AN INTERSTELLAR ORIGIN FOR THE BERYLLIUM 10 IN CAIS. S. J. Desch, *Department of Terrestrial Magnetism, Washington DC, USA (desch@dtm.ciw.edu)*, G. Srinivasan, *Physical Research Laboratory, Ahmedabad, India (srini@prl.ernet.in)*, Harold C. Connolly, Jr., *Kingsborough College, Brooklyn NY, USA (HConnolly@kbcc.cuny.edu), Rutgers University, Piscataway NJ, USA, American Museum of Natural History, New York NY, USA.*

Background: Excesses of ^{10}B have been correlated with beryllium content in calcium-aluminum-rich inclusions (CAIs), showing that the objects incorporated the short-lived ($t_{1/e} = 2.18$ Myr) radionuclide ^{10}Be when they formed [1-5]. The "canonical" ^{10}Be / ^{9}Be ratio has been taken to be 9×10^{-4} [1]. Of the 16 CAIs and three hibonite residues [6] measured to date, all are within a factor of 2 of this value, and only one CAI [5] exceeds this value significantly. We also adopt this canonical ratio, although an initial ratio twice as large is suggested by some of the data [3,5].

Because ^{10}Be decays on Myr timescales, it must have formed just prior to the formation of the solar system; therefore it potentially can constrain models of solar system formation. While production in stellar explosions has been suggested [7,8], abundant beryllium production apparently requires energetic spallation reactions between C, N or O nuclei and H or He nuclei. If production outside the solar system could be ruled out, then spallation would have to occur within the solar nebula, in an environment such as proposed in the 'X-wind" model [9,10]. Indeed, ^{10}Be has been cited as the "smoking gun" proving the existence of energetic particles within the solar nebula, implicating the X-wind model [10]. This significance of ^{10}Be for solar nebula irradiation models hinges entirely on whether production of ^{10}Be outside of the solar nebula can be ruled out.

Two analyses have sought to rule out production of ^{10}Be by galactic cosmic ray (GCR) spallation. Gounelle et al [10] used a simplistic model to compute the evolution of ^{10}Be and ^{9}Be over Galactic history. They recognized a central difficulty with this approach: the abundance of ^{9}Be depends on the entire Galactic history, but the ^{10}Be abundance is sensitive only to the previous ≈ 5 Myr. If the GCR flux were to increase by a factor of 6 in the few Myr prior to solar system formation (relative to the GCR flux of the previous 8 Gyr), the Gounelle et al [10] model would explain the meteoritic ratio. McKeegan et al [1] adopted a more robust approach, estimating a steady-state ratio based on the known abundance of ^{9}Be, an assumed production rate of ^{9}Be in the Galaxy from cosmic rays, and a production ratio ^{10}Be / ^{9}Be ≈ 0.1. They compute ^{10}Be / ^{9}Be $\approx 8 \times 10^{-6}$, only 1 % of the canonical ratio. We find the ^{10}Be production rate is 9 times greater than this, but still we concede that the increases in the GCR flux just prior to solar system formation, by about one order of magnitude, are required for direct reactions to account for the meteoritic ^{10}Be / ^{9}Be ratio. On this basis, GCRs have been rejected as the source of ^{10}Be.

An interstellar origin for the ^{10}Be in CAIs has been ruled out prematurely. In this abstract, we describe calculations of the contribution to the solar system ^{10}Be from GCRs. We find that the dominant contribution to ^{10}Be in the solar nebula was from ^{10}Be cosmic rays that were stopped in the molecular cloud core from which our solar system formed. The total contribution of GCRs, direct reactions plus trapping, yields a ratio ^{10}Be / ^{9}Be $\approx 3.2 \times 10^{-4}$, only a factor of 3 below the canonical ratio. Moreover, we show that an increase in the GCR flux 4.5 Gyr relative to today of 2-3 is likely, and estimate the initial ratio in the solar nebula to have been ^{10}Be / ^{9}Be $\approx 8 \times 10^{-4}$. Contributions to ^{10}Be from GCRs should not be ruled out, and they may be the sole source of ^{10}Be in the solar nebula. We discuss this conclusion and its implications.

