From Lithium to Uranium: Elemental Tracers of Early Cosmic Evolution
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Production of ^{6}Li by cosmological cosmic rays

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Abstract. Very recent observations of the ^{6}Li isotope in halo stars reveal a ^{6}Li plateau about 1000 times above the predicted BBN abundance. We calculate the evolution of ^{6}Li versus redshift generated from an initial burst of cosmological cosmic rays (CCRs) up to the formation of the Galaxy. We show that a pregalactic production of the ^{6}Li isotope can account for the ^{6}Li plateau observed in metal poor halo stars without additional over-production of ^{7}Li. The derived properties of the CCRs could then be used to put constraints on the physics and history of the objects, such as Pop III stars, possibly responsible for these early cosmic rays. Consequently, we consider the evolution of ^{6}Li in the Galaxy. Since ^{6}Li is also produced by Galactic cosmic ray nucleosynthesis, we argue that ^{6}Li can be depleted in halo stars with metallicities between [Fe/H] = −2 and −1.

Keywords. Nuclear reactions, nucleosynthesis, abundances, early universe

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1. Introduction

The origin and evolution of lithium, beryllium and boron (LiBeB), is correlated to several very different aspects of nucleosynthesis - Big Bang, non thermal, stellar nucleosynthesis. This variety is reflected in the different questions covered by this Symposium. While there is a good agreement between the Big Bang nucleosynthesis (BBN) predicted values and observed ones of deuterium and helium abundances, this is not the case for ^{7}Li (see review by Coc & Vangioni in this proceedings). Indeed, the BBN mean value of the ^{7}Li abundance is between 4.15 and 4.9×10^{-10} (Cyburt 2004; Cuoco *et al.* 2004; Coc *et al.* 2004), while the observed value in population II metal-poor halo stars is constrained by the Spite plateau (Spite & Spite 1982) to be about 1.2–2×10^{-10} (see Ryan in this proceeding).

While a fraction of ^{7}Li is produced in the Big Bang, the BBN production of ^{6}Li, Be and B results in abundances which are orders of magnitude below that observed in halo stars. The very low abundances of these isotopes predicted by BBN imply that their most plausible production process is the interaction of Galactic Cosmic rays (GCRs) with the interstellar medium (e.g. Vangioni-Flam, Cassé, & Audouze 2000). Of these isotopes, ^{6}Li is of particular interest. BBN production of ^{6}Li is dominated by the nuclear reaction D$(\alpha,\gamma)^6$Li. At the baryon density deduced from observations of the anisotropies of the Cosmic Microwave Background (CMB) radiation by WMAP (Spergel *et al.* 2003), its BBN value is $^6\mathrm{Li/H}\simeq10^{-14}$ (Thomas *et al.* 1993; Vangioni-Flam *et al.* 1999); which implies a primordial ratio $^7\mathrm{Li}/^6\mathrm{Li}\simeq10^4$. ^{6}Li has recently been measured in halo stars (see Asplund and Inoue in this proceeding) thus offering new constraints on the very early evolution of this isotope. These new observations hint at unexpectedly high ^{6}Li abundance in some stars at very low [Fe/H]. Indeed, the observed $^7\mathrm{Li}/^6\mathrm{Li}$ ratio is of the order of 10 to be compared with the $^7\mathrm{Li}/^6\mathrm{Li}$ BBN one. Thus, the ^{6}Li observed in very metal poor halo stars is probably due to an early pregalactic production.

This proposed process has then to produce a sufficient amount of ^{6}Li, but should not be accompanied by a large production of ^{7}Li as compared to the BBN. This is a strong constraint, which is required if one does not want to increase the ^{7}Li discrepancy mentioned above. Of particular importance is the $\alpha+\alpha$ reaction that leads to the synthesis of ^{6}Li (as well as ^{7}Li) and is efficient very early in the evolutionary history of the Galaxy. Suzuki & Inoue (2002) discuss the possibility of ^{6}Li production in the beginning of the galaxy formation through GCR generated during structure formation (see also in this proceeding). Jedamzik (2000) considers the decay of relic particles, during the epoch of the Big Bang nucleosynthesis, that can also yield to a large primordial abundance of ^{6}Li. However, Ellis, Olive & Vangioni (2005) have recently shown some difficulties for such a solution due to the D/^{3}He constraint. In Rollinde, Vangioni & Olive (2005) (RVO), we consider the synthesis of lithium due to the interaction of cosmological cosmic rays (CCRs), produced at an early epoch, with the intergalactic medium (IGM, as first suggested by Montmerle 1977). In this paper, we quickly review the origin and galactic evolution of the rare element LiBeB (§ 2). We will then explain the basic scheme of the $\alpha+\alpha$ process and the main results obtained by RVO (§ 3). We discuss how observations could be used in a near future to constrain the history of cosmological structure formation (§ 4).

