Lithium-Beryllium-Boron: 
Origin and Evolution

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Abstract

The origin and evolution of Lithium-Beryllium-Boron is a crossing point between different astrophysical fields: optical and gamma spectroscopy, non thermal nucleosynthesis, Big Bang and stellar nucleosynthesis and finally galactic evolution. We describe the production and the evolution of Lithium-Beryllium-Boron from Big Bang up to now through the interaction of the Standard Galactic Cosmic Rays with the interstellar medium, supernova neutrino spallation and a low energy component related to supernova explosions in galactic superbubbles.
1 Introduction

Light element nucleosynthesis is an important chapter of nuclear astrophysics. Specifically, the rare and fragile light nuclei, Lithium, Beryllium and Boron (LiBeB) are not generated in the normal course of stellar nucleosynthesis (except \(^7\)Li, in the galactic disk) and are, in fact, destroyed in stellar interiors. This characteristic is reflected in the low abundance of these simple species.

A glance to the abundance curve [1] suffices to capture the essence of the problem: a gap separates He and C. At the bottom of this precipice rests the trio Li-Be-B. They are characterized by the simplicity of their nuclear structure (6 to 11 nucleons) and their scarcity in the Solar System and in stars.

Indeed, they are rare because they are fragile and, apparently a selection principle at the nuclear level has operated in nature. Due to the fact that nuclei with mass 5 and 8 are unstable, the Big-Bang nucleosynthesis (BBN) has stopped at A = 7, and primordial thermonuclear fusion has been unable to proceed efficiently beyond lithium. Figure 1 represents the calculated abundance by number of the light elements as a function of the baryon over photon ratio produced in the Big Bang.

The Big Bang production of \(^6\)Li is dominated by the D \((\alpha, \gamma)\) \(^6\)Li reaction [98], [16], [17], [14]. No direct measurement of the cross section of this reaction has been performed below 1 MeV. However, the Coulomb breakup technique
[12] provides an indirect estimate which is in qualitative agreement with the theoretical extrapolation at low energy of Mohr et al. (1994) [13]. Recently, the European Collaboration between nuclear physicists and astrophysicists led by Marcel Arnould (NACRE: European Astrophysical Compilation of Reaction Rates) has delivered a consistent compilation of thermonuclear reaction rates of astrophysical interest, among them is the D (α,γ) 6Li reaction [7]. They conclude that the reaction rate based on the Mohr et al. [13] S factor is the most relevant. This rate is similar to that of Caughlan and Fowler (1988) [8], in the temperature range of cosmological interest. The two estimates agree to within a few percents. Nollet et al. (1997) [14] have considered all the published evaluations of this reaction rate. However, most of the extrapolations at low temperature depart considerably from the Kiener et al. 1991 [12] estimate except that of [13]. Following the recommendation of Kiener (1998, private communication) and [7] we have adopted the Mohr estimate. Note that the upper limit given by [9] is much higher. This upper limit is indeed related to the bad sensitivity of the detector used (Kiener, private communication). The 10B and 11B abundances are calculated with updated reactions rates, including the new 10B(p,α)7Be reaction (adopted from [15]). Clearly, the calculated primordial Be and B abundances are negligibly small, compared to 6Li. The standard BBN is hopelessly ineffective in generating 6Li, 9Be, 10B, 11B. [16], [11].

Thus, stars are necessary to pursue the nuclear evolution bridging the gap between 4He and 12C much later, through nuclear fusion.

Up to recently, the most plausible formation agents of LiBeB were thought to be Galactic Cosmic Rays (GCRs) interacting with interstellar CNO. Other possible origins have been also identified: primordial and stellar (7Li) and supernova neutrino spallation (for 7Li and 11B). In contrast, 6Li, 9Be and 10B are pure spallative products. Be is very precious to astrophysics since it is monoisotopic, thus the elemental measurement is also an isotopic measurement. On the other hand, Li and B have two stable isotopes and an isotopic measurement is necessary to separate 6 and 7, 10 and 11, which is very difficult, specifically in stars.

6Li presents a special interest since fortunately, the 6Li/7Li ratio has been measured recently in a few halo stars, offering a new constraint on the early galactic evolution of light elements. Optical measurements of the beryllium and boron abundances in halo stars have been achieved by the 10 meter KECK telescope and the Hubble Space Telescope. These observations indicate a quasi linear correlation between Be and B vs Fe, at least at low metallicity (mass fraction of elements heavier than helium), contradictory at first sight, to a dominating GCR origin of the light elements which predicts a quadratic relationship (see appendix, section 10). As a consequence, the theory of the origin and evolution of LiBeB nuclei has to be reassessed. Aside GCRs, which are thought to be accelerated in the general interstellar medium (ISM) and which create LiBeB through the break up of interstellar CNO by their fast protons and alphas, Wolf-Rayet stars (WR) and core collapse supernovae (SNII) grouped in superbubbles could produce copious amounts of light elements via the fragmentation in flight of rapid carbon and oxygen nuclei (called hereafter low energy
component, LEC) colliding with H and He in the ISM. In this case, LiBeB would be produced independently of the interstellar medium chemical composition and thus a primary origin is expected (see appendix, section 10). These different formation processes are discussed in the framework of a galactic evolutionary model. More spectroscopic observations (specifically of O, Fe, Li, Be, B) in halo stars are required for a better understanding of the relative contribution of the various mechanisms. Future tests on the injection and acceleration of nuclei by supernovae and Wolf Rayet relying on high energy astronomy will be invoked in the perspective of X ray astronomy and the European INTEGRAL satellite.

Thus, light element research impacts several important astrophysical problems, specifically, the origin and the evolution of cosmic rays, galactic chemical evolution, X and gamma-ray astronomies and indirectly BBN through Li.

The questions posed are: What are the main agents of nonthermal nucleosynthesis and what are their relative contributions at different galactic epochs? What is the origin of the present epoch GCRs, are they accelerated out of the average ISM or out of supernova ejecta, and what was their past composition? Was there a population of low energy nuclei, specifically C and O, responsible for primary LiBeB production?

This review is dedicated to David Schramm, our exemplary colleague and friend, who has largely contributed to the development of this astrophysical field.

