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The role of gravitational supernovae on the galactic evolution of the LiBeB isotopes

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ABSTRACT

The observed Be and B relationships with metallicity clearly support the idea that both elements have a primary origin and that are produced by the same class of objects. Spallation by particles accelerated during gravitational supernova events (SNII, SNIb/c) seems to be a likely origin. We show, in the context of a model of chemical evolution, that it is possible to solve the Li, Be and B abundance puzzle with the yields recently proposed by Ramaty et al. (1997) provided that SNII are unable to significantly accelerate helium nuclei and that different mechanisms are allowed to act simultaneously.

Key words:
Galaxy:abundances; nucleosynthesis; supernovae:general

1 INTRODUCTION

The origin of the light elements is still an open question in Astrophysics. It is widely accepted that standard Big Bang nucleosynthesis can only produce ^{7}Li. The primordial abundance produced of this isotope is one order of magnitude below Solar System values and roughly coincides with that observed by Spite & Spite (1982) in the hot halo dwarfs (*the lithium plateau*). For this reason, it is generally accepted that such an abundance is representative of the primordial nucleosynthesis and that, since the LiBeB isotopes do not have a cosmological origin, they must be created by galactic activity.

It is well known that the interaction of cosmic rays (CR) with the interstellar medium

(ISM) can play an important role in the production of the LiBeB isotopes (Reeves, Fowler & Hoyle 1970). In fact, the bulk of the ^{6}Li, ^{9}Be and ^{10}B Solar System abundances can be naturally accounted with the standard model of galactic cosmic ray (GCR) nucleosynthesis. In this model, high energy protons and alpha particles collide with heavier nuclei (CNONe) present in the ISM to produce the light element isotopes (Meneguzzi, Audouze & Reeves 1971). This model fails, however, to explain the present ^{7}Li abundance and the Solar System ^{7}Li/^{6}Li and ^{11}B/^{10}B ratios. Furthermore, during the last decade, many observational studies have shown a linear relationship between Be and B abundances in metal-poor stars and the metallicity ([Fe/H]) (Rebolo et al. 1988; Gilmore et al. 1992; Boesgaard 1995; Molaro et al. 1997; Duncan et al. 1997). This *primary* behaviour cannot be easily explained by the standard GCR model: e.g Prantzos et al. (1993) used an ad-hoc hypothesis concerning the time evolution of the CR's escape-length, Abia et al. (1995) introduced artificial time dependences of the CR flux with the metallicity and the star formation rate and Casuso & Beckman (1997) considered differential astration [see also Tayler (1995) and Yoshii, Kajino & Ryan (1997)]. The reason for using these hypotheses is that in the standard GCR model the LiBeB production rates are proportional to the global metallicity of the ISM and to the CR flux. Since the latter is assumed to be proportional to the supernova rate it is, in consequence, also proportional to the production rate of metals in the galaxy. Such a dependence would predict a slope of about two in the B and Be relationships with [Fe/H] rather than a slope of one as the observations show. Furthermore, Duncan et al. (1997) and García-López et al. (1998) have recently shown a nearly constant B/Be ratio of ~ 20 in dwarf stars for a wide metallicity range, although the uncertainties in this ratio are important⋆. This value is still compatible with the idea of a spallative origin of Be and B (e.g Fields, Olive & Schramm 1994). Since this ratio is similar to that observed in the Solar System (Anders & Grevesse 1989) it cannot have experienced large variations during the galactic evolution, which strongly supports the idea of a similar origin for Be and B.

