Spallative production of Li, Be and B in supernova remnants

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Abstract

We calculate the light element production induced by the explosion of an isolated supernova in the ISM. We use a time-dependent model and consider energetic particles accelerated at the forward (process 1) and reverse (process 2) shocks. Both processes are primary, but are shown to underproduce Be and B in the early Galaxy. The reasons for this failure are analyzed and used to determine what basic characteristics a model should involve in order to be successful. Quite remarkably, we find that these requirements seem to converge toward a model involving superbubbles as the site of particle acceleration out of a metal-rich material. Such a model is presented in the accompanying paper OG.3.2.51.

1 Introduction:

In the past few years, there has been a renewal of interest in the nucleosynthesis of the light elements, namely Li, Be and B (or LiBeB for short). This was prompted by a wealth of new observational data showing a distinct linear correlation between the abundance of LiBeB and the metallicity in metal-poor halo stars. This is in contrast with the expected *quadratic correlation*, corresponding to an increase of LiBeB proportionaly to the square of the metallicity (for a review of the theoretical aspects and references to the observational works, see e.g. Vangioni-Flam et al. 1998). This so-called *LiBeB problem* is all the more interesting that it is very 'pure', from an astrophysical point of view. Indeed, if we except ^{7}Li (which is produced to some extent by the big bang nucleosynthesis) and ^{11}B (which may be produced by neutrino-induced spallation in the supernova explosions), the light elements are generally believed to have only one production mechanism, namely the nuclear spallation of C, N or O nuclei induced by the interaction of energetic particles (EPs) with the interstellar medium (ISM). As a consequence, the Be production rate (for example) can be deduced straightforwardly from the rate of encounters of energetic H and He nuclei with C, N and O nuclei at rest in the ISM (direct spallation), *plus* the rate of encounters of energetic C, N and O nuclei with H and He nuclei at rest in the ISM (inverse spallation). If the EPs are accelerated out of the ISM and interact with the overall ISM material, as was generally assumed, the above rates of encounters should be approximately the same (neglecting the effects of selective acceleration and energy losses), and proportional to the ambient (ISM) abundance of C, N and O, i.e. to the metallicity, Z, or equivalently to the integrated number of supernovae, $\mathrm{SN}(t)$ having exploded since the Galaxy formed.

Considering now the energy source of the EPs, it seems reasonable to assume that the main component comes from the explosion of supernovae. The number of EPs in the ISM is thus proportional to the supernova explosion rate, $\dot{\mathrm{SN}}(t)$, so that the Be production rate is proportional to $\mathrm{SN}(t)\dot{\mathrm{SN}}(t)$. Integrating over time, we find the well known result that the Be abundance should be proportional to $\mathrm{SN}(t)^2$, i.e. to the square of the metallicity. The simple analysis above also shows that the only way to obtain the observed linear increase of the Be abundance without invoking a new energy source (stronger than the SN power!) is to make sure that the Be production rate in the ISM does not actually depend on the ambient metallicity. The only way to achieve this for the direct spallation reactions is that the EPs do not interact with the average ISM. As for the inverse spallation reactions, they must be induced by C and O nuclei accelerated *not* out of the ambient ISM, otherwise their number would be proportional to Z, which we want to avoid. Interestingly enough, there are two ways to satisfy the above requirements while keeping the basic assumption that the EPs responsible for the light element production in the early Galaxy are related to the explosion of individual supernovae in the ISM. It is these two ways that we examine below in detail, calculating the total Be production following one given supernova explosion, and averaging the Be yield over a given initial mass function (IMF).