In section 2, we decline the story of the subject matter, in section 3 the production ratios of the light isotopes are presented. Sections 4 and 5 are devoted to standard Galactic Cosmic Rays, the traditional agents of creation of LiBeB. Section 6 introduces and describes a new spallative component made of low energy nuclei, possibly distinct from GCRs. Section 7 briefly summarises neutrino spallation, section 8 integrates all these processes in the framework of a galactic evolutionary model. Finally, section 9 concludes and presents the prospects of LiBeB research.

2 LiBeB story

A general trend in nature is that complex nuclei are not proliferating: the abundance of the elements versus the mass number draws a globally decreasing curve. In the whole nuclear realm, LiBeB are exceptional since they are both simple and rare. Typically, in the Solar System, Li/H = 2 \times 10^{-9}, B/H = 7 \times 10^{-10}, Be/H = 2.5 \times 10^{-11} \text{[1]}, whereas C/H = 3.5 \times 10^{-4} and O/H = 8.5 \times 10^{-4}.

The local isotopic ratios, measured in meteorites are known with excellent precision. ^{11}B/^{10}B = 4 \text{[43]}, ^{7}Li/^{6}Li = 12.5 \text{[1]}.

Stellar nucleosynthesis, quiescent or explosive, forge the whole variety of nuclei from C to U but LiBeB nuclei are destroyed in the interior of stars, except ^{7}Li which is produced in AGB and novae. The destruction temperatures are 2, 2.5, 3.5, 5.3 and 5 millions of degrees for ^{6}Li, ^{7}Li, ^{8}Be, ^{10}B and ^{11}B respectively. It is worth noting that ^{7}Li and ^{11}B could be produced by neutrino spallation in helium and carbon shells of core collapse supernovae, respectively
[96], [91]; however, this mechanism is particularly uncertain depending strongly on the neutrino energy distribution.

It is clear that another source is necessary to generate at least $^6\text{Li}$, $^9\text{Be}$, $^{10}\text{B}$ and this is a non thermal mechanism, namely the break up of heavier species (CNO, mainly) by energetic collisions, also called spallation.

The LiBeB story has been rich and moving. The genesis of LiBeB was so obscure to Burbidge et al (1957) [6] that they called X the process leading to their production. Then came Hubert Reeves and his colleagues.

A very active and talented group of nuclear physicists, led by René Bernas: Eli Gradstjjan, Robert Klapish, Marcelle Epherre, Francoise Yiou and Grant Raisbeck used the mass spectroscopy techniques in order to determine the spallation cross sections induced by 155 MeV protons on C and O. H. Reeves and E. Schatzman were lucky enough to collaborate with this group. The paper Bernas et al. (1967) [5] based on a better knowledge of the spallation nuclear reaction cross sections has been determining to the understanding of the genesis of LiBeB.

The second happy circumstance was the encounter between Hubert Reeves and Bernard Peters (one of the discoverers of the heavy Cosmic Rays). B. Peters draw the attention of H. Reeves on the fact that the LiBeB/CNO ratio is about $10^{-6}$ in the standard abundances (Solar System) and 0.25 in the GCRs. H. Reeves proposed at once the scenario concerning the LiBeB nucleosynthesis [78]: contrary to most of the nuclear species LiBeB are formed by the "spallative " encounter between the energetic GCR particles and the interstellar medium (ISM).

In a seminal work, Meneguzzi, Audouze and Reeves (1971) (MAR) [62] gave the complete calculations. Considering the fast p, α in the GCRs interacting with CNO in the ISM, they were able to make quantitative estimates of the LiBeB production on the basis of cross section measurements notably made in Orsay [71].

However, this study, relying on the local and present observations (LiBeB and CNO abundances, cosmic ray flux and spectrum) was based on an extrapolation over the whole galactic lifetime assuming that all the parameters are constant. This result accounted fairly well for the cumulated light element abundances but obviously not for their evolution which, at that time, was unknown. The pertinence of the MAR proposal is illuminated by the simple and beautiful fact that the hierarchy of the abundances $^{11}\text{B} > ^{10}\text{B} > ^9\text{Be}$ is reflected in the cross sections [75] (see figure 4). This is another proof that nature follows the rules of nuclear physics. $^6\text{Li}$, $^9\text{Be}$ and $^{10}\text{B}$ were nicely explained but problems were encountered with $^7\text{Li}$ and $^{11}\text{B}$. The calculated $^7\text{Li}/^6\text{Li}$ ratio was 1.2 against 12.5 in meteorites. Stellar sources of $^7\text{Li}$ appeared necessary. The estimated $^{11}\text{B}/^{10}\text{B}$ ratio was 2.5 instead of 4 in meteorites. An ad-hoc hypothesis drawing on unobservable low energy protons operating through the $^{14}\text{N}(p,x)^{11}\text{B}$ reaction was advocated [77].

New measurements of Be/H and B/H from KECK and HST, together with $[\text{Fe/H}]$ [118], [110] [44] [105], [119], [107], [109] in very low metallicity halo stars came to set strong constraints on the origin and evolution of light isotopes.
The evolution of BeB was suddenly uncovered over about 10 Gyr, taking [Fe/H] as an evolutionary index. A compilation of Be and B data is presented in figures 2 and 6. The most striking point is that log(\(\text{Be}/\text{H}\)) and log(\(\text{B}/\text{H}\)) are both quasi proportional to [Fe/H] (this notation means the log of the number abundance normalized to its solar value), at least up to [Fe/H] = -1 and that the B/Be ratio lies in the range 10 - 30 \[107\]. Note however, two discrepant points in the boron diagram (figure 6) at the lowest [Fe/H]. This is mainly due to the huge NLTE correction on B data \[112\], \[32\] that increases the departure from a straight line. It is important to take a careful look to this delicate correction. Moreover, NLTE corrections on Fe have also to be considered \[88\].

This linearity came as a surprise since a quadratic relation was expected from the GCR mechanism (see section 4). It was a strong indication that the standard GCRs are not the main producers of LiBeB in the early Galaxy. A new mechanism of primary nature was required to reproduce these observations: it has been proposed that low energy CO nuclei produced and accelerated by massive stars (WR and SN II) fragment on H and He at rest in the ISM. This low energy component (LEC) has the advantage of coproducing Be and B in good agreement with the ratio observed in Pop II stars (figure 6, \[39\], \[91\], \[93\], \[72\], \[73\]).

