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Testing the primary origin of Be and B in the early galaxy

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Abstract. Beryllium and boron measurements in metal poor stars have had a major impact on our understanding of the origin of the light elements in the universe. Two types of models have been proposed to explain the linear rise of the Be and B abundances as a function of iron observed in metal poor halo stars. In both cases, this linearity indicates that freshly synthesized C and O are accelerated by Type II supernovae and subsequently fragmented into Be and B. One mechanism advocates shock acceleration in the gaseous phase of superbubbles excavated by collective SNII explosions. Because of their short lifetimes, only the most massive stars (with an initial mass greater than 60 $M_\odot$) do not drift out of superbubbles, and participate in BeB production. The second mechanism is based on the acceleration of the debris of grains formed in the ejecta of all SNIIs (originating from stars with initial mass greater than 8 $M_\odot$). Here again, fresh C and O are sped up to cosmic ray energies by shocks.

We propose a possible test to discriminate between the two scenarios. If supernovae of all masses are involved in BeB production, the Be/Fe ratio is constant, since both elements are produced in the same events. Alternatively, when only the most massive stars are involved in Be production, Be/Fe is enhanced at very early times because of the shorter lifetimes of these stars. This predicted difference in the behavior of Be/Fe could be tested by high quality observations at [Fe/H] $\lesssim -3$.

We also note that the solution invoking only the most massive supernovae mimics a flat evolution of both Be/H and B/H as a function of Fe/H at low metallicity, and could thus resemble a "plateau" for these elements despite a lack of a primordial Big Bang nucleosynthesis origin. Consequently, there may be no need to invoke inhomogeneous Big Bang models to explain the initial production of BeB should a plateau be discovered.

Key words: cosmic rays – Galaxy: abundances – Galaxy: evolution – nuclear reactions, nucleosynthesis, abundances

1. Introduction

The origin and evolution of light elements (^{6}Li, ^{7}Li, ^{9}Be, ^{10}B, and ^{11}B) is an important chapter in the development of nuclear astrophysics. In the 70's and 80's the problem of Li, Be and B (hereafter LiBeB) nucleosynthesis has been considered essentially solved by Galactic Cosmic Ray (GCR) spallation (Meneguzzi, Audouze & Reeves 1971, Reeves 1994). The constituent nuclei of the GCRs, protons and α particles, as well as C, N and O (hereafter CNO), form LiBeB via spallation on stationary nuclei in the interstellar medium (ISM). ^{7}Li which has additional sources of production is an exception, as is ^{11}B since the ^{11}B/^{10}B isotopic ratio is not correctly predicted by GCR nucleosynthesis. An artificial solution for the B isotopic ratio had been proposed, based on a non-observable low energy spike in the GCR energy spectrum, the so-called "carrot" (Meneguzzi & Reeves 1975).

New observations in the late 80's prompted a reassessment of the question as to the origin of LiBeB. Be abundance measurements in halo stars were achieved down to [Fe/H] = -1.5 (Rebolo et al. 1988, Ryan et al. 1990). As is generally the custom, square brackets will denote logarithmic abundance ratios by number relative to the solar value. A good fit of the Be evolution was obtained within the limited range of these observations (Vangioni-Flam et al. 1990) by considering the progressive CNO enrichment of the ISM due to stellar production and injection throughout the lifetime of the Galaxy, and supposing that the GCR flux is proportional to the SN rate (SN shocks serving only to accelerate particles out of matter of the same metallicity as that of the interstellar medium). At that time, these evolutionary effects on both GCR nucleosynthesis and the ISM, were sufficient to explain the behavior of Be vs. Fe. Subsequently, however, data were obtained at even lower metallicities for beryllium (Gilmore et al. 1992, Ryan et al. 1994, Boesgaard & King 1993) and a few boron abundance measurements were made over a wide metallicity range (Duncan et al. 1992, Edvardsson et al. 1994). These observations indicated a quasi linear relationship between both Be and B vs. Fe, instead of the quadratic relationship expected if the GCR were accelerated out of the ISM. This increased the general perplexity of potential solutions (Pagel 1991) and gave rise to a new wave of research (Duncan et al. 1992, Walker et al. 1993, Feltzing & Gustaffson 1994, Vangioni-Flam et al. 1994, Cassé et al. 1995, Fields et al. 1995, Bykov 1995, Tayler 1995, Ramaty et al. 1996, Vangioni-Flam & Cassé 1996). The primary origin of beryllium and boron (i.e. the fact that the production rate is independent of the ISM metallicity) indicates that these elements result from the spallation of fresh products of nucleosynthesis (primarily from C and O), rather than nuclei accumulated in the ISM. Thus, we are presented with the challenge to find an appropriate mechanism different from the traditional GCR picture which has become problematic for two reasons. First, as we noted above, if the cosmic rays are accelerated out of the ISM and interact in the ISM, the rising CNO/H abundance in the ISM leads to cumulative Be and B abundances which depend quadratically on the ISM metallicity, and thus is in disagreement with the observations. In addition, Be production in the early Galaxy by GCR accelerated out of the ISM requires the supply of extraordinarily large amounts of energy to the cosmic rays (Ramaty et al. 1997; Ramaty, Kozlovsky & Lingenfelter 1998).

