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Letter to the Editor

Bimodal production of Be and B in the early Galaxy

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Abstract. Recently models based on the acceleration of metal-rich material inside superbubbles have been proposed to account for the observed abundances of Be and B in metal-poor halo stars. We analyse some of the implications of these models for the distribution of the Be/O and B/O abundance ratios. In particular, we discuss the possible scatter in the data and argue that LiBeB production in the very early Galaxy was probably bimodal, with isolated supernovae giving rise to a low-efficiency mechanism, and collective supernovae exploding in an OB association inducing a high-efficiency mechanism. This should produce two populations of halo stars, one with high L/M ratios (light elements/metals), and the other with L/M ratios about ten times lower. The relative weight of these two populations depends on the fraction of supernovæ exploding inside superbubbles. In this context, we discuss the recent observation of the B-depleted, Li-normal star HD 160617 (Primas, et al., 1998), as well as the reported spread in the Be data at $[\mathrm{Fe/H}] \sim -2.2$ (Boesgaard, et al., 1999b). Finally, we predict that Be will be found to be even more deficient than B in HD 160617.

Key words: acceleration of particles – nuclear reactions, nucleosynthesis, abundances – ISM: cosmic rays – Galaxy: abundances

1. Introduction

In the last decade, the high sensitivity of the KECK telescope and the HST has allowed numerous observations of the Be and B abundances in halo stars having very low metallicities, down to $[\mathrm{Fe/H}] = -3$, i.e. $\mathrm{Fe/H} \sim 10^{-3}(\mathrm{Fe/H})_\odot$ (e.g. Molaro, et al., 1997; Duncan, et al., 1997; Garcia-Lopez, et al., 1998). These observations show a clear proportionality between the Be, B and Fe abundances. Considering that the light elements are secondary nuclei synthesized by spallation from C and O nuclei (Reeves, et al., 1970), it had been expected instead that their abundance would increase as the square of the metallicity (Vangioni-Flam, et al., 1990). This *secondary behavior* follows directly from the standard Galactic Cosmic Ray Nucleosynthesis (GCRN) scenario (Meneguzzi, et al., 1971), in which most of the Be and B are produced by energetic protons and α particles interacting with C and O nuclei accumulated in the ISM (direct spallation).

The most natural way to account for the unexpected constancy of the Be/Fe and B/Fe ratios is to assume that Be and B nuclei are mainly produced by *reverse spallation*, i.e. by energetic C and O nuclei accelerated shortly after their release into the interstellar medium (ISM), and interacting with ambient H and He nuclei (Duncan, et al., 1992; Cassé, et al., 1995). This makes the production rates independent of the ambient metallicity, and the amount of light elements (L elements) in the Galaxy therefore increases jointly with the most abundant metals (M elements), namely C, O and Fe. This behavior is refered to as *primary*, and has been shown to follow naturally from the assumption that most of the supernova (SN) explosions occur in OB associations. This is the heart of the so-called superbubble models, whose main lines we recall in Sect. 2.

Some recent observations have suggested that [O/Fe] continues to decrease at the lowest metallicities, rather than reaching a “plateau” value which is the same for all metal-poor stars. These observations are still controversial (Fulbright & Kraft, 1999), although they could be accounted for by allowing for different ‘mixing times’ for the freshly ejected Fe and O nuclei in the ISM (Ramaty, et al., 1999). They have raised the question whether a primary process for Be and B production in the early Galaxy is still needed (Fields & Olive, 1999). According to both energetics considerations (Ramaty, et al., 1999; Parizot & Drury, 2000) and a detailed analysis of the available data (Fields, et al., 2000), it is now widely agreed that the answer is yes, at least at a metallicity lower than a so-called transition metallicity, Z_t, say for $\log(Z_\mathrm{t}/Z_\odot) \equiv [\mathrm{O/H}]_\mathrm{t} \lesssim -1.5$. In this paper, we concentrate on the very early Galaxy, when the primary behavior dominates, and discuss the implications of the superbubble model for the distribution of the (light elements)/(metals) ratios (namely Be/O and B/O, or L/M for short) in very metal-poor stars.

