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The superbubble model for LiBeB production and Galactic evolution

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Abstract. We show that the available constraints relating to ^{6}LiBeB Galactic evolution can be accounted for by the so-called superbubble model, according to which particles are efficiently accelerated inside superbubbles out of a mixture of supernova ejecta and ambient interstellar medium. The corresponding energy spectrum is required to be flat at low energy (in E^{-1} below 500 MeV/n, say), as expected from Bykov's acceleration mechanism. The only free parameter is also found to have the value expected from standard SB dynamical evolution models. Our model predicts a slope 1 (primary) and a slope 2 (secondary) behaviour at respectively low and high metallicity, with all intermediate slopes achieved in the transition region, between 10^{-2} and $10^{-1}Z_\odot$.

1. Introduction

Galactic nucleosynthesis and chemical evolution are about how a given element is produced in the universe and how its abundance evolved from the primordial universe on. In the case of the light elements, it is widely agreed that the nucleosynthesis occurs through spallation reactions induced by energetic particles (EPs) interacting with the interstellar medium (ISM). In these reactions, an heavier nucleus (most significantly C, N or O) is 'broken into pieces' and transmuted into one of the lighter ^{6}Li, ^{7}Li, ^{9}Be, ^{10}B or ^{11}B nuclei. Except for ^{7}Li, this spallative nucleosynthesis is thought to be the main (if not the only) light element production mechanism. The case of ^{11}B is slightly more complicated, as neutrino-induced spallation in supernovae (the so-called ν-process) is sometimes invoked to increase the B/Be and ^{11}B/^{10}B ratios which one would expect should the light elements be produced by nucleo-spallation alone.

Concerning the Galactic evolution of light element abundances, Fields et al. (2000) have recently re-analyzed the available data as a function of O/H, discussing the uncertainties associated with the methods used to derive the O abundance, the stellar parameters and the incompleteness of the samples. According to their results, Be and B evolution can be described in terms of two distinct production processes: i) a primary process dominating at low metallicity and leading to a linear increase of the Be and B abundances with respect to O – 'slope 1' – followed by ii) a secondary process compatible with the standard expectations of the Galactic cosmic ray nucleosynthesis scenario (GCRN) – 'slope 2'. This behaviour is characterized by a transition metallicity, $Z_\mathrm{t} \equiv (\mathrm{O/H})_\mathrm{t}$, below which the Be/O and B/O ratios are constant and above which they are proportional to O/H. Although the value of Z_t is rather uncertain because very few data points have yet been reported at $Z < Z_t$, energetics arguments show that a primary process *is* indeed required below, say, $10^{-2} Z_\odot$ (Parizot & Drury 1999a,b,2000b, Ramaty et al. 2000), and therefore the very existence of a transition metallicity separating a primary from a secondary evolution scheme seems reasonably well established. In spite of the current large uncertainties on the exact value of Z_t, Fields et al. find a range of possible values between $10^{-1.9}$ and $10^{-1.4}(\mathrm{O/H})_\odot$ (see also Olive, this conference).

This two-slope picture seems to reconcile the two competing theories for light element nucleosynthesis, namely GCRN which predicts a secondary behaviour for Be and B evolution (e.g. Vangioni-Flam et al. 1990, Fields & Olive 1999), and the superbubble model which predicts a primary behaviour at low metallicity (Parizot & Drury 1999b,2000b, Ramaty et al. 2000). However, we show here that when applied to the whole lifetime of the Galaxy (not only to the early Galaxy), the superbubble model *alone* actually predicts the entire two-slope behaviour inferred from observations, and accounts for all the qualitative and quantitative constraints currently available. Implications for particle acceleration inside a superbubble (SB) are also analyzed.

2. Description of the SB model

The superbubble model is based on the observation that most massive stars are born in associations, and evolve quickly enough to explode as SNe in the vicinity of their parent molecular cloud. The dynamical effect of repeated SN explosions in a small region of the Galaxy is to blow large bubbles – superbubbles – of hot, rarefied material, surrounded by shells of swept-up and compressed ISM. The interior of superbubbles consists of the ejecta and stellar winds of evolved massive stars *plus* a given amount of ambient ISM evaporated off the shell and dense clumps passing through the bubble. The exact fraction of the ejecta material inside the SB is not well known, and can be expected to vary with time and from one SB to another. However, this fraction, which we note x, is all we need to know in order to fully determine the mean composition of the matter inside SBs. Noting $\alpha_{\mathrm{ej}}(\mathrm{X})$ and $\alpha_{\mathrm{ISM}}(\mathrm{X})$ the abundances of element X among the SN ejecta and in the ISM, respectively, we can indeed write the abundance of X inside the SB as:

$$\alpha_{\mathrm{SB}}(\mathrm{X}) = \mathrm{x}\alpha_{\mathrm{ej}}(\mathrm{X}) + (1 - \mathrm{x})\alpha_{\mathrm{ISM}}(\mathrm{X}). \qquad (1)$$

