LITHIUM-BERYLLIUM-BORON EVOLUTION: FROM MENEGUZZI, AUDOUZE AND REEVES 1971 UP TO NOW

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We review the main sources of LiBeB production and show that a primary mechanism is at work in the early Galaxy involving both ejection and acceleration of He, C and O at moderate energy, which by nuclear interaction with H and He produce light isotopes. The precise measurement of the Be abundance at [Fe/H] = -3.3 and of $^6\text{Li}$ in halo stars find an explanation in this framework. Thus, the preservation of $^6\text{Li}$ in the atmosphere of metal poor stars implied, points toward the fact the Spite plateau reflects the primordial value of Li. Consequently, it can be used as a baryodensitometer.

1 Basic facts and historical perspective

LiBeB are exceptional since they are both simple and rare. In the Solar System, their abundances amount to Li/H = 2.10$^{-9}$, B/H = 7.610$^{-10}$ and Be/H = 2.510$^{-11}$, respectively, whereas isotopic ratios of lithium and boron are $^7\text{Li}/^6\text{Li} = 12.6$, $^{11}\text{B}/^{10}\text{B} = 4$. Indeed they are rare because their nuclei are fragile. The fact that nuclear structures with $A = 5$ and $8$ are violently unstable has limited primordial nucleosynthesis by thermonuclear fusion to $^7\text{Li}$. Effectively, Standard BBN is hopelessly ineffective in generating $^6\text{Li}$, $^9\text{Be}$, $^{10}\text{B}$, $^{11}\text{B}$. Stellar nucleosynthesis (quiescent or explosive) produces nuclei from C to U but destroy LiBeB, since their burning temperature is especially low.

Another mechanism (different from fusion) is thus necessary to yield LiBeB. This one is the break-up of CNO by spallation. It is worth noting that among light isotopes, Li, is special, since it owes its origin to numerous sources, involving processes as different than BBN ($^7\text{Li}/H$ about 10$^{-10}$), nuclear spallation ($< 2.10^{-10}$), neutrino spallation in SNII ($< 2.10^{-10}$), and
stellar nucleosynthesis through low mass stars and novae (about $10^{-9}$).

The origin of LiBeB is an old problem. Initially, the debate has opposed supporters of a Stellar/Circumstellar origin to those of an interstellar origin related to Galactic Cosmic Rays (Reeves and collaborators). In a seminal work Meneguzzi, Audouze and Reeves (1971), MAR have given credence to the second explanation. They were able to devise a consistent scenario linking measurements of local abundances, spallation cross sections and the measured GCR flux. The merit of their work is the clear identification of the production process i.e. the Galactic Cosmic Rays / ISM interaction, essentially via fast (p,$\alpha$) impacting on CNO. Furthermore, MAR offered a quantitative estimate of the present production rate of each isotope, and integrating over time (assuming a constant rate) they got local (cumulated) abundances that compare favorably with that of $^6\text{Li}$, $^9\text{Be}$ and $^{10}\text{B}$ in the solar system.

The beauty of the spallative interpretation is that the abundance hierarchy: B11, B10, Be9 is reflected by the production cross sections. This is a gratifying proof that nature follows nuclear physics! It is worth emphasizing that alpha induced reaction have lower energy threshold than the corresponding proton reactions. This is of importance for the postulated low energy component associated to superbubbles (see below). Despite the success of the MAR approach, some problems remained however, concerning the $^7\text{Li}/^6\text{Li}$ ratio ( the calculated production ratio is 1.2 and the observed one in meteorites is 12.6). Thus other sources of $^7\text{Li}$ were required, namely stars that can produce it through the fusion of $^4\text{He}$ and $^3\text{He}$. Also the $^{11}\text{B}/^{10}\text{B}$ ratio was discrepant (2.5 against 4 in meteorites). Thus an ad-hoc hypothesis was proposed: the production of $^{11}\text{B}$ by a low energy flux, not observable in the solar cavity.

2 Production processes and ratios

In the 70’, LiBeB observations were limited to the Solar System and closeby stars. Since the 90’s they have been continuously pushed down to lower and lower metallicities. The great surprise was to find linear correlations between both Be, B and Fe up to [Fe/H] = -1, whereas a quadratic relation was expected from the GCR theory.

