the last several Myr is not feasible without a detailed reconstruction of the solar energetic particle fluxes and spectra over the last several Myr. Using values within the range seen for contemporary solar flares reproduces the values reported in Nishiizumi & Caffee (2001) of 0.13 ± 0.05 ^{10}Be cm^{-2} s^{-1} for $p \sim 3.2$.

REFERENCES

Alexander, R. D., & Armitage, P. J. 2006, ApJ, 639, L83
Brownlee, D. 2008, Phys., Today, 61, 30
Caffee, M. W., Hohenberg, C. M., Swindle, T.D., & Goswami, J. N. 1987, ApJ, 313, L31
Calvet, N., Briceno, B., Hernandez, J., Hoyer, S., Hartmann, L., Sicila-Aguilar, A., Megeath, S. T., & D'Alessio, P. 2005, AJ, 129, 935
Chaussidon, M, & Gounelle, M. 2007, C.R. Geoscience, 339, 872
Chaussidon, M., Robert, F., & McKeegan, K.D. 2006, Geochim. Cosmochim. Acta, 70, 224
Choi, M., Hamaguchi, K., & Lee, J. 2008, ApJ, 687, 406
Desch, S. J., Srinivasan, G., & Connolly, H. C. 2003, Lunar Planet Sci. Conf., 34, 1394
Donati, J. F., et al. 2007, MNRAS, 380, 1297
Donati, J. F., et al. 2008, MNRAS, 386, 1234
Dullemond, C., Hollenbach, D., Kamp, I., & D'Alesio, P. 2006, in Protostars and Protoplanets V, ed. P. Reiperth, D. Jewitt, & K. Keil (Tucson, AZ: Univ. Arizona Press)
Duprat, J., & Tatischeff, V. 2008, New Astron., Rev., 52, 463
Feigelson, E. D., Garmire, G. P., & Pravdo, S. H. 2002, ApJ, 572, 335
Getman, K., Feigelson, E., Broos, P., Micela, G., & Garmire, G. 2008a, ApJ, 688, 418
Getman, K., Feigelson, E., Broos, P., Micela, G., & Garmire, G. 2008b, ApJ, 688, 437
Getman, K., Feigelson, E., Garmire, G., Broos, P., & Wang, J. 2007, ApJ, 654, 316
Giardino, G., Favata, F., Micela, G., Sciortino, S., & Winston, E. 2007, A&A, 463, 275
Goswami, J. N., Marhas, K. K., & Sahijpal, S. 2001, ApJ, 549, 1151
Gounelle, M., Chaussidon, M., & Montmerle, T. 2007, C.R. Geoscience, 339, 885
Gounelle, M., Shu, F. H., Shang, H., Glassgold, A. E., Rehm, K. E., & Lee, T. 2001, ApJ, 548, 1051
Gounelle, M., Shu, F. H., Shang, H., Glassgold, A. E., Rehm, K. E., & Lee, T. 2006, ApJ, 640, 1163
Gregory, S. G., Jardine, M., Simpson, I., & Donati, J. F. 2006, MNRAS, 371, 999
Grimberg, A., et al. 2006, Science, 314, 1133
Hamaguchi, K., Corcoran, M., Petre, R., & White, N. 2005, ApJ, 623, 291
Hartmann, L. 1998, Accretion Processes in Star Formation (Cambridge: Cambridge Univ. Press)
Hartmann, L., Calvert, N., Gulbring, E., & D'Alessco, P. 1998, ApJ, 495, 385
Jaeger, M., Wilmes, S., Kölle, V., Staudt, G., & Mohr, P. 1996, Phys. Rev. C, 54, 423
Jardine, M., Gregory, S. G., & Donati, J.-F. 2007, in IAU Symp. 243, Star Disk Interaction in Young Stars, ed. J. Bouvier & I. Appenzeller (Cambridge: Cambridge Univ. Press), 51
Johns-Krull, C. M. 2008, in IAU Symp. 259, Cosmic Magnetic Fields: From Planets, to Stars and Galaxies, ed. K. G. Strassmeier, A. G. Kosovichev, & J. E. Beckman (Cambridge: Cambridge Univ. Press), 345
Jull, A. J. T., Lal, D., & Donahue, D. J. 1995, Earth Planet. Sci. Lett., 136, 693
Lang, B. 2001, Encyclopedia of the Sun (Cambridge: Cambridge Univ. Press)
Lee, T., Shu, F. H., Glassgold, A. E., & Rehm, K. E. 1998, ApJ, 506, 898
Leya, I., Wieler, R., & Halliday, A. N. 2003, ApJ, 594, 605
Lodders, K. 2003, ApJ, 591, 1220
Long, M., Romanova, M. M., & Lovelace, R. V. E. 2008, MNRAS, 386, 1274
Liu, C., & Wang, H. 2009, ApJ, 696, L27
Mandzhavidze, N., Ramaty, R., & Kozlovsky, B. 1997, ApJ, 489, L99
Marhas, K. K., & Goswami, J. N. 2003, Lunar Planet. Sci. Conf., 34, 1303
Marhas, K. K., & Goswami, J. N. 2004, New Astron. Rev., 48, 139
Marhas, K. K., Goswami, J. N., & Davis, A. M. 2002, Science, 298, 2182
McKeegan, K. D., Chaussidon, M., & Robert, F. 2000, Science, 289, 1334
Nishiizumi, K., Arnold, J. R., Kohl, C. P., Caffee, M. W., Masarik, J., & Reedy, R. C. 2009, Geochim. Cosmochim. Acta, 73, 2163
Nishiizumi, K., & Caffee, M. W. 2001, Science, 294, 352
Nishiizumi, K., Imamura, M., Caffee, M. W., Southon, J. R., Finkel, R. C., & McAninch, J. 2007, Nucl. Instrum. Methods Phys. Res. B, 258, 403
Phinney, D., Whitehead, B., & Anderson, D. 1979, Proc. Lunar Planet Sci. Conf., 10, 885
Preibisch, T., & Feigelson, E. 2005, ApJS, 160, 390
Prisinzano, L., et al. 2008, ApJ, 677, 401
Robitaille, P. 2006, Progress Phys., 2, 17
Reedy, R. C., & Marti, K. 1991, in The Sun in Time, ed. C. P. Sonnet, M. S. Giampapa, & M. S. Mathews (Tucson, AZ: Univ. Arizona Press), 260
Romanova, M. M., & Lovelace, R. V. E. 2006, ApJ, 645, L73
Shu, F. H., Nojita, J., Ostriker, E., Wilken, F., Ruden, S., & Lizano, S. 1994, ApJ, 429, 781
Shu, F. H., Shang, H., Glassgold, A. E., & Lee, T. 1997, Science, 277, 1475
Shu, F. H, Shang, H., & Lee, T. 1996, Science, 271, 1545
Sisterson, J. M., et al. 1997, Nucl. Instrum. Methods Phys. Res. B, 123, 324
Stelzer, B., et al. 2007, A&A, 468, 463
Sugiura, N., Shuzou, Y., & Ulyanov, A. A. 2000, Meteorit. Planet. Sci., 35, A154
Telleschi, A., Guedel, M., Briggs, K. R., Audard, M., & Palla, F. 2007, A&A, 468, 425
Ward-Thompson, D. 1996, Ap&SS, 239, 151
Wolk, S. J., Harnden, F. R., Flaccomio, E., Micela, G., Favata, F., Shang, H., & Feigelson, E. D. 2005, ApJS, 160, 423
Wolk, S. J., Spitzbart, B. D., & Bourke, T. L. 2006, AJ, 132, 1100