LiBeB and the Origin of the Cosmic Rays

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Abstract. Be abundances at low metallicities have major implications on cosmic ray origin, requiring acceleration out of fresh supernova ejecta. The observed, essentially constant Be/Fe fixes the Be production per SNII, allowing the determination of the energy supplied to cosmic rays per SNII. The results rule out acceleration out of the metal-poor ISM, and favor Be production at all epochs of Galactic evolution by cosmic rays having the same spectrum and source composition as those at the current epoch. Individual supernova acceleration of its own nucleosynthetic products and the collective acceleration by SN shocks of ejecta-enriched matter in the interiors of superbubbles have been proposed for such origin. A new Monte-Carlo based evolutionary code, into which the concept of Be and Fe production per supernova is explicitly built in, yields the supernova acceleration efficiency, 2% for the refractory metals and 12% for all the cosmic rays.

1 Introduction and Overview

It is well known \cite{1} that cosmic ray interactions have an important role in producing the Galactic inventories of Li, Be and B (hereafter LiBeB), in particular Be, \textsuperscript{6}Li and \textsuperscript{10}B which are almost certainly produced solely in cosmic ray interactions. Up until recently LiBeB research was dominated by the standard Galactic cosmic ray (hereafter sGCR) paradigm which posits that the current epoch cosmic rays are accelerated out of an ambient medium of solar composition, and that at all past epochs the composition of the source particles of the cosmic rays was scaled to solar using the ISM metallicity at that epoch. The excess of the observed Be abundances in low metallicity stars over the sGCR prediction was discussed \cite{2} as early as 1991, the focus of the discussion being on whether or not the excess was due to contributions from Big Bang nucleosynthesis. But recent calculations \cite{3} show that the Big Bang contribution to Be production is insignificant in comparison with the available Be data at even the lowest metallicities. However, these Be observations have major implications on cosmic ray origin.

As additional Be data accumulated (see \cite{4} for a recent compilation), it became clear that the dependence of log(\text{Be}/H) on [Fe/H] is essentially linear, not quadratic, as predicted by the sGCR paradigm. (Chemical or isotopic symbol ratios denote abundance ratios by number and $[\text{Fe}/\text{H}]=\log(\text{Fe}/\text{H})-\log(\text{Fe}/\text{H})_{\odot}$.) The implications of the linear evolution become more obvious \cite{5} when log(\text{Be}/Fe), rather than log(\text{Be}/H) is considered (Fig. 1a). Here the horizontal line provides \cite{5} the best fit to the data for $[\text{Fe}/\text{H}]<-1$. Fe production in this epoch \cite{6} is dominated by core-collapse supernovae (hereafter SNII), with an IMF averaged Fe yield per SNII of $\sim0.1M_{\odot}$, essentially independent of metallicity \cite{7}. This constancy, coupled with the observed constant Be/Fe, requires that, on average, about $0.1 \times 1.45 \times 10^{-6} \times (9/56) = 2.3 \times 10^{-8}M_{\odot}$ of beryllium be produced per SNII, independent of [Fe/H]. Under the sGCR paradigm,
The best fit, for [Fe/H] < -1, implies that $2.3 \times 10^{-8} \, M_\odot$ of Be are produced per average SNII. The decrease at higher [Fe/H] is due to contributions of Type Ia supernovae which make Fe but very little Be. (b) - Energy in cosmic rays per SNII required to produce this Be mass. The cosmic ray source composition is metallicity independent for the CRS model and metallicity scaled for the sGCR model. $X_{\text{esc}} \simeq 10 \, \text{g cm}^{-2}$ is the current epoch cosmic ray escape length; in the early Galaxy it could have been different, depending on the density and magnetic structure of the early Galactic halo. When $X_{\text{esc}} \to \infty$, the cosmic rays are trapped in the halo until they are either stopped by Coulomb collisions or destroyed by nuclear reactions; this choice of escape length yields the lowest $W_{\text{SN}}$ for the given Be production.

One solution to this problem was suggested [8], following the reported [9] detection with COMPTEL/CGRO, of C and O nuclear gamma ray lines from the Orion star formation region. These gamma rays were attributed to a postulated low energy cosmic ray (LECR) component, and it was suggested that such LECRs might be responsible for the Be (and B) production in the early Galaxy. The motivation for this idea (hereafter the LECR model) was the indication (based on the reported spectrum of the line emission) that the LECRs in Orion are enriched in C and O relative to protons and $\alpha$ particles (see [10] for review and [11] for extensive calculations of LiBeB production by LECRs). It was suggested [12, 11, 13] that such enriched LECRs might be accelerated out of metal winds of massive stars and the ejecta of supernovae from massive star progenitors (>60$M_\odot$) which explode within the bubble around the star formation region due to their very short lifetimes. These arguments led to the suggestion [14, 15] that the composition of the LECRs could be independent of Galactic metallicity, thus allowing them to reproduce the linear evolution of Be and B in the early Galaxy. The problem with this model is its energetic inefficiency, as we shall see. In addition, the validity of the Orion gamma ray line observations has been questioned by the COMPTEL team (private communication, V. Schönfelder, 1998).

