The Galactic Evolution of Beryllium and Boron

Brian D. Fields
Astronomy Department, 1002 W. Green St., University of Illinois, Urbana, IL 61801, USA

Keith A. Olive
Theoretical Physics Institute, School of Physics and Astronomy, University of Minnesota, Minneapolis, MN 55455, USA

Abstract. The galactic chemical evolution of Be and B provides unique information about the origin and history of cosmic rays. The available Pop II data demonstrate that Be and B have a Galactic source, probably in one or more kinds of spallation processes. However, the data are not unequivocal about the nature of Be and B origin, as encoded in the primary or secondary (linear or quadratic) scaling with metallicity. We summarize a careful analysis of the trends among Be, B, Fe, and O observations. We show that if O/Fe is constant, some other cosmic ray origin or component is needed. On the other hand, if O/Fe is not constant, as recent data suggest, then the data could indicate a standard cosmic ray origin, wherein the abundances of cosmic rays scale with those of the ISM. We suggest future observational tests which will distinguish several proposed scenarios of LiBeB and cosmic ray origin.

1. Introduction

Lithium, beryllium, and boron (hereafter, LiBeB) have a rich nucleosynthetic history. Indeed, the very low binding energy of the LiBeB isotopes leaves these nuclides at a thermodynamic disadvantage. LiBeB are all burned at fairly low stellar temperatures, and stars are in fact net destroyers of LiBeB. Thus these elements have unusual origins. On the one hand, $^7$Li is in part primordial, and both $^7$Li and $^{11}$B appear to have a component due neutrino-induced interactions in supernovae. On the other hand, $^6$Li, Be, and $^{10}$B are the “orphans” of nucleosynthesis, made neither in stars nor in the big bang—instead, their origin lies in the cosmic rays.

Reeves, Fowler, & Hoyle (1970) noted that all of LiBeB are produced by cosmic-ray interactions with the interstellar medium (ISM). These authors furthermore showed that the present cosmic-ray flux, traversing the ISM for the duration of the Galaxy, yields LiBeB abundances that are consistent by and large with observed solar system levels. The production rate calculations were refined by Meneguzzi, Audouze, & Reeves (1971), who confirmed the basic success of the mechanism, but also noted that $^7$Li seemed to require an extra source (later, boron isotopic measurements suggested more $^{11}$B was also required). Indeed,
cosmic ray nucleosynthesis remained the standard picture for LiBeB production from its proposal until the late 1980’s (see also Audouze 1999).

In the past decade, the simple view of LiBeB origin was enriched (i.e., complicated) by the addition of new data. The heroic observation of Be (and later, B) in old, metal poor halo stars revealed how these elements evolve as a function of metallicity. To appreciate the great impact of these results one must first note that the expected LiBeB evolution is readily calculated within the standard picture of cosmic ray origin and acceleration. In this picture, cosmic rays are accelerated by supernovae, and have a composition reflecting that of the ISM (see, e.g., Ellison 1999 and Meyer 1999 and references therein). This leads to a “secondary” dependence of Be and B on their targets, as follows. In the early Galaxy, the rate of Be production is dominated by spallation of cosmic ray protons on interstellar oxygen, which produces Be atoms at the rate \( \frac{d\text{Be}}{dt} \sim O \sigma \Phi_p \). Each factor in the rate expression has a different dependence on metallicity. Oxygen is produced by supernovae, so \( O \propto N_{SN} \), the cumulative number of supernovae. The spallation cross section \( \sigma \) does not depend on the metallicity, while the cosmic ray flux scales as the supernova rate, \( \dot{N}_{SN} \). Thus we have \( \frac{d\text{Be}}{dt} \propto O \frac{dO}{dt} \) which integrates to \( \text{Be} \propto O^2 \), i.e., a logarithmic slope of 2. This prediction of a quadratic dependence of spallogenic nuclei on metallicity comes about due to the need for target elements as seeds in the ISM, and thus is also called a “secondary” dependence (vs. the “primary” metals).