Calculation: For the present-day GCR flux in the solar neighborhood, we adopt the proton flux derived from Voyager and Pioneer measurements at 60 AU [11]. For kinetic energies per nucleon E in the range 10 MeV/n $< E <$ 4 GeV/n, we fit the interstellar proton flux shown in Figures 2 and 4 to within 10 % using: $F_p = 9.6 \times 10^4\,(E + 850)^{-2.6}$ cm^{-2} s^{-1} sr^{-1} (MeV/n)$^{-1}$, where E is in MeV/n. The ionization rate derived from this flux is consistent with the rates observed in molecular cloud cores within several hundred pc today [12]. Uncertainties in the derived flux by factors of 2 exist, and the flux can vary over kpc scales in the Galaxy by factors of 2 [12]. For the composition of the cosmic rays, we adopt ratios He/H $= 0.074$ and CNO/H $= 0.0023$ from Figure 4 [11], C/CNO $= 0.45$ from [13] and other sources, Be/C = 0.055 at low energies from [14], and ^{10}Be/Be $= 0.08$ from [14,15]. We have multiplied by an additional factor of 0.8 to account for decreased metallicity 4.5 Gyr ago. Because all of these ratios are applicable at low (~ 100 MeV/n) energies, the flux of ^{10}Be nuclei should lie within tens of percent of $4.6 \times 10^{-6}\,F_p$. We multiply these fluxes by 4π steradians, because magnetic mirroring and focusing in molecular cloud cores do not affect the flux [16]. As GCRs pass through a cloud core, they lose energy ionizing the gas and are slowed. Using equation 2 of [17], we calculate the minimum kinetic energy per nucleon E_c that a ^{10}Be GCR must have if it is to penetrate a column density Σ. At early times in the collapse, when $\Sigma = 0.01$ g cm^{-2}, $E_c \approx 5$ MeV/n, while at later times, when $\Sigma = 0.25$ g cm^{-2}, $E_c \approx 30$ MeV/n. Approximately 1 % of all ^{10}Be GCRs have $E < E_c$ and are stopped.

As for direct reactions, we adopt solar ratios of CNO nuclei as follows: C/H $= 2.45 \times 10^{-4}$, N/H $= 8.5 \times 10^{-5}$ and O/H $= 4.9 \times 10^{-4}$ [18], and x_{Be9} = Be/H $= 2.6 \times 10^{-11}$ [19]. For the cross sections for ^{10}Be-producing reactions between GCR protons and α particles and cloud core CNO nuclei, we use the semi-empirical formulae of [15], using the parameters of Table 7 for proton reactions, which dominate by a factor of 5 over α reactions. For lack of better data, we adopted constant cross sections above threshold of 5 mb for all α reactions, which probably overestimates our final ratio by a few percent. By integrating the energy-dependent flux over the energy-dependent cross sections, and summing over all possible combinations of proton and α collistions with CNO nuclei, we derive a rate at which ^{10}Be nuclei are produced per H atom of $R_{direct} \approx 2.7 \times 10^{-29}$ s^{-1}, about 10 times greater than the rate assumed by [1]. The ^{10}Be so produced have very low energies, $<$ 10 MeV/n [20], and are easily retained in the cloud core.

Within the cloud core the rate of change of the ratio is $d/dt(^{10}\mathrm{Be}/^{9}\mathrm{Be}) = [F_{Be10}(E < E_c)1.4m_H/\Sigma(t) + R_{direct}]$ $/x_{Be9} - (^{10}\mathrm{Be}/^{9}\mathrm{Be})/t_{1/e}$. Trapping of ^{10}Be GCRs will dominate, so it is important to calculate $\Sigma(t)$, the column density of the cloud core as a function of time. We use the magnetic cloud core collapse model of Desch and Mouschovias [21], in which magnetic fields retard collapse for several Myr while $\Sigma \approx 0.01$g cm^{-2}. When column densities reach about 0.02g cm^{-2}, as a result of ambipolar diffusion, magnetic fields can not longer prevent dynamic collapse, which then proceeds on roughly the free-fall timescale. These primary characteristics of the model match observations [22] well. We integrate $d/dt(^{10}\mathrm{Be}/^{9}\mathrm{Be})$ over time and find the following results.