2 Light element production in supernova remnants:

As an isolated supernova (SN) explodes in the ISM, a large amount of kinetic energy ($E_{\rm SN} \sim 10^{51}$ ergs) is released, causing two shock waves to develop: i) a forward shock, containing an energy of about $E_{\rm fwd} \simeq E_{\rm SN} \simeq 10^{51}$ ergs, expanding outward and sweeping up the circumstellar medium, which is quite close to the primordial gas in the very early Galaxy (metallicity $Z \simeq 0$), and ii) a reverse (reflected) shock, containing an energy of order $E_{\rm rev} = \theta_{\rm rev} E_{\rm SN} \sim 10^{50}$ ergs, directed towards the remnant star and sweeping up the SN ejecta, rich in freshly synthesized metals. As is known from both theory and observations, shocks accelerate some of the particles flowing through them up to supernuclear energies (i.e. above the nuclear thresholds of order a few MeV/n), and distribute these energetic particles (EPs) over an approximately power law spectrum with slope ~ 2 in momentum. The efficiency of the acceleration process is generally of order $\theta_{acc} \simeq 0.1$, which means that about 10 % of the shock energy is finally imparted to the EPs. Once accelerated, the particles diffuse in the surrounding medium and interact with the ambient matter, to produce light elements by spallation. The two shocks just mentioned are thus at the origin of two distinct processes for Be nucleosynthesis, which we now evaluate (more details and extensive analytical and numerical calculations can be found in Parizot and Drury, 1999a,b).

2.1 Description of processes 1 and 2: In process 1, induced by the forward shock of the supernova, particles from the ISM are accelerated during the whole Sedov-like expansion phase, at the end of which the shock becomes radiative and the acceleration efficiency quickly drops. Assuming that the acceleration process is not chemically selective, the composition of the EPs has to be that of the ISM, as in the standard scenario, recalled in the introduction. Concerning the target medium, however, it has to be realized that most of the EPs are actually confined within the supernova remnant (SNR) until the end of the Sedov-like phase, as they are trapped inside the ‘diffusion barrier’ located just downstream of the shock (the confinement is especially efficient for the low energy EPs which are the most numerous and the most efficient in inducing spallation reactions). As a consequence, the target material interacting with the EPs is made of a mixture of the metal-rich SN ejecta and the material swept-up by the shock, i.e. the (metal-poor) ambient ISM. Anticipating the detailed calculation, it is easy to see that i) the main contribution to the Be production will come from the direct spallation reactions (because the target is much richer in C and O than the EPs, due to the SN ejecta), and ii) the Be production rate will be independent of the ambient ISM metallicity, as the SN ejecta will strongly dominate the metallicity inside the SNR. According to the above study, this ensures that the Be abundance in the ISM be proportional to Z, as observed.

The second process which we consider (process 2) is associated with the reverse shock of the supernova. As mentioned, the particles are then accelerated out of the ejecta, which are very rich in C and O (much more than the ISM). As a consequence, i) the Be production rate will be dominated by inverse spallation reactions, and ii) it will be independent of the ambient ISM metallicity again (as the accelerated material actually has nothing to do with the ISM!). Just as for process 1, the EPs are largely confined within the SNR until the shock becomes radiative, at the end of the Sedov-like phase. Adiabatic losses must therefore be considered during this phase, requiring the use of a time dependent model.

2.2 Need for a time-dependent model The dynamics of the SNR evolution is indeed particularly important for our calculations, for a number of reasons: i) when the magnetic diffusion barrier (downstream of the forward shock) drops at about the end of the Sedov-like phase, $t \equiv t_{\rm end}$, the EPs are free to leave the SNR and diffuse away in the ISM, which is essentially devoid of metals in the early stages of Galactic evolution, so that process 1 stops at $\sim t_{\rm end}$; ii) the EPs suffer adiabatic losses which depend on the expansion rate of the SNR, and thus on time (as some of the EPs slow down to energies below the spallation thresholds, the Be production efficiency obviously decreases); iii) the Be production efficiency (number of nuclei produced per erg in EPs) is very high shortly after the explosion, because the SNR material is rich in C and O, but then suffers a dilution effect as this material gets poorer and poorer due to the SNR expansion and the dilution of the ejecta by the swept-up ISM; iv) the acceleration of the EPs itself cannot be considered as a stationary