The BeB observations in Pop II (summarized below and in Duncan 1999) emerged amidst expectations of a quadratic scaling. Instead, the data indicated a log slope (vs \([\text{Fe/H}]\)) close to 1, for both Be and B—i.e., the data seem to show that Be and B are primary (again, vs \([\text{Fe/H}]\)). This result came as a surprise, and has led many authors to conclude that the standard cosmic ray scenario is at best incomplete or at worst simply incorrect. Proposed explanations include a new component of accelerated particles, or a revision of GCR acceleration; these will be discussed below. On the other hand, it has been emphasized recently that the apparently primary nature of Be and B implicitly rests on an assumption that O/Fe is constant in halo stars. If O/Fe is not constant, as recent observations suggest (below and in Garcia-Lopez 1999), then it is possible that standard cosmic ray nucleosynthesis may yet be revived (Fields & Olive 1999a,1999b).

Below we will compare the predictions for different models LiBeB evolution. Fortunately, current models predict evolutionary trends with differences which future observations can discriminate. The data will reveal the nature of LiBeB production in the early Galaxy.

2. LiBeB and Metals: Pop II Trends

Li elemental and isotopic abundances are discussed in Olive & Fields (1999). Here we concentrate on the Be and B data in halo stars.

2.1. Be and B Data

The past decade has seen much progress in BeB abundances in Pop II stars (Duncan 1999 and reference therein). From heroic first observations, now trends have emerged. To model LiBeB evolution, one needs accurate abundance data. In turn, to infer abundances from measured line profiles requires atmospheric
models. These models can adopt different assumptions, notably that of LTE vs NLTE, see e.g., Kiselman (1999). Even within a particular model, the stellar parameter inputs ($T_{\text{eff}}$, gravity, [Fe/H]) can vary when obtained using different methods.

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 | $-3 \leq [\text{Fe/H}] \leq -1$ | $1.21 \pm 0.12$ | $0.63 \pm 0.11$ | $-0.18 \pm 0.16$ |
| O/H          | Balmer | $-2.5 \leq [\text{O/H}] \leq -0.5$ | $1.76 \pm 0.28$ | $1.84 \pm 0.58$ | $-0.81 \pm 0.44$ |
| Fe/H         | IRFM   | $-3 \leq [\text{Fe/H}] \leq -1$ | $1.30 \pm 0.13$ | $0.77 \pm 0.13$ | $0.01 \pm 0.14$ |
| O/H          | IRFM   | $-2.5 \leq [\text{O/H}] \leq -0.5$ | $1.38 \pm 0.19$ | $1.35 \pm 0.30$ | $0.00 \pm 0.17$ |

To get accurate BeB trends versus metal indicators, it is essential to use a uniform data set. That is, the abundances must be derived using consistent assumptions about LTE/NLTE, and a set of stellar parameters derived in the same way. In literature, more than one method exists for determining stellar parameters, giving qualitatively similar but quantitatively different results; these differences can obscure BeB trends if one naively adopts data using more than one method. 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.

Results appear in Table 1; stellar parameter techniques as indicated; B is NLTE. The data are described by the log slopes, e.g., $\omega_{\text{BeFe}}$, defined by $[\text{Be}] = \omega_{\text{BeFe}} [\text{Fe/H}] + \text{const}$, where $[A/B] = \log (A/B)/\log (A/B)_\odot$; and $[A] = 12 + \log (A/H)$. These slopes are fit over the Pop II metallicity ranges indicated. In Table 1, we indeed see that the Be-Fe and B-Fe slopes are near 1, for both sets of stellar parameters (we will discuss BeB-O trends below in §3). We also see systematic differences due to the choice of stellar parameters: in Balmer case, the Be and B slopes are not equal, and B slope less than one, while the IRFM gives Be and B slopes consistent with each other, but different from the Balmer values. These differences highlight the importance of uniform data sets, and emphasize the need for a consistent determination of stellar parameters.

2.2. O and Fe Data

In the spallation process, the nucleosynthetic origin of Be and B are directly traced by oxygen rather than iron. This distinction is essential to understand in Pop I, where O/Fe has long been known to decrease with [Fe/H]. In Pop II, it has commonly been claimed that O/Fe is constant, in which case the O-Fe distinction is not important in determining Be and B origin. Moreover, different methods (i.e., different lines) used to determine oxygen abundances in Pop II have been reported to give conflicting results. Thus, iron has been the metallicity indicator of choice, and iron slopes have been used as indicators of Be and B origin.