A straightforward interpretation of these results is that the net production rate of Be and B does not depend on the metallic abundance in the ISM, i.e. the light-element production is not dominated by protons and alpha particles colliding with CNO nuclei but by these nuclei colliding with ambient protons and alpha-particles, probably in regions of massive star formation heavily enriched in these nuclei. The γ-ray observations from the Orion

⋆ This B/Be value is obtained taking into account N-LTE effects in the derivation of B and Be abundances nebulae (Bloemen et al. 1994) provide additional support to this point of view since they are consistent with line emission from $^{12}C^*$ and $^{16}O^*$ produced by a large flux of low-energy (< 100 MeV/nucleon) nuclei enriched in C and O. This might represent the first evidence of the existence of a considerable low-energy component in the spectrum of CRs (at least locally), as was suggested by different authors (Meneguzzi, Audouze & Reeves 1971; Canal, Isern & Sanahuja 1980). Since the ejecta of gravitational supernovae (type II, Ib/c) naturally match the above conditions, these objects have been proposed as preferential sites for LiBeB spallation production (Gilmore et al. 1992). The ejecta in these explosions are indeed heavily enriched in CO nuclei and, under some conditions (type Ib/c supernovae), the concentration of these nuclei might even exceed that of H and/or He. Because the yield of CO nuclei in supernovae is almost independent of the metallicity of the progenitor star, the LiBeB produced by spallation during supernova outcomes would have a primary character as is observed for Be and B.

In fact, within the framework of a galatic evolutionary model, Vangioni-Flam et al. (1996) studied the production of Be and B, assuming a low-energy spectrum of the form $\mathrm{q(E)} \sim \mathrm{E}^{-\mathrm{n}}$, with $n = 9$, and constant for $\mathrm{E} \leq 30$ MeV/n in the CRs associated with Orion-like regions. They were able to explain the observed behaviour of Be and B vs. [Fe/H], and they obtained upper and lower limits for the contribution of this mechanism to the galactic evolution of Be and B abundances. Their results show that this mechanism might contribute up to 70% of the observed Be and B abundances and that standard GCR nucleosynthesis is not the main source of ^{9}Be and B in the galaxy. Recently, Ramaty et al. (1997; hereafter RKLR) studied the influence of different spectra and chemical compositions in the CRs produced by supernova on the LiBeB production. They showed from energetic arguments that due to the amount of Be necessary to account for its linear behaviour with [Fe/H], the CNO-rich, He-poor and H-poor CR source compositions are favoured. The observed Be/Fe ratio requires the investment of about 3×10^{49} to 2×10^{50} erg per gravitational supernova in these metallic CR, depending on whether or not H and He are accelerated with metals. Similar arguments led them to conclude that these CRs should have a hard-energy spectrum extending up to at least 50 MeV/n. From the constancy of the observed Be/Fe ratio and metallicity, they also derived the necessary Be yield per supernova that is needed. Assuming a ^{56}Fe yield per SNII (Woosley & Weaver 1995) of ~ 0.11 $\mathrm{M}_\odot$, they obtained a Be yield of 2.8×10^{-8} $\mathrm{M}_\odot$ (within a factor of two of uncertainty from the observed Be/Fe ratio), almost irrespective of the progenitor star metallicity.

In this paper we have assumed that the Be yield from RKLR is representative of the Be produced per gravitational supernova. Since this yield automatically sets the corresponding Li and B yields for a given CR spectrum and chemical composition, we use this to study the impact of such objects on the galactic evolution of the light element abundances. We discuss the results in the framework of different scenarios for the progenitors of type II and Ib/c supernovae and possible mechanisms for the CR acceleration in such objects.

2 THE MODEL

We use the same evolutionary model and approximations for the solar neighbourhood as in Abia, Canal & Isern (1991), which assumes an exponential unenriched infall with an e-folding time of 4.5 Gyr, and age of the galaxy of 13 Gyr. The adopted initial mass function, assumed to be constant in space and time, is that from Scalo (1986) in the mass range $0.5 \leq M/M_{\odot} \leq 100$ and the stellar life-times are from Talbot & Arnett (1971). With these assumptions, the main characteristics of the solar neighbourhood are well reproduced (age-metallicity relation, current fraction of gas, the G-dwarf problem etc.).