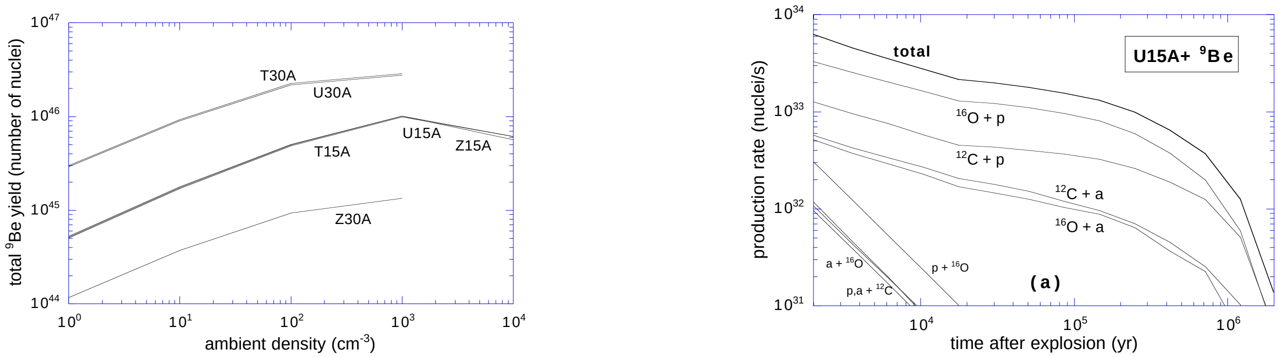

Figure 1: (left) Integrated Be yields obtained by process 1 for the SN explosion model U15A (WW95), as a function of the ambient density; (right) Detailed Be production rates by process 2 as a function of time for the same model, i.e. a SN progenitor of 15 $M_\odot$ and initial metallicity $Z = 10^{-4} Z_\odot$.

process, since as the shock expands, its power decreases as $1/t$, and the EP injection rate inside the SNR follows approximately the same law.

In a time-dependent model, the crucial physical ingredient is the so-called injection function, which indicates how many EPs are accelerated per unit time, and with what energy spectrum. For process 1, we use the standard shock acceleration spectrum, normalized to 10 % of the shock power, at any time. Acknowledging the fact that the lifetime of the reverse shock is short compared to the other relevant time-scales, we further assume that the acceleration of the EPs involved in process 2 takes place instantaneously at the sweep-up time, $t_{\rm sw}$. The injection function is thus a delta function normalized so that 10 % of the reverse shock energy goes into the EPs. More details about processes 1 and 2 and the corresponding injection functions can be found in Parizot & Drury (1999a,b), together with extensive numerical estimates and a detailed discussion of the various parameters involved. A complete description of the time dependent model used here can also be found in Parizot (1999).

3 Results and analysis:

The integrated Be yield (of one supernova) by process 1 is shown in Fig. 1a as a function of the ambient density for different models of SN explosion (taken from Woosley & Weaver, 1995), which differ in their inputs (initial mass and metallicity of the progenitor, explosion energy and velocity of the ejecta) and outputs (masses of each element ejected). We find that higher densities imply larger numbers of Be nuclei synthesized, although at least two orders of magnitude lower than those implied by the data ($\sim 4\,10^{48}$ atoms of Be per supernova, if comparison is made with the Fe - see Ramaty et al. 1997 - or $\sim 6\,10^{47}$ Be/SN if comparison is made with O - see Parizot & Drury 1999a,b). The conclusion of this quantitative study is that, although process 1 reproduces the observed primary behavior of Be (proportionality to Z), it cannot be the major source of Be and other light elements in the Galaxy. Analyzing the reason for this failure, we are left with two possibilities: either there is not enough energy in the process, or the spallation efficiency is too low, that is the C and O-rich ejecta are too much diluted by the ambient metal-free gas. Now this is not a small conclusion, as finding a process involving more energy than a SN and metallicities larger than inside a SNR seems rather challenging.