The carrot of Meneguzzi & Reeves (1975) (introduced to explain ^{11}B), having the same GCR composition, is also problematic because the B production by low energy cosmic rays should give rise to a quadratic relationship instead of a linear one exactly as in the high energy case. Moreover on theoretical grounds, a low energy spike throughout the galactic history would lead to an overproduction of Be and B (Lemoine et al. 1998). Finally, Li would be overproduced in the early galaxy by the $\alpha + \alpha$ reactions, spoiling the observed (primordial) Li plateau.

Accelerated particle reactions are not the only sources of boron since carbon spallation by neutrinos in core collapse supernovae (Types II and Ib, hereafter SNII) can also contribute significantly to ^{11}B production (Woosley et al. 1990; Olive et al. 1994, Woosley &Weaver 1995, Vangioni-Flam et al. 1996; Ramaty et al. 1997). This mechanism is particularly interesting because it yields mainly ^{11}B, making ν-induced spallation important for the explanation of the meteoritic B isotopic ratio, ^{11}B/^{10}B = 4.05$\pm$0.2 (Chaussidon & Robert 1995). Vangioni-Flam et al. (1996) found that the neutrino contribution to the total B production should amount to at most $\sim$30%. If the cosmic ray spectrum extends to high energies, ^{11}B production by neutrino spallation is always required since such cosmic rays are not capable of reproducing the meteoritic ratio, but again a $\sim$30% contribution to the total B production from neutrinos appears sufficient (Ramaty et al. 1997).

As the spallation of C, N and O is the only significant source of Be, the linear dependence of [Be/H] with respect to [Fe/H] (at least up to [Fe/H] = -1), or equivalently the approximate constancy of [Be/Fe], implies that a mechanism whereby C and O are accelerated above the spallation thresholds and impinge on the ambient H and He is operative. SNII's are the most plausible sources of accelerated C and O in the early Galaxy. Accelerated N, however, makes only a very minor contribution since it is highly underproduced in SNII's. Among the different scenarios proposed to explain the linear evolution of Be and B, we consider the following two, which shall subsequently be referred to as models (a) and (b).

In model (a) Be and B are produced both by low energy nuclei (hereafter LEN), highly enriched in C and O relative to H and He, and standard GCR accelerated out of the ISM (Cassé, Lehoucq & Vangioni-Flam 1995, Meyer et al., 1997, Ellison et al., 1997). The latter is only dominant at late times in the evolution of the Galaxy. This model was motivated by the observations of a linear dependence of Be and B on Fe which implies a primary source for their production and the observations of C and O deexcitation gamma ray line emission from Orion (Bloemen et al. 1994; 1997). It was suggested (Bykov 1995, Parizot et al. 1997) that the required population of C and O enriched LEN could result from the acceleration, by an ensemble of weak shocks in superbubbles, wherein the seed particles for acceleration originate from the winds of massive stars and the ejecta of supernovae from massive star progenitors. Only the most massive stars (M>60 $M_\odot$), that is those which explode within superbubbles due to their very short lifetime, should be involved in this scenario. In the early Galaxy, these extended acceleration sites would be sustained essentially by SNII exploding in OB associations (Samland 1998). Later on, in the disk phase, WR stars would also participate, since the stellar winds intensify at increasing metallicities (Meynet et al. 1994). The scenario further assumes that the metallicity of the LEN component is independent of the average Galactic metallicity, thereby dominating the Be production in the halo phase ([Fe/H] $\lesssim$ -1 with the GCRs taking over in the disk phase (Vangioni-Flam et al. 1996, 1997).