A primary origin, in this language, means a production rate independent of the interstellar metallicity (\(Z\): mass fraction of elements heavier than helium). In
this case, the cumulated abundance of a given light isotope L is approximately proportional to Z. At variance, standard GCRs offer a secondary mechanism because it should depend both on the CNO abundance of the ISM at a given time and on the intensity of cosmic ray flux, itself assumed to be proportional to the SN II rate (see appendix, section 10).

Indeed, the Be-Fe and B-Fe correlations taken at face value reveal a contradiction between standard GCR theory and observation. But, since oxygen is the main progenitor of BeB, the apparent linear relation between BeB and Fe could be misleading if O was not strictly proportional to Fe [111], [4]. Thus the pure primary origin of BeB in the early Galaxy could be questioned [51], [52], [25]. However, the oxygen measurements themselves are confronted to many difficulties [114], [23], [54]. On the theoretical side, the situation is not better. The $[\alpha/Fe] \text{ vs } [Fe/H]$ where $\alpha = Mg, Si, Ca, S, Ti$ [106], [120] show a plateau from $[Fe/H] = -4$ to -1. On nucleosynthetic grounds, it would be surprising that oxygen does not follow the Si and Ca trends. Moreover, using the published nucleosynthetic yields [97], [121] it is impossible through galactic evolutionary models to fit the log(O/H) vs [Fe/H] relation of Israelian et al. (1998) [111] and Boesgaard et al. (1999) [4] since the required oxygen yields are unrealistic. Thus the subject is controversial.

Concerning lithium, a compilation of the data is shown in Figure 2 [113] and [117]. The Spite plateau extends up to $[Fe/H] = -1.3$. Beyond, Li/H is strongly increasing until its solar value of $2 \times 10^{-9}$.

A stringent constraint on any theory of Li evolution is avoiding to cross the Spite’s plateau below $[Fe/H] = -1$. Accordingly, the Li/Be production ratio should be less than about 100.

Recent measurements of $^6\text{Li}$ have been made successfully in two halo stars, HD84937 and BD +26 3578 at about $[Fe/H] = -2.3$ [56], [103], [57], [40], [81], yielding $^6\text{Li}/^7\text{Li}$ about 0.05. The great interest of $^6\text{Li}$, (as shown by [102]) besides of being an indicator of stellar destruction [101], [10], [41], [123] is to represent a pure spallation product as $^7\text{Be}$ and participate to constrain the global LiBeB evolution. Moreover, the $^6\text{Li}/^9\text{Be}$ ratio (clearly non solar in two halo stars since its amounts to 20 - 80, [28]) bears information on ancient non thermal nuclei.

To summarize, we can give six observational constraints on LiBeB evolution:

1. Be and B proportional to Fe
2. Li/Be < 100 up to $[Fe/H] = -1$
3. B/Be = 10-30
4. $^{11}\text{B}/^{10}\text{B} = 4$ at solar birth
5. $^{7}\text{Li}/^{6}\text{Li} = 12.5$ at solar birth
6. $^6\text{Li}/^7\text{Li} = 0.05$ and $^6\text{Li}/^9\text{Be} = 20$ to 80 (to be confirmed) at $[Fe/H]$ about -2.3

We recall that the observational O - Fe relation is central to the interpretation since specifically the production of Be is directly related to O and not to Fe.
3 Production ratios of LiBeB isotopes

3.1 Cross sections

The physics of interest for us is that of the heavy ions accelerators. It implies a beam of fast nuclei (injected and subsequently accelerated), a target and an interaction between both.

The result of a nuclear collision depends on i) the composition of the beam, ii) the relative velocity of the projectile and the target nuclei, and thus the energy spectrum of the beam and iii) the target composition. All these dependencies are quantified by the cross section.

For a monenergetic beam, the number of favourable events per second or reaction rate is given by
\[ r_{ij} = n_in_j\sigma v, \]
or, equivalently, by the product \( n_i\sigma\phi \) where \( n_i \) is the number density of the target and \( \phi \) the flux of the projectiles. For an energy distribution, the reaction rate is averaged on the velocity distribution function \( \phi(v) \). In most of the astrophysical situations, the energy distribution of the projectile is violently non thermal. The spectra that can be parametrized as power laws of the form
\[ N(E)dE = kE^{-\gamma}dE \]
are customary. Stellar nucleosynthesis implies low energies (1 keV-100 keV) and high densities \( (10^2 - 10^9 \text{ g.cm}^{-2}) \). By contrast, spallative nucleosynthesis implies high energies (1 MeV-100 GeV) and very low densities \( (1-10^3 \text{ atoms.cm}^{-3}) \). Expressed in (MeV/n) unit, the cross sections of direct reactions \((1 + 2 > 3)\) and reverse \((2 + 1 > 3)\) where beam and target have been exchanged, are identical due to the velocity conservation in energetic collisions.

In the thermonuclear context, the energy of the nuclei is below the Coulomb barrier, and the cross section is dominated by the Coulomb penetration factor. Cross sections are factorised as follows:
\[ \sigma(E) = \left(\frac{1}{E}\right)_S S(E).\exp\left(-2\pi\eta\right) \]
where \( \eta = Z_1Z_2/hv \)

The first term (square of the associated wavelength) is of geometric nature, the second, called astrophysical factor, is related to the internal structure of the target nucleus and the third, the Coulomb penetration factor, is by far the most influential.

In general, the production cross sections, and thus the production ratios of the various isotopes are very different, which explains the abundance disparities at the end of the Big Bang nucleosynthesis. In the high energy non thermal context, on the contrary, the penetration factor tends to 1. This, added to the nuclear similarity of light nuclei leads to spallative production rates of \(^6\text{Li}, ^7\text{Li}, ^9\text{Be}\) and \(^{10}\text{B}, ^{11}\text{B}\) relatively similar.

The excitation functions (variations of the cross sections as a function of energy/n) are presented in figure 3.