The second assumption of the SB model is that the material inside superbubbles is efficiently accelerated by a combination of shocks produced by SN explosions and supersonic stellar winds, secondary shocks reflected by other shocks or clumps of denser material, and a strong magnetic turbulence created by the global activity of all the massive stars. Two different SB models have been proposed so far, assuming different EP compositions and energy spectra. In our model (Parizot & Drury 1999b,2000b), we follow Bykov & Fleishman (1992) and Bykov (1995,1999) and argue that the SB acceleration process produces a rather flat spectrum at low energy, namely in E^{-1}, as expected from multiple shock acceleration theory (Markowith & Kirk 1999), up to a few hundreds of MeV/n, say. Above this value, the spectrum of the superbubble EPs (SBEPs) is either cut off through a steep power-law or turned into the standard cosmic ray source spectrum (CRS), in E^{-2}. The exact behaviour of this so-called 'SB spectrum' at high energy is important in itself and should be derived from a detailed calculation of the particle acceleration, but we do no consider it here, as it is not relevant to our problem (most of the LiBeB production arises from the most numerous low-energy particles anyway). The other SB model proposed so far (Ramaty & Lingenfelter 1999, Ramaty et al. 2000) assumes that the SBEPs *are* actually the cosmic rays and thus their energy spectrum is the standard CRS spectrum ($Q(p) \propto p^{-2}$).

To summarize, the essence of the SB model is that repeated SN explosions occurring in OB associations lead to the acceleration of EPs having either the CRS spectrum or the SB spectrum, and a composition given by Eq. (1), where the only free parameter is the proportion of the ejecta inside the SB: x. In principle, x can be derived from the study of SB evolution dynamics, coupled with a gas evaporation model. But we shall first study LiBeB evolution for itself with no external prejudice about the value of x, and therefore consider it as a free parameter which we vary from 0 (i.e. SBEPs have the ambient ISM composition) to 1 (i.e. SBEPs are made of pure SN ejecta). Later, we compare the value derived from the LiBeB constraints with the value expected from standard SB dynamical models.

3. Be and B Galactic evolution

3.1. Qualitative features

Having parameterized our problem as above, we can easily calculate the Be/O production ratio in the Galaxy as a function of $Z_{\mathrm{ISM}} \equiv (\mathrm{O/H})_{\mathrm{ISM}}$. We consider SBs blown by 100 SNe exploding continuously over a lifetime of 30 Myr. We then integrate the Be production rates induced by the SBEPs and divide the result by the total O yield (added up assuming a Salpeter IMF and SN yields from Woosley & Weaver 1995). The result is plotted in Fig. 1 for various values of x and the two investigated spectra. The main difference between the latter is the Be production efficiency, i.e. the number of Be produced per erg of SBEP. Apart from the SB spectrum being more efficient, both figures show distinctively the sought-for two-slope behaviour, with a transition metallicity Z_{t} depending on the actual value of x. This behaviour derives directly from Eq. (1). Replacing X by O there, we see that the abundance of O among the SBEPs is essentially $x\alpha_{\mathrm{ej}}(\mathrm{O})$ at low metallicity, and $(1-x)\alpha_{\mathrm{ISM}}(\mathrm{O})$ above a transition metallicity $Z_{\mathrm{t}} \sim \frac{x}{1-x} Z_{\mathrm{ej}}$ (where $Z_{\mathrm{ej}} \sim 10 Z_{\odot}$). Therefore, remembering that O is the main progenitor of Be, we find that the SB model predicts a primary behaviour below Z_{t} (production efficiency independent of Z_{ISM}), and a secondary behaviour above Z_{t}, since the SB model is then essentially identical to the GCRN model (except maybe for the assumed energy spectrum).