In a series of publications, co-authored with H. Reeves [16, 17, 18], we calculated the energy, $W_{\text{SN}}$, in cosmic rays per core collapse supernova, needed to produce the required amount of Be. $W_{\text{SN}}$ depends on the composition of both the ISM and the cosmic rays, on the energy spectrum of the cosmic rays, and on the cosmic ray escape
length from the Galaxy, \(X_{\text{esc}}\) measured in g cm\(^{-2}\). In Fig. 1b we show \(W_{\text{SNII}}\), as a function of [Fe/H] for two values of \(X_{\text{esc}}\), and for two Galactic cosmic ray origin models: a proposed CRS model for which the cosmic rays at all [Fe/H] have the same source composition and spectrum as the current epoch cosmic rays, and the sGCR model for which the cosmic rays are accelerated out of a metallicity dependent ISM with an energy spectrum that is also identical to that of the current epoch cosmic rays. The ambient ISM composition for both models is solar, scaled with \(10^{[\text{Fe}/\text{H}]}\), except that we allowed O/H to increase by 0.5 dex for [Fe/H] < −1 (see [19], figure 8.5). We also increased the sGCR cosmic ray C/H and O/H relative to the corresponding metallicity dependent ISM values by factors of 1.5 and 2, respectively, consistent with the abundances expected for the shock accelerated ISM [20]. We see that the sGCR model requires that the cosmic ray energy supply per SNII not only be metallicity dependent, which is unlikely, but also unreasonably large, exceeding the total available ejecta kinetic energy (~1.5×10\(^{53}\)erg) when [Fe/H] < −2. This reinforces the previous conclusion that cosmic rays accelerated out of the average, metal poor ISM cannot be responsible for the Be production in the early Galaxy.

For the CRS model, on the other hand, \(W_{\text{SNII}}\) is essentially constant (Fig. 1b), equal to the very reasonable value of ~10\(^{50}\) erg/SNII, practically the same as the energy supplied per supernova to the current epoch cosmic rays [21]. That these two energies are consistent, led to a different cosmic ray paradigm, the direct acceleration out of fresh supernova ejecta, at least for the refractory metals [5, 22, 23]. The linearity of the Be evolution is a straightforward consequence of such a model. To account for the various features of the cosmic rays, two related CRS scenarios were developed. The first considers the individual supernova shock acceleration of its own nucleosynthetic products [22], while the second addresses the collective acceleration by successive SN shocks of ejecta-enriched matter in the interiors of superbubbles [23]. In the individual supernova model, freshly formed high velocity grains in the slowing ejecta reach the forward supernova shock which then accelerates the grain erosion products. The superbubble model emphasizes the fact that the bulk of the SNIIs occur in the cores of superbubbles where the ambient matter is likely to be dominated by fresh supernova ejecta. In both scenarios, grain erosion products play a central role. They provide an explanation for the observed cosmic ray enrichment of the highly refractory Mg, Al, Si, Ca, Fe and Ni relative to the highly volatile H, He, N, Ne, Ar, an idea developed in detail previously for sGCR acceleration [23]. In both the individual supernova and superbubble scenarios, the accelerated C and O originate from grains, O from oxides (MgSiO\(_3\), Fe\(_2\)O\(_4\),Al\(_2\)O\(_3\),CaO) and C mainly from graphite. The CRS model based on acceleration within superbubbles differs from the LECR model discussed above in that it relies on essentially all the SNIIs, and not just those originating from massive stellar progenitors, and because it accelerates cosmic rays with a spectrum extending to relativistic energies, rather than just to low energies. It is these differences that avoid the energetic difficulties of the LECR model. Furthermore, while both the individual supernova and the superbubble scenarios address the origin of the current epoch, well observed cosmic rays, there is no hard evidence for the existence of a separate LECR component. Such evidence could come from the discovery of Galaxy-wide nuclear deexcitation gamma ray line emission (see [24, 25]).

