Time dependent models for Li, Be and B production in the early Galaxy

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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. The reasons for this failure are analyzed and used to propose a possible alternative, based on the acceleration of particles inside superbubbles.

1. Introduction

Boosted by a wealth of new data on the Be and B abundances in very metal-poor stars of the Galactic halo (e.g. Gilmore et al. 1992; Duncan et al. 1992,1997; Ryan et al. 1994; Edvardsson et al. 1994; Kiselman & Carlsson 1996; Molaro et al. 1997; Garcia-López et al. 1998), theoretical studies of the light element production and evolution in the early Galaxy have considerably developed during the past few years, and contributed to renew the nature of the questions asked in this context (e.g. Feltzing & Gustafsson 1994; Reeves 1994; Cassé et al. 1995; Fields et al. 1995; Ramaty et al. 1996,1997; Vangioni-Flam et al. 1998). While everyone working in this field seems to agree that the Be atoms observed in the halo stars were synthesized by spallation reactions of C and O involving energetic particles accelerated in the interstellar medium (ISM), it is still not clear what kind of material is actually accelerated, where the acceleration takes place, by which mechanism, and how efficient it is.

As a guide towards the answer to such questions, special attention has been paid to the shape of the evolution of Be and B abundances in the early Galaxy, as a function of metallicity. Indeed, contrary to what had been expected, these light element abundances show a linear growth with respect to Fe, indicating that Be and B are produced by a primary process. By this, it is meant that Be and B production does not depend on the ISM metallicity, and is intrinsically (though probably indirectly) linked to the activity of massive stars, just as the C, O or Fe production, i.e. independently of a prior enrichment of the ISM.

To account for these new data, several primary mechanisms have been proposed in which the light elements are produced through the spallation of energetic C and O nuclei accelerated out of freshly synthesized material (supernova ejecta, winds of Wolf-Rayet stars, etc.) and interacting with the ambient (metal-poor) ISM. These mechanisms reproduce quite well the qualitative behavior of Be and B as compared to the common metallicity tracers (they are made for

\[1\]to appear in “Galaxy Evolution: connecting the distant universe with the local fossil record”, eds. M. Spite and F. Crifo, Les Rencontres de l’Observatoire de Paris, Kluwer, Dortrecht
this). However, the question of energetics, i.e. quantitative agreement with the data, proves very difficult (e.g. Ramaty et al. 1997) and is still mostly unsolved. Therefore, while concentrating on the shape of Be and B Galactic evolution admittedly gave important clues towards the identification of their origin, we feel that the problem of energetics should now be addressed more directly, as the constraint it provides proves powerful enough to rule out many qualitatively acceptable mechanisms.

In this contribution, we study two primary processes which could be expected to be especially efficient in producing light elements, and though show that they do not resist quantitative analysis. Looking into the reason for this failure, we argue about possible ways to alleviate the major problems and propose an alternative scenario based on the acceleration of the enriched material filling the interior of superbubbles. We adopt a ‘conservative picture’ for the metallicity, in which the Galactic abundances of O and Fe are assumed to be proportional. It should be kept in mind, however, that this picture is being put seriously into question by recent observational analysis (Israelian et al. 1998; Boesgaard et al. 1998; García-López, these proceedings), so that the primary behavior of Be and B relative to their main progenitor, O, may not be as firmly established as one had thought. In particular, Fields and Olive (1999) have argued that the canonical secondary process involving Galactic cosmic rays (GCRs) cannot be completely ruled out on the basis of current data (see also Fields, these proceedings). This difficulty could however be regarded as another reason to concentrate mainly on the energetics of light element production, as the qualitative behavior itself is not yet well established.

The key quantitative feature derived from the data, is the approximately constant Be/Fe abundance ratio in the halo stars: \( \text{Be/Fe} \approx 1.6 \times 10^{-6} \) (Ramaty et al. 1997). It suggests that each ejection of Fe in the ISM by SN explosion must be accompanied, on average, by the corresponding amount of spallative Be production, as deduced from the above ratio. A similar requirement can be obtained to compare the Be and O yields to the observed values, by noting that the spallation processes under study must at least account for the least constraining (i.e. easiest to explain) point in the data giving the Be abundance as a function of [O/H]. This statement is independent of any assumption about the genuine primary, secondary or any other behavior of Be evolution. What we are asking to the models, at this stage, is not to reproduce the whole Galactic evolution of Be, but only one point in the data (which is unquestionably a minimal requirement). As we investigate primary processes here, we know that the Be/O abundance ratio they produce will in fact be constant. Therefore, we obtain the minimal required yield of Be per oxygen nucleus ejected in the ISM by merely dividing the abundance of O by that of Be in the least constraining star observed. Using the most recent compilation by Fields and Olive (1999), we obtain \( \text{Be/O} \approx 7.5 \times 10^{-9} \) (or \( \sim 6 \times 10^{17} \) nuclei of Be per solar mass of O).