However, recent studies of oxygen abundances in Pop II (García-López 1999; Israelian, García-López, & Rebolo 1998; Boesgaard, King, Deliyannis, & Vogt 1999) claim agreement among the methods. Furthermore, these studies have
shown that O/Fe does vary significantly. Namely, O/Fe increases towards low metallicities.

Following these recent studies, we allow for changing O/Fe by writing

$$\frac{[O/Fe]}{[Fe/H]} = \omega_{O/Fe}[Fe/H] + \text{const}$$  \hspace{1cm} (1)

fit over Pop II metallicities: $-3 < [Fe/H] < -1$. Israelian et al. (1998) find $\omega_{O/Fe} = -0.31 \pm 0.11$; i.e., O/Fe variation seen at the 3\(\sigma\) level. Very recently, Boesgaard, King, Deliyannis, & Vogt (1999) have also reported variations in O/Fe, with $\omega_{O/Fe} = -0.35 \pm 0.03$. The two groups’ results are completely consistent with each other, but quite inconsistent with $\omega_{O/Fe} = 0$ (i.e., O \(\propto\) Fe). Variations in O/Fe directly impact the BeB situation, as we now discuss.

3. O/Fe and the Phenomenology of BeB Origin

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 $\omega_{O/Fe} \neq 0$, which means that

$$[O/H] = [O/Fe] + [Fe/H] = (1 + \omega_{O/Fe})[Fe/H] + \text{const}$$  \hspace{1cm} (2)

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

$$\omega_{AFe} = \omega_{AO}(1 + \omega_{O/Fe})$$  \hspace{1cm} (3)

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

$$\omega_{AFe} = 1 + \omega_{O/Fe} = 0.69 \pm 0.11$$  \hspace{1cm} (4)

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 $A$ secondary versus O, so that $\omega_{AO} \equiv 2$. Now eq. (3) gives

$$\omega_{AFe} = 2(1 + \omega_{O/Fe}) = 1.38 \pm 0.22$$  \hspace{1cm} (5)

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.

Finally, if $A$ is secondary and another species $B$ primary, then their slopes differ, and thus their ratio scales with iron according to a slope

$$\omega_{B/A,Fe} = \omega_{BFe} - \omega_{AFe} = -(1 + \omega_{O/Fe}) = -0.69 \pm 0.11$$  \hspace{1cm} (6)

On the other hand, if two elements are both primary (or both secondary) then their slopes should be the same, and and their ratio the same. Thus, ratios of the LiBeB nuclides provide a key test for theories of nucleosynthesis origin.
We emphasize that the foregoing analysis is purely phenomenological. That is, if \( \omega_{\text{O}/\text{Fe}} \neq 0 \), 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 to the recent measurements) then this would establish the need for primary Be and B.

4. Models for Primary LiBeB

The recent [O/Fe] data seems to indicate that Be has a secondary origin, as predicted by standard cosmic ray nucleosynthesis (see §5). On the other hand, the same analysis shows that B is apparently primary, and thus requires a production mechanism outside of standard cosmic ray nucleosynthesis. Given this, and the present inability of the BeBOFe data to definitively discriminate between primary and secondary scenarios, it is certainly important to study mechanisms for primary LiBeB production.

Several mechanisms for producing primary LiBeB use energetic particles and spallation/fusion of interstellar material. However, these processes avoid the standard quadratic scaling with metallicity by invoking CNO particle compositions that are constant in time (and thus metallicity), so that the ratio of energetic CNO/p\( \alpha \) remains fixed, at least roughly (contrary to the standard picture in which cosmic-ray CNO scales with the ISM metallicity). Then at early times, when the ISM abundances of CNO is down, LiBeB production is dominated by the “reverse” process of cosmic ray CNO on interstellar H and He. In this case, the Be production rate is \( \frac{d\text{Be}}{dt} \sim H \sigma \Phi_{\text{O}} \) where the cross section \( \sigma \) and hydrogen abundance \( H \) are time-independent. The accelerated particle flux \( \Phi_{\text{O}} \) scales with the supernova rate (or, equivalently, to the star formation rate), so that \( \Phi_{\text{O}} \propto \dot{N}_{\text{SN}} \propto \frac{d\text{O}}{dt} \). Thus we have \( \frac{d\text{Be}}{dt} \propto \frac{d\text{O}}{dt} \), and Be \( \propto \) O. Thus LiBeB and heavy elements are essentially co-produced.