The B isotopic ratio, \(^{11}\text{B}/^{10}\text{B}= 4.05\pm0.2\) in meteorites [26] and 3.4±0.7 in the current epoch ISM [28], has major implications on the origin of this element. These
Evolution

We consider a one-zone model, representing the halo of the early Galaxy, and limit our treatment to the first $10^{9}$ years of Galactic evolution, as this low metallicity ([Fe/H] $\leq -1$) era conveys the most unambiguous information on cosmic rays origin. We assume that the halo ISM mass accumulates exponentially, and we remove mass by star formation and by outflow to the disk. In the Monte Carlo simulation we set

ratios exceed the predictions of both the CRS and sGCR models. LECRs could account for these data, either if the accelerated particles were confined to very low energies ($\sim 10$ MeV/nucleon), which is energetically untenable, or if their spectrum is artificially chosen to yield nuclear interactions predominantly at $\sim 30$ MeV/nucleon, which is also improbable (see [18]). The excess $^{11}$B is most likely the result of $^{12}$C spallation by neutrinos in SNIIs [29].

Concerning Li, it is clear that the bulk of the $^7$Li at all epochs of Galactic evolution did not originate in cosmic ray interactions. On the other hand, all of the $^6$Li is most likely cosmic ray produced. The CRS model predicts that $^6$Li/Be is about 5 at all metallicities, depending somewhat on the uncertainties in the $\alpha\alpha$ cross section at high energies (see [6]). This value is quite consistent with the meteoritic ratio of 5.8 [18]. At low metallicities, higher values of $^6$Li/Be were reported [31], but the uncertainties in these data are very large.

To explore these problems, we have developed a Monte-Carlo based evolutionary code into which the concept of Be and Fe production per supernova is explicitly built in. The treatment allows the easy investigation of a variety of hitherto ignored processes, such as the delay in Be production relative to Fe production due to the propagation of the cosmic rays, and the dependencies of the cosmic ray composition and ejecta kinetic energy on supernova progenitor mass.
For $-2.5 < [\text{Fe/H}] < -1$ the only free parameter is the refractory cosmic ray acceleration efficiency, $\eta_{\text{refr}}$, equal to 0.018 and 0.63 for the two models, respectively. The effects seen at lower [Fe/H] are discussed in the text.

Fe production is due to the $>10 \, M_\odot$ stars which explode as SNIIs. We calculate the Fe mass and production time for every such star using SNII yields \cite{7} at zero metallicity and stellar lifetimes. The Fe production rates are shown in Fig. 2b for the two choices of mass loss. The production rate goes through a maximum between a few tens and a hundred Myr. As the average Fe yield per SNII is $\sim 0.1 \, M_\odot$, the corresponding maximum SNII rate is 10-30/century. We calculate the Fe content of the ISM by delaying, due to transport and mixing, the deposition of the synthesized Fe. In the simulation we choose the mixing time randomly in the interval 0 to $\tau_{\text{mix}}$. The resultant Fe abundance evolution is shown in Fig. 2c for $\tau_{\text{mix}}=10$ Myr. We see that $[\text{Fe/H}]$ is indeed $\sim -1$ at 1 Gyr, with a somewhat larger value for the case of larger star formation and lower outflow rate. As we shall see, variations in $\tau_{\text{mix}}$ can have significant effects on Be/Fe, B/Be and $^{11}$B/$^{10}$B at very low [Fe/H].

We carry out a similar procedure for Be. Here we distinguish two cases which are analogous to the CRS and LECR models discussed above. In the first one (CRS), we assign to each $>10 \, M_\odot$ star an ejecta kinetic energy $W_{\text{ej}}$, using the values given in \cite{7}. We then assume that each corresponding SNII imparts $\eta_{\text{refr}} W_{\text{ej}}$ ergs to refractory cosmic rays and take $\eta_{\text{refr}}$ to be independent of progenitor mass. Next we calculate the relative abundances of the refractories (C:O:Mg:Al:Si:Ca:Fe:Ni) as a function of progenitor mass, using the ejected masses from \cite{7} and assuming \cite{22} that the O abundance is determined by the amount of O in oxides (MgSiO$_3$, Fe$_3$O$_4$, Al$_2$O$_3$, CaO) and that the fraction of C that condenses in grains is the same as that of the highly refractories Mg, Al, Si and Fe. Then by employing the LiBeB production code developed previously \cite{18}, with $E_0=10$ GeV/nucleon appropriate for high energy cosmic rays, we calculate the total Be mass produced by each SNII in the simulation. For
the second case (LECR), we follow a similar procedure, except that we only consider
>60 M⊙ progenitors and take \(E_0=30\) MeV/nucleon. The only free parameter in these
calculations is \(\eta_{\text{refr}}\). The time interval between cosmic rays acceleration and Be pro-
duction can be quite large due to cosmic ray transport. Therefore, for both cases we
delay the Be production relative to that of the Fe, employing randomly distributed
delay times in the range 0 - 10 Myr (CRS) and 0 - 1 Myr (LECR), valid for an ISM
density of 1 H cm\(^{-3}\). The delay for LECRs is smaller because they interact on shorter
time scales than their high energy counterparts.