The production rate of species L is a function of target composition and of the projectile characteristics (composition and energy spectrum):

$$dN(L)/dt = N_T < \sigma > \phi$$

One distinguishes two cases: If $p$ and alphas are the projectiles and interstellar CNO, the targets, one deals with a Secondary Production mechanism. The fast protons and alphas of the standard GCR react on CNO at rest.
in the ISM, giving rise to LiBeB nuclei. Then:

$$dN(L)/dt = N_{CNO} < \sigma > \phi_{\alpha p}$$

Making the reasonable assumption that SNII both produce and eject O (essentially) and accelerate GCR (through the shock waves they produce), one gets:

$$\phi(t) \propto SN(t) \propto dO/dt.$$ The flux decreases as time increases.

$$N_{CNO}(t) \propto SN(t) \propto O.$$ The target abundance increases as time increases.

Then,

$$dBe/dt \propto dO/dt.$$ and $$Be/H \propto (O/H)^2.$$ 

Conversely, if C and O are the projectiles, and H and He the targets, the case is different because H and He do not evolve significantly in the course of the galactic lifetime, their abundance being essentially fixed by the big-bang nucleosynthesis. One deals, in this case with a Primary Production process.

$$dN'(L)/dt = N_{H-He} < \sigma > \phi_{CO}$$

$$\phi(t) \propto SN(t) \propto dO/dt.$$ Then,

$$dBe/dt \propto dO/dt$$ and $$Be/H \propto O/H.$$ 

This primary process as been astrophysically associated with galactic superbubbles (SB) which are interstellar cavities produced by the collective effect of SN and WR. In these low density regions fresh products of nucleosynthesis (essentially O in our case) accumulate and are accelerated by shock waves induced by successive supernovae. In the following we will call Superbubble Accelerated Particles (SAP) the fast component related to these objects. Standard GCR and SAP have in common the acceleration agent: type II Supernovae. But, they could differ by i) the source composition, SAP being enriched w.r.t GCR in O and specifically He (by a factor 3), and this has a strong bearing on the $^6$Li problem (see below) ii) the energy spectrum: the mean energy of GCR is presumably higher than that of SAP, 1GeV/n typically, against say 100 MeV/n. It is expected that SAP, due to their low energy do not escape easily from the SB regions, and even if they escape, they cannot enter the solar cavity due to the repelling effect of the solar wind. Thus, in this case there is some chance that SAP interacting with the dense shells enclosing superbubbles could produce C and O gamma ray lines and the LiBe feature (a combination of two broad lines around 450 keV). An existence test of this low energy He and O rich component is the gamma ray emission of local OB associations/superbubbles (Cyg OB2, PerOB2, Orion, Vela). This is a good prospect for the European INTEGRAL mission (J. Paul, this meeting).

Above all the two mechanisms in question (standard GCR and SAP) differ by the type of production process, secondary in the case of standard GCR, $(BeB \propto O^2)$ and primary in the case of SAP $(BeB \propto O)$. Before closing this section on physical production processes of light elements, it is worth men-
tionning another primary mechanism, neutrino spallation, which takes place
within supernovae. It is expected to generate significant amounts of $^{11}B$ and
$^7Li$ but not Be. However, Nadyozhin (this conference) has warned us that
the discussion is not closed. Indeed many uncertainties are yet attached to
this mechanism.

3 Empirical O-Fe correlations and evolutionary models

The $[O/Fe]$ behaviour at low metallicity is a central issue, since the physical
correlation is between BeB and O, the products and the progenitor, whereas
the observable one is between BeB and Fe. According to the lines analysed
(IR triplet, $[OI]$ or permitted OI), the estimates of the O abundance differ.
Over a long period, work largely based on the forbidden OI doublet ob-
served in giants has established that $[O/Fe]$ levels off below $[Fe/H]=-1$
at about 0.5 dex. Consequently, the observed proportionality between Be and
Fe leads naturally to the proportionality between Be and O. Thus, this implies
a clear primary origin of BeB.

Subsequently data were released based on UV OH and IR triplet leading
to $[O/Fe] = 0.35 [Fe/H]$. The proportionality between Be and Fe leads in
this case to the correlation: $\log(\text{Be}/\text{H})$ proportional to about 1.6 $[O/H]$. Thus
the slope of the correlation is between 1 and 2, a quite ambiguous situation,
in which a purely secondary origin linked to GCR is still possible $^{11}$).