2. Galactic processes and LiBeB production

In standard GCR nucleosynthesis (Reeves, Fowler & Hoyles 1970) LiBeB nuclei are produced by spallation when protons and αs in the cosmic rays impinge on ISM C, N, or O. LiBeB is also produced when CNO in the cosmic rays are spalled by ISM protons and αs, in superbubbles. As such, spallation requires heavy elements ('metals') to be present in either the energetic particles or the ISM. Specifically, $\alpha+\alpha$ fusion reactions lead to the production of the lithium isotopes. Note that ^{7}Li and ^{11}B also receive contributions from the $\nu-process$ (Woosley *et al.* 1990; Olive *et al.* 1994; Vangioni-Flam *et al.* 1996).

The spallation of CNO in the ISM is a secondary process so these abundances scale as the square of a metallicity tracer such as O, or Fe if [O/Fe] is constant, at low values of [Fe/H]. Motivated by the observational fact that the log of the Be and B abundances appear to scale linearly with [Fe/H] it has been proposed that the bulk of cosmic rays are not only accelerated in the general ISM, but also in the metal-rich interiors of superbubbles (Cassé, Lehoucq & Vangioni-Flam 1995), specifically at low metallicity. Because the superbubble composition is enriched in metals, any cosmic rays which are accelerated in superbubble interiors would have a composition which is both metal-rich and time-independent. The low-energy component of the hard energy spectra associated with superbubbles results in the primary production of Be and B. We refer to this process as LEC. Both the LEC and standard GCR nucleosynthesis are responsible for the observed LiBeB abundances all along the galactic evolution. In this model, the flux of galactic cosmic rays is normalized so as to correctly reproduce the solar value of Be/H. The overall flux is the only parameter available in GCR nucleosynthesis, and as a consequence the abundance of ^{6}Li is a prediction of the model. Observed abundances of Be and B and the correlated galactic evolutionary model are plotted versus [Fe/H] in Figure 1 (left panel). Note that the Be abundance measured at very low metallicity in VLT observations (shown as octagon) are explained within this GCR+LEC scenario and also that the addition of the $\nu-process$ increases slightly the predicted B abundance.

At low metallicity, Lithium production is dominated by primordial BBN (the Spite plateau) (Figure 1, right panel). The GCR production of ^{6}Li predicted by the galactic evolution as described above, is shown in Figure 1 (right panel). As expected the

