Probing Cosmic Ray Origin With Beryllium and Boron

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Abstract

The propagation of cosmic rays through the interstellar medium (ISM) inevitably produces LiBeB nuclei, and the accumulation of these elements over lifetime of galaxy can broadly account for the solar LiBeB abundances. Furthermore, data in old (Population II) stars provides crucial new information: the LiBeB trend versus heavy element abundances traces the Galactic evolution of LiBeB. We summarize the results a careful analysis of the trends among Be, B, Fe, and O. We show that if O/Fe is not constant, as recent data suggest, then the data are consistent with a "standard" cosmic ray origin, wherein the abundances of cosmic ray primaries scale with those of the ISM. On the other hand, if O/Fe is constant, some other cosmic ray origin or component is needed. We suggest future observational tests which will distinguish several recent scenarios of LiBeB and cosmic ray origin.

1 Introduction:

Beryllium and Boron (as well as ^{6}Li) are the orphans of nucleosynthesis. ^{7}Li is made in the big bang, but ^{6}Li, Be, or B (hereafter ^{6}LiBeB) are not produced in any significant quantity. Nor are ^{6}LiBeB made in stars: these nuclei are all weakly bound, and are burned at moderate stellar temperatures; thus stars destroy rather than produce ^{6}LiBeB. Reeves, Fowler, & Hoyle (1970) first realized that LiBeB find their origin in cosmic ray interactions (both spallation and $\alpha + \alpha$ fusion) with interstellar medium (ISM) nuclei. Indeed, LiBeB production inevitably accompanies cosmic ray propagation; Reeves, Fowler, & Hoyle showed that the accumulation of LiBeB by this mechanism is sufficient to broadly explain the solar ^{6}LiBeB abundances.

In the past decade this connection between cosmic rays and LiBeB has been pushed further, as the *evolution* of LiBeB abundances can reveal the origin and history of the cosmic rays that produced them. Namely, ^{6}LiBeB abundances have been measured in many young (Population I) disk stars and old (Population II) halo stars in our Galaxy. The ^{6}LiBeB abundances are thus measured as a function of stellar metallicity. Since stars monotonically increase the Galactic metal abundance, the LiBeB data at low metallicity ($[\mathrm{Fe/H}] \leq -1$)[1] provides unique information about cosmic ray evolution the early Galaxy. In fact, the expected ^{6}LiBeB evolution is simple, once one adopts a model for cosmic ray origin. In what we term the standard model, Galactic cosmic rays (GCRs) are accelerated by supernovae, with a composition that traces that of the ISM. Thus the cosmic ray flux $\Phi \propto \dot{N}_{\mathrm{SN}}$, the Type II supernova rate; since supernovae also produce heavy elements such as oxygen, $\Phi \propto d\mathrm{O}/dt$. These cosmic rays spall the "target" nuclei CNO, which in the early Galaxy are dominated by oxygen. Thus we have the production rate $d\mathrm{Be}/dt \sim \mathrm{O}\ \sigma_{p\mathrm{O}\rightarrow\mathrm{Be}}\ \Phi \propto \mathrm{O}\ d\mathrm{O}/dt$. This integrates to the predicted scaling with the heavy element O: $\mathrm{Be} \propto \mathrm{O}^2$, a quadratic dependence. We thus refer to Be and B evolution in this picture as "secondary," since the production rate depends on abundance of the "seed" nucleus O. This standard model prediction is however in apparent contradiction with the abundance data: a roughly linear scaling ("primary" evolution) is observed between Be and iron (also a metal indicator). This discrepancy has been interpreted as incompleteness or outright failure of the standard cosmic ray picture.

A partial resolution of this problem comes from the so-called ν-process, whereby ^{11}B is made by neutrino spallation in the carbon shells of supernovae (Woosley et al. 1990). However, this process makes only ^{11}B, so many authors have presented new cosmic ray models (Ramaty et al. 1997; Vangioni-Flam et al. 1998) designed to reproduce the observed roughly linear BeB-Fe relation. Here, however, we summarize our suggestion that problem may instead arise from a confounding of the BeB-Fe and BeB-O slopes (Fields & Olive 1999a).

[1]Using the notation $[A/B] = \log_{10}(A/B) - \log_{10}(A/B)_\odot$. Thus $[\mathrm{Fe/H}] = -1$ implies Fe/H = $10^{-1}(\mathrm{Fe/H})_\odot$.