Concerning the supernova scenarios, we consider that type Ia supernovae are the outcome of the merging of two white dwarfs in a binary system, their rates being calculated as in Bravo, Isern & Canal (1993). For type Ib and type II supernovae (see below for type Ic) we assume that they are the outcome of the gravitational collapse of massive stars ($M \geq 12$ $M_{\odot}$). It is currently accepted that SNIb are caused by the explosion of the most massive stars, those that have lost their H–rich envelope (probably Wolf–Rayet stars) and even, in some cases, the He–rich one. The outcome will be then a *metallic supernova* in the sense of a CNO-rich and H(He)-poor ejecta, which, according to RKLR, are the energetically favoured supernovae to produce LiBeB by spallation. With these assumptions, our model has to fit the observed evolution of the [CNO/Fe] ratios with metallicity (McWilliam 1997) and the present supernova rates in our galaxy. Assuming that our galaxy is of the Sb morphological type with a luminosity of 2×10^{10} $L_{\odot}$, Capellaro et al. (1997) estimate for our galaxy 4 ± 1 SNIa, 2 ± 1 SNIb+c and 12 ± 6 SNII per millenium, i.e. SNIa/SNIb+c/SNII=1/0.5/3 within a 50% of uncertainty. Finally, if we assume a fixed Be yield per gravitational supernova, we have to reproduce the observed LiBeB abundance evolution, which becomes a prediction of the model.

Throughout the calculations we have assumed a primordial contribution to the lithium abundance of ^{7}Li/H=1.72×10^{-10} (Bonifacio & Molaro 1997) and the contribution of the standard GCR model. We have included the contribution of GCRs using the approximations of the leaky-box model (Meneguzzi, Audouze & Reeves 1971). The flux and the spectrum of CRs have been obtained assuming a spectrum q(E) $\propto$ E$^{-2.7}$ at the source, a scape-length of 10 gcm^{-2} and He/H= 0.08, both constant in time. We assume that the abundances of the CNO nuclei in the accelerated particles scale with the global metallicity (Z/Z$_\odot$) keeping the abundance ratios observed today in the CR's flux. The temporal evolution of the abundance of CNO targets in the ISM has also been taken into account. In fact, this is a prediction of our model. Figures 1 and 2 show the evolution of the Be and B abundances assuming the sole contribution of GCRs and normalizing their spectra at the source to obtain the present-day Be abundance. As expected, the predicted Be and B evolution is steeper than the observed one (continuous line) and the typical spallation B/Be$\sim$ 10 value and the ^{11}B/^{10}B ratio which is always close to 2 are obtained (Figures 3 and 4, continuous line). Furthermore, this model also fails to reproduce the present Li abundance (Figure 5, continuous line).

Now, we introduce the LiBeB production by spallation in gravitational supernovae. We limit ourselves to the case in which the CR particles accelerated in supernovae have a typical shock spectrum similar to that used by RKLR, which extends up to kinetic energies E $\sim$ 10 GeV/n. Once the spectrum has been fixed, and the yield of Be per supernova explosion adopted ($\sim 3 \times 10^{-8}$ M$_\odot$), the Li and B yields only depend on the specific composition of the accelerated particles and ambient medium. If we assume that all gravitational supernovae (SNII and SNIb/c) contribute to the abundances of LiBeB isotopes, we have to consider two different chemical compositions (see Table 1):

Case 1: Ejecta representative of typical SNII (RKLR, model 2, Table 3). This is obtained averaging, with the IMF as a weight, the chemical composition in the ejecta of supernovae from stars in the mass range 12-40 M$_\odot$. The resulting composition resembles that of the present-day CR abundances except that they are less abundant in ^{12}C and protons relative to ^{16}O. The resulting Li and B yields per supernova normalized to that of Be are: ^{6}Li/^{7}Li/^{9}Be/^{10}B/^{11}B=6.9/10/1/4/12.