4.1. Accelerated Particles as Primary Sources

One proposal for a “metal-enriched” accelerated particle component invokes a large flux of low-energy (\( \lesssim 100 \) MeV/nucleon) particles dominated by heavy nuclei. This suggestion was initially motivated by reports of \( \gamma \)-ray line emission from Orion, which suggested a low-energy flux dominated by C and O. Cassé, Lehoucq, & Vangioni-Flam (1995) immediately pointed out that energetic particles of this kind are precisely what is required to give a primary LiBeB evolution; as did Ramaty, Kozlovsky, Lingenfelter (1995). The Orion \( \gamma \)-ray detections have since been retracted (Bloemen 1999), but even so, the original Orion data served a useful purpose in that it stimulated a renewed interest in accelerated particle interactions outside of standard GCR paradigm.

Indeed, the work on the putative Orion \( \gamma \)-rays led to a different but related mechanism: particle acceleration in superbubbles. These regions are the seats of intense star formation, and composed of young stars and rarefied gas which has been enriched by massive stellar winds and by supernova explosions. The stellar winds in these regions produce weak shocks, which necessarily lead to particle acceleration with the required enriched composition (Vangioni-Flam et
al. 1998; Lemoine, Vangioni-Flam, & Cassé 1998). As reviewed by Bykov (1999) and Parizot (1999), the weak shocks lead to steep spectra, i.e., the fluxes are dominated by low-energy particles. Thus the particle energies and compositions are similar to the Orion case.

While the above scenarios invoke metal-enriched low-energy particles, a recent proposal (Ramaty, Kozlovsky, Reeves, Lingenfelter 1996; Higdon, Lingenfelter, & Ramaty 1998; Ramaty & Lingenfelter 1999) instead suggests that the Galactic cosmic rays themselves are in fact composed of material accelerated from fresh supernova ejecta. This scenario thus challenges the standard assumption that cosmic rays are accelerated out of the ISM. In this model the particle composition is that of supernova ejecta, which themselves are essentially metallicity-independent, and hence Be and B are primary.

Finally, we note a suggestion of Tayler (1995) which has received less attention and has not been modeled in any detail. Tayler notes that a primary Be and B relation would arise if star formation and cosmic ray interactions occur predominantly within objects of globular cluster scales. The basic idea is that star formation occurs in a clustered fashion, within giant molecular clouds of mass \( \sim 10^{5-6} M_\odot \). The gas in these clouds will be substantially enriched by supernovae, with a metal composition that is nearly independent of the cloud’s initial composition (especially in the halo phase). The fixed target composition thus leads to a primary BeB origin.

4.2. The Neutrino Process

While the preceding models all lead to primary origins for all of the LiBeB nuclides, one mechanism, the neutrino process (\( \nu \)-process) leads is a primary source only of \(^{11}\text{B} \) and \(^7\text{Li} \). In supernova explosions thermal neutrinos (of all species) emerge from the hot core and traverse the outer layers prior to the propagation of the shock. These neutrinos can “spall” the nuclei they encounter, most likely removing a single nucleon (Woosley et al. 1990; Woosley & Weaver 1995; Hartmann 1999). Specifically, in the carbon shell, reactions of the form \(^{12}\text{C}(\nu, \nu'p)^{11}\text{B} \) or \(^{12}\text{C}(\nu, \nu' n)^{11}\text{C}(\beta)^{11}\text{B} \) can produce \(^{11}\text{B} \), but not, as it turns out, significant amount of \(^{10}\text{B} \) or Be. In the helium shell, two-step reactions such as \(^4\text{He}(\nu, \nu'p)^3\text{H}(\alpha, \gamma)^7\text{Li} \) can produce mass-7 (but not significant mass-6). The yields of these nuclei (Woosley & Weaver 1995) are uncertain, but taken at face value, they can be a significant source of \(^{11}\text{B} \) and possibly of \(^7\text{Li} \) as well.