2. The superbubble models

In the very early Galaxy, the interaction of energetic particles (EPs) having the ISM composition would produce very little Be and B, because the C and O nuclei are so rare. Simple energetics considerations thus indicate that Be and B can be significantly produced only if the EPs have a composition richer in C and O than the global ISM. This is the reason why the only viable models proposed so far involve the acceleration of C- and O-rich material inside a superbubble (Higdon, et al., 1998; Parizot & Drury, 1999c,2000, Bykov, 1999; Ramaty et al., 1999; Bykov., et al., 2000). Indeed, repeated SNe occurring in an OB association are known to generate a superbubble (SB) with a typical radius of order 300 pc, filled with hot, tenuous gas, and composed of the metal-rich ejecta of the SNe having already exploded, possibly diluted by the swept-up ambient material (of essentially zero metallicity in the early Galaxy).

As discussed in detail in Parizot & Drury (1999c), the SB models for Be and B Galactic evolution are based on the following sequence of events: 1) CNO nuclei are ejected by SNe inside the superbubble; 2) the CNO nuclei are mixed with some ambient, metal-poor material; 3) the resulting material (including CNO) is accelerated; 4) LiBeB is produced by spallation through the interaction of these ‘superbubble energetic particles’ (SBEPs) with the metal-poor material in the supershell and at the surface of the adjacent molecular cloud; 5) the LiBeB produced is mixed with the CNO ejected by the SNe, which leads to a unique value of the L/M ratios throughout the superbubble (and part of the supershell); 6) new stars form by condensation of this gas, after possible dilution by ambient, metal-poor gas (from the supershell or the adjacent molecular cloud. All these new stars then have the same L/M ratios, but possibly different overall metallicity.

Apart from this common ‘astrophysical background’, the models proposed differ in some of their assumptions, notably relating to the composition and spectrum of the metal-rich EPs. Ramaty et al. note that the current composition and spectrum of the cosmic rays (CRs) provide a Be production efficiency sufficient to explain the high L/M ratios observed in halo stars. This is reminiscent of the original result of Meneguzzi et al. (1971), which is the heart of the GCRN scenario for light element production (Vangioni-Flam, et al., 1990; Fields & Olive, 1999): multiplying the light element production rates from GCRs by the age of the Galaxy, one obtains approximately the total amount of Be and B present today in the Galaxy. However, while the GCRN scenario assumes that the CR composition follows that of the ISM (i.e. is richer and richer in C and O) and therefore does not reproduce the primary behavior of Be and B in the early Galaxy, Ramaty et al. assume that the CR composition does not change during the whole Galactic evolution. This is indeed expected if the CRs are made of SN ejecta accelerated inside a superbubble, by the shock of subsequent SNe. Their composition is then almost independent of the ISM metallicity, provided that the SN ejecta are not well mixed with the ambient matter before the acceleration occurs.

In our model (Parizot & Drury, 1999c), we argue that an acceleration mechanism different from the diffusive shock acceleration could occur inside SBs, because of the specific physical conditions prevailing there (hot, tenuous gas, strong magnetic turbulence, multiple weak shocks…). Such a mechanism has been described by Bykov (1995,1999) and leads to a different energy spectrum, which we refer to as the ‘SB spectrum’, and

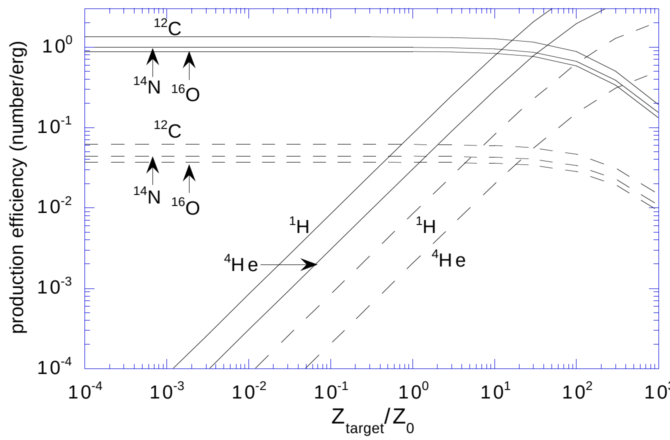

Fig. 1. Be production efficiency by spallation for different projectiles, in numbers of Be nuclei produced per erg of EPs injected, as a function of the ISM (target) metallicity. Plain: SB spectrum. Dashed: CRS spectrum.

which is flatter than the cosmic-ray source spectrum (CRS) at low energy, say below a few hundreds of MeV/n (for a discussion, see Parizot & Drury, 2000). The actual shape of the spectrum above this ‘break’ (whether a steep power-law or the standard CRS shape in p^{-2}) is irrelevant here, since it does not affect the Be and B production efficiency. We adopt the following shape for the SB spectrum: $Q(E) \propto E^{-1}$ up to $E_{\rm break} = 500$ MeV/n, and $Q(E) \propto E^{-2}$ above.