Case 2: The chemical composition of the ejecta from metallic supernovae (RKLR, model 4, Table 3) is taken to be similar to that of the presently observed CR abundances except for H=He=0. In this case the relative yields are: ^{6}Li/^{7}Li/^{9}Be/^{10}B/^{11}B=2.8/4.4/1/4/10.

Table 1.

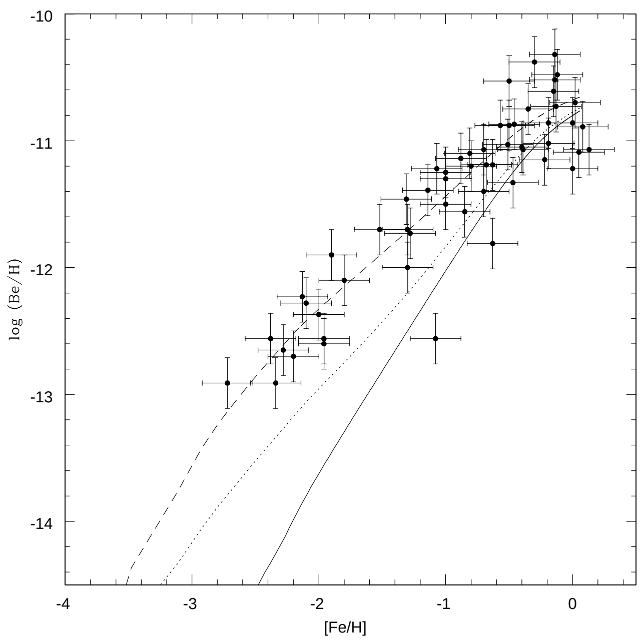

Figure 1. Predicted Be/H vs. [Fe/H] evolution. Continuous line: GCR model alone. Short dashed line: GCR model plus case 1 + case 2. Dotted line: GCR model + case 2 and allowing a fraction A ~ 0.15 of the massive stars in the range 12-40 $M_{\odot}$ to become SNIb/c (see text). Be abundances are taken from the literature (see text). Error bars are indicative.

3 EVOLUTION OF THE LIGHT ELEMENTS

Figures 1 and 2 show the evolution of the Be and B abundances vs. [Fe/H] respectively (short-dashed lines). In all cases it has been assumed that SNIb + c/SNII ≈ 0.2, in agreement with observations. A GCR contribution has also been included to reproduce the present Be abundance. The evolution of the Be abundance is in perfect agreement with the observations while B seems slightly underproduced in the entire metallicity range.

Figures 3 and 4 show the evolution of the B/Be and $^{11}B/^{10}B$ ratios (short–dashed lines). Because of the deficit in the B production, the evolution of the B/Be ratio is marginally consistent with observations at low metallicity. We obtain B/Be≈ 14 instead of 20 as suggested by the observations (Duncan et al. 1997; Garcia–López et al. 1998). Furthermore, this value decreases to ~ 10, which is clearly smaller than the Solar System ratio†. This drop is due to the progressive importance of the GCR production. Both the B/Be and the $^{11}B/^{10}B$ ratios display a maximum around [Fe/H]~ -2.5. The maximum values reflect the average B/Be and $^{11}B/^{10}B$ production ratios in gravitational supernovae (see Table 1). As the metallicity increases these ratios evolve to their GCR values. A similar peak was also

† It is worth noting that the solar B abundance is still uncertain, varying from B/H$\approx 2\times10^{-10}$ to 7×10^{-10} in carbonaceous chondrites (Anders & Grevesse 1989), to the photospheric value of 4×10^{-10} (Khol et al. 1977)