The detailed time dependent Be production rate by process 2 is shown in Fig. 1b, and the integrated yields, averaging over the IMF and normalized to the observationally required values (see above), are shown in Fig. 2 as function of the IMF index ($x = 2.35$ for Salpeter IMF). Process 2 is thus found to fail quantitatively by about two orders of magnitude when comparison is made with Fe, and one when it is made with O. Note that the latter is the most relevant, however, as O is the direct progenitor of Be and the SN Fe yields may not be well understood theoretically (cf. Parizot & Drury 1999c). Normalized Be yields obtained by process 2 not considering the adiabatic losses are also shown on Fig. 4. They are a factor 3 to 4 higher, which demonstrates

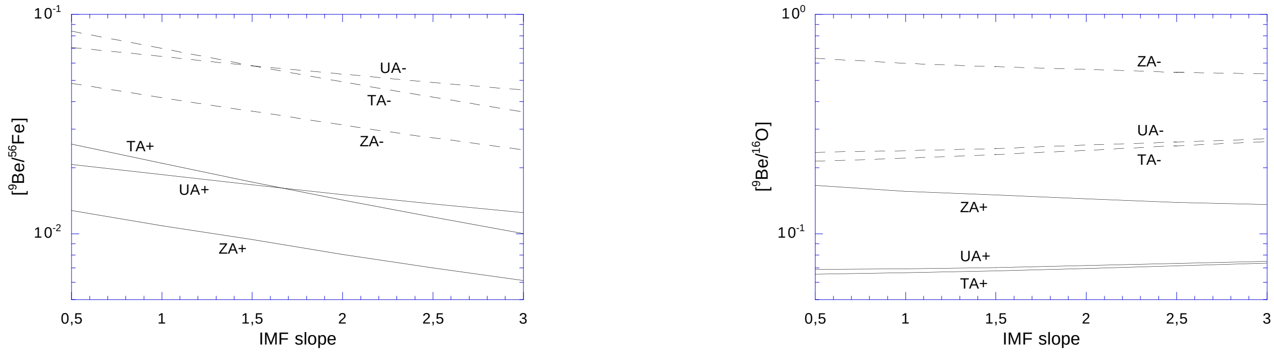

Figure 2: Be/Fe and Be/O yield ratios obtained by process 2 after averaging over the IMF and normalizing to the observational values, as a function of the IMF logarithmic index. Dashed lines correspond to the same models with the adiabatic losses turned off.

the importance of these energy losses and the need for time dependent calculations.

4 Towards a solution of the light element production puzzle:

The above results provide important clues towards a solution of the Be evolution problem in the early Galaxy. Our process 1 (acceleration of particles from the ISM) fails because the target is too poor in C and O, but this cannot be improved. On the other hand process 2 (acceleration of particles from the ejecta) fails because of adiabatic losses (factor of 3–4) and because the reverse shock is less energetic than the forward shock (factor of ~ 10). Now both problems may be avoided in a model in which particles are accelerated in the interior of superbubbles (SBs), taking advantage of the collective effect of SNe in an OB-association, instead of isolated SNe (Bykov, 1995). In such a superbubble model (Parizot et al., 1998; Higdon et al., 1998), particles are accelerated out of the enriched material ejected by earlier massive stars (through winds and SN explosions), just as in our process 2, but this is now done by the forward shock, instead of the reverse one. A factor of about 10 in energy could therefore be gained. Moreover, adiabatic losses may be avoided because of the low expansion rate of an evolved superbubble. This would provide an other factor of 3, pushing the Be yields at the level of the required values, derived from the observations. In the accompanying paper OG.3.2.51, we invistigate the SB model in some detail, and show that it is indeed successful. More results and precise description of the SB model can be found in Parizot & Drury (1999c).

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