To summarize the situation, three mechanisms operate: i) Standard GCR
(secondary) ii) SAP (primary) iii) Neutrino Spallation (primary).

Different models have been proposed to explain the evolution of BeB. i)
A pure secondary Standard GCR mode based on variable $[O/Fe]$. This
one has to confront the following difficulties: is $[O/Fe]$ really increasing at
low metallicities? Many observers would be reluctant to accept this variation.
Why O nucleosynthesis should be special compared to other alpha elements?
Also the energetics of the BeB production in this case is quite demanding in
the early Galaxy (Ramaty this conference).

ii) A pure primary component arising from SF assimilated to GCR. Galac-
tic Cosmic Rays in this view becomes primary. But it seems that their
source composition cannot be reconciled with the SAP/SN one. Moreover
this kind of model suffers from an underproduction of $^6Li$ in the halo due to
lack of incident alphas.

iii) An hybrid model giving consecutive roles to SAP (acting in the halo)
and standard GCR (active in the disk) seems to fulfil the essential observa-
tional constraints $^{12}$.

Accurate oxygen abundances of old, metal poor stars are required if one
desires to reach a satisfactory solution of the halo BeB issue. Indeed, a lot of efforts have been put recently on observations and atmosphere modelisation and a special session of the IAU at Manchester 2000 has been devoted to the O-Fe correlation. The general feeling is that the flat (or slightly increasing) [O/Fe] vs [Fe/H] at decreasing Fe/H is favoured. The need for a primary component in the early Galaxy is thus strengthened. Moreover, the recent observation of Primas et al (2000) indicating a flattening of the Be-Fe relation at very low metallicity, reinforces a primary origin of Be through the most massive stars in agreement with the prediction of Vangioni-Flam et al (1998). Thus a big-bang origin of Be is not required to explain these data.

4 The case of Lithium 6 and 7

Recently much work has been devoted to the non thermal production of Li in the early Galaxy, especially via the reaction $\alpha + \alpha$. An important condition has to be fulfilled: lithium should not be overproduced at low metallicity. In other words, the Spite plateau should not be traversed by the rising Li. Recent observations on $^6\text{Li}$ in halo stars, amounting to $^{6}\text{Li}/^{7}\text{Li}$ about 2 to $5\times10^{-2}$ (Cayrel and Asplund, this conference) set new constraints on spallative processes in the early Galaxy. Indeed GCR (either standard as proposed by Fields and Olive or of primary type as proposed by Ramaty et al) are not sufficient to explain the observed $^6\text{Li}$ abundances due to their low alpha content contrary to SAP, enriched in alphas. In the SAP context, it is probable that $^6\text{Li}$ is almost intact in the atmosphere of halo stars, meaning that $^7\text{Li}$, much less fragile, has essentially its big-bang value. Accordingly, Li becomes an interesting baryon density indicator (Coc et al, Olive, this conference).

5 Conclusion

Spallation is confirmed as the production process of $^6\text{Li}$, Be, B. The present observational trend is that Fe-O is quite flat at low metallicities indicating a that primary production mechanism (SAP) is predominant in halo phase. $^6\text{Li}$ observations strengthen this assumption since they require an alpha-rich fast component in the early Galaxy. In the disk phase, standard GCR take increasing importance. The agent of acceleration common to both SAP and GCR is SNII. The favored sources of low energy nuclei (SAP) are massive stars gathered in OB associations and exploding in superbubbles.

For the future, the needs are the following:
- concerning the observational aspect, simultaneous observations O, Fe, Be,
B, $^6\text{Li}$ and $^7\text{Li}$ in halo stars would be the most welcome. In this context VLT missions are very promising. A detection of the O* gammy-ray lines and the LiBe feature by INTEGRAL (to be launched in 2002) would be a clue to the existence of a low energy He-O rich non thermal component. Finally, we would like to draw attention on an intriguing possibility, offering a new nucleosynthetic site for LiBeB, namely hypernovae. Nomoto’s velocity and composition profiles of exploding CO cores associated to Nadyozhin’s analytic treatment of outer layers, allow to determine the number and energy spectrum of C and O particles ejected and the LiBeB they produce by impacting on the surrounding medium. The O + $\alpha$ reactions are favoured due to their low energy threshold. A simple rescaling of the work of Fields et al (1996) shows a generous production of LiBeB.

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