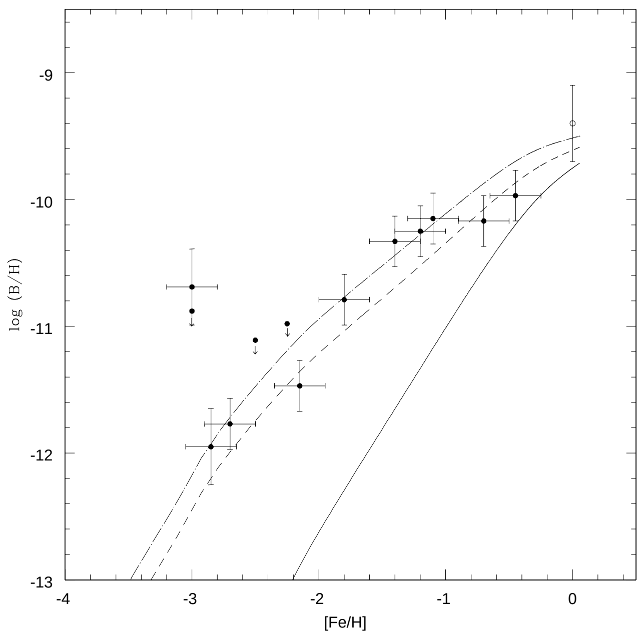

Figure 2. Predicted evolution of B/H vs. [Fe/H]. Continuous line: GCR model alone. Short dashed line: GCR model plus case 1 + case 2. Dash-dotted line: GCR + case 1 and case 2 + including a ^{11}B production by neutrinos of $\sim 3.0 \times 10^{-7}$ $M_\odot$ per gravitational supernova. Data are from García-López et al. (1998).

obtained by Vangioni-Flam et al. (1996). Note however, that there is no evidence for this maximum in the B/Be observations.

The failure to reproduce the B/H vs. [Fe/H] relationship and the B/Be and ^{11}B/^{10}B ratios strongly suggests the existence of an additional source of ^{11}B like neutrino spallation in gravitational supernovae (Domogatski & Nadyozhin 1977; Woosley & Weaver 1995). This mechanism also produces noticeable quantities of ^{7}Li. Since the yields are strongly dependent on the neutrino temperature (a question requiring further study), we have adopted the values necessary to fit the B observations. Figures 2 to 4 (dash–dotted lines) show the results of such a contribution for a ^{11}B neutrino yield of $\sim 3 \times 10^{-7}$ $M_\odot$ per gravitational supernova (note that all stars with M$\geq$ 12 $M_\odot$ can produce ^{7}Li and ^{11}B by neutrino spallation). This value is not inconsistent with the nominal value quoted by Woosley & Weaver (1995) of 6.5×10^{-7} $M_\odot$ and is also in agreement with the production range estimated by RLKR of (2 to 7×10^{-7} $M_\odot$ per supernova). With the above neutrino yield, the predicted B/H vs. [Fe/H] evolution agrees very well with observations as does the B/Be ratio in the whole metallicity range. Concerning the ^{11}B/^{10}B ratio, we obtain a value higher than 4 at early times, although this decreases to ~ 3 at [Fe/H]$\sim$ 0.0. Again, as the time increases, this ratio approaches the GCR value of ~ 2. Nevertheless, we believe that it should not be difficult to get exactly the Solar System ratio of ^{11}B/^{10}B$= 4.05 \pm 0.05$ (Chaussidon & Robert 1995) at