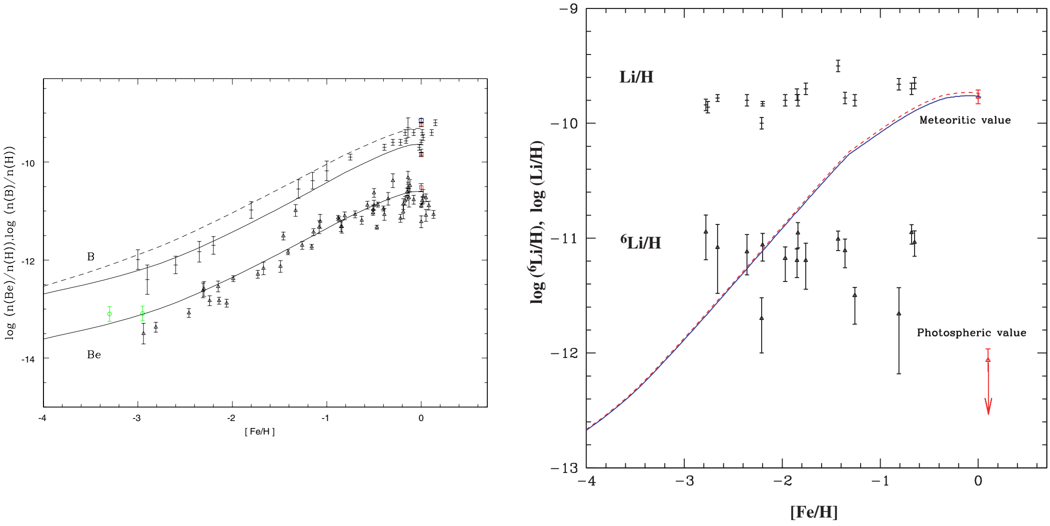

Figure 1. Evolution versus [Fe/H] of abundances of beryllium and boron (left panel), lithium (^{7}Li+^{6}Li) and ^{6}Li (right panel). *left panel:* the observed galactic evolution of Be/H and B/H is well explained by the GCR+LEC model (solid lines), including the VLT measurements of Be/H at lowest metallicity (Primas *et al.* 2000a, 2000b; shown as light octagons). The solar abundance is reproduced for boron with the addition of the $\nu-process$ (dashed line). *right panel:* The recent VLT/UVES determinations of abundances of ^{6}Li in low metallicity stars (see Asplund in this proceeding) hint at a plateau. The solar abundance of ^{6}Li from meteorites (Lodders 2003) and the upper limit to the solar photospheric abundance (Asplund, Grevesse & Sauval 2004) are also shown. Full line : galactic evolution of ^{6}Li with new nuclear data, dashed line : the same with old nuclear data.

logarithmic slope of [^{6}Li/H] versus [Fe/H] is 1 (Fields & Olive 1999; Vangioni-Flam *et al.* 1999). The new VLT/UVES data, as presented in this proceeding by M. Asplund, are overplotted. Note that the Subaru/HDS observations, presented by S. Inoue, confirm the following trends. Yet, as shown, the recent observations hint at a plateau over a large range of metallicities, which clearly disagrees with predictions of this model. As explained above, we will now show how the interaction of α particles from CCRs and helium at rest in the IGM can explain the high ^{6}Li abundance in those population II stars.

3. Cosmological Cosmic Rays Scenario

Our formalism is directly derived from the work of Montmerle (1977). CCRs are assumed to be produced in a single burst correlated e.g. to a very early generation of Pop III stars at a given redshift z_s. Compared to 1977, the existence of stars at high redshift is better justified today thanks to the analysis of the CMB by WMAP that indicates an early epoch of reionization (see also Daigne and Vangioni, in this proceeding). The possibility of escape of the CRs from those structures is discussed in e.g. Berezinsky, Blasi & Ptuskin (1997), Zweibel (2003) and Samui, Subramanian & Srianand (2005). Clearly, there are several viable mechanisms for the production of CCRs and just as clearly, there is a great deal of uncertainty surrounding it. Besides, cosmology is much more constrained than in 1977. In particular, a flat universe with a non-zero cosmological constant is now favored (Spergel *et al.* 2003).

3.1. *Procedure*

The basic scheme is the following. Some specific sources, located at high redshift $z_{\rm s}$, produce CCRs, including α particles, with a flux $\Phi_\alpha(E,z)$ (Eqs (1) and (4) in RVO). These particles will then interact with the helium present at rest in the general IGM and produce both isotopes of the lithium, l, through the $\alpha+\alpha$ reaction:

$$\frac{\partial N_{l,\,\rm H}(E,z)}{\partial t} = \sigma_l(E) K_{\alpha p} \Phi_\alpha(4\,E,z) \quad [({\rm Gev/n})^{-1}\,{\rm s}^{-1}]. \tag{3.1}$$

σ_l is the cross section for ^{6}Li or ^{7}Li, and $K_{\alpha p}$ is the abundance by number of ^{4}He/H. Since this interaction takes place in the cosmological context of an expanding universe, the lithium produced is diluted. However, the density of hydrogen is diluted by the same factor, so the abundance $[l/{\rm H}]$ due to the production of lithium at a given redshift does not evolve afterwards. So we can simply integrate the local production over z.