As can be seen from Fig. 1, this spectrum makes the light element production more efficient than the standard CRS spectrum, so that the same amount of Be and B can be produced by less metal-rich EPs. In particular, the observed L/M ratios in halo stars can still be accounted for if one allows for a perfect mixing of the SN ejecta with the metal-free material swept-up and evaporated off the supershell, before the acceleration occurs (Parizot & Drury, 1999c,2000). This is suggested by the comparison between the mixing time inside a superbubble ($\sim 10^6$ yr; see Parizot & Drury 1999c) and the typical age of a superbubble ($\sim 3\,10^7$ yr). In the following, we analyse the common and distinctive implications of the above models for the distribution of the L/M ratios in halo stars.

3. Intrinsic scatter in the L/M ratios

As recalled above, the constancy of the L/M ratios in the framework of SB models relies on the mixing of the primary SN ejecta with the secondary light elements produced by the SBEPs, before the formation of a new generation of stars. In practice, however, such a mixing cannot be perfect and the value of the local L/M ratio is expected to vary from one place to another. In addition, the formation of new stars can occur before all the massive stars explode and/or the induced LiBeB production occurs. As a result, stars with somewhat different L/M ratios should form from a given superbubble, and this should be observed as a scatter in the Be and B data. This is a common prediction of any SB model. However, quantitatively, the amplitude of the scatter depends on the mixing of the gas inside the SB, and of the SB gas with the ambient supershell. Therefore, a model which assumes that the SN ejecta are well mixed with the ISM evaporated inside the SB (Parizot & Drury) predicts a smaller dispersion than a model in which the SBEPs are almost pure ejecta (Ramaty et al.), not diluted with ambient gas. The exact distribution of the L/M ratios expected in the framework ot these two models is not calculated in this paper, because it depends on the details of the gas dynamics inside the SB and the surrounding shell, as well as on the star formation dynamics. Instead, we argue that the accumulation of Be, B and O data could optimistically provide an interesting way to constrain the models, through the statistical description of the scatter in the elemental ratios.

In fact, one might already conclude from the very existence of a well defined correlation between Be and O (or B and O) that the secondary light elements must be quite well mixed with the primary ejecta (CNO) before new stars form. This is an argument in favour of our model, because a good mixing between the CNO inside the SB and the LiBeB produced in the SB shell first requires a good mixing of the gas inside the SB itself. However, stronger conclusions cannot be drawn until more data are available and the error bars become small enough to allow for a direct measure of the scatter in the L/M ratios. It is worth noting also that a larger dispersion should be found for Be than for B, since part of the boron is expected to be produced along with C and O in the course of SN explosions (by neutrino-spallation; Woosley, et al., 1990), and thus be 'ready-mixed' inside the SBs.

The above source of scatter in the L/M ratios is inherent in the SB models. It results from the fact that the light elements are produced in a different place from CNO, namely in the shell rather than inside the SB, where the gas in well mixed. In the following section, we discuss another source of dispersion in the L/M ratios of low-metallicity stars, resulting from the fact that SBs do not cover the whole volume of the Galaxy and therefore an other Be and B production mechanism dominates in the regions distant from SBs.

4. Bi-modal LiBeB production

The vast majority of spallogenic Li, Be and B nuclei are produced by particles of relatively low-energy, which are just the most numerous. Now since only the SBEPs of highest energy can diffuse away from superbubbles, through the dense shell, without losing their energy through coulombian losses, the LiBeB production induced by the SBEPs outside the superbubbles is very small. Any isolated supernova exploding in the 'unperturbed' ISM (i.e. far from SBs) then enriches the ambient gas with freshly synthesized C and O without being accompanied by an equivallent production of LiBeB. The gas around such a SN can thus show very low L/M ratios, unless another mechanism produces LiBeB in the same region. Several processes can be invoked for that purpose. First, the standard GCRN: the shocks created by isolated SNe accelerate CRs from the unperturbed ISM (mostly protons and α-particles) which then interact with the ambient CNO. The ISM abundance of CNO being very low in the early Galaxy, the resulting LiBeB production efficiency is much smaller than in SBs. The corresponding L/M production ratios are represented in Fig. 2: they increase linearly with metallicity, as expected for GCRN.