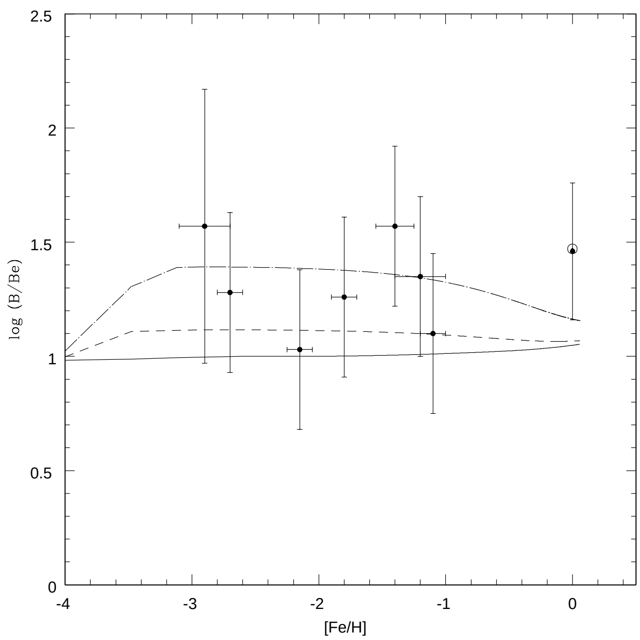

Figure 3. Evolution of the B/Be ratio. Continuous line: GCR model olone. Short dashed line: GCR + case 1 and case 2. Dash-dotted line: GCR + case 1 and case 2 with $\sim 3.0 \times 10^{-7}$ $M_\odot$ of ^{11}B production by neutrinos. Observed $(B/Be)_{N-LTE}$ ratios are from García López et al. (1998). The data point at [Fe/H]=0.0 denotes the Solar System ratio.

[Fe/H]$\approx$ 0.0 just using other evolutionary models constructed with parameters that are still compatible with the observational constraints. In our case, to obtain the Solar System value we need to increase the ^{11}B neutrino yield to $\sim 6 \times 10^{-7}$ $M_\odot$ (still within the theoretical limits), but in this case ^{11}B is overproduced (see Fig. 4 dotted line).

Figure 5 displays the evolution of the Li abundance (dotted line) when an averaged ^{7}Li yield due to neutrinos of $\sim 3 \times 10^{-7}$ $M_\odot$ (Woosley & Weaver 1995) per gravitational supernovae is included. The predicted evolution is compatible with the lithium plateau but fails to account for the present Li abundance and, in consequence, the Solar System ratio ^{7}Li/^{6}Li= 12.5[‡]. Therefore an extra-source of ^{7}Li is needed, probably with a longer lifetime than gravitational supernovae. The long dashed–dotted line of Figure 5 illustrates the behaviour of Li when the contribution of AGB stars in the mass range 1.5-8 $M_\odot$ is included according to the parametrization of Abia, Isern & Canal (1995). In this case, we can adjust not only the evolution of the Li abundance, but we also obtain a ^{7}Li/^{6}Li= 12.5 ratio at the epoch of the Solar System formation.

The above situation presents, however, an important problem concerning the acceleration of the particles in SNII. It seems quite difficult to accelerate the freshly nucleosynthesized

‡ ^{6}Li is not produced by neutrino spallation

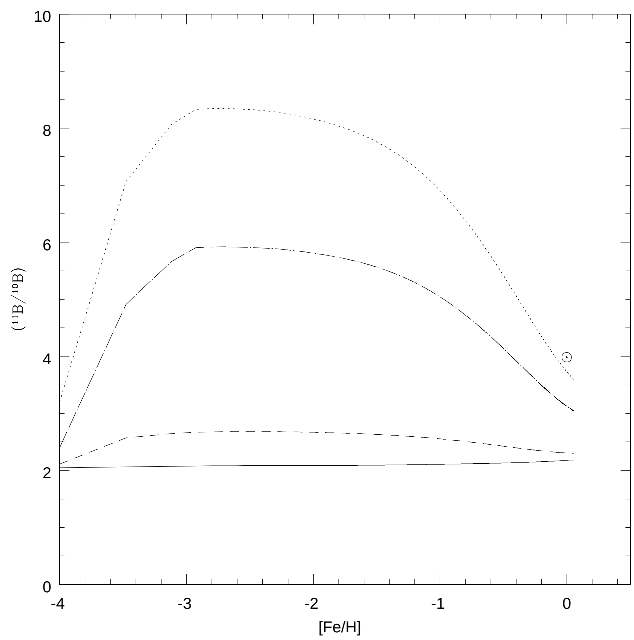

Figure 4. Evolution of the ^{11}B/^{10}B ratio. Continuous line: GCR model only. Short dashed line: GCR + case 1 and case 2 *without* ^{11}B production by neutrinos. Dash-dotted line: GCR + case 1 and case 2 *with* ^{11}B production by neutrinos. Dotted-line: GCR + case 1 and case 2 but forcing a ^{11}B production by neutrinos to match a ratio ~ 4 at [Fe/H]≈ 0.0 (see text). Dotted circle denotes the Solar System ratio