The \( \alpha + \alpha \) reaction, leading to the synthesis of \(^6\text{Li}\) and \(^7\text{Li}\) plays a peculiar role in astrophysics since it is the only reaction that implies nuclei of Big Bang origin. It is fertile even at zero metallicity and thus it is a source of \(^6\text{Li}\) and \(^7\text{Li}\) in the early Galaxy. Its excitation function is particular due to its low threshold.
Figure 3: LiBeB production cross sections as a function of the energy per nucleon updated by [74]. From top to bottom and left to right, reactions on C, N, and O induced by protons, $\alpha + \alpha$; same reactions but with alpha particles. These graphs have been kindly supplied by Reuven Ramaty.

and its decline at high energy. For more details on the nuclear physics see Reeves (1994), [77])

### 3.2 Input parameters

Thus, four parameters are influential to the spallative production of light elements: the reaction cross sections, the energy spectrum of fast nuclei, the composition of the beam and the composition of the target.

Cross sections are well measured [75] and have been updated recently by [74].

The adopted spectra are generally of two kinds:

1. GCR: $N(E)dE = kE^{-2.7}dE$ above a few GeV/n with a flattening below (e.g. [59] and [66]).

2. LEC: Shock wave acceleration with a cut at $E_0$ of the form $N(E)\,dE = kE^{-1.5}\exp(-E/E_0)\,dE$ [72], propagated in the ISM.

The source composition of GCR is well determined [108]. It is p and $\alpha$ rich
(H/O = 200, He/O = 20) contrary to the possible source composition of the LEC (see section 6). The most obvious contributors to LEC are supernovae, Wolf-Rayet and mass loosing stars [39], [72], [73]. It is worth noting that in the early Galaxy, supernovae play a leading role since at very low metallicity stellar winds are insignificant.

Table 1 shows a sample of compositions used by different authors: solar system (SS) for comparison ([72] from [1]), cosmic ray source (CRS) ([72] from [115]), wind of massive stars (W40) ([68] from [116]), composition of grain products (GR) ([72] and [60]), 40 Mo supernova at $Z = 10^{-4}$ Z⊙ from [97], 35 Mo supernova of solar metallicity ([72] from [124]). The two supernovae, though at different metallicities, (SN40 at low metallicity and SN35 at solar metallicity), give similar yields due to the fact that metallicity dependent mass loss has not been taken into account in the stellar models. Resulting elemental and isotopic ratios (B/Be, $^{11}$B/$^{10}$B, $^6$Li/$^9$Be) for different compositions and $E_0$ can be found in [72] and [122].

Note that N is insignificant and that Type II supernovae are O-rich whereas the winds of massive stars are C and He-rich. These abundance differences are important since the highest $^{11}$B/$^{10}$B ratios are produced by C-rich beams through $^{12}$C(p,x)$^{11}$B and the highest $^6$Li/$^9$Be ratios are produced by He and O rich compositions.

Figure 4: Production ratios of $^{11}$B/$^{10}$B (a), B/Be (c) and $^6$Li/$^9$Be (d) and energetics (b) as a function of cut-off energy $E_0$ in the strong shock case, kindly supplied by Reuven Ramaty [72].

Figure 4 shows a sample of production ratios together with the associated
energetics for different source compositions as a function of the cut-off energy in the case of a strong shock spectrum. The values of the ratios at high Eo converge toward the GCR points. The data (ChR, FOS, AG) are from [43] [53] and [1]. The source compositions are following. CRS: cosmic ray source, SS: solar system, WC: Wolf-Rayet, SN35, SN60: supernovae with 35 and 60 Mo progenitors, GR: grains. Figure (4.b) represents the energy injected under the form of fast nuclei necessary to produce 100 Mo of boron (which is in order of magnitude the mass of boron in the whole Galaxy). The target composition is that of the present ISM taken as the solar one. The horizontal bar indicates the total energy released by $2 \times 10^7$ SN, which corresponds roughly to the total number of SN having exploded since the birth of the Galaxy.

<table>
<thead>
<tr>
<th>Element</th>
<th>SS</th>
<th>CRS</th>
<th>W40</th>
<th>GR</th>
<th>SN40(low Z)</th>
<th>SN35(Zo)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>1200</td>
<td>220</td>
<td>80</td>
<td>2</td>
<td>37</td>
<td>27</td>
</tr>
<tr>
<td>He</td>
<td>120</td>
<td>22</td>
<td>25</td>
<td>0</td>
<td>8.8</td>
<td>7.6</td>
</tr>
<tr>
<td>C</td>
<td>0.47</td>
<td>0.87</td>
<td>1.6</td>
<td>0.3</td>
<td>0.09</td>
<td>0.08</td>
</tr>
<tr>
<td>N</td>
<td>0.13</td>
<td>0.04</td>
<td>-</td>
<td>0.03</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>O</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
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</tr>
</tbody>
</table>

The fourth parameter, i.e., the composition of the target (ISM) varies from the birth of the Galaxy up to now. The extensive study of [72] and [122] shows that there are only slight differences in the results when the ISM metallicity is varied between Z=0 (early galaxy) and Z=0.02 (at present).

4 Standard Galactic Cosmic Rays (GCRs): acceleration and propagation

4.1 High energy cosmic rays

Galactic cosmic rays represent the only sample of matter originating from beyond the Solar System. They are constituted by bare energetic nuclei stripped from their electrons. Their energy density (about $1 \text{eV cm}^{-3}$ [94] similar to that of stellar light and that of the galactic magnetic field), indicate that they are an important component in the dynamics of the Galaxy. A key point for our purpose is that, as said above, GCRs are exceptionnally LiBeB rich ($\text{LiBeB/CNO} = 0.25$) compared to the local (Solar System) matter ($\text{LiBeB/CNO} = 10^{-6}$).  

The energy spectrum of the GCRs can be described by a power law above a few GeV/n (section 3.2). Below 1GeV/n, the nuclei are repelled by the solar wind and it is difficult to deduce from the observations near earth, the interstellar spectrum.

Diffuse shock acceleration is now the leading paradigm in cosmic ray physics (for a review see [49], [50], [45]). In this mechanism, each passage of the shock
front produces an energy increment. Diffusion allows confinement in the shock region, and after many crossings of the shock (both ways), the particles acquire sufficient energy (gyroradius) to leak out.

