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Spallative production of Li, Be and B in superbubbles

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Abstract

We investigate the spallative production of the light elements (Li, Be and B) associated with the evolution of a superbubble (SB) blown by repeated supernova explosions in an OB association. It is shown that if about ten percent of the SN energy can power the acceleration of particles from the material inside the SB, the observed abundances of LiBeB in halo stars, as a function of O, can be explained in a fully consistent way over several decades of metallicity. We investigate two different energy spectra for the EPs: the standard cosmic ray source spectrum and a specific 'SB spectrum' as results from Bykov's SB acceleration mechanism. We find that the latter spectrum is more efficient in producing LiBeB, and that the SNR spectrum can be reconciled with the observational data if an imperfect mixing of the SN ejecta with the rest of the SB material and/or a selective acceleration is invoked (enhancing the C and O abundance amongst the EPs by a factor of ~ 6). One consequence of the model is that the observed linear growth of Be and B abundances as a function of the metallicity expresses a dilution line rather than a continuous, monotonic increase throughout the Galaxy. We also find that the recent ^{6}Li observations in halo stars fit equally well in the framework of the SB model (see Parizot & Drury, 1999c, for more details).

1 Introduction:

New observational data on the abundance of the light elements (Li, Be and B, or LiBeB for short) in the halo stars has led to a reconsideration of the LiBeB nucleosynthesis processes in the Galaxy. It is generally accepted that these elements are mainly produced by spallation, as a result of the interaction between energetic particles (EPs) and the interstellar medium (ISM) (except for the part of ^{7}Li which is primordial and a possibly significant fraction of the ^{11}B with neutrino-spallative origin). However, the standard scenario in which the EPs are cosmic rays accelerated out of the ISM and interacting with the whole Galactic gas predicts a quadratic increase of the Be (and B, and ^{6}Li) abundance with respect to the ambient metallicity, in contradiction with the observational data showing a linear increase instead (e.g. Ramaty et al., 1997; Vangioni-Flam et al., 1998). In an accompanying paper (these proceedings, OG.3.1.18) we have analysed two possible scenarios accounting naturally for this qualitative behavior of the Be abundance, without dropping the basic idea that Be is produced by spallation reactions induced by EPs accelerated from isolated supernovae (SNe) in the ISM. However, we have shown that none of these processes can fulfill the quantitative requirements, and in fact underproduce Be by one or two orders of magnitude. Analysing the reasons for the failure of both standard and revised scenarios, we have suggested that a model in which the EPs are accelerated within superbubbles (SBs) should considerably improve the situation. Here, we investigate such a model and show that it can indeed account for the qualitative *and* quantitative behavior of LiBeB evolution in the early Galaxy. Interestingly enough, this model does not require any additional sources of energy, but only takes advantage of the collective effects of supernovae exploding in OB associations, instead of individual (isolated) explosions.

2 Description of the superbubble model:

As is known from the observations, most of the massive stars in the Galaxy are formed in associations (Melnik and Efremov, 1995) and generate superbubbles which expand owing to the cumulated energy released by several consecutive SNe. The SB interior is filled with hot ($T > 10^6$ K), tenuous ($n \leq 10^{-2}$) gas, made of i) the ejecta of previous supernovae and possible winds of massive stars and ii) the interstellar material evaporated off the shell or embedded clouds. When a new supernova explodes within an already formed superbubble, part of its energy powers some acceleration process and goes into EPs which then induce spallation reactions by which a certain amount of LiBeB is produced.

To calculate the actual EP chemical composition, at any time of the SB evolution, we assume that it reflects the mean composition inside the SB, resulting from a perfect mixing between the SN ejecta and the evaporated material, whose mass is derived from the standard SB evolution model (e.g. Mac Low & McCray, 1988). This composition is shown in Fig. 1 as a function of time, for different models of SN explosion (taken from Woosley & Weaver, 1995; hereafter WW95), ambient densities and mechanical luminosities of the OB association. Note that we have plot the so-called reduced metallicity of the EPs, defined as the abundance ratio (by number) $\zeta = (\mathrm{C+O})/(\mathrm{H+He})$, which we found to be a convenient and sufficient parameter to evaluate the LiBeB production efficiency. As can be seen in Fig. 1, ζ is about 30 to 100 times lower than the reduced metallicity of the pure ejecta, which results from the dilution of the EPs with the very metal-poor ISM gas.