Incidentally, it is interesting to note that the SB model can be considered as a correction of the GCRN scenario, taking into account the chemical inhomogeneity of the early Galaxy. Indeed, since particle acceleration occurs precisely in those places where metals are released (i.e. superbubbles), the SBEP composition is considerably richer in O than the average ISM, as long as the SN ejecta dominate the O content of the SBs. Afterwards, it makes little difference, as far

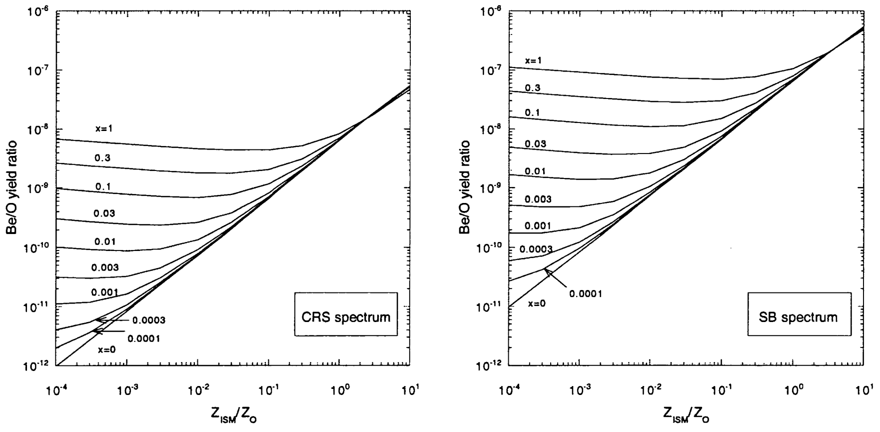

Figure 1. Be/O yield ratios obtained with the CRS spectrum (left) and the SB spectrum (right), as a function of the ambient metallicity, for various values of the mixing parameter, x. The Be yield is calculated for a SBEP total energy of 10^{50} erg per SN.

as composition is concerned, whether the EPs producing LiBeB are accelerated inside SBs or in the regular ISM.

Finally, we see from Fig. 1 that the predicted slope 1 and slope 2 correlations between Be and O are limit behaviours for very low and very high metallicity respectively. Depending on the value of x, any intermediate value for the Be-O slope is reached over a given range of stellar metallicity. This is in contrast with what would arise if the two-slope behaviour were to be explained in terms of two different mechanisms (e.g. the SB model at low Z and GCRN at high Z). In that case, indeed, one would have a sharp change of slope at the precise metallicity where the secondary process becomes dominant, with no intermediate values. Of course, expected physical fluctuations of the parameters would weaken this effect, and current observational error bars prevent us from distinguishing conclusively between the two pictures. But we argue that the observed 'slope 1.45' behaviour reported by Boesgaard & Ryan (this conference) can be explained (in principle) only if there is a continuous *transition* from slope 1 to slope 2 within a *unique* model (as in the SB model above), rather than two unrelated models with a slope 2 eventually superseding a slope 1.

3.2. Quantitative features

Quantitatively, the Be/O ratio at low metallicity derived from the observations is about $4\,10^{-9}$ (Parizot & Drury 2000b). This can be achieve either by the CRS spectrum model, provided $x \sim 50\%$, or by the SB spectrum model, provided $x \sim 2or3\%$ (see Fig. 1). So far, both models are equally acceptable since we chose not to accept any prejudice about the value of x from outside the restricted field of LiBeB evolution. But when considering the transition metallicity associated with the two possible models, we see that the CRS spectrum implies $Z_{\rm t} \gtrsim 10^{-1} Z_{\odot}$, well outside the range derived by Fields et al. On the other hand, the value of $Z_{\rm t}$ predicted by SB spectrum model falls exactly in the required range.

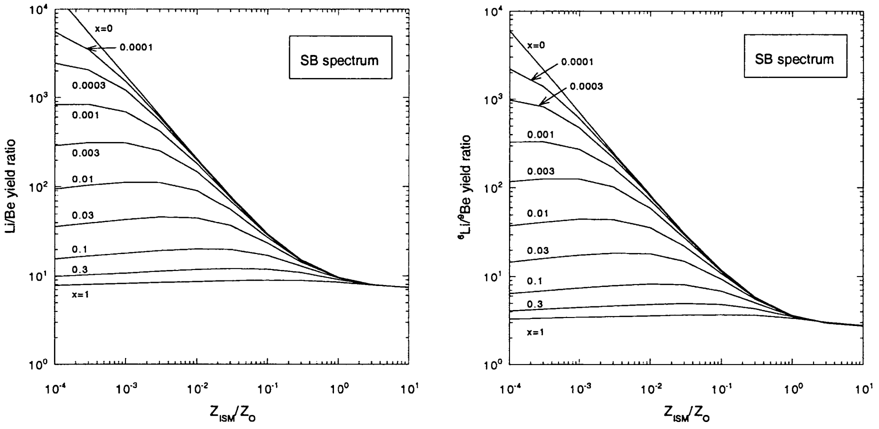

Figure 2. Li/Be (left) and ^{6}Li/^{9}Be (right) production ratios obtained with the SB spectrum model, as a function of the ambient metallicity, for various values of the mixing parameter, x.

