COSMIC LITHIUM-BERYLLIUM-BORON STORY

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Abstract. 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 $^7\text{Li}$) and are, in fact, destroyed in stellar interiors. This characteristic is reflected in the low abundance of these simple species. Up to recently, the most plausible interpretation was that Galactic Cosmic Rays (GCR) interact with interstellar CNO to form LiBeB. Other origins have been also identified: primordial and stellar ($^7\text{Li}$) and supernova neutrino spallation ($^7\text{Li}$ and $^{11}\text{B}$). In contrast, $^9\text{Be}$, $^{10}\text{B}$ and $^6\text{Li}$ are pure spallative products. This last isotope presents a special interest since the $^6\text{Li}/^7\text{Li}$ 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, which, at first sight, is contradictory to a dominating GCR origin of the light elements which predicts a quadratic relationship. As a consequence, the theory of the origin and evolution of LiBeB nuclei has to be refined. Aside GCRs, which are accelerated in the general interstellar medium (ISM) and create LiBeB through the break up of CNO by 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 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. These different 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 gamma-ray line astronomy will be invoked in the perspective of the European INTEGRAL satellite.

1. Introduction

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, \( \text{Li}/\text{H} = 2 \times 10^{-9} \), \( \text{B}/\text{H} = 7 \times 10^{-10} \), \( \text{Be}/\text{H} = 2.5 \times 10^{-11} \) (Anders and Grevesse 1989). 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 beyond lithium. The standard BBN is hopelessly ineffective in generating \( ^{6}\text{Li}, ^{9}\text{Be}, ^{10}\text{B}, ^{11}\text{B} \) (fig 1). Thus, stars were necessary to pursue the nuclear evolution bridging the gap between \( ^{4}\text{He} \) and \( ^{12}\text{C} \) much later, through nuclear fusion.

Stellar nucleosynthesis, quiescent or explosive, forge the whole variety of nuclei from C to U but they destroy LiBeB in the interior of stars, except \( ^{7}\text{Li} \) which is produced in AGB and novae. The destruction temperature are 2, 2.5, 3.5 and 5.3 millions of degrees for \( ^{6}\text{Li}, ^{7}\text{Li}, ^{9}\text{Be}, \) and \( ^{10}\text{B} \) respectively. Finally, \( ^{7}\text{Li} \) and \( ^{11}\text{B} \) could be produced by neutrino spallation in carbon shells of core collapse supernovae (Woosley et al. 1990, Vangioni-Flam et al. 1996); 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 non thermal mechanism is 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) that they called \( X \) the process leading to their production. Then came Hubert Reeves and his students. In a semi-
nal work, Meneguzzi, Audouze and Reeves (1971) identified the production process, i.e. the Galactic Cosmic Rays - Interstellar Medium interaction. Exploiting 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 (Raisbeck and Yiou, 1971, 1975). However, this estimate, based 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 their idea is illuminated by the simple and beautiful fact that the hierarchy of the abundances $^{11}$B > $^{10}$B > $^9$Be is reflected in the cross sections (Read and Viola, 1984). This is another proof that nature follows the rules of nuclear physics. $^6$Li, $^9$Be and $^{10}$B were nicely explained but problems were encountered with $^7$Li and $^{11}$B. The calculated $^7$Li/$^6$Li ratio was 1.2 against 12.5 in meteorites. Stellar sources of $^7$Li appeared necessary. The estimated $^{11}$B/$^{10}$B ratio was 2.5 instead of 4 in meteorites. An ad-hoc hypothesis drawing on unobservable low energy proton operating through the $^{14}$N(p,x)$^{11}$B reaction was advocated (see Reeves 1994 for a review).

New measurements of Be/H and B/H from KECK and HST, together with [Fe/H] (Rebolo et al. 1988, Gilmore et al. 1992, Duncan et al. 1992, Boesgaard and King 1993, Ryan et al. 1994, Duncan et al. 1997, García-López et al. 1998) 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 known over about 10 Gyr, taking
[Fe/H] as an evolutionary index. A compilation of Be and B data is presented in fig 2. The most striking point is that log(Be/H) and log(B/H) are both quasi proportional to [Fe/H], at least up to [Fe/H] = -1 and that the B/Be ratio lies in the range 10 - 30 (Duncan et al.

This linearity came as a surprise since a quadratic relation was expected from the GCR mechanism. 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: low energy fast 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 2 and Vangioni-Flam et al.

A primary origin, in this language, means a production rate independent of the interstellar metallicity. 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.

Note however, the two discrepant points in the boron diagram at the lowest [Fe/H]. This is mainly due to the huge NLTE correction on the data (Kiselman and Carlsson 1996) that increases the departure from a straight line. It is important to take a careful look to this delicate correction.