The energy required to sustain the GCR energy density can be supplied by supernovae [94]. Thus SN are not necessary the sources of GCR nuclei, but their acceleration agents. Recurrently models assuming that they are both the reservoir and the accelerating engine have been proposed. The last version of this idea [60], though attractive has been criticized. This does not mean that fast nuclei originating from supernovae do not exist at all. If they exist they are different from GCR and should be called differently (see section 6).

In the simplest (linear) shock acceleration theory, the resulting momentum distribution function $f(p)$ is a power law of the form $p^{-3r/(r-1)}$, where $r$ is the compression factor, which is a function of the Mach number ($r = 4M^2/(M^2-1)$). Thus for a strong shock, ($M >> 1$), $r = 4$ and $f(p)$ is proportional to $p^{-4}$, which corresponds to an energy spectrum proportional to $E^{-2}$ at high energy. The observed proton spectrum ($E^{-2.7}$) is slightly steeper due to an easier escape of high energy nuclei (see figure 5). Once launched in space, these nuclei are deviated by the magnetic field irregularities and they lose memory of their birth place. The propagation is of the diffusive type. Each time they reach the border of the Galaxy (badly defined) they can escape or return to the galactic disk where they suffer ionization energy losses and nuclear interactions. The Galaxy, in this context is like a leaky box. The influential parameter is the mean escape length, $\lambda$ (or the related confinement time). At every moment on their way, the fast nuclei lose energy (by ionization and heating of the ISM) and can be destroyed in flight by a collision with other nuclei sitting in the ISM.

The propagation equation reads
\[ \frac{dN(E)}{dt} = Q(E) - \frac{N(E)}{\tau} + \frac{d}{dE} \left[ b(E)N(E) \right] = 0 \]
(assuming a steady state). $Q(E)$ is the source (injection) spectrum, $b(E)$ is the energy loss rate by collisions with ambient electrons. The loss time $\tau$ is the harmonic mean of the confinement time and the nuclear destruction time. The energy distribution is modified in the course of the propagation since energy losses are energy dependent. Dividing by the mean density of the ISM one get
\[ \frac{d\phi(E)}{dx} = q(E) - \frac{\phi(E)}{\lambda} + \frac{d}{dE}[\omega(E)\phi(E)] = 0 \]
with $\omega(E) = dE/dx(\text{MeV}/(g \cdot \text{cm}^{-2}))$.

The equilibrium spectrum (or interstellar spectrum) is solution of this equation. It is over this spectrum and not the source spectrum that the cross sections have to be averaged to get the production rates and ratios.

### 4.2 Low energy cosmic rays and the carrot

At low energy (less than 100 MeV/n) the particles are thermalized before leaking from the Galaxy and being destroyed by nuclear collisions. Thus the propagation equation simplifies considerably since the Galaxy is now like a closed box. In this case, the production efficiency of LiBeB is maximal because fragments of nuclear collisions are quickly thermalized and integrated in the interstellar gas;
Figure 5: Spectrum of protons calculated through a diffusion-convection model [66] as a function of the kinetic energy. Solid line: model with no reacceleration and an injection spectrum index 2. Dashed line : interstellar spectrum of [79]. Dash-dotted line: medium spectrum [65], kindly supplied by Andrew Strong.

The low energy part of the problem is often overlooked, whereas the key of the question could lie below 100 MeV/n since the peak of the cross sections are about at 20 - 30 MeV/n and even lower for alpha induced reactions. This is due to the large uncertainties affecting the interstellar flux of fast nuclei in this energy range.

The propagation equation is now:
\[ q(E) + \frac{d}{dE} [ \omega(E) \phi(E) ] = 0 \]

Furthermore, as we said, the \(^{11}\text{B}/^{10}\text{B}\) ratio produced by GCR spallation, amounting to 2.5 (MAR, [62]) is somewhat different from the meteoritic value (4). MAR assumed the existence of a considerable excess of GCR at low energy, (5 - 40 MeV/n). This additional flux, called carrot, if existing, would enhance the production of \(^{11}\text{B}\) via the reaction \(\text{p} + ^{14}\text{N} \rightarrow ^{11}\text{B}\).

It is worth noting that the composition of this carrot was taken as the GCR one and thus has to be considered as a secondary source and cannot be invoked to explain the linear evolution of B, indicated by the data.

The difficulty is that this component cannot be observed in the earth vicinity. Indeed, below about 1 GeV/n, the energy distribution of GCR in interstellar space can only be determined indirectly since most particles are excluded from the Galaxy (only about 20 percent is remaining, [61]).

on the contrary in the high energy case most of the LiBeB produced in flight escape from the Galaxy (only about 20 percent is remaining, [61]).

The low energy part of the problem is often overlooked, whereas the key of the question could lie below 100 MeV/n since the peak of the cross sections are about at 20 - 30 MeV/n and even lower for alpha induced reactions. This is due to the large uncertainties affecting the interstellar flux of fast nuclei in this energy range.

The propagation equation is now:
\[ q(E) + \frac{d}{dE} [ \omega(E) \phi(E) ] = 0 \]

Furthermore, as we said, the \(^{11}\text{B}/^{10}\text{B}\) ratio produced by GCR spallation, amounting to 2.5 (MAR, [62]) is somewhat different from the meteoritic value (4). MAR assumed the existence of a considerable excess of GCR at low energy, (5 - 40 MeV/n). This additional flux, called carrot, if existing, would enhance the production of \(^{11}\text{B}\) via the reaction \(\text{p} + ^{14}\text{N} \rightarrow ^{11}\text{B}\).

It is worth noting that the composition of this carrot was taken as the GCR one and thus has to be considered as a secondary source and cannot be invoked to explain the linear evolution of B, indicated by the data.

The difficulty is that this component cannot be observed in the earth vicinity. Indeed, below about 1 GeV/n, the energy distribution of GCR in interstellar space can only be determined indirectly since most particles are excluded from the Galaxy (only about 20 percent is remaining, [61]).
the solar cavity by the solar wind and the theory of solar modulation is too uncertain to demodulate the observed flux, especially at the lowest energies.