In model (b) Be and B are produced by standard GCRs accelerated at all epochs of Galactic evolution from the ejecta of supernovae (Ramaty et al. 1997; 1998). This model, motivated by the observed, essentially constant [Be/Fe] in the early Galaxy, envisions the acceleration of the erosion products of high velocity refractory grains formed in a supernova ejecta (Lingenfelter, Ramaty & Kozlovsky 1998). These authors have shown that sufficient O is incorporated in refractory Al_2O_3, $MgSiO_3$, Fe_3O_4 and CaO to account for the GCR source O abundance. They have further argued that the GCR source C abundance could also be understood if the fraction of C ejecta incorporated in refractory grains (mainly graphite) is the same as that of the other main refractories, and they have shown that the standard arguments against the acceleration of the refractory metals out of supernova ejecta are model dependent and answerable in principle. It is thus possible that at all epochs of Galactic evolution the standard GCR would contain sufficient C and O to explain the linear Be evolution. In this scenario, individual SNII with progenitors of the same mass range as that responsible for Fe production (M>8 $M_\odot$) participate in the production of Be and B. Note that the evolution of Be/Fe would be somewhat similar to that of O/Fe since Be, O and Fe are coproduced by SNII at least up to [Fe/H] = -1. If all SNII from 8 to 100 $M_\odot$ participate in oxygen production, the evolution of O/Fe will be similar to that of Be/Fe in model (b).

If the Be in the early Galaxy is indeed produced by particles whose acceleration is related to short-lived very massive stars, then the difference in the lifetimes of the progenitors of Be and Fe and the relative number of stars implied in each case, could also affect the evolution of Be/Fe. In the present paper we shall critically examine the evolution of B and Be in the early Galaxy, taking into account: i) the relative Be yields associated to each mass domain considered and ii) potential time dependent effects due to the mass dependence of the lifetimes of the stellar progenitors of the core collapse supernovae responsible for the production of B and Be. In the following, we reproduce the observed Be evolution through a Galactic evolutionary model and explore the correlated behavior of B considering three plausible B/Be production ratios, in agreement with the results of the nuclear spallation models of various compositions and energy spectra (Vangioni-Flam et al. 1996, Ramaty et al. 1997). The wide range of B/Be ratios explored leaves room for neutrino spallation.

In what follows, we will examine whether or not it is possible, using the existing data on B and Be, to distinguish between models a) and b). In Sect. 2, we will describe the current status of the B and Be data. In Sect. 3, we will describe and develop the proposed test to distinguish between the models and present the results of our calculations. Our conclusions are found in Sect. 4.

2. Data

There is a three-fold advantage in studying Be. First, abundant data exist over a large range of metallicities. It is a pure spallation product not contaminated by neutrino-spallation as is $^{11}\mathrm{B}$ and $^{7}\mathrm{Li}$ or by the stellar production as $^{7}\mathrm{Li}$. And finally, its measured abundance is not significantly altered by NLTE effects which in the case of B are difficult to estimate. For these reasons, we will focus primarily on Be.

The last decade has seen considerable progress since the early observations of Rebolo et al. (1988) and Ryan et al. (1990) of a total of ten low metallicity halo dwarf stars, all yielding upper limits with three potential determinations of a Be abundance. Since then, there have been at least 50 new observations of 25 additional halo dwarfs (Gilmore et al. 1992, Boesgaard & King 1993, Ryan et al. 1994, Primas 1995, Rebolo et al. 1993, Garcia-Lopez, Severino, & Gomez 1995, Thorburn & Hobbs 1996, Molaro et al. 1997). We have compiled the Be data from the literature and show the Be abundances as a function of [Fe/H] in Fig. 1. The data have been combined systematically so that each point corresponds to a single star. Where multiple observations of a star are found, the Be abundances are first adjusted by taking a common set of stellar parameters (surface temperature, surface gravity and metallicity) followed by a weighted average of the different observations. When possible, we have assumed temperatures as given by Fuhrmann, Axer, & Gehren (1993). For example, we have found seven distinct measurements of HD 140283. The Be abundances range from $\log$(Be/H) = -13.25 to -12.85 with assumed surface gravities running from 3.2 to 3.56, temperatures from 5540 to 5814, and metallicities from -2.2 to -2.77. Here, we have taken g = 3.4, T = 5814, and [Fe/H] = -2.6, which reduces the range for $\log$(Be/H) to -13.11 to -12.87 and yields an average $\log$(Be/H) = -12.97 $\pm$ 0.07 for this star.