4.3. Comparing Primary Models

By definition, all primary models predict similar BeB scalings with metallicity. These models are thus challenging to distinguish observationally. However, the models do have real differences in their predictions over the full span of metallicities, which enables observational discrimination with high-quality data. An instructive case study is provided by Vangioni-Flam, Ramaty, Olive, & Cassé (1998), who compared the predictions of the “superbubble” model with the “direct acceleration” model. They found that the two lead to differences in Be and Be/B evolution which are detectable with good Be data at [Fe/II] \( \lesssim -3 \). This result is encouraging as it shows that observational tests can determine not only the basic character of LiBeB origins (primary versus secondary) but can also discriminate among specific detailed production scenarios.
5. Models for Standard Cosmic Ray Nucleosynthesis

Models for standard cosmic ray nucleosynthesis are important for at least two reasons. (1) As discussed in §3, O/Fe observations may suggest that Be has a purely secondary origin. If this is so, then standard GCR nucleosynthesis may be the only source of Be, thus making it a crucial part of the LiBeB discussion. Furthermore, in Pop II, the Li isotopes are primary even in standard GCR, since $\alpha + \alpha$ fusion dominates and thus the target He atoms have essentially constant (i.e., mostly primordial) abundances. Thus, even if there are other (e.g., primary) sources of Li, standard GCR can produce $^6$Li and $^7$Li at comparable or even larger levels. (2) If indeed GCRs are accelerated out of the ISM, then this mechanism occurs and is operative throughout the Galactic history. Even if other (primary) sources contribute to LiBeB, this process must be included and indeed is significant at late times. With this in mind, we now review standard GCR nucleosynthesis and its effect on LiBeB chemical evolution.

5.1. Cosmic Ray Nucleosynthesis

The details of the GCR model used here are presented in Fields & Olive (1999a); the formalism and model-dependences is discussed in detail in Fields, Olive, & Schramm (1994). To briefly summarize the main points; LiBeB production rates are calculated within within the leaky box model, following Meneguzzi, Audouze, & Reeves (1971). The cosmic ray source spectrum is $q(E) \propto (E + m_p)^{-2.7}$ for all particles, and the source composition at time $t$ are taken to be the ISM abundances at that epoch. The propagation model includes losses due to ionization, nuclear inelastic collisions, and escape; the latter is parameterized by a constant escape pathlength $\Lambda_{esc} = 11$ g cm$^{-2}$.

5.2. Galactic Chemical Evolution

LiBeB production is included in a chemical evolution model, described in Fields & Olive (1998). Briefly, the model uses the Woosley & Weaver (1995) yields for supernovae, including the $\nu$-process yields. For stars in the 1–8 $M_\odot$ range, the van den Hoek & Groenewegen (1997) yields are adopted. Stellar lifetimes are accounted for, i.e., the instantaneous recycling approximation is not made. Both closed box and galactic wind models 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 $\phi \propto M_{gas}$.

The O/Fe ratio as computed in the model does indeed rise towards low metallicities. However, while this is in qualitative agreement with the O/Fe data, the predicted slope is too shallow, so that the lowest metallicity points are missed. Because the model’s predicted O/Fe slopes are too small, it is unable to test the impact of the observed O/Fe slope on LiBeB evolution. Thus, we have simply adopted an Fe evolution such that $[\text{Fe/H}] = [\text{O/H}]/(1 + \omega_{O/Fe})$, with $\omega_{O/Fe} = -0.31$, the Israeliian et al. (1998) value. We still rely on our code to compute the evolution histories we believe are simple i.e., those of $^6$LiBeB and O. However, we use the observed O/Fe dependence to get Fe, rather than the ab initio Fe yields which are model-dependent (e.g., Type Ia and Type II contributions) and uncertain (mass cuts).
Figure 1. (a) Results for closed box model with IMF $\xi \propto m^{-2.65}$; 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).

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 $\nu$-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 $\nu$-process, which we allow to vary due to uncertainties in the neutrino temperature. To fix these parameters, we require that $^{11}$B/$^{10}$B = $(^{11}$B/$^{10}$B)$_\odot$ = 4.05 at $[\text{Fe/H}] = 0$, which sets the $\nu$-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 $[\text{Fe/H}] = 0$.

5.3. Results

Figure 1 shows BeB versus O and LiBeB versus Fe for the closed box model; Figure 2 shows B/Be versus Fe. We see that the models provide a good fit to the data for both the abundances and the ratios. This example from a full chemical evolution model supports the conclusion of our phenomenological
Figure 2. $B/Be$ versus $Fe$, with Pop II abundance data derived using the Balmer set of atmosphere parameters (see text). *Top:* closed box model, *middle:* outflow model, *bottom:* outflow model shown with IRFM data.

analysis (§3): it is possible that $^6\text{LiBeB}$ evolution can be explained solely by a combination of standard GCR nucleosynthesis and the $\nu$-process.