Limits on the low energy GCR flux (including the carrot) has been set by Lemoine et al. (1998) [59] running a galactic evolutionary model, in order to avoid overproduction of Be. A carrot of the kind assumed by MAR and Meneguzzi and Reeves (1975) [61] is excluded since it would lead to strong overproduction of LiBeB at solar birth. Only the lower spectrum proposed in the literature was consistent with the Solar System beryllium abundance. Apart this global (integrated) argument there are now rather secure means to get informations on the low energy spectrum. Strong and Moskalenko [66], [82] [33] have worked out a three dimensional model of GCR propagation and confinement taking into account all observables (cosmic-ray composition, gamma rays, electrons, positrons, synchrotron radiation and antiprotons,). They conclude that the low energy spectrum is depressed (figure 5). This conclusion has an impact on the production rate of the light elements since i) it excludes the carrot and ii) the decrease of the flux at low energy deduced confirms the restriction set by [59] on the lower end of the spectrum and it leads to a good fit of the local LiBeB abundances.

5 Are Galactic Cosmic Rays a truly secondary component?

As shown above, the CR origin impacts on the galactic evolution of LiBeB elements. In the light of the linear relationship between BeB and Fe, certain authors have asked themselves if GCRs could be primary sources, at the expense of modifications in the physical picture of the origin of the accelerated nuclei.

Indeed, since according to the reservoir of the accelerated nuclei (interstellar medium or supernova remnants loaded with fresh products of nucleosynthesis), the production process of LiBeB is secondary or primary (i.e. dependent or independent of the interstellar metallicity Z). A pure ISM origin would lead to a slope 2 in the correlation between LibeB and O (or Fe) whereas the SN origin would lead naturally to slope 1 (see appendix, section 10). The debate on the origin and evolution of the light elements has shifted i) to the origin and very nature of the GCRs and ii) on the possible existence of a distinct low energy component (section 6).

Concerning the status of GCRs, the question has recently been revived in the LiBeB Conference in Paris, December 1998 [34].

Maurice Shapiro [30], representing the traditional trend, assumed that the cosmic rays are preaccelerated by coronal mass ejection (CME) driven shocks on low mass cool stars and accelerated further on by passing SN shock waves. Cassé and Goret (1978) [36] first pointed out that the difference between the compositions of the GCR source and the solar photosphere might be due to selection according to the first ionization potential (FIP) of the elements. The FIP effect is now well established as the cause for the differences between the
photospheric abundances and those of both the corona and the solar energetic particle in gradual events [76]. The fact that these energetic particles are accelerated by CME driven shocks in the corona is what drives the argument for the stellar origin of the GCR injection. However, arguments against this FIP based stellar origin were recently obtained from observations of ultraheavy nuclei in the cosmic rays [95].

According to Lingenfelter et al. (1998) [60], the current epoch GCRs could come from each supernovae accelerating their own freshly produced refractory material.

According to Meyer and collaborators, the current epoch GCRs originate from an average ISM of solar composition as in a classical proposal since the composition of the external layers of stars is identical to that of that of the ISM where they are born. Interstellar dust plays an important role in determining the abundances [64], [46]. In any case, an additional contribution from Wolf-Rayet circumstellar material enriched in freshly synthesized C and above all $^{22}$Ne is needed to explain the $^{22}$Ne observed in GCRs [37], [63]. This WR component counts as a primary source, at least at present, but it is quite difficult to assert its importance in the early Galaxy.

The difficulties involved in the acceleration process of the SN model have been emphasized by Ellison and Meyer (1999) [24]. While the most significant shortcoming of this individual supernova model is the conflict with the delayed acceleration (see just below), Lingenfelter et al. (1998) [60] show how the averaging of the supernova nucleosynthetic yields over the initial mass function and supernova types, as well as the inclusion of the effects of refractory dust grains formed in the ejecta, lead to a GCR source composition in good agreement with the observations. Moreover, Meyer and Ellison (1999) [27] stressed that the heavy $s$ elements, and more specifically Sr, Zr, Ba and Ce, are not underabundant in GCR. They are thought to be produced in AGB stars and it is difficult to interpret this observation in terms of acceleration of SN material only.

Observations of the electron capture radioisotope $^{59}$Ni in GCR and its decay product $^{59}$Co [19], have been performed with an instrument on the ACE mission. $^{59}$Ni decays by electron capture with a half life of $7.6 \times 10^4$ years. However the decay is suppressed if the acceleration time scale is shorter than the lifetime because the atom is stripped as it is accelerated [38]. The fact that much more $^{59}$Co than $^{59}$Ni is observed, suggests a delay ($\sim 10^5$ years) between explosive nucleosynthesis of iron-peak nuclei (under the form of their radioactive progenitors) and their acceleration to cosmic-ray energies. This makes it unlikely that individual supernovae accelerate their own ejecta. This conclusion is corroborated by energetic arguments.

Obviously, the acceleration of average ISM matter is consistent with the implied delay between nucleosynthesis and acceleration. But this delay is also consistent with acceleration of ejecta matter in superbubbles where multiple supernova shocks accelerate accumulated supernova ejecta on average time scales at least as long as the implied delay ([55] and section 6) and are more energetically favourable than single supernovae [47, 48].
6 Low energy nuclei from superbubbles: a primary process

As soon as the Hubble and Keck observations of BeB vs Fe were released, the necessity of a primary component has been felt [44], [91], [72]. The existence of intense fluxes of fast C and O nuclei in the early Galaxy appeared unescapable. This LEC component is, in all likelihood, physically linked to the superbubble scenario.

The physical conditions in superbubble cavities would lead to fast nuclei with hard energy spectra at low energies up to a cutoff at an energy which is still nonrelativistic due to a combination of weak reflected shocks and turbulence [22, 20, 68, 69, 70, 21]. These are the low energy nuclei which have been postulated to produce the bulk of the Be and B at low metallicities [91]. On the other hand, as pointed out by Higdon et al. (1998) [55, 31], since these giant superbubbles are thought to fill up a large fraction of the ISM, they are also the most likely site for the acceleration of the GCRs, which of course show no cutoff up to very high ultrarelativistic energies. Indeed the ingredients of a powerful ion accelerator are gathered in superbubbles due to copious injection of matter and energy by massive stars. WR and SN ejections in the common pot and supersonic material in the form of winds and supernova ejecta able to generate recurrent shock waves. Recent work by Parizot and Drury (1999) [70] shows that SBs produce Be and other light elements at the less energetic cost. They could be the key of the thorny energetic problem of the production of Be in the halo. Superbubbles [69], [55] thus appear as the most promising sites of acceleration of fresh products of nucleosynthesis, either as a separate low energy component or the GCRs themselves [20], [22]. Indeed, both the low energy nuclei and standard components could be produced by superbubbles at different stages of their evolution.