The Be-Fe and B-Fe correlations taken at face value show a contradiction between 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 were not strictly proportional to Fe (Israelian et al. 1998).
and Boesgaard et al. 1998). Thus the pure primary origin of BeB could be questioned (Fields and Olive 1998). However, the oxygen measurements themselves are confronted to many difficulties (Mac Williams 1997, Cayrel, Spite and Spite, private communication). On the theoretical side, the situation is not better. The $[\alpha/Fe]$ vs $[Fe/H]$ where $\alpha = Mg, Si, Ca, S, Ti$ (Cayrel 1996, Ryan et al. 1996) show a plateau from about $[Fe/H] = -4$ 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 (Woosley and Weaver 1995, Thielemann, Nomoto and Hashimoto 1996) it is impossible to fit the log(O/H) vs $[Fe/H]$ relation of Israelian et al. (1998) and Boesgaard et al. (1998) since the required oxygen yields are unrealistic. Thus the subject is controversial.

Concerning lithium, a compilation of the data is shown in Lemoine et al. (1997) and Molaro et al (1997). 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 to 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 $[Fe/H] = -2.3$ (Hobbs and Thorburn 1997, Cayrel et al. 1998, Smith et al. 1998), yielding $^6\text{Li}/^7\text{Li}$ about 0.05. The great interest of $^6\text{Li}$, besides of being an indicator of stellar destruction (Pinsonneault et al. 1998, Chaboyer 1998, Cayrel et al. 1999, Vauclair and Charbonnel 1998) is to represent a pure spallation product as $^9\text{Be}$.

Lithium-6 has different sources, a secondary one and two primary ones: i) fast $(p,\alpha)$ on CNO at rest (this secondary process related to GCRs should not be efficient in the early galaxy), ii) fast CO on H, He (primary) and iii) specifically $\alpha + \alpha$ at low energy (primary). The non thermal fusion reaction $\alpha + \alpha$ produces almost equal amounts of $^6\text{Li}$ and $^7\text{Li}$ at low energy and the cross section above 100 MeV is specially low (Read and Viola 1984). The second and third processes are associated to LEC. Consequently, this LEC is specially fertile in lithium isotopes.

Preliminary estimates of the $^6\text{Li}/^9\text{Be}$ ratio have been performed for few Pop II stars but with a large uncertainty (20 - 80). This range of values is much higher than the $^6\text{Li}/^9\text{Be}$ ratio generated by the present GCR (6). This could indicate that this ratio is varying all along the galactic evolution (Vangioni-Flam et al. 1998b, Fields and Olive 1998).

To summarize, we can give six observational constraints on LiBeBe 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 related to O. Most of the observers find oxygen proportional to Fe.

2. Basic physical parameters of non-thermal nucleosynthesis of LiBeB

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 (Read and Viola 1984) and have been updated recently by Ramaty et al. (1997).

The adopted spectra are of two kinds:
1. GCR: $N(E) dE = k E^{-2.7}$ above a few GeV/n with a flattening below (e.g. Lemoine et al. 1998).
2. LEC: Shock wave acceleration with a cut at $E_0$ of the form $N(E) dE = k E^{-1.5} \exp(-E/E_0) dE$ (Ramaty et al. 1996), propagated in the ISM.

The source composition of GCR is well determined (e.g. Du Vernois 1996). It is $p$ and $\alpha$ rich ($H/O = 200$, $He/O = 20$) contrary to the possible source composition of the LEC. The most obvious contributors to LEC are supernovae, Wolf-Rayet and mass losing stars (Cassé et al. 1995, Ramaty et al. 1996, 1997, 1998). It is worth noting that in the early galaxy, supernovae play a leading role since at very low metallicity the stellar winds are insignificant. Table 1 shows a sample of compositions used by different authors: solar system (SS) for comparison (Ramaty et al. 1996 from Anders and Grevesse 1989), cosmic ray source (CRS) (Ramaty et al. 1996 from Mewaldt 1983), wind of massive stars (W40) (Parizot et al. 1997 from Meynet et al. 1994), composition of grain products (GR) (Ramaty et al. 1996 and Lingenfelter et al. 1998), 40 Mo supernova at $Z = 10^{-4}$ Zo (Parizot et al. 1999 from Woosley and Weaver 1995), 35 Mo supernova of solar metallicity (Ramaty et al. 1996 from Weaver and Woosley 1993). The two supernovae, though at different metallicities, (SN40 and SN35), give similar yields due to the fact that metallicity dependent mass loss has not been taken into account. Resulting elemental and isotopic ratios (B/Be, $^{11}\text{B}/^{10}\text{B}$, $^{6}\text{Li}/^{9}\text{Be}$) for different compositions and $E_0$ can be found in Ramaty et al. (1996) and Vangioni-Flam et al. (1997).
Table 1: Source Composition

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

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 $^{11}\text{B}/^{10}\text{B}$ ratios are produced by C-rich beams through $^{12}\text{C}(p,x)^{11}\text{B}$ and the highest $^{6}\text{Li}/^{9}\text{Be}$ ratios are produced by He and O rich compositions.