By calculating the energy production per Be atom one may link the Be production to the needed energy budget (see Ramaty & Lingenfelter 1999 and references therein). Specifically, one wishes to know the cosmic ray input energy per supernova, $\Delta E_{\text{CR}}/\Delta N_{\text{SN}} = \dot{E}_{\text{CR}}/\dot{N}_{\text{SN}}$ for each epoch $t$, where $E_{\text{CR}}$ and $N_{\text{SN}}$ are the aggregate injection energy and supernova number over the Galactic history. The energetics can be related to the observed Be abundances if one neglects the astration of Be, and thus assumes that the stellar Be/Fe ratio is always an accurate reflection of the total integrated Be and Fe production; this assumption is good in Pop II but not in Pop I. Once making this assumption, the energy per supernova is

$$\frac{\dot{E}_{\text{CR}}}{\dot{N}_{\text{SN}}} = \frac{\dot{E}_{\text{CR}}}{\dot{M}(\text{Be})} \frac{\dot{M}(\text{Be})}{\dot{M}(\text{Fe})} \frac{\dot{M}(\text{Fe})}{\dot{M}(\text{O})} \frac{\dot{M}(\text{O})}{\dot{N}_{\text{SN}}}$$

(7)

One can compute the terms in eq. (8) using (1) the well-defined ratio of the Be production rate $\approx \dot{M}(\text{Be})$ to $\dot{E}_{\text{CR}}$; (2) the observed Be/Fe data, which satisfies $\text{Be}/\text{Fe} \propto \dot{M}(\text{Be})/\dot{M}(\text{Fe})$ if the Be-Fe relation is a power law; (3) the chemical evolution model results for $\dot{M}(\text{Fe})$, $\dot{M}(\text{O})$, and $\dot{N}_{\text{SN}}$. 

9
Figure 3. The cosmic ray input energy per supernova. The upper solid curve is for a Be-Fe slope in Pop II of $\omega_{\text{BeFe}} = 1.3$; the lower solid curve has $\omega_{\text{BeFe}} = 1.2$; the short-dashed curve has $\omega_{\text{BeFe}} = 1.0$; and the long dashed curve uses the $1 - \sigma$ limit of $\omega_{\text{BeFe}} = 1.4$.

As noted by Ramaty & Lingenfelter (1999 and refs. therein) this analysis points out severe problems with standard GCR nucleosynthesis if one uses the observed Be-Fe trends and takes O/Fe constant in Pop II. In this case, all terms in eq. (8) are constant in metallicity except the first, which scales as $1/Z$, since this is the abundance of target species. This implies that the cosmic ray energy input increases over its present value by a factor of $10^3$ at [Fe/H] = −3. We have implemented eq. (8) in our code for the case of constant O/Fe and constant Be/Fe, the result appears as the short-dashed curve in Figure 3. While this gives a bad fit to the energetics, one should recall that one would not consider such a model anyway, as a constant O/Fe implies that Be and B are both nearly linear versus O, in which case a secondary source will of course fail to fit the data.

The situation changes dramatically, however, if O/Fe is not constant. Both solid curves in Figure 3 use $\omega_{\text{O/Fe}} = -0.31$. The upper solid curve has the Balmer value $\beta = 0.2$, leading to an energetic increase of a factor $\sim 7$; the lower solid curve has the IRFM $\beta = 0.3$, leading to a factor $\sim 3.5$ increase. These results thus bracket our estimate and give a sense of the effect of uncertainties in Be-Fe. To see the effect of the whole range of uncertainties, we have plotted in the long-dashed curve the results for $\beta = 0.4$ and $\omega_{\text{O/Fe}} = -0.4$, both within $1 - \sigma$ of the IRFM slopes. Here we see that the energetic requirement actually decreases. In any case, we find that within the errors of the observations, the energetic requirements for our scenario are not severe, due largely to the effect of changing O/Fe, and somewhat to the nonzero Be/Fe slope. We note that different ingredients of this calculation are subject to uncertainty. However, for the model we have adopted (the solid curves in Figure 3), the energetics are satisfactory, and do not rule out this scenario.
6. Observational Tests of LiBeB Origin

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. At any rate, when the basic Be and B origins are clearly established, further, very accurate data can distinguish among candidate models, along the lines suggested by Vangioni-Flam, Ramaty, Olive, & Cassé (1998).