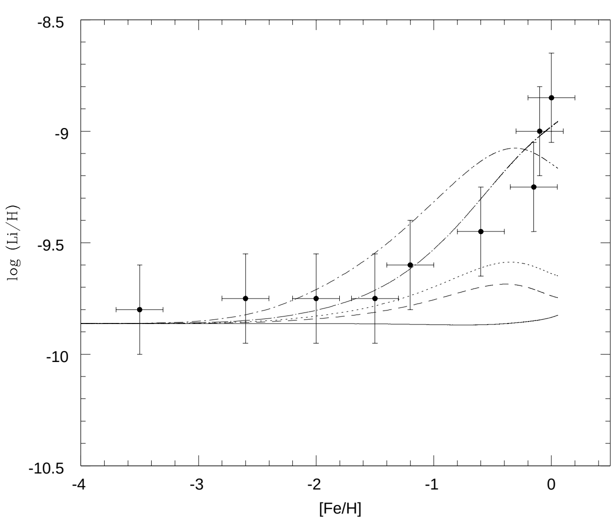

Figure 5. Predicted evolution of the lithium abundance. Data represent the upper envelope of the lithium abundances derived from hot dwarf stars (Rebolo, Molaro & Beckmann 1988). Continuous line: GCR model only. Short dashed line: GCR + case 1 and case 2. Dotted line: the same as in the previous case but including neutrino spallation (see text). Long dash-dotted line: all the above cases plus the ^{7}Li production in AGB stars (see text). Short dash-dotted line: GCR plus case 1 and case 2 but considering CO-poor accelerated particles in SNII explosions (case 1).

matter (CNO nuclei) by the forward SNII shock, since the shock is formed ahead of the region containing the bulk of this matter. In this case, the most important spallation reactions for LiBeB production would be those between alpha-particles and protons colliding with alpha-particles and CNO nuclei forming part of the local circumstellar gas composition. Then, due to the low CNO abundances in CR and ambient medium, a *secondary* behaviour for Be and B is expected. Feltzing & Gustafsson (1994) showed that even assuming a high CNO abundance in the circumstellar gas close to the supernova, very high local CR fluxes ($\geq 10^5$ cm^{-2}s^{-1}) are required in order to reproduce the Be and B linearity with metallicity. This would imply γ–ray fluxes above those observed from supernova remnants and the Galaxy. One possible solution to this problem (as mentioned by RKLR) is to accelerate particles from matter freshly nucleosynthesized by the *reverse* SNII shock. Since this reverse shock will mainly affect the inner matter of the ejecta, the accelerated particles would be depleted of H and He. However, it seems improbable that this reverse shock could form and, even if it did, it would be unlikely it could survive long enough to accelerate particles to the appropriate energies for spallation reactions (Ellison, Drury & Meyer 1997). Detailed studies are still needed to confirm these concepts.

Since it seems that SNIb/c are the sole supernovae capable of accelerating the CO nuclei with a suitable chemical composition, we have also examined the minimum number of these supernovae needed to account for the observations. We assume that a fraction A of the stars that normally explode as SNII, i.e. those in the mass range 12-40 M$_\odot$, can also produce SNIb/c if they are members of close binary systems with the appropriate parameters (Nomoto, Iwamoto & Suzuki 1995). However, to reproduce the Be/H vs. [Fe/H] relationship, A has to be ~ 0.4. Such a value of A means a very high efficiency of SNIb/c formation in close binary systems. In this case, the predicted ratio between SNIb+c and SNII rates would be a factor 3 higher than that observed in our galaxy, which seems quite improbable even taking into account the uncertainties in the determination of supernova rates. Nevertheless, the observed B evolution can still be reproduced using a reasonable value for A(~ 0.15), but increasing the ^{11}B neutrino yield per supernova to its estimated upper limit. However, in this case Be is clearly underproduced (see Fig. 1 dotted line). If this is the case, another primary source of ^{9}Be must then be invoked. A similar result was obtained by Vangioni-Flam et al. (1996).