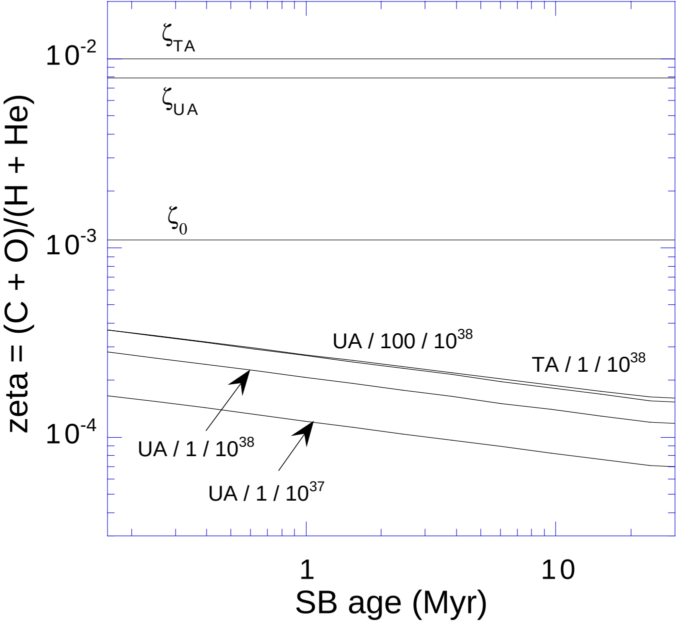

Figure 1: Evolution of the reduced metallicity, ζ, over the superbubble lifetime (here, $\tau_{\mathrm{SB}} = 30$ Myr). The labels indicate, respectively, the SN model used (from WW95), the ambient density (in cm^{-3}) and the mechanical power (in $\mathrm{erg\,s}^{-1}$). Also shown are the solar reduced metallicity (ζ_0), and the reduced metallicity corresponding to the pure ejecta for models UA and TA of WW95 (the compositions have been averaged over the Salpeter IMF).

We then assume that the power imparted to the EPs is, at any time, a fraction $\theta = 0.1$ of the total mechanical power supplied by the OB association. As for the EP energy spectrum, we investigated two different forms: i) a standard shock acceleration spectrum, i.e. $Q(p) \propto p^{-4}$, which we call the 'SNR spectrum' to emphasize that it originates at an isolated SNR, and ii) a 'SB spectrum', $Q(E) \propto E^{-\alpha}\exp(-E/E_0)$, where $\alpha = 1$ or 1.5, and E_0 is a cut-off energy of typically a few hundreds of MeV/n. This spectrum is taken as an approximate of the time-dependent source spectrum derived from an acceleration model relevant to the specific physical conditions prevailing within a SB (Bykov and Fleishman, 1992; Bykov, 1995,1999). Finally, we assumed that the main target for the EPs is the shell around the SB, whose composition is basically that of the ISM (which we take as 10^{-4} (models U) to 10^{-2} (models T) times the solar metallicity).

3 Results and analysis:

To compare the results of our SB model with the observations, we need to calculate the LiBeB as well as the Fe and O yields of the SB at the end of its life. The former are the output of our time-dependent calculations, while the latter are taken from the SN explosion models of WW95, averaged over the IMF, and multiplied by the number of SNe in the OB association. A successful LiBeB production model will then be a model which reproduces all the observed chemical abundance ratios, i.e. the isotopic and elemental ratios of the light elements on the one hand, and the Be/O ratio on the other hand. The question of the LiBeB abundance ratios has been studied in detail in previous works (e.g. Ramaty et al. 1997, Vangioni-Flam et al. 1998, Vangioni-Flam and Cassé 1999), so we focus here on the Be/O ratio. Although the situation is not totally clear from the observational point of view (e.g. Fields & Olive, 1999; hereafter FO99), we assume that the Be/O ratio is constant at low metallicity, because this is what the SB model actually predicts, and thereby derive a value of $\sim 7.5\,10^{-5}$ from the available observational data (e.g. FO99), which implies a yield of $\sim 6\,10^{47}$ nuclei of Be per SN.

The main result obtained with the SB model is shown in Fig. 2. More results, an extensive description of the model and a detailed discussion of its parameters and implications can be found in Parizot & Drury (1999c). Figure 2 shows the total Be yield for different spectra, as a function of the cut-off energy, E_0. The horizontal dashed line corresponds to the observed value of the Be/O ratio. As can be seen, the results of our SB model are in very good agreement with the observations if the EP spectrum is of the SB type, with a cut-off energy of a few hundreds of MeV/n. Interestingly enough, this is just the energy range predicted within the SB acceleration model (e.g. Bykov and Fleishman, 1992). On the other hand, the standard SNR spectrum leads to a Be yield a factor of 6 too low, which rules out this spectrum unless strongly selective acceleration (enhancing the C and O abundances relative to H and He by a factor of 6) is invoked.

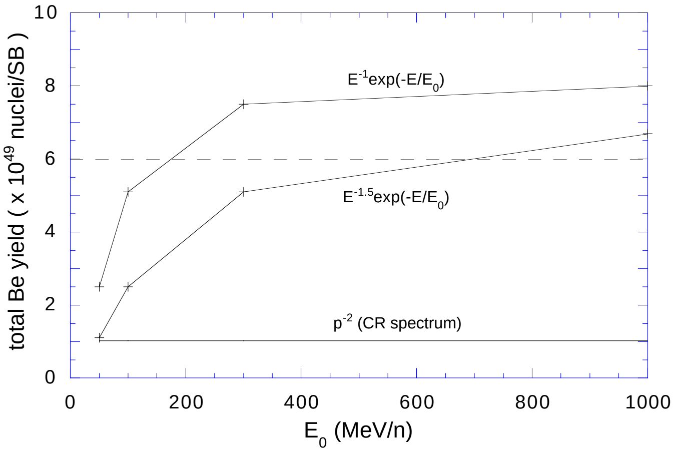

Figure 2: Total Be yields of a SB for different EP spectra, as a function of the cut-off energy, E_0. For the SNR spectrum, the cut-off energy is irrelevant, and we show a constant yield. The dashed line corresponds to the yield required to explain the observed Be/O ratio (see text). In this SB model, a total of 100 SNe have exploded during the SB lifetime of 30 Myr.