Fig. 3 shows log(Be/Fe) vs. [Fe/H], where the normalization to the data yields the
fraction of supernova kinetic energy going into refractory cosmic rays, \(\eta_{\text{refr}} = 0.018\)
and 0.63 for the CRS and LECR cases, respectively. The much larger LECR value
is due to the less frequent >60 M⊙ progenitors explosions and to the less efficient Be
production by LECRs \[18\]. The acceleration of volatile elements (in particular protons
and α particles) that should accompany the acceleration of the metals requires more
energy. For the current cosmic ray source composition, the ratio of the total energy
in cosmic rays per SNII and the SNII ejecta energy is 0.12 for the CRS case and
4.3 for the LECR case. While this CRS value is very reasonable, the LECR value
is clearly excessive and would invalidate the model, unless the SNIIIs of very massive
progenitors only accelerate metals. The energetic efficiency of the LECR case could
also be improved by choosing a harder accelerated particle spectrum (e.g. \(E_0 \simeq 70\)
MeV/nucleon \[18\]) and a progenitor mass cutoff smaller than 60 M⊙.

The behavior of log(Be/Fe) at [Fe/H]< −3 shows interesting effects. An increase
in Be/Fe, caused by the short lifetimes of the very massive progenitors, was predicted
for an LECR case previously \[4\]. The \(\tau(\text{mix})=1\) Myr curve in Fig. 3b shows that
predicted evolution. The introduction of a mixing time for Fe enhances the effect.
On the other hand, for the CRS case (Fig. 3a) where the Be production is delayed,
the effect can be canceled or even reversed, depending on the mixing time relative to
the Be production time.

We treat the evolutions of \(^{10}\)B and the cosmic ray produced \(^{11}\)B in the same
fashion as the Be evolution. For the \(\nu\)-produced \(^{11}\)B we use the SNII yields \[6\]
at zero metallicity scaled by a factor \(f_\nu\), and treat the evolution similar to that of
the Fe. We determined $f_\nu$ by requiring that when the effects of mixing and cosmic ray production times become negligible ($[\text{Fe}/\text{H}] \gtrsim -2$, Fig. 4b), $^{11}\text{B}/^{10}\text{B} = 4$, the meteoritic value \cite{27} at $[\text{Fe}/\text{H}]=0$. We thus obtain $f_\nu=0.28$ (CRS) and 0.13 (LECR).

In a past calculation \cite{14}, $^{11}\text{B}/^{10}\text{B}$ was shown to be $\sim 7$ at $[\text{Fe}/\text{H}] \sim -2$ and to decrease toward 4 at higher metallicities. This resulted from the added contribution of the sGCR at $[\text{Fe}/\text{H}] > -1$. But we suspect that the increase \cite{7}, by a factor of $\sim 2$, of the $\nu$-produced $^{11}\text{B}$ per SNII with increasing $[\text{Fe}/\text{H}]$, was not taken into account in that calculation, an effect that would have canceled the decrease and would have allowed $^{11}\text{B}/^{10}\text{B} \simeq 4$ at $[\text{Fe}/\text{H}] \sim -2$, as in our calculation. For the CRS case (Fig. 4a) the calculated B/Be for $-3 < [\text{Fe}/\text{H}] < -1$ is 17-21 and 24-21 for $\tau(\text{mix})=30\text{Myr}$ and $1\text{Myr}$, respectively. These are in good agreement with the observations (e.g. B/Be=20$^{\pm 10}$ \cite{34}). For the LECR case and the same $[\text{Fe}/\text{H}]$ range, B/Be is 24-26, also in agreement with the data. We note that the total B in both the CRS and LECR cases includes $\nu$ production. For $[\text{Fe}/\text{H}] < -3$, both B/Be and $^{11}\text{B}/^{10}\text{B}$ exhibit interesting effects. The very large $^{11}\text{B}/^{10}\text{B}$ (Fig. 4b) is the consequence of delayed cosmic ray production and possible, prompt $\nu$-induced production in SNIIs.

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