The steady-state ratio from direct reactions is 0.7×10^{-4}, while the nearly constant ratio from trapped ^{10}Be GCRs is 2.5×10^{-4}. Together, using the GCR flux in the solar neighborhood today, we would predict ^{10}Be / ^{9}Be $= 3.2 \times 10^{-4}$, with factor-of-two uncertainties because of the lack of knowledge about the GCR flux beyond 1 kpc from the Sun, and lack of good data on the GCR flux at low energies ($\sim$ 10 MeV/n). Additionally, we note that many models of LiBeB galactic evolution must assume a GCR flux that was much higher 4.5 Gyr ago than today's flux by factors $\mathcal{F} = 2.1$ [23] and $\mathcal{F} = 2.9$ [24]. This is corroborated by models of star formation history in the Galaxy, which identify a burst in star formation around the epoch in which the Sun formed [25]. Star formation rates (which the GCR flux is proportional to) at least 1.5 times higher 4.5 Gyr ago seem likely, and rates much higher are possible [25]. We adopt $\mathcal{F} = 2.5$ and estimate ^{10}Be / ^{9}Be $= 8 \times 10^{-4}$, with uncertainties of a factor of two or more.

Conclusions: We now enumerate some implications of our finding that, to within a factor of two uncertainties, the ^{10}Be / ^{9}Be ratio in CAIs is entirely accounted for by contributions from galactic cosmic rays. First, because ^{10}Be is produced in the molecular cloud core stage, we expect its distribution to be fully spatially homogeneous. All primitive objects (e.g., CAIs) formed at the birth of the solar system should share a common ^{10}Be / ^{9}Be ratio. This is supported by the tight ($<$ factor of 4) range of values observed in CAIs and hibonites, and by the fact that in no CAI which has been searched has ^{10}Be been shown to have been absent.

Second, production of ^{10}Be is decoupled from ^{26}Al and ^{41}Ca. We estimate ratios ^{26}Al / ^{27}Al $< 10^{-8}$ and ^{41}Ca / ^{40}Ca $< 10^{-13}$, orders of magnitude below their canonical values in CAIs. We attribute the origin of these short-lived radionuclides to other processes, such a supernova injection, that occurred after the solar nebula began its evolution. This decoupling is supported by the lack of observable ^{26}Al in the FUN inclusion Axtell 2771 [3] and the Murchison hibonites [6], both of which have canonical ^{10}Be.

Third, production of ^{10}Be is decoupled from production of the CAIs themselves. Significantly, we allow for formation of CAIs in a solar-composition gas, since we do not invoke coproduction of ^{10}Be with the other short-lived radionuclides. We note that petrographic and geochemical evidence, from REE abundances, Ti^{+3}/Ti^{+4} ratios in clinopyroxene, hibonites, FeNi oxide and sulfide assemblages [26], and vanadium valence states [27] all constrain the oxygen fugacity in the environment in which CAIs formed, and in which their precursors condensed, to be near solar. These constraints are violated by the X-wind model [9,10], in which CAI precursors condense in an environment 10^{6} times more oxidizing than solar. If we were to restore the C, N and O in the X-wind environment to their solar proportions, production of ^{10}Be would be increased by a factor of 4. Coproduction of ^{26}Al and ^{41}Ca would be much more difficult under these circumstances.

Fourth, because ^{10}Be is homogenized in the cloud core, we identify the Be-B system as an excellent chronometer of early solar nebula events. As an example, we can attribute the spread in ^{10}Be / ^{9}Be ratios among CAIs to decay of ^{10}Be for different lengths of time before isotopic closure. The maximum time interval implied, between CAIs Efremovka E54 [1] and E65 [5], is then 3.0 $\pm$ 1.3 Myr. These CAIs are both igneous type B CAIs, implying that they were melted by a heating event similar to that which melted the chondrules [28]. We note that a similar time duration based on U-Pb systematics, between melting of Allende and Efremovka CAIs and Acfer 059 chondrules, is remarkably similar: 2.7 $\pm$ 1.1 Myr [29]. The use of Be-B systematics as a chronometer is consistent with other work that shows a 3 Myr spread in CAI/chondrule ages.

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