As it stands, two opposite positions can be adopted within the framework of the SB model: i) holding on to the SB acceleration mechanism of Bykov et al. and thus to the SB spectrum, because it does not require any selective acceleration, or ii) preferring to invoke selective acceleration and keep the usual SNR (cosmic ray source) spectrum, because it does not require a different acceleration mechanism. Both points of view seem to be acceptable in the current state of knowledge (although we feel that the former is the most tantalizing), and provide genuine solutions to the LiBeB evolution problem in the early Galaxy, as we have shown. Additional theoretical work, relating to the SB acceleration mechanism on the one hand, and to the selectivity of the CR acceleration mechanism under the physical conditions prevailing in a SB, on the other hand, is now needed to decide between these two stances.

Interestingly enough, a full solution of the LiBeB problem therefore appears to be able to provide important information about related fields in high energy astrophysics. For instance, one important remaining questioning about energetic particles in the Galaxy concerns the part of the spectrum below 1 GeV/n, since its spectrum and composition cannot be measured directly at Earth. In particular, it is possible that a second component of EPs, with different origin, spectrum and composition, exists at low energy ($E \leq 1$ GeV/n) and is superimposed to the ordinary CRs. Now since virtually all the spallative LiBeB nuclei are likely to be produced by these low energy cosmic rays, it is clear that strong constraints on their characteristics should come out of a detailed study of the light element evolution in the Galaxy. The results presented here seem to indicate that the SBs could well be the source of an important component of EPs, dominating the usual CRs at low energy, and therefore being responsible for most of the LiBeB production in the Galaxy.

4 Conclusion and predictions:

One of the main original features of our model is that it implies a decoupling between the metallicity of the stars and their age, or in other words, a non monotonic Galactic enrichment. In particular, stars formed at the same time can have metallicities spreading over two orders of magnitude or more. Indeed, our calculations show that a SB developing in the early Galaxy within an medium of metallicity, say, $10^{-4}Z_\odot$, provides $\sim 10^5\,M_\odot$ of gas enriched to $\sim 10^{-1}Z_\odot$, with the observed Be/O and LiBeB abundance ratios. This gas then mixes with the ambient low-metallicity gas and collapses to form stars of various metallicities, ranging from, say, 10^{-4} to $10^{-1}Z_\odot$, depending on the amount of dilution with the interstellar gas (resp. complete dilution and no dilution at all). Evidently, all these stars show the same abundance ratios (i.e. those of the SB itself), and the linear increase of the Be and B abundances with the stellar metallicity is, in this model, the manifestation of a *dilution line*. This special feature of the SB model may be tested observationally, and further implies that about the same number of stars should be expected at all Z. This is in contrast with the expectations of a scenario in which Be, B, O and Fe abundances build up continuously and monotonically in the Galaxy. Indeed, in such a model, more stars should be expected at low metallicity, because they form at a time when the star formation rate is higher. In fact, the SB model even predicts an increasing number of stars at increasing metallicity, because the new generation of stars (at the end of the SB lifetime) should be distributed between Z_{ISM} and $Z_{\mathrm{SB}} \sim 10^{-1} Z_{\odot}$, and Z_{ISM} irremediably increases.

Finally, our model seems to suggest that two distinct populations of stars should be found in the halo, namely stars formed in the vicinity of superbubbles, and stars formed out of ISM material which has not been processed by SBs. This set of stars should show very different LiBeB abundances, as expected from the activity of isolated SNe, rather than collective ones, in an OB association. Indeed, the LiBeB production within isolated SNRs has been calculated by Parizot & Drury (1999a,b), and shown to lead to Be/O ratios about one order of magnitude lower than those obtained in the SB model. These isolated SNe should however be responsible for the general, continuous increase of the ISM metallicity, and the stars formed from this gas are expected to lay on a specific part of the diagram showing, say, the Be abundance as a function of Fe/H, namely on a line about one order of magnitude lower than the line corresponding to the stars formed from the SB processed gas. This is another prediction of the model (unless *all* the SNe occurred in OB associations in the early Galaxy). Unfortunately, the B and Be abundance is obviously very hard to measure in these stars, since it is expected to be so low. Most probably, observations will provide upper limits on these abundances. In this respect, it is very interesting to note that only upper limits have been reported for 7 stars in the sample gathered by FO99. Although more observational work and proper statistics would be needed, these stars might represent a first piece of evidence in favour of a 'bimodal' LiBeB production in the Galaxy, that is to say from *correlated* and *isolated* SN explosions.

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