This idea needs further observational substantation. Possible diagnostics of low energy particle interactions are i) non thermal X-rays in the 0.5 to 1 keV range due to atomic deexcitation in fast O following electron capture and excitation [84], [86] [85] and ii) gamma- ray lines produced by nuclear excitation of C, O [72], [68] and \(^{7}\)Li + \(^{7}\)Be formed by the alpha + alpha reaction [87]. For the time being, after the official withdrawal of the Orion gamma-ray results, [3] and the preliminary announcement of a detection of an excess between 3 and 7 MeV in the direction of Vela [89] a hint to the existence of a large population of MeV/n nuclei comes from the X-ray emission of the galactic ridge [85]. The observation or non observation of C, O lines at 4.4 and 6.1 MeV and of the Li-Be feature close to 500 keV by the INTEGRAL satellite [125] will be the strongest test of the superbubble hypothesis [68] [87] which are at the moment the best proposed sites of acceleration of low energy nuclei enriched in C and O.
7 Neutrino spallation: a primary process

Neutrino spallation is a source of $^{7}$Li and $^{11}$B via the interactions of neutrinos (predominantly $\nu_\mu$ and $\nu_\tau$) on nuclei, specifically on $^4$He and $^{12}$C [96], Woosley and Weaver (1995) [97], hereafter WW. The lithium and boron yields are quite sensitive to the temperature of the $\mu$ and $\tau$ neutrinos, in which there is a fair amount of uncertainty. As a result, the overall yields of $^{7}$Li and $^{11}$B have considerable uncertainties. $\nu$-process nucleosynthesis was incorporated into a model of galactic chemical evolution (Olive et al. (1994) [67] and Vangioni-Flam et al. 1996 which have included the LEC component [91]) with the primary purpose of augmenting the low value for $^{11}$B/$^{10}$B produced by standard GCR nucleosynthesis. To correctly fit the observed ratio of 4, it was found that the yields of WW had to be tuned down by a factor of about 2 to 5 to avoid the overproduction of $^{11}$B. Tuning down the $\nu$-process yields ensured as well that the production of $^{7}$Li was insignificant, and did not affect the Spite plateau. For a review see [26].

Note that if taking the full yield, all galactic boron would be produced by $\nu$ spallation. This could be a problem since $^9$Be is not coproduced and $^{7}$Li overproduced. Thus, this mechanism acts as a complement to nuclear spallative process at a level estimated to at most 20 percent concerning $^{11}$B, if one wants to fulfill the observational constraints presented in section 2 [91].

8 Galactic evolution of light elements

Analyzing all the physical parameters discussed above, two main LiBeB producers emerge, the first one is the standard GCR in which fast p,$\alpha$ nuclei interact with CNO in the ISM. This process seems unable to produce sufficient amounts of LiBeB at the level observed in the halo stars. However, a recent study [51] [52] based on the O - Fe relation derived by [111] and [4] at low metallicity (still controversial, see section 2) try to fit the observational constraints with a pure standard GCR (secondary production) component, but has difficulties with the B/Be ratio and possibly with energetic constraints at very low metallicity.

The second one, LEC, invokes fragmentation of CO nuclei in flight by collision with H and He in the ISM. Massive stars are able in principle to furnish freshly synthesized C and O and accelerate them via the shock waves they induce in their surroundings. This mechanism is probably related to superbubbles.

Finally, neutrino spallation is helpful to increase the $^{11}$B/$^{10}$B ratio up to the value observed in meteorites. It is also a primary process since it implies the break up of C within supernovae and not in the ISM. However it cannot be the unique mechanism to produce light elements since it does not make $^9$Be.

These different mechanisms are included in a galactic evolutionary model to follow the whole evolution of each isotope.

In brief, the characteristics of the standard galactic evolution model used [2, 90, 91, 93, 51, 52] are the following:

No instant recycling approximation, in other terms account is taken of the
Figure 6: Beryllium and Boron evolution vs \([\text{Fe/H}]\). The halo evolution (\([\text{Fe/H}] < -1\), is dominated by the LEC component linked to massive stars. As far as B is concerned, there is room for a small contribution for \(\nu\) spallation. [93] [42]

time delay of matter ejection by low mass stars. The cosmic ray flux and that of the LEC are taken proportional to the supernova rate (itself proportional to the star formation rate). The GCR production rate is time dependent through the growth of CNO in the ISM which is followed by the model (equipped with the relevant yields). The mass distribution of stars at birth, or initial mass function is proportional to \(M^{-2.7}\) from 0.4 to 100 Mo as usual. The star formation rate (SFR) is taken proportional to the gaz mass fraction all along the galactic life. The stellar lifetimes are taken from [116]. The composition of the ejecta is that calculated by WW. The model, of course, takes into account the destruction of LiBeB in stars. The SNI rate is taken constant, with the value observed today. This simple model is sufficient to map the evolution of each Light isotope in the abundance-abundance diagram (L-O and L-Fe plots).

The theoretical evolutionary curve of Be is normalized on the solar abundance of this element.

Concerning beryllium and boron, in this context, the main results are the following: the quasi-linearity (Be-B vs Fe) is easily reproduced thanks to the action of the LEC (fig 6, [93]). Standard GCRs contribute no more than about 30 per cent to Solar System values. The B/Be ratio is in the range 10-30 as observed. The value 30 leaves enough room for neutrino spallation to reach \(^{11}\text{B}/^{10}\text{B} = 4\) at solar birth, but this contribution is marginal [91].

The \(^{6}\text{Li}/\text{H}\) ratio can also be explained in the framework of the same model.
this without piercing the Spite plateau (figure 7). In this figure, showing the evolution of $^6$Li/H vs [Fe/H], it can be seen that GCR is overwhelmed by LEC. The decrease of the $^6$Li/$^9$Be ratio could be explained in terms of the variation of the composition of superbubbles in the course of the galactic evolution, being O rich at start due to SNII and becoming more and more C rich due to the increasing contribution of mass loosing stars.