As a conclusion, the SB model is fully consistent with the observations provided that i) the SBEP spectrum is flattened at low energy (in E^{-1}), and ii) the SN ejecta amount to a few percent of all the matter present inside SBs.

Now let us extend the scope of our study. Quite remarkably, the first condition above is exactly what is expected from the SB acceleration model developed by Bykov et al. As for the second condition, it is in perfect agreement with the dynamical model for SB evolution worked out by Mac Low & Mc Cray (1988). In other words, had we looked beforehand for a theoretically preferred value of x, we would have chosen just the particular value which turns out to account for the various constraints of Be Galactic evolution. Therefore, our results actually bring support not only to the SB model as the natural framework for Be and B evolution studies, but also to the SB acceleration model and standard SB dynamics.

Concerning B, unfortunately, only qualitative constraints can be checked against the SB model (successfully in this instance), since either a significant ν-process or a LECR component is required anyway to account for the observed B/Be and ^{11}B/^{10}B ratios. However, Li does provide additional quantitative constraints. First, in order not to break the Spite plateau, the Li/Be production ratio must be lower than $\sim$ 100. This is shown to be satisfied for any value of x greater than about 1% in Fig. (2a). Second, the measurement of the ^{6}Li abundance in two halo stars of metallicity $Z \simeq 10^{-2.3} Z_\odot$ indicates that the ^{6}Li/^{9}Be ratio in these stars should be in the range 20–80 (see Vangioni-Flam, Cassé, & Audouze 2000 and references therein), in contrast with the solar value of $\sim$ 6. This could not be explained if the proportion of SN ejecta inside SBs were of the order of 50% (CRS spectrum model). However, it is quite remarkable again that the value of a few percent derived from the SB spectrum model is totally consistent with the observed value of the ^{6}Li/^{9}Be ratio, both a low metallicity and at solar metallicity.

4. Conclusion

The SB model described above has been shown to be fully consistent with the qualitative and quantitative constraints of LiBeB Galactic evolution: 1) it explains the inferred two-slope behaviour in the framework of one sole model; 2) it provides the correct value of Be/O at low metallicity; 3) it predicts the correct value of the transition metallicity; 4) it does not break the Spite plateau; 5) it is consistent with the ^{6}Li/^{9}Be ratio at any metallicity. Most importantly, these successes rely on the value of only one free parameter, namely the proportion of SN ejecta inside a SB. The value which we find is of the order of a few percent, i.e. exactly in the range derived from standard SB dynamical evolution. Likewise, the SB model is found to be successful only if the SBEPs have the SB spectrum, i.e a flattened shape at low energy (in E^{-1}). But this is exactly what is predicted by the SB acceleration model of Bykov et al. As a conclusion, the SB model appears to account for all the available constraints about LiBeB evolution by making only the most standard assumptions about the involved models relating to other fields of astrophysics. This may be considered as lending support to these models as well.

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References

Bykov A. M. 1995, Space Sci. Rev., 74, 397

Bykov A. M. 1999, in "LiBeB, cosmic rays and gamma-ray line astronomy", ASP Conference Series, eds. R. Ramaty, E. Vangioni-Flam, M. Casse, K. Olive

Bykov A. M., & Fleishman G. D. 1992, MNRAS, 255, 269

Fields B. D., & Olive K. A., 1999, ApJ, 516, 797

Fields B. D., Olive K. A., Vangioni-Flam E., & Cassé M. 2000, submitted to ApJ (astro-ph/9911320)

Mac Low M. M., & McCray R., 1988, ApJ, 324, 776

Markowith A., & Kirk J. G. 1999, A&A, 347, 391

Parizot E., & Drury L. 1999a, A&A, 346, 686

Parizot E., & Drury L. 1999b, A&A, 349, 673

Parizot E., & Drury L. 2000a, A&A, submitted

Parizot E., & Drury L. 2000b, A&A, submitted

Ramaty R., & Lingenfelter R. E. 1999, in "LiBeB, cosmic rays and gamma-ray line astronomy", ASP Conference Series, eds. R. Ramaty, E. Vangioni-Flam, M. Casse, K. Olive

Ramaty R., Scully S. T., Lingenfelter R. E., & Kozlovsky B. 2000, ApJ, in press (astro-ph/9909021)

Vangioni-Flam, E., Cassé, M., Audouze, J., & Oberto, Y. 1990, ApJ 364, 586

Vangioni-Flam, E., Cassé, M., & Audouze, J. 2000, submitted to Physics Reports

Woosley S. E., & Weaver T. A. 1995, ApJSS, 101, 181