$$[l/{\rm H}](z) = [l/{\rm H}]_{\rm BBN} + \int_z^{z_{\rm s}} \int \frac{\partial N_{l,\,\rm H}(E,z')}{\partial t}\, {\rm d}E\, |{\rm d}t/{\rm d}z'|\, {\rm d}z'\,.$$

Yet, the density of αs in the CCR and of ^{4}He in the IGM decreases as $(1+z)^3$. Since the production of lithium at a given z is proportional to these two densities, it decreases as $(1+z)^6$. Therefore, the *differential increase of the Lithium abundance* in (3.1) still decreases rapidly with z.

Then, at a $z = z_{\rm gal} \simeq 3$, our Galaxy forms and inherits the Lithium abundance present in the IGM at this stage. This corresponds to the *PIE observed in the early formed stars.*

3.2. *Early production of* ^{6}Li

Figure 2 (left panel) shows the predicted evolution of the lithium (^{6}Li or ^{7}Li) abundance versus redshift from the BBN values to the formation of the Galaxy at $z = z_{\rm gal}$ within this scenario. The primordial ratio ^{7}Li/^{6}Li is about 10000. The evolution of the ^{6}Li abundance displays a rapid jump just after the production of CCR, which is assumed to happen at different values for $z_{\rm s}$ (100, 30 or 5). After this early jump, a plateau is reached, as expected given the double dilution of helium in IGM and CRs mentioned above. The final abundance of ^{6}Li is constrained by the level of the PIE observed in MPHS (Figure 1). Thus, the amount of CR produced at high redshift (i.e. the normalisation of Φ_α) is fixed to reproduce this level at $z = z_{\rm gal}$. There is no observational or theoretical constraints today on the CR energy density and spectrum at those high redshifts. Note that the amount required, if scaled to the local universe is not in contradiction with the constraints on temperature or on the amount of CR in the Galaxy (see RVO for more details).

Since the cross sections for production of ^{6}Li and ^{7}Li are of the same order, the additional production of ^{7}Li is of the order of the ^{6}Li one, and is therefore negligible compared to the BBN value. Therefore, this additional production due to CCRs will not increase the known discrepancy with the Spite plateau.

3.3. *Galactic evolution*

The right panel of Figure 2 shows the predicted evolution of ^{6}Li and ^{7}Li in the ISM of our Galaxy, versus metallicity. The lower solid curve corresponds to the current model of GCR+LEC described in § 2. The addition of a pregalactic PIE at $z = z_{\rm gal}$ yields to the upper curve and explains the data at low metallicity. To explain the data at higher [Fe/H] (>-2), one must argue that depletion has lowered the abundance of ^{6}Li. This is perhaps reasonable as the depth of the convection zone is increased at higher metallicity for a fixed surface temperature. We note that many of the stars observed only reveal