2. Light element production in supernova remnants

In this paper, we investigate the Li, Be and B production associated with the explosion of an isolated SN in the ISM. As the SN explodes, a large amount of kinetic energy \( (E_{\text{SN}} \approx 10^{51} \text{ ergs}) \) is released, causing two shock waves to develop:
1. a forward shock, containing an energy of about $E_{\text{for}} \simeq E_{\text{SN}} \simeq 10^{51}$ 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

2. a reverse (reflected) shock, containing an energy of order $E_{\text{rev}} = \theta_{\text{rev}} E_{\text{SN}} \sim 10^{50}$ 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 $\sim 2$ in momentum. The efficiency of the acceleration process is generally of order $\theta_{\text{acc}} \simeq 0.1$, 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.

2.1. Description of process 1

In process 1, induced by the forward shock of the SN, 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, i.e. essentially primordial gas (devoid of metals) in the early stages of Galactic chemical evolution. Concerning the target medium, 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). Indeed, the acceleration itself is due to the ability of this downstream region (hosting strong magnetic turbulence and waves) to diffuse back ionized particles so they can pass through the shock front many times. As a consequence, the target material interacting with the EPs should be expected to be made of a mixture of the metal-rich SN ejecta and the material already swept-up by the shock, i.e. metal-free ISM.

The main nuclear reactions involved in this Be production process are thus direct spallation reactions in which energetic protons (and $\alpha$ particles) interact with freshly synthesized C and O nuclei ejected by the SN. It is therefore a primary process, as the total Be yield associated with each supernova does not depend on the prior enrichment of the ISM, but only on the quantity of O (and C) ejected by the supernova and the dynamics of the SNR evolution. The latter is particularly relevant to our calculations, for a number of reasons. It should be clear, first, that the process only last as long as the diffusion barrier is efficient enough to retain the EPs in the interior of the SNR, where metal-rich material is encountered. Now this barrier is expected to drop at the end of the Sedov-like phase, $t \equiv t_{\text{end}}$, when the shock becomes radiative and the magnetic waves
dissipate on a short time-scale. After $t_{\text{end}}$, the EPs are free to leave the SNR and diffuse away in the whole Galaxy. Since the latter is essentially devoid of metals in the early stages of its evolution, no significant spallative nucleosynthesis can be expected after $t_{\text{end}}$, which therefore marks the end of our process 1.

The second reason why dynamics is so important in this study is that while the EPs are confined within the expanding remnant, they suffer adiabatic losses which lower their energy. Some of the EPs thus slow down to energies below the spallation thresholds, which obviously causes a decrease of the Be production efficiency. These energy losses need to be taken into account carefully, and make it impossible to use standard steady-state models to calculate the total Be yield associated with the supernova explosion.

A third feature which makes the use of time dependent models necessary is the dilution effect of the target. Shortly after the explosion, the composition of the SNR material is very rich in C and O, so that the Be production efficiency (number of nuclei produced per erg in EPs) is high. But this target material gets poorer and poorer as the SNR expands and the ejecta are diluted by the swept-up ISM. For a given energy in the form of EPs, the Be production rates therefore keep decreasing as time flows from the explosion ($t = 0$) to $t_{\text{end}}$. Finally, the acceleration of the EPs itself cannot be considered as a stationary process. Indeed, as the shock expands, its power decreases as $1/t$, and the rate at which EPs are injected inside the SNR follows approximately the same law.

### 2.2. Description of process 2

The second process of light element production which we consider here is associated with the reverse shock of the SN. As already mentioned, the particles are then accelerated out of the ejecta, and their composition is very rich in C and O (much more than the surrounding medium). As a consequence, most of the Be producing reactions will be inverse spallation reactions, i.e. in-flight spallation of energetic C and O interacting with H and He nuclei at rest in the ambient medium. This provides a primary process again, as the metallicity of the target has no influence on the total Be yield.