Table 1: Pop II logarithmic slopes for Be and B versus Fe and O

metal tracer	method	metallicity range	Be slope	B slope	B/Be slope
Fe/H	Balmer	$-3 \leq [\mathrm{Fe/H}] \leq -1$	1.21 ± 0.12	0.65 ± 0.11	-0.18 ± 0.15
O/H	Balmer	$-2.5 \leq [\mathrm{O/H}] \leq -0.5$	1.76 ± 0.28	1.84 ± 0.58	-0.81 ± 0.44
Fe/H	IRFM	$-3 \leq [\mathrm{Fe/H}] \leq -1$	1.30 ± 0.13	0.77 ± 0.13	0.01 ± 0.14
O/H	IRFM	$-2.5 \leq [\mathrm{O/H}] \leq -0.5$	1.38 ± 0.19	1.35 ± 0.30	0.00 ± 0.17

That is, if the O/Fe ratio is constant in the early Galaxy, then indeed the BeB-Fe data is indicative of primary BeB-O, driving the need for a new or augmented picture of cosmic ray origins. However, new data suggests that O/Fe is *not* constant. Furthermore, the observed O/Fe variation may allow for secondary Be and primary B. As a result, one may explain LiBeB evolution with just standard GCRs and the ν-process(Fields & Olive 1999a). Fortunately, this scenario can be readily distinguished from others invoking new cosmic ray origins, as discussed in §4.

2 Abundance Data

We will focus here on Be and B; a detailed discussion of ^{6}Li may be found in Fields & Olive (1999b). To model LiBeB evolution, one needs accurate abundance data. In turn, to infer abundances from measured line profiles requires the use of stellar atmospheric models. To get accurate BeB trends versus metal indicators, it is essential to use a uniform data set. The abundances must be derived using consistent assumptions, that is, a set of stellar parameters derived in same way. In the literature, more than one method exists for determining stellar parameters, giving qualitatively similar but quantitatively different results. Here, we will present results for data which uniformly use stellar parameters derived via (1) the infra-red flux method (IRFM) and (2) Balmer lines. For further details, see Fields & Olive (1999a) and references therein. Slopes for BeB-Fe appear in Table 1.

The BeB-Fe slopes are commonly quoted, but do not directly indicate BeB origin since O and not Fe is the spallation target. Iron acts as a (more easily measured) surrogate. It has commonly been claimed that Pop II stars show that O/Fe is constant, in which case the O-Fe distinction is not important in determining Be and B origin. However, recent studies of oxygen abundances in Pop II (Israelian, García-López, & Rebolo 1998; Boesgaard, King, Deliyannis, & Vogt 1999) claim that O and Fe are *not* simply proportional. Namely, O/Fe *increases* towards low metallicities. In particular, $[\mathrm{O/Fe}] = \omega_{\mathrm{O/Fe}}[\mathrm{Fe/H}] + const$, where the O/Fe log slope $\omega_{\mathrm{O/Fe}} = -0.31$. Variations in O/Fe directly impact our interpretation of the BeB data, as follows.

3 BeB Slopes and Cosmic Ray Nucleosynthesis

3.1 Phenomenological Analysis Motivated by the Israelian et al. (1998) results, we henceforward will allow O/Fe to vary in Pop II, and will explore the consequences of this variation. Thus, we will put $\omega_{\mathrm{O/Fe}} \neq 0$, which means that

$$[\mathrm{O/H}] = [\mathrm{O/Fe}] + [\mathrm{Fe/H}] = (1 + \omega_{\mathrm{O/Fe}})[\mathrm{Fe/H}] + \mathrm{const} \tag{1}$$

Consider the evolution of nuclide $\mathcal{A} \in \mathrm{LiBeB}$. Since O/Fe varies, the slopes $\omega_{\mathcal{A}\mathrm{O}}$ and $\omega_{\mathcal{A}\mathrm{Fe}}$ will differ. In particular, up to an additive constant, $[\mathcal{A}] = \omega_{\mathcal{A}\mathrm{O}}(1 + \omega_{\mathrm{O/Fe}})[\mathrm{Fe/H}]$ which means that the O and Fe slopes are related by

$$\omega_{\mathcal{A}\mathrm{Fe}} = \omega_{\mathcal{A}\mathrm{O}}(1 + \omega_{\mathrm{O/Fe}}) \tag{2}$$

Consider the case in which $\mathcal{A}$ is primary versus O, so that $\omega_{\mathcal{A}\mathrm{O}} \equiv 1$. Substituting the Israelian et al. (1998) O/Fe slope in eq. (3) gives

$$\omega_{\mathcal{A}\mathrm{Fe}} = 1 + \omega_{\mathrm{O/Fe}} = 0.69 \pm 0.11 \tag{3}$$

Note that this is nearly the same as B-Fe slope determinations in Table 1. Furthermore, we see that a changing O/Fe slope requires that primary elements (vs O) must have slope vs Fe *less than 1*.