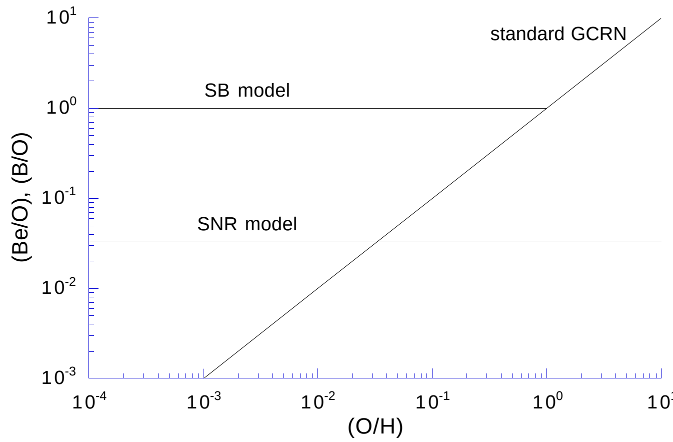

Fig. 2. Schematic view of the L/M production ratios as a function of the ISM metallicity, as expected from the GCRN scenario, the SB model and the SNR model (Parizot & Drury, 1999a,b). The abscissa is normalized to the metallicity when GCRN dominates the LiBeB production, i.e. approximately between $[\mathrm{O/H}] = -1.5$ and -2 (Fields, et al., 2000; Parizot & Drury, 2000), and the ordinate to the L/M ratios at this time. The intrinsic scatter around each line is not shown.

If this were the only production mechanism of light elements in the unperturbed ISM, one should expect to find extremely low L/M ratios at very low Z. However, we have shown in Parizot & Drury (1999a,b) that most of the metal-free CRs accelerated at the shock of an isolated SN are actually confined inside the supernova remnant (SNR) during the Sedov-like phase, and interact there with freshly ejected C and O nuclei to produce significant amounts of Be and B. This means that isolated SNe also produce LiBeB locally, where it is easily mixed with the fresh CNO. We evaluated the production efficiency for this mechanism to be about one order of magnitude lower than in superbubbles. The resulting L/M ratios are then about 10 to 30 times below the most common values (obtained with the SB model), and should be considered as a lower limit for L/M ratios in halo stars (provided no depletion occurs after star formation, as can be checked from the Li abundance). This is represented by the lower horizontal line in Fig. 2.

At very low metallicity, we thus predict a bimodal production of Be and B, with SBEPs leading to a high efficiency mechanism (any of the SB models) and CRs accelerated at the shock of isolated SNe leading to a low efficiency mechanism (SNR model, Parizot & Drury, 1999a,b). This results in a bimodal distribution of the L/M ratios, as schematically shown in Fig. 3 (left). Note that the relative weight of the two 'modes' depends on the fraction of stars exploding in OB associations, and the fraction of stars forming far from SBs. At higher metallicity, when the Be and B production by GCRN exceeds that of the SNR model, the distance between the peaks gets smaller, and it is hard to distinguish between bimodality and the scatter described in the previous section. This is shown in Fig. 3 (right).

The ideal picture described above would be correct if there were no mixing between the gas processed inside SBs (or their