For the standard GCR model of §5, we predict that all primary to secondary ratios should vary according to eq. (7). 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.

7. Conclusions

Lithium, beryllium, and boron have a unique nucleosynthetic history which is at the intersection of cosmology, cosmic rays, and chemical evolution. Parts of this history are clear: $^7$Li is produced cosmologically, while $^6$LiBeB are not, and the source of $^6$LiBeB is surely spallogenic. However, the nature of the more detailed history of LiBeB evolution is uncertain and currently the subject of vigorous debate. The current Pop II LiBeB data have enough uncertainty that even the basic issue of primary versus secondary origin has been cast into doubt. Several well-motivated models now exist, and can be discriminate by a larger and better data set.

Thus, the LiBeB field is in the healthy position of examining fundamental issues LiBeB origin which bear directly on the question of cosmic ray origin. What makes the situation exciting is that these question can be addressed directly by observations which are difficult but feasible. Central issues are the
primary versus secondary nature of each of the LiBeB elements, and the auxiliary but central issue of the O/Fe. We strongly encourage observations of the kind described in the previous section, and eagerly anticipate their results. Whatever they may show, the new data will go far to the establish origin and nature of cosmic rays in early galaxy.

Acknowledgments. BDF would like to thank the organizers for a very enjoyable and stimulating meeting. The work of KAO was supported in part by DoE grant DE-FG02-94ER-40823 at the University of Minnesota.

References
Audouze, J. 1999, these proceedings
Bloemen, H. 1999, these proceedings
Boesgaard, A.M., King, J.R., Deliyannis, C.P., & Vogt, S.S. 1999, AJ, 117, 492
Bykov, A. 1999, these proceedings
Cassé, M., Lehoucq, R., & Vangioni-Flam, E. 1995, Nature, 373, 318
Duncan, D.K. 1999, these proceedings
Ellison, D. 1999, these proceedings
Fields, B.D., & Olive, K.A. 1998, ApJ, 506, 177
Fields, B.D., & Olive, K.A. 1999a, ApJ, 516, in press (astro-ph/9809277)
Fields, B.D., & Olive, K.A. 1999b, New Astr., in press (astro-ph/9811183)
Fields, B.D., & Olive, K.A., & Schramm, D.N., 1994, ApJ, 435, 185
García-López, R. 1999, these proceedings
Hartmann, D. 1999, these proceedings
Higdon, J.C., Lingenfelter, R.E., & Ramaty, R. 1998, ApJ, 509, L33
Israelian, G., García-López, R., & Rebolo, R. 1998, ApJ, 507, 805
Lemoine, M., Vangioni-Flam, E., Cassé, M. 1998, ApJ, 499, 735
Meneguzzi, M., Audouze, J., & Reeves, H. 1971, A&A, 15, 337
Meyer, J.-P. 1999, these proceedings
Olive, K.A., & Fields, B.D. 1999, these proceedings (astro-ph/9902297)
Parizot, E. 1999, these proceedings
Ramaty, R. & Lingenfelter, R.E. 1999, these proceedings (astro-ph/9903200)
Ramaty, R., Kozlovsky, B., & Lingenfelter, R.E., 1995, ApJ, 438, L21
Ramaty, R., Kozlovsky, B., Lingenfelter, R.E., & Reeves, H. 1997, ApJ, 488, 730
Reeves, H., Fowler, W.A., & Hoyle, F. 1970, Nature, 226, 727
Tayler, R.J. 1995, MNRAS, 273, 215
van den Hoek, L.B., & Groenewegen, M.A.T. 1997, A&AS, 123, 305
Vangioni-Flam, E., Ramaty, R., Olive, K.A. & Cassé, M. 1998, A&A, 337, 714
Vangioni-Flam, E., Cassé, M., Cayrel, R., Audouze, J., Spite, M., & Spite, F. 1999b, New Astronomy, submitted (astro-ph/9811327)
Woosley, S.E., Hartmann, D., Hoffman, R., Haxton, W. 1990, ApJ., 356, 272
Woosley, S.E. & Weaver, T.A. 1995, ApJS, 101, 181