On the other hand, consider the case of $\mathcal{A}$ secondary versus O, so that $\omega_{\mathcal{A}\mathrm{O}} \equiv 2$. Now eq. (3) gives

$$\omega_{\mathcal{A}\mathrm{Fe}} = 2(1 + \omega_{\mathrm{O/Fe}}) = 1.38 \pm 0.22 \quad (4)$$

which is consistent with the Be-Fe slope determinations in Table 1. Note also that a secondary slope versus O corresponds to a slope considerably less than 2 versus Fe.

We emphasize that the foregoing analysis is purely phenomenological. That is, if $\omega_{\mathrm{O/Fe}} \neq 0$, this necessarily has an impact on Be and B slopes and inferred evolution, *independent of any model*. Thus, if variations in halo star O/Fe are confirmed, this effect must be taken into account in *any* discussion of LiBeB evolution. By the same token, if O/Fe were found to be constant in Pop II (contrary the recent measurements) then this would establish the need for primary Be and B.

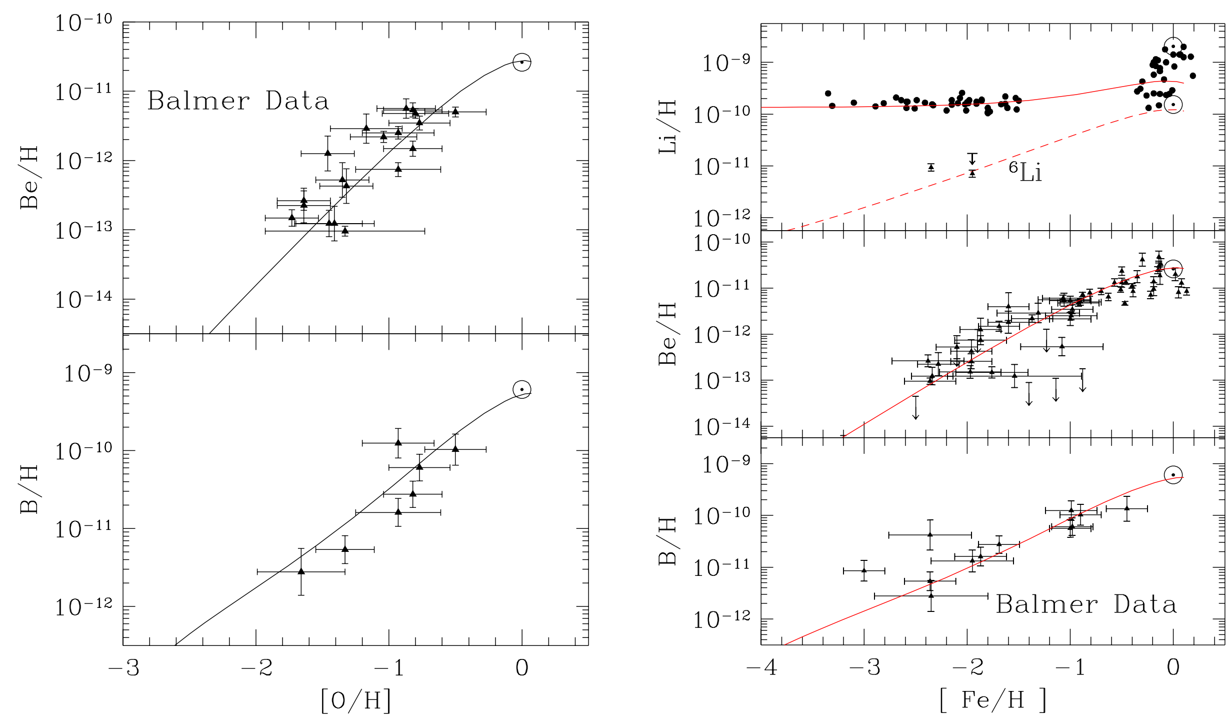

Figure 1: (a) Results for chemical evolution model. *Top:* Be versus O and *bottom:* B versus O. Pop II abundance data derived using the Balmer set of atmosphere parameters (see text).
(b) As in (a), *Top:* Li and ^{6}Li, *middle:* Be, and *bottom:* B versus Fe. Elemental data are described in the text; ^{6}Li points described in Olive & Fields (1999b).