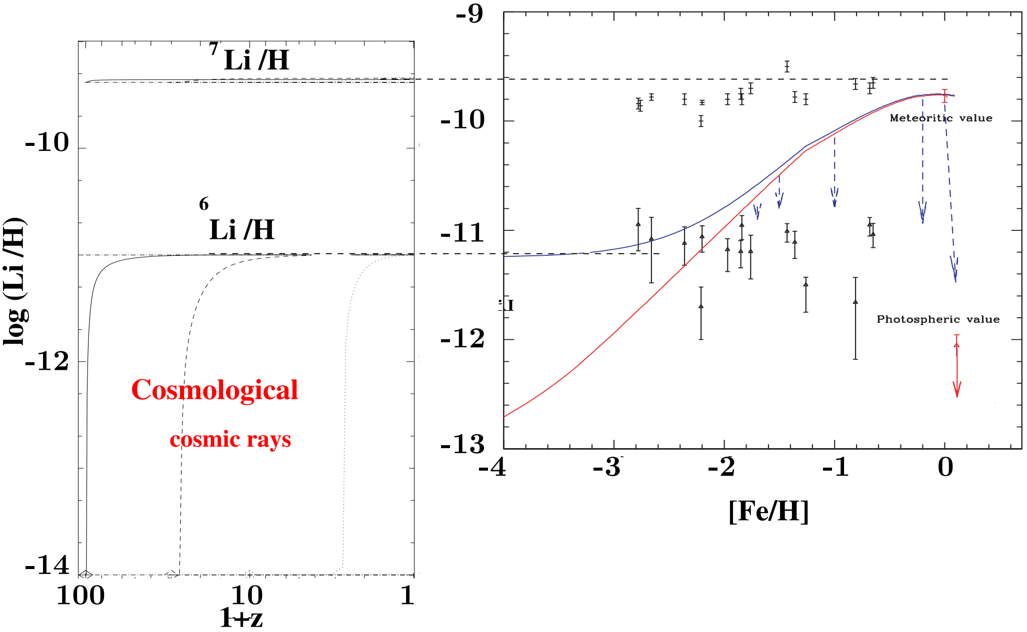

Figure 2. Evolution of the ^{6}Li and ^{7}Li abundances in the intergalactic medium (left panel) and in the Galaxy (right panel). *left panel* : The redshift of the initial CCR burst z_s is chosen to be 5, 30 and 100. The different predicted evolutions of lithium abundance versus redshift, through the CCR interaction with IGM, are represented by the dotted, dashed and solid lines respectively. The initial abundances of the lithium isotopes are fixed according to BBN calculations while the abundance of ^{6}Li is imposed to be $10^{-11.2}$ at the redshift of the formation of the Galaxy, $z_{\rm gal} = 3$. These choices fix the amplitude of the CCR flux (see § 3.1). We find that the primordial abundance of ^{7}Li is increased by less than 10% from z_s to $z_{\rm gal}$. *right panel* : Observations are as in Figure 1. The prompt initial enrichment, as produced by CCRs, is continued from the left panel with dashed lines. The lower solid line corresponds to the ^{6}Li/H prediction by a GCR model only. The addition of the PIE (upper solid line) explains the observations at low metallicity while an increasing ^{6}Li depletion (dashed arrows) is still required at high metallicity.

upper limits to the ^{6}Li abundance. That is, in roughly 15 examples of stars with similar temperatures and metallicities as those shown, no ^{6}Li was detected. The lack of ^{6}Li in some stars, coupled with the dispersion seen in the data may also indicate that some depletion of ^{6}Li has occurred in some of these stars. Indeed, the difference between the solar photospheric and meteoritic values corresponds to a destruction of ^{6}Li of at least a factor of about 200. In this model, we would argue that the destruction of ^{6}Li is negligible at $[\mathrm{Fe/H}] < -2$ where the calculation from galactic processes crosses the plateau.

4. Conclusion

The existence of the Spite plateau indicates that low metallicity halo stars could be representative of the primordial BBN abundance, although the discrepancy with predictions based on WMAP results is still an issue. On the other hand, the hint for a plateau in ^{6}Li at very low metallicity, and at a higher abundance than predicted in standard BBN (by a factor of 1000), requires an additional process that produces ^{6}Li in a pregalactic phase. The process studied in this paper involves the interaction of α particles present in early cosmological cosmic rays with primordial helium present in the intergalactic medium.

We have shown that it is possible to produce sufficient quantities of ^{6}Li, without the additional over-production of ^{7}Li. However, the existence of this plateau needs to be confirmed with additional observations of ^{6}Li in stars with metallicities lower than -3.

The description of this process has now to go further than the single burst approximation. The CCR production could be related to the formation of Pop III stars (Daigne *et al.* 2004). The influence of this process in the production/destruction of other elements, such as Be, B and D, will also be studied. The level of the ^{6}Li plateau may then provide a strong constraint on the CCRs production, and hence on its total energy, which could be compared to constraints derived from the thermal history of the IGM (e.g. Samui, Subramanian & Srianand 2005).

Finally, the recent measurements of light element abundances (in particular B) in damped Ly-α systems, as reviewed by J.X. Prochaska in this proceeding (see also Prochaska, Howk & Wolfe 2003), may open a new era for this field. Indeed, the processes involved in the nucleosynthesis could be probed at high redshift and their universality could then be questionned. Furthermore, such an analysis could be done in a near future using GRBs, located at high z, and detected e.g. by the space mission ECLAIRs.

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