Fields and Olive [51, 52] using the new O-Fe correlation and considering only the GCR component have also reproduced both solar and popII $^6$Li in a quite natural way. The proportions between the different production processes could be modified if the new O-Fe relation is verified but even in this case, a primary component operating in the very early galactic phase cannot be excluded.

Figure 7: $^6$Li and $^7$Li evolution vs [Fe/H]. Horizontal full line: Li abundance, essentially $^7$Li. Full oblique line: LEC contribution to $^6$Li. Data points concern the two observed stars, (total Li and $^6$Li respectively). Dash-dotted line: GCR contribution to the $^6$Li abundance taking the classical flat O/Fe relation.[92].

In both scenarios, the evolutionary curve of $^6$Li crosses the halo observations meaning that $^6$Li is almost essentially intact in the envelope of stars in which it is measured. $^7$Li in turn, more tightly bound than $^6$Li, is even less destroyed, thus the mean value of the Spite plateau reflects nicely the Big Bang $^7$Li abundance. This reinforce the use of $^7$Li as a cosmological baryometer as shown also recently by the observational and theoretical analyses of [29] [100] [104].
9 Conclusion and perspectives

The confrontation of theory with observations, and the crossing of the boundaries of experiment and theory, has permitted theorists, observers and experimentalists to clarify fundamental questions on the origin and evolution of light elements. Different evolutionary scenarios concerning LiBeB production by accelerated particles in the Galaxy, remain viable.

1. The delay (∼10^5 years) between nucleosynthesis and acceleration, implied by the ^59Co and ^59Ni cosmic-ray data, is consistent with both acceleration of average ISM matter or ejecta matter in superbubbles.

2. A low energy component distinct from standard GCRs appears necessary, specifically in the early Galaxy, but needs to be more observationally rooted.

3. Future X-ray and gamma-ray line observations should help to clarify the very existence of the low-energy nuclei which are able to generate LiBeB in a primary mode, and if these low energy cosmic rays indeed exist, determine their energy spectrum. In spite of the problems encountered in the observation and analysis of the Orion region, the Vela region should be a prime target for the INTEGRAL mission.

4. The new [O/Fe] vs. [Fe/H] observations may make it necessary to refine the model in which GCR nucleosynthesis, taken as a secondary process, is combined with nucleosynthesis by low energy nuclei originating from superbubbles, which is a primary process. The contribution of each component will have to be adequately rescaled to account for the enhanced contribution of the secondary process; the contribution of neutrino spallation would also depend on this rescaling, but it will stay, in any case, marginal.

5. New abundance measurements of ^6Li close to [Fe/H] = −2.3, integrated in the framework of galactic evolutionary models, indicate that this nucleus is not significantly depleted in the observed stars and therefore Li (mostly ^7Li which is less fragile than ^6Li) is essentially intact in halo stars (Spite plateau). This makes Li an excellent indicator of the baryonic density of the Universe. The ^6Li Galactic evolution can be made consistent with the other light nuclei.

Thus, the simplistic vision of the origin and evolution of LiBeB has developed into a complex array of possibilities due to the wealth of observational discoveries. Nevertheless, the originally proposed fundamental mechanism remains preserved, namely the nuclear spallative process which is the only one to coproduce the light isotopes in the right proportion.

The needs for the future are the following:

On the theoretical side it would be necessary:

i) to check NLTE corrections on B abundances (and perhaps Fe) at very low Z.

ii) to develop and refine SN II models, especially at very low Z and high mass.

On the observational side, it would be desirable to get measurements of ^6Li, ^7Li, ^9Be, ^10B, ^11B, O, Fe in the same halo stars and to get ^6Li/^7Li and ^11B/^10B ratios in stars of both populations (pop I and pop II).
Finally, the observation of C, O and Li-Be gamma-ray lines are important objectives of the INTEGRAL satellite following the road open by the COMPTON GRO satellite.

10 Appendix

A clear distinction should be made between a primary production mechanism and a secondary one, in the sense of the galactic evolution. Indeed, in the plausible hypothesis that the GCR flux $\phi$ is proportional to the supernova rate $dN(SN)/dt$, the rate of increase of $L/H$, $L$ standing for beryllium or boron is:

$$\frac{d(L/H)}{dt} = z(t) \langle \sigma \phi(t) \rangle$$

where $z(t)$ is the evolving CNO fraction by number and $\langle \sigma \phi(t) \rangle$ the energy averaged of the production cross section times the flux. Since $z$ is proportional to $N(SN)$, the integrated number of SN up to time $t$, and $\phi$ is proportional to $dN(SN)/dt$, we have, assuming a constant spectral shape,

$$\frac{d(L/H)}{dt} = \alpha N(SN) \frac{dN(SN)}{dt} \frac{L/H}{\alpha z^2}$$

On the contrary, freshly synthesized C and O nuclei injected/accelerated in SN ejecta or superbubbles would lead to a primary production of LiBeB, independent of the interstellar medium metallicity, by fragmentation of these species on the surrounding H and He nuclei. So the production rate is independent of metallicity $z$, and the cumulated abundances $L/H$ are proportional to $z$.

For example, to illustrate our purpose, we calculate the production rate of Be by protons fragmenting interstellar CNO by the GCR process:

$$\frac{dN(Be)}{dt} = N(CNO) \sigma \phi$$

Dividing by $N(H)$, the hydrogen number density, one gets the rate of increase of the Be/H ratio as a function of $z$ defined as $N(CNO)/N(H)$:

$$\frac{d}{dt}(Be/H) = z(t) \sigma \phi(t)$$

The present rate of increase of Be/H, calculated from realistic numerical values, $N(CNO)/N(H) = 10^{-3}$, $\sigma = 5 \text{mb}$, $\phi = 10 \text{cm}^{-2} \text{s}^{-1}$, for $E > 30 \text{ MeV}$ is about $10^{-28} \text{s}^{-1}$, which integrated over the galactic lifetime ($10^{10}$ yrs) leads to Be/H about $10^{-11}$ in qualitative agreement with the Solar System value, which is encouraging. However, this rough calculation does not take into account the temporal variation of the parameters.

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To close this review, we would like to pay a last homage to Dave Schramm; his vision to bring together astrophysics, nuclear physics, particle physics and cosmology has had a true impact on our understanding of the Universe.

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