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, implying that the use of time dependent models is again required. An important difference with process 1 is that the production of light elements keeps going on after $t_{\text{end}}$, and therefore the rate at which EPs are injected inside the SNR follows approximately the same law.

The last physical ingredient which is needed to calculate to spallation rates during the process is the so-called injection function, specifying how many EPs are produced by the acceleration mechanism per unit of time, and with what energy spectrum. As for process 1, we use the standard shock acceleration spectrum, normalized to 10% of the shock power. Acknowledging the fact that the lifetime of the reverse shock is short compared to the other relevant time-scales, we assume that the injection of the EPs takes place instantaneously at the sweep-up time, $t_{\text{sw}}$.

More details about processes 1 and 2 and the injection functions will be find in Parizot and Drury (1999a,b), together with extensive numerical estimates and
3. Numerical results and analysis

3.1. Results for process 1

The Be production rate by process 1 is shown in Fig. 1a as a function of time, for different ambient densities. As already noted, the process is efficient only during the Sedov-like phase of the SNR expansion, which can be seen to shrink as the ambient density increases. However, the target density is correspondingly higher, which implies higher spallation rates as well. The total, integrated yields are shown in Fig. 1b as a function of density for different explosion models of SN explosions. The latter have been taken from Woosley and Weaver (1995) (hereafter WW95), and 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), which are relevant to our calculations. We find that higher densities imply larger numbers of Be nuclei synthesized. However, even in the most favorable cases, the numbers obtained are still at least two orders of magnitude lower than those implied by the data ($\sim 4 \times 10^{48}$ atoms of Be per supernova; see Ramaty et al. 1997). The conclusion of this quantitative study is that, although process 1 reproduces the observed primary behavior of Be (slope 1 in the evolution diagram), 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 supernova and metallicities larger than inside a supernova remnant seems rather challenging. It should be noted also that process 1 is in any case more efficient than the standard process called Galactic cosmic-ray nucleosynthesis (GCRN), in which the forward shock of SNe accelerate the ambient ISM, just as in process 1, but the interaction with C and O nuclei occurs...
in the whole Galaxy, where these elements are much more diluted than inside a supernova remnant. As a consequence, the failure of process 1 also implies that of standard GCRN, at least in the earliest stages of Galactic evolution.

3.2. Results for process 2

The time dependent production rates by process 2 are shown in Fig. 2 for both $^9$Be and $^6$Li. Integrated yields, normalized to the observationally required values (see Sect. 1) are shown in Fig. 3 as a function of the SN progenitor’s mass and in Fig. 4 after averaging over the initial mass function (IMF), as function of the IMF index ($x = 2.35$ for Salpeter IMF).

It can be seen that process 2 also fails 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, as O is the direct progenitor of Be and the SN Fe yields may not be well understood theoretically. 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 the importance of these energy losses and the need for time dependent calculations.
Figure 4. 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.

4. Towards a solution of the light element production puzzle

The results presented in this paper 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. 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.

Additional work is however needed to work out the details of an effective SB model. The main uncertainties pertain to the composition of the EPs and to their acceleration mechanism. Parizot (1998) and Parizot et al. (1998) argued that the ‘accelerable material’ in a SB is made of the averaged wind and SN ejecta of the most massive stars, and that the EP spectrum is hard, with a low-energy cut-off (a few 100 MeV/n), as arises from the SB acceleration models by Bykov and Fleishman (1992). Higdon et al. (1998) also adopted a SB model and justified the previous assumption about composition by geometrical arguments, but used the usual shock acceleration mechanism, and thus the usual cosmic-ray spectrum. Now although we all would like to accelerated enriched material, we cannot be sure that this is actually the case in a SB until the mixing of the stellar ejecta with the evaporated ISM off the SB shell has been estimated properly. As for the acceleration process, a key question seems to be: what is the fate of a SNR shock in a highly turbulent, tenuous and high temperatured medium such as the interior of a SB? If the SNR is essentially unaffected, then
we should expect standard shock acceleration and a typical CR spectrum. On the other hand, if the energy released by the explosion turns into turbulence on a short time-scale, then the acceleration mechanism proposed by Bykov and co-workers should be adopted, leading to a different energy spectrum, and thus to a component of EPs distinct from the ordinary CRs. This crucial question will be addressed in future works.

Acknowledgments. This work was supported by the TMR programme of the European Union under contract FMRX-CT98-0168.

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