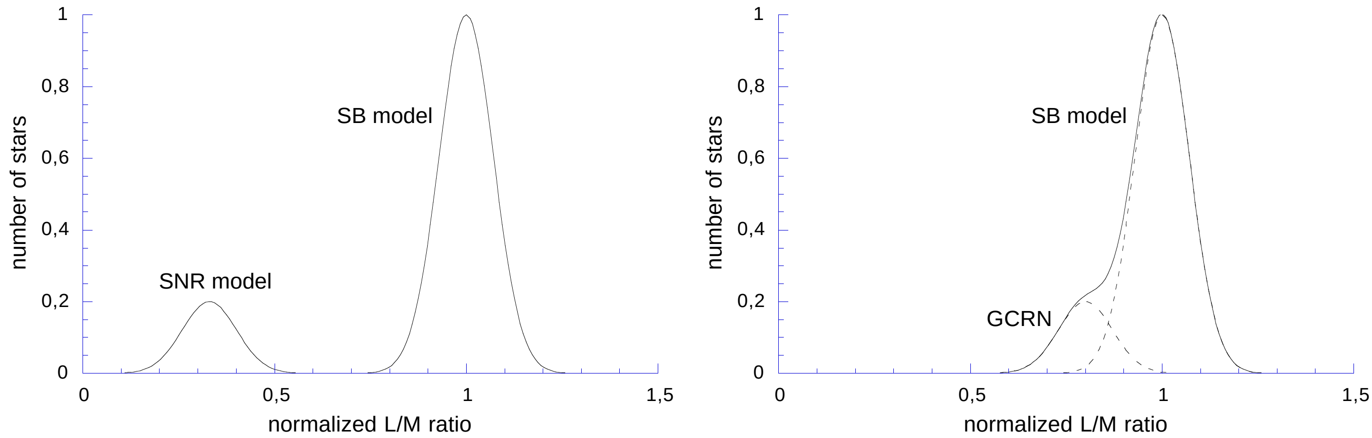

Fig. 3. Schematic view of the histogram expected for the L/M ratios in low-metallicity stars. Left: very metal-poor stars, $(\mathrm{O/H}) \leq 10^{-2}$ with the normalization of Fig. 2. Right: intermediate metallicity, here (O/H) $= 0.8$.

shells) and the general ISM. In practice, this is only true during the first few 10^8 years of Galactic chemical evolution, when the Galaxy is still largely inhomogeneous. Later on, gas with high L/M ratios will 'pollute' the gas with low L/M ratios, leading to a broad L/M distribution, rather than two distinct peaks. Therefore, data at very low-metallicity (say at $\mathrm{O/H} \lesssim 10^{-3}(\mathrm{O/H})_\odot$) are needed to fully test the model. Most importantly, since the Li abundance in the early Galaxy is dominated by the primordial ^{7}Li, and thus unaffected by spallative processes, only Be and B should be underabundant in the low L/M stars. The latter should thus show normal Li abundance, and underabundant Be and B. Interestingly enough, Primas et al. (1998) reported such a behavior for the population II star HD 160617, with a deficiency of ~ 0.5 dex in B, at [Fe/H] ~ -1.8. As recalled by the authors, no stellar depletion process can be responsible for the low B abundance observed, as any such process would deplete Li much more than Be, because of its lower nuclear destruction temperature.

We also wish to draw attention on the recent report by Boesgaard et al. (1999c) on two pairs of stars, (HD 84927, BD +203603) and (HD 94028, HD 219617), having the same stellar parameters (which limit the risk of systematic errors in the derivation of the elemental abundances) but Be abundances differing by as much as 0.3 and 0.6 dex, respectively, at metallicities around [Fe/H] ~ -2.1 and ~ -1.5 (or [O/H] ~ -1.4 and ~ -0.85). This amounts to "depletion" factors of respectively 2 and 4. It is still not clear whether these differences are due to variations in the Be production efficiency or to poor mixing of the SN ejecta with the gas containing the secondary elements produced by spallation (cf. Sect. 3). Additional observations at lower metallicity should allow us to draw more compelling conclusions in the next few years.

5. Conclusion

We have shown that the SB models predict a scatter in the L/M ratios observed in halo stars. In the next few years, the statistical analysis of this scatter (measured thanks to smaller error bars) should provide information about the SB dynamics and the star formation mechanism around SBs. The accumulation of data should allow us to distinguish between the two current SB models (good or poor mixing of the gas inside and around SBs).

The models also predict a 'bi-modal' production of Be and B in the early Galaxy, with collective SNe giving rise to a high-efficiency mechanism providing the observed L/M ratios (SB model), and isolated SNe giving rise to a low-efficiency mechanism and L/M ratios 10 to 30 times lower (SNR model). Both processes are local, respectively inside superbubbles (or their shells) and inside SNRs, and independent of the ambient ISM metallicity, as required by the observed or inferred constancy of the L/M ratios at very-low metallicity. In addition to these processes, the standard GCRN is expected to occur on the Galactic scale, but at a lower rate until the ISM metallicity reaches about 3 to 10% of the solar metallicity. In any case, if two populations of stars can be identified with respectively high and low L/M ratios, the determination of their relative weight will give information about the statistics of SN explosions in OB associations.

We also predict that Be will be found more deficient than B in the so-called B-depleted stars, of which HD 160617 could only be a first example. On the other hand, if low-metallicity stars can be observed with both strongly deficient Be *and* B, with approximately the same apparent "depletion", this would imply that the primary component, i.e. the ν-process, is not dominant for B, and that we have to find an other process to account for the observed ^{11}B/^{10}B ratio. This would put a strong constraint on light element production, probably requiring the existence of very abundant low-energy 'cosmic-rays' ($E \sim 10-30$ MeV/n), powered by an energy source still to be determined.

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