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 Ramaty et al. (1996) and Vangioni-Flam et al. (1997) shows that there are only slight differences in the results when the ISM metallicity is varied between 0 (early galaxy) and Zo (now), except perhaps concerning the $^{11}\text{B}/^{10}\text{B}$ ratio.

3. LiBeB production mechanisms and galactic evolution

Analyzing all the physical parameters discussed above, two main LiBeB producers emerge, the first one is the standard GCR (spectrum 1) in which fast p,α 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 (Vangioni-Flam et al. 1996). A recent study (Fields and Olive 1998) based on the O - Fe relation derived by Israeli et al. (1998) and Boesgaard et al. (1998) at low metallicity (still controversial) try to fit the observational constraints with a pure standard GCR (secondary production) component, but has problems with the B/Be ratio among other things.

The second one, reverse to the GCR mechanism, 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. This mechanism is related to superbubbles (S) through a scenario proposed by Bykov (1995), Parizot (1998) and Vangioni-Flam et al. (1998a). Here only the most massive stars ( greater than about 60 Mo) contribute due their short lifetime. Originally proposed in relation with the observation of gamma ray line from Orion it remains as a distinctive possibility after the withdrawal of the COMPTEL
results on this molecular complex (Bloemen et al. 1998) and the announcement of a possible excess of gamma rays in the 3-7 MeV range from the Vela region. Possible observations in X-rays seem to substantiate this scenario (Tatischeff et al. 1998). 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 (Winkler 1997) will be the strongest test of the superbubble hypothesis (Parizot et al. 1997).

The acceleration of grain debris in supernovae (scenario G) is another version of a primary mechanism (Lingenfelter et al. 1998, Ramaty, these proceedings). The G model leads to quite different predictions concerning the evolution of Be, B and $^{6}$Li only at very low metallicity (Vangioni-Flam et al. 1998a,b) because all SN II (10 - 100 Mo) are implied rather than the most massive ones in the S scenario.

Finally, neutrino spallation (Woosley et al. 1990, Woosley and Weaver 1995, Vangioni-Flam et al. 1996) 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 $^{12}$C within supernovae and not in the ISM. However it cannot be the unique mechanism to produce light elements since it does not produce $^{9}$Be. Moreover, it has been shown that its contribution is only marginal (Vangioni-Flam et al. 1996).

These different mechanisms are included in a galactic evolutionary model (Vangioni-Flam et al. 1996, 1998a,b) to follow the whole evolution of each isotope.

Concerning beryllium and boron, in this context, the main results are the following: the quasi-linearity (Be-B vs Fe) is easily reproduced (fig 2). Standard GCR 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 $^{11}$B/$^{10}$B = 4 at solar birth.

The $^{6}$Li/H ratio can be explained in the framework of the same superbubble model (Vangioni-Flam et al. 1998b, Cayrel et al. 1998) this without piercing the Spite plateau (fig 3). 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 (Vangioni Flam et al. 1998b). Moreover, the evolutionary curve of $^{6}$Li crosses the halo observations (fig 3) 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
Recent LiBeB observations indicate that a primary component is probably at work in the early Galaxy, presumably related to core collapse supernovae. Promising scenarios have been presented implying respectively the acceleration of freshly synthesized C and O in superbubbles and/or grains debris around supernovae (see also Ramaty in these proceedings).

New $^6$Li observations put strong constraints on the composition and spectrum of an early population of fast particles. The superbubble model is also able to reproduce the $^6$Li observation, until the local meteoritic value (fig 3). A low energy component originally O rich and becoming progressively C rich due to the strengthening of stellar winds at increasing metallicities is required to explain the high $^6$Li/$^9$Be observed in a few halo stars with respect to the one measured in meteorites. But a definitive conclusion should wait confirmation.

Essentially no destruction of $^6$Li and $^7$Li is implied by the evolutionary curve of $^6$Li. As a consequence, $^7$Li is a good baryonic density indicator for cosmology. The needs for the future are the following:

On the theoretical side it would be necessary:

i) to check NLTE corrections on B abundances since two bothering points remain at very low Z.

ii) to develop and refine SN II models, specially at very low Z and high mass, $M_o > 60$ Mo.

On the observational side, it would be desirable to get measurements of $^6$Li, $^7$Li, $^9$Be, B, O, Fe in the same halo stars and to get $^{11}$B/$^{10}$B ratios in
various stars. A first step in this goal has been accomplished by Rebull et al. (1998).

Finally, the observation of C, O and Li-Be gamma-ray lines are important objectives of the INTEGRAL satellite which will open up an European era in gamma-ray astronomy (Parizot et al. 1997, Cassé et al. 1998).

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