3.2 Chemical Evolution Model

LiBeB production is included in a chemical evolution model Fields & Olive (1999a). Briefly, the model uses published nucleosynthesis yields for supernovae (which including the ν-process), as well as the yields of intermediate mass stars. Stellar lifetimes are accounted for, i.e., the instantaneous recycling approximation is not made. Models with galactic winds and without them ("closed box") were explored, and each was able to provide a good fit to the LiBeB results. Here we focus on the simple case of the closed box model. For the models shown, the IMF is $\xi \propto m^{-2.65}$, and the star formation rate is $\psi \propto M_{\mathrm{gas}}$. To test the impact of the observed O/Fe slope on LiBeB evolution, we have adopted an Fe evolution such that $[\mathrm{Fe/H}] = [\mathrm{O/H}]/(1 + \omega_{\mathrm{O/Fe}})$, with $\omega_{\mathrm{O/Fe}} = -0.31$, the Israelian et al. (1998) value. We rely on our code to compute the evolution histories of ^{6}LiBeB and O. GCR nucleosynthesis appears in chemical evolution as a source term for LiBeB. We take the total cosmic ray flux $\Phi \propto \psi$, the star formation rate. The other LiBeB sources included are the primordial component of ^{7}Li, and the ν-process contributions to ^{11}B and ^{7}Li. We do not include other ^{7}Li sources (e.g., AGB stars), and thus do not fit the observed Pop I Li abundances.

There are two free parameters for the LiBeB evolution: (1) an overall normalization to the GCR contributions to LiBeB, which effectively measures the mean Galactic cosmic ray strength today versus that at the formation of the solar system; and (2) the overall normalization of the ν-process, which we allow to vary due to uncertainties in the neutrino temperature. To fix these parameters, we require that $^{11}\mathrm{B}/^{10}\mathrm{B} = (^{11}\mathrm{B}/^{10}\mathrm{B})_\odot = 4.05$ at $[Fe/H] = 0$, which sets the ν-process normalization. The GCR component is scaled using ^{6}Li, ^{9}Be, and ^{10}B, which have no other contributions. Namely, normalization is to the average of the normalizations of each of these three to the solar values at [Fe/H] = 0.

Figure 1 shows BeB versus O and LiBeB versus Fe for the closed box model. We see that the models provide a good fit to the data. This example from a full chemical evolution model supports the conclusion of our phenomenological analysis (§3): it is possible that ^{6}LiBeB evolution can be explained solely by a combination of standard GCR nucleosynthesis and the ν-process.

4 Discussion

It is above all essential to establish the primary versus secondary character of Be and B. As noted in §§2-3, the current data are inconclusive on this point, though the recent O/Fe slopes suggest that Be is secondary and B primary. For the standard GCR model of §5, we predict that all primary to secondary ratios should vary with metallicity. On the other hand, in primary models all ^{6}LiBeB ratios should be roughly constant. Thus, the most decisive measurements are those that test whether these key ratios are seen to vary.

1. The B/Be ratio. Current data are sparse, and also inconclusive due to atmosphere uncertainties.
2. The O/Fe ratio in Pop II. The O/Fe slope is of course critical to measure accurately. Good measurements of oxygen for all stars with Be and B abundances would also allow a direct determination of the Be-O and B-O slopes without using Fe as an intermediary.
3. The ^{6}Li/Be ratio. Current data are sparse and uncertain, but show a rise of ^{6}Li/Be towards low metallicity, consistent with standard GCR. However, more ^{6}Li data is needed, and it would be particularly useful (however difficult!) to have ^{6}Li over a large enough range of [Fe/H] to see a convincing trend.
4. The ^{11}B/^{10}B ratio. Data thus far consists of only one point, which is uncertain due to possible blending lines. However, the presence of blending could be tested observationally.

We reiterate that in the analysis of future results, uniform and consistent stellar atmospheres are critical for deriving accurate LiBeB-OFe trends. With these data, we can soon determine observationally the origin and evolution of cosmic rays in the Galaxy.

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