Lithium-6 : Evolution from Big Bang to Present

Elisabeth Vangioni-Flam
Institut d’Astrophysique de Paris
98bis Boulevard Arago
75014 Paris, France

Michel Cassé
Service d’Astrophysique
DSM, DAPNIA, CEA
Orme des Merisiers 91191 Gif sur Yvette, France

and

Institut d’Astrophysique de Paris
98bis Boulevard Arago
75014 Paris, France

Roger Cayrel
Observatoire de Paris
61 avenue de l’Observatoire
75014 Paris, France

Jean Audouze
Institut d’Astrophysique de Paris
98 bis Bd Arago
75014 Paris, France

Monique Spite
Observatoire de Paris-Meudon
92125 Meudon, CEDEX France

and

François Spite
Observatoire de Paris-Meudon
92125 Meudon, CEDEX France
ABSTRACT

The primordial abundances of Deuterium, $^4$He, and $^7$Li are crucial to determination of the baryon density of the Universe in the framework of standard Big Bang nucleosynthesis (BBN). $^6$Li which is only produced in tiny quantities and it is generally not considered to be a cosmological probe. However, recent major observational advances have produced an estimate of the $^6$Li/$^7$Li ratio in a few very old stars in the galactic halo which impacts the question whether or not the lithium isotopes are depleted in the outer layers of halo stars, through proton induced reactions at the base of (or below) the convective zone. Here, we use i) an empirical relation, independent of any evolutionary model, to set an upper limit on the $^6$Li rise compatible with the very existence of the Spite’s plateau (i.e. the flat lithium abundance measured in very old stars of the halo of our Galaxy of different iron content) and ii) a well founded evolutionary model of light elements based on spallation production (Vangioni-Flam et al. 1997, 1998).

Indeed, $^6$Li is a pure product of spallation through the major production reactions, fast oxygen and alphas interacting on interstellar H, He (especially in the early Galaxy). The rapid nuclei are both synthesized and accelerated by SN II. In this context, the $^6$Li evolution should go in step with that of beryllium and boron, recently observed by the Keck and HST telescopes. $^6$Li adds a new constraint on the early spallation in the Galaxy. In particular, if confirmed, the $^6$Li/$^9$Be ratio observed in two halo stars (HD 84937, BD +26°3578 = HD 338529) gives strong boundary conditions on the composition and the spectrum of the rapid particles involved.

Both methods converge to show that $^6$Li is essentially intact in halo stars, and a fortiori $^7$Li, which is more tightly bound. Moreover, extrapolating empirical and theoretical evolutionary curves to the very low metallicities, we can define a range of the $^6$Li abundance in the very early Galaxy consistent with Big Bang nucleosynthesis ($5.6 \times 10^{-14}$ to $3.10^{-13}$). Following the evolution at increasing metallicity, we explain the abundance in the solar system within a factor of about 2. The whole evolution from Big Bang to present is reasonably reproduced, which demonstrates the general consistency of the present analysis of $^6$Li.

The baryonic density derived from both lithium isotopes is between 1.5 to 3.5 per cent of the critical one, in good agreement with the determination based on independent analyses. Consequently, thanks to these new data and theoretical developments, we show that $^6$Li can be used to establish stellar $^7$Li abundances.
as a valid tracer due to the fact that it allows to reinforce the Spite’s plateau as a primordial test of BBN; on the other hand, its early evolution can be used to corroborate the calculated BBN abundances. In the framework of this work, a pregalactic $\alpha + \alpha$ process producing $^6\text{Li}$ is not necessary. Finally, thanks to $^6\text{Li}$, the physics of spallative production of light elements should be more easily mastered when more data will become available.

Subject headings: Cosmic-rays, Galaxy : abundances, Nucleosynthesis, Big Bang Nucleosynthesis
1. Introduction

$^6$Li is a rare and fragile isotope. Indeed, this nucleus is destroyed in stellar interiors at temperatures higher than $2 \times 10^6$ K. In hot (low mass) stars composing the Spite’s plateau, according to the depth of the external convection this isotope could survive partially or totally in stellar atmospheres (where they are observed) even though this represents at most a few percents of the stellar mass. The preservation of the stellar surface layer in these stars has been well established by the observation of the (more durable) $^7$Li isotope (Spite & Spite, 1982). It is well known that the lithium isotope is found to have a nearly constant abundance independent of metallicity (for $[\text{Fe/H}] < -1.3$) and temperature (for surface temperatures $\gtrsim 5500$ K). The lithium plateau is generally regarded to represent the primordial abundance of $^7$Li and is of key importance to understanding Big Bang Nucleosynthesis (see e.g. Fields et al. 1996, Schramm and Turner 1998). Unlike $^7$Li, $^6$Li is not produced in large quantities in the Big Bang ($^6$Li/$^7$Li $\sim 0.001$, see e.g. Figure 1), but rather by non thermal reactions (spallation) induced by energetic collisions of fast nuclei with the interstellar medium (ISM).

There is of course a nagging uncertainty as to whether or not the observed $^7$Li abundance in the plateau stars is in fact representative of the primordial abundance or partially depleted by non-standard stellar processes. The discovery by Spite and Spite (1982) of a quasi constant Li abundance, independent of the stellar metallicity, now confirmed down to very low values (about $[\text{Fe/H}] = -4$) is a landmark of the BBN theory. The observed Li/H ratio of about $1.6 \times 10^{-10}$ has been widely confirmed (Spite 1997, Bonifacio and Molaro 1997) and taken at face value is concordant with standard BBN calculations. However, some stellar models originally aimed at explaining the paucity of lithium in the sun and other Pop I stars, extrapolated to low metallicity, predict a significant depletion of $^7$Li in the external layers of halo stars (Deliyannis et al. 1990, Charbonnel et al. 1992) due to burning at the base of the convective envelope. The depletion factor is model dependent and open to debate (e.g. Pinsonneault et al. 1992, 1998, Chaboyer 1998, Vauclair and Charbonnel 1998). The fates of $^6$Li and $^7$Li are linked in the atmospheres of stars, but $^6$Li has a lower destruction temperature than $^7$Li ($2.0 \times 10^6$ K versus $2.5 \times 10^6$ K). Thus, the observation of $^6$Li in stellar atmospheres provides a very strong constraint on the depletion factors and consequently on the effective primordial values of the