4 CONCLUSIONS

1) Type Ib/c supernovae seem to be key objects for the production of Be and B by spallation. However, due to their low rates in the galaxy, an additional contribution to the Be and B production by spallation due to type II supernovae is needed. Using a reasonable shock spectrum for the CR source, it is possible to explain the observed linear relation of Be and B abundances with metallicity although a neutrino contribution to B is necessary to account for the observed B/Be~ 20. In this situation, the standard GCR model would play a minor role in the early evolution of the Be and B abundances. Additional sources of ^{7}Li are still necessary to account for the evolution of its abundance. Objects with longer lifetime than supernova like AGB stars (and/or novae) seem to be necessary. A multi-source nature of this element is thus obvious.

2) This scenario has a serious problem with the acceleration of CO-rich and HHe-poor matter in SNII ejecta to sufficient energies for spallation reactions. It is not clear how a huge Li production (due to $\alpha + \alpha$ reactions) in SNII relative to that of Be and B can be avoided if the acceletared particles are CO-poor. If that is the case a production ratio Li/Be≥ 100 is predicted for a wide variety of CR spectra. This high Li production would be incompatible with the lithium plateau observed at low metallicity as shown in Figure 5 (short dash- dotted line).

3) The CR source spectrum shape associated with supernova explosions is another crucial point. It must extend to high kinetic energies (E≥ 50 MeV/n) in order for this scenario to be energetically plausible and to avoid the overproduction of Li with respect to Be and B. Studies of LiBeB production using other CR spectra, not strict power laws, deserve special attention.

4) The existence of an additional source of ^{11}B seems obligatory in order to explain the Solar System's ^{11}B/^{10}B= 4.05 value. Production of ^{11}B by neutrino spallation seems to be the best candidate. In this case, a ^{11}B/^{10}B ratio higher than 4 at low metallicities is predicted, which might be tested by using very high resolution spectroscopy on very large telescopes (Rebull et al. 1997).

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Table 1. LiBeB production ratios for specific cosmic ray and ambient medium compositions

	Accelerated		Particles[a]			Ambient		Medium[b]			Production ratios [c]
	H	^{4}He	^{12}C	^{14}N	^{16}O	H	^{4}He	^{12}C	^{14}N	^{16}O	^{6}Li/^{7}Li/^{9}Be/^{10}B/^{11}B
GCR	240	19	0.76 $Z/Z_\odot$	0.04 $Z/Z_\odot$	$Z/Z_\odot$	1	0.08	ISM	ISM	ISM	3/4.7/1/3.6/7.8
Case 1	100	20	0.19	0.01[d]	1	1	0.08	ISM	ISM	ISM	6.9/10/1/4/12
Case 2	0	0	0.80	0.05	1	1	0.08	ISM	ISM	ISM	2.8/4.4/1/4/10

[a] In all the cases it is assumed a CR's escape-length of 10 gcm^{-2}

[b] The CNO abundances in the interstellar medium (ISM) are those calculated from the chemical evolution model. The ratio ^{4}He/H in the ambient medium is assumed to be constant in time for all models.

[c] The LiBeB production ratios in the standard GCR model change with time because the evolution of the CNO abundances. In the table the current (t∼ 13 Gyr) ratios are shown.

[d] The abundance of ^{14}N in the ejecta of SNII is strongly dependent on the metallicity of the progenitor star. However, this has little effect on the LiBeB production ratios. We adopt here the ^{14}N abundance representative of the ejecta in a SNII of $Z\sim Z_\odot$.