The large number of Be observations in low metallicity halo stars have shown that the Be/H abundance ratio increases approximately linearly with [Fe/H] up to at least one tenth of the solar metallicity. Because of the multiple observations of many of the halo dwarfs, the errors in the determined Be abundances are relatively small. In contrast, the Fe abundances are particularly uncertain, and in one case, the assumed values of [Fe/H] differ by as much as $\sim$ 0.6 dex. As a conservative estimate for the error in [Fe/H], we have taken 0.2 dex. A linear regression on the data for $\log$(Be/H) vs. [Fe/H] (for [Fe/H] $<$ -1) then yields

$$\log(\mathrm{Be/H}) = (-10.03 \pm 0.18) + (1.18 \pm 0.10)[\mathrm{Fe/H}] \qquad (1)$$

Clearly, this regression indicates a predominantly primary origin for beryllium (secondary Be would give a slope of 2 rather than 1.18 as in Eq. (1)). As yet, the data show no signs of revealing a plateau which could be interpreted as a primordial value for Be as in the case of Li (though see below for a complication on this interpretation). This is of course not a surprise since in standard big bang nucleosynthesis calculations the primordial value of Be/H is $10^{-18} - 10^{-17}$ (Thomas et al. 1993, Delbourgo-Salvador & Vangioni-Flam 1994). Also of interest, is the ratio $\log$(Be/Fe) vs. [Fe/H] as is shown in Fig. 2. Adopting a solar value of $\log$(Fe/H) = -4.465, the weighted mean of the values in Fig. 2 (again for [Fe/H] $<$ -1) is $\log$(Be/Fe) = -5.84 $\pm$ 0.05.

The boron data is taken from Duncan et al. (1997) and Garcia-Lopez et al. (1998) and is also shown in Fig. 1. For those stars in which Be observations can be found, stellar parameters were again chosen uniformly. A fit to the (NLTE) boron data for [Fe/H] $<$ -1 yields

$$\log(B/H) = (-9.50 \pm 0.17) + (0.67 \pm 0.09)[Fe/H] \qquad (2)$$

This fit is actually somewhat flatter than what one would expect due to a simple primary explanation of the origin of B and is due to the two somewhat discrepant points at the lower metallicities. These points show a higher B abundance in part due to the NLTE corrections at low metallicity (Kiselman 1994, Kiselman & Carlsson 1996). Fig. 3 shows the ratio B/Be as a function

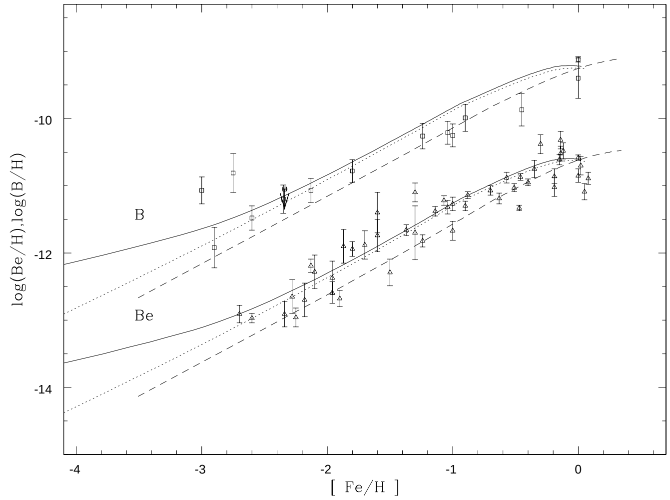

Fig. 1. The evolution of $\log$(Be/H) and $\log$(B/H) with respect to [Fe/H]. The data points for beryllium and boron have been described in the text. The solid curves represent the reference model discussed in Sect. 3, corresponding to a mass range of Be producers between 60 – 100 $M_\odot$, model a). The dotted curve shows the resulting evolution when the source of BeB is extended down to 8 $M_\odot$, model b). The dashed curve shows the effect of varying the iron yields with the stellar mass (Woosley & Weaver 1995) in model b).

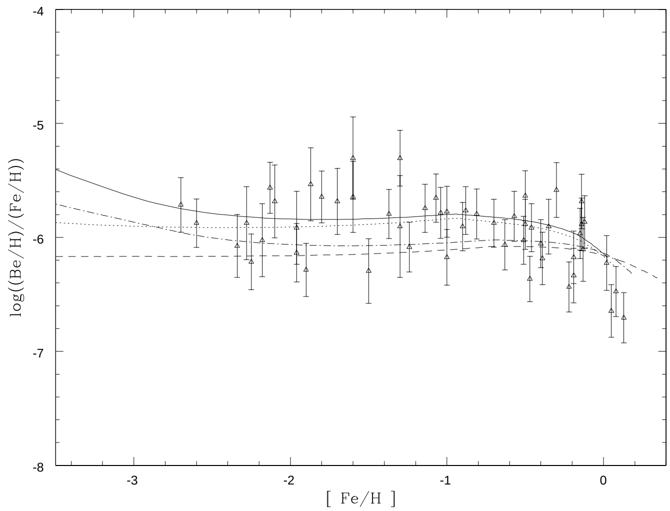

Fig. 2. As in Fig. 1 for the evolution of log(Be/Fe) as a function of [Fe/H]. Also shown by the dot dashed curve is the case of a variable iron yield in model a).

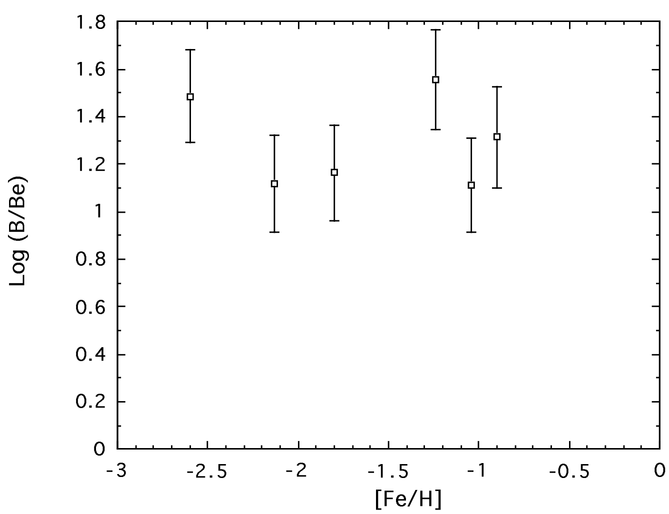

Fig. 3. The data for B/Be as a function of [Fe/H].

of [Fe/H] taking Be abundances from the previously described compilation. Because of the low statistics and because of the relatively large errors in the ratio B/Be, determining a mean value from the data is difficult. Converting an average of the log values of B/Be gives $\langle \mathrm{B/Be} \rangle \simeq 20 \pm 4$, whereas a straight average of the unlogged ratio gives $\langle \mathrm{B/Be} \rangle \simeq 16 \pm 3$. Alternatively, if one assumes that the departure from a linear relationship (in their logs) between B,Be and Fe is simply statistical, assuming a linear fit to the data, gives B/Be $\simeq 26 \pm 21$. The data at present is clearly open to interpretation and more data particularly boron data is needed. As we will argue below more data of both B and Be at low metallicity ([Fe/H] $<$ -3) is needed to learn more about the origin of elements. Thus, in the following we will consider B/Be ratios of 10, 20, and 30.

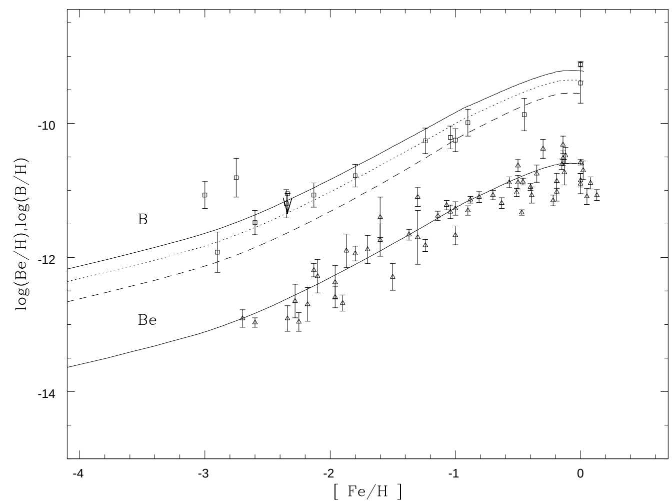

Fig. 4. As in Fig. 1, the evolution of log(Be/H) and log(B/H) with respect to [Fe/H]. The solid curves represent the reference model discussed in the text. Also shown is the resulting evolution when the B/Be yield is fixed at 20 (dotted curve) and at 10 (dashed curve).

3. Models and results

As described above, we compare the behavior of Be and B in the two scenarios selected. To this aim, we exploit differences in both the production processes and astrophysical sites. To summarize, the main differences are as follows. The mass domain for stars participating in BeB nucleosynthesis are 60 – 100 $M_\odot$ for model (a). This mass range is related to the acceleration of gaseous elements in superbubbles. For models (b), the mass range is 8 – 100 $M_\odot$ in relation to the acceleration of grain debris by individual SNII. The variations in composition and spectra are parameterized by the three values of the B/Be ratio. This last parameter (especially for B/Be = 30) also takes into account the possibility of ^{11}B production by neutrino spallation.

In the framework of galactic evolution, model (a) combines two components, the primary LEN playing a major role in the early Galaxy, plus the secondary standard GCR being influential in the galactic disk, with a composition reflecting that of the ISM. The intensity of both mechanisms at each time step is taken to be proportional to the SN rate. Model (b) has a continuous primary component which has a constant source composition. The determining difference with respect to the standard GCR is its primary nature since the composition of the fragmenting nuclei emanates directly from SN and not from the ISM.

In this study we use the formalism developed in Vangioni-Flam et al. (1996). In that work, three components playing a role in the production of the LiBeB elements were considered. To obtain the linear relation between log(Be/H) and [Fe/H] (similarly for B/H), a LEN source from stars more massive than 60 $M_\odot$ was included (C and O interacting on ambient H and He). Standard galactic cosmic ray (GCR) nucleosynthesis (fast p's and α's on ambient CNO) was added. Finally, ν-process nucleosynthesis was taken into account, albeit at a rate less than predicted in the models of Woosley & Weaver (1995) to adjust the ^{11}B to ^{10}B ratio and avoid ^{7}Li overproduction in the early Galaxy. Models (a) and (b) are followed in the same way, except that the standard GCR is absent in model (b) and that its mass domain is extended. Here, the neutrino component is included simply through the varying B/Be ratio.

Before we arrive at our results, a few remarks are useful concerning the neutrino spallation process described in Vangioni-Flam et al. (1996). In that work, a pronounced effect on both the ratios of ^{11}B/^{10}B and B/Be due to ν-spallation was discussed. In both of these ratios, a bump at [Fe/H] $\approx$ -2, was predicted. The bump was due to the fact that ν-process production of ^{11}B which occurs in all stars more massive than about 8 $M_\odot$ is superimposed on other components. At very low metallicity, the contribution of the LEN component is dominant, so it imposes its own B/Be and ^{11}B/^{10}B ratios. Subsequently, the bulk of neutrino spallation happens later due to the time delay correlated to the lifetime of the stars with M $< 60\,M_\odot$. The result is an increase of both ratios, due to the fact that Be and ^{10}B are not produced in the neutrino process while ^{11}B is copiously produced. If the nucleosynthesis of these isotopes was limited to these two processes, there would be a fixed value for the isotopic ratios at [Fe/H] $\gtrsim -2$. But, as the star formation rate is continuously declining, GCR nucleosynthesis, which is included as a separate component, becomes predominant when CNO in the ISM reaches significant abundances. Since its proper production ratios are lower than the other components, B/Be and ^{11}B/^{10}B decreases, and a bump appears.

We note that the ν-process was also predicted to have an effect on the B/Be ratio for standard GCR nucleosynthesis due the combination of a primary source for ^{11}B and only secondary sources for ^{10}B and Be (Olive et al. 1994, Fields, Olive & Schramm, 1995). While there is no data for ^{11}B/^{10}B at low metallicities, it was argued by Duncan et al. (1997) that the lack of evidence for a bump in the B/Be data (shown here in Fig. 3) minimizes a ν-process contribution to ^{11}B. In model (b) however, since the mass domain involved in the production of all isotopes of interest is 8 – 100 $M_\odot$, it is clear that the B/Be and ^{11}B/^{10}B ratios are constant over the galactic lifetime whether or not neutrino spallation is operating. This model freezes out all of the light isotopic and elemental ratios from start, so it is strongly constrained specifically by the solar abundances. Note that neutrino spallation is a necessity in model (b) to get the correct ^{11}B/^{10}B at the solar epoch. In this model, a bump in B/Be or ^{11}B/^{10}B is not predicted.

One should bear in mind however that the data are scarce and somewhat dispersed. A neutrino contribution of the order of 30 % cannot be excluded even in model (a). A constraint concerning neutrino spallation could come from ^{7}Li which should not be overproduced at low metallicity in order to save the Spite plateau (see Fig. 1 in Vangioni-Flam et al. 1996). Model (a), thanks to its combined production processes does not require neutrino spallation to fit the data, although in order to account for the meteoritic B isotopic ratio the LEN component must be confined to very low particle energies, requiring that large amount of energy be supplied to the LEN (Ramaty et al. 1997). Given a dramatic improvement in the data for B/Be, a constant ratio as a function of [Fe/H], would imply either model (a) with a greatly reduced ν-spallation contribution, or a model such as (b).

Returning to our main goal, we now try to ascertain to what extent the models can be tested by the existing and future data. To this end, we will consider models in which the site for the production of fast C and O nuclei are SNII, in the mass range 8 – 100 $M_\odot$ (model b) and in the mass range 60 – 100 $M_\odot$ (model a) since the mass domain is in fact the most discriminating characteristic. We will also consider variations in the iron yield. Generally we have assumed that the iron yield is 0.07 $M_\odot$ over the entire range 8 – 100 $M_\odot$ as observed in SN 1987 A. Alternatively, we will assume a yield of 0.07 $M_\odot$ of Fe below 20 $M_\odot$, and a yield proportional to the progenitor mass (Woosley & Weaver 1995) at higher masses. It is clear that at [Fe/H] < -1 the Fe contribution of SNIa is insignificant. We adjust also the B/Be ratio (at a fixed value of Be) to 10, 20, 30 corresponding to a range of possible compositions and energy spectra of the primary component in agreement with the observations (Sect. 2).

One can also vary the parameters of galactic chemical evolution such as the initial mass function (IMF) or the star formation rate (SFR). We have chosen a simple power law form for the IMF $\phi(m) \propto m^{-2.7}$ which is appropriate for massive stars (Scalo 1986, Kroupa & Tout 1997). Lowering the slope to a Salpeter value of 2.35, changes the overall number of massive stars and perhaps minimizes the GCR contribution to Be production in model (a). We will not consider a variation in the IMF any further here. We consider a SFR which is proportional to the gas mass fraction, $\psi = 0.3\sigma$. Varying the SFR would affect the evolution of B, Be, and Fe with respect to time, however, here we are only considering the evolution of B and Be with respect to Fe and the exact form of the SFR is unimportant. Our reference model is taken from Vangioni-Flam et al. (1996) and assumes a constant iron yield, LEN from only the most massive stars ($>$60 $M_\odot$) with B/Be set at 30. Departures from the assumption of a closed box evolutionary model will be considered elsewhere (Fields et al. 1998).

The evolution of Be/H and B/H are displayed in Figs. 1 and 4 and the ratio Be/Fe in Fig. 2. The solid curves in all of the figures correspond to our reference in model (a) described above. While it is clear that this model adequately describes the Be/H data, it falls short of the two lowest metallicity B/H observations which have been corrected due to NLTE effects (Kiselman 1994, Kiselman & Carlsson 1996, Garcia-Lopez et al. 1998). The corrections in these two points are about 0.8 and 0.9 dex, i.e. nearly an order of magnitude in abundance.

The effect of decreasing the lower limit of the progenitor mass down to 8 $M_\odot$is shown in Figs. 1 and 2 by the dotted curves. The net consequence is a reduced Be and B abundance at early times (low [Fe/H]). In terms of the ratio Be/Fe, this corresponds to a flat evolution vs [Fe/H] since now Be and Fe are produced in the same stars. This can be explained as follows: In both cases, iron is produced by all SNIIs (8 – 100 $M_\odot$). If one assumes that Be is only produced by the most massive stars (model a), the cumulative production of Be is concentrated in a narrower range of masses, and then, each relevant SNII should produce more BeB per Fe nucleus ejected than in the other case (where the Be production is from 8 – 100 $M_\odot$). Since these stars are short lived, they give rise to a higher Be/Fe, at the very beginning of the galactic evolution. The required increase in the BeB yield per ejected Fe nucleus has energetic consequences that have been explored by Ramaty et al. (1997).

Hopefully, the predicted different evolutionary curves will be tested in the near future but at present, given the present range of data, [Fe/H] $>$ -3, it is not possible to distinguish between these different sets of assumptions. More observations at lower metallicity ([Fe/H] $<$ -3) are needed. Note that the effect of shortening the mass range for the sources of the LEN flattens the evolution curves at low metallicity (solid curve in Fig. 1). This begins to have the appearance of a plateau-like evolution. Another mechanism for producing a plateau in Be/H at the lowest metallicities, accretion of interstellar matter during repeated encounters of the metal deficient halo stars with gas in the Galactic plane was suggested by Yoshii et al. (1997). This mechanism, however, requires that the Be evolution be steeper than that of Fe. But the constancy of (Be/Fe (see Fig. 2) clearly shows that this is not the case. Therefore, if a plateau in Be and B vs Fe shows up observationally, one could not necessarily conclude that Big Bang nucleosynthesis (Orito et al. 1997 and references therein) took place under inhomogeneous conditions in the early Universe.

Also shown in Figs. 1 and 2 are the effects of varying the iron yields in massive stars as described above (Woosley & Weaver 1995). Shown in these figures by the dashed lines are the results of varying the iron yield in model b) and thus should be directly compared with the dotted curves. Due to the the normalization at [Fe/H] = 0, we find a shift in the curves relative to the case of a constant iron yield in model b). This is because massive stars give off more Fe for a fixed amount of Be and B produced. As expected this corresponds to a diminished Be/Fe ratio as seen in Fig. 2. Also shown in Fig. 2 is the effect of the varying iron yield in model a). The effect is the same, and more importantly still allows for the distinction between models a) and b) at very low metallicity. The dispersion in the data and the lack of very low metallicity data make it difficult at this time to distinguish between the various models. Note that in all cases, the contribution of SNIa to the iron production is included as follows : each SNIa produces 0.6 Mo and the rate of explosion is taken constant, about 0.2 Snu (SN per 100yr and by 10^{10}LBo), as observed (Cappellaro et al. 1997).

Finally, we have considered the effects of the variation of the B/Be ratio in the LEN models. In the reference model, the B/Be ratio was chosen to be 30. In Fig. 4, we show the results for $\log$(B/H) vs. [Fe/H] for B/Be = 30 (solid curve), 20 (dotted curve) and 10 (dashed curve). Given the uncertainties in the data, all of these choices must be deemed consistent (with the same caveat concerning the two lowest metallicity points described above). The case with B/Be = 10 can of course more easily accommodate a higher rate of GCR nucleosynthesis but this would lead to a modification to the late evolution of Be or an increased contribution from ν-spallation (cf. Vangioni-Flam et al. 1996).

4. Conclusion

Be and B nucleosynthesis by galactic cosmic rays accelerated out of the interstellar medium predicts a secondary origin for Be and B so that they evolve with the square of the metallicity. In contrast, the data have shown that these elements track the iron abundance linearly and therefore require a new source for their production. Two possible primary components have been compared, a low energy nuclear component accelerated in galactic superbubbles (M > 60 $M_\odot$, model a) and C and O from grain debris accelerated by supernova shock waves (M > 8 $M_\odot$, model b). We predict a different behavior for Be/H and B/H at [Fe/H] < -3 according to the domain of masses of the Be producers. For stars between 8 – 100 $M_\odot$ there is a strict linearity whereas, if the mass range is reduced (60 – 100 $M_\odot$) there is a flattening of the evolution curve at very low metallicity. The existing Be and B data are presently not sufficient to distinguish between the various models. New data at low metallicities, [Fe/H] $<$ -3, are essential for this purpose. Finally, the restricted mass range of the LiBeB stellar progenitor (case a) flattens the evolutionary curve and it appears plateau-like. This trend could interfere with a possible interpretation in terms of inhomogeneous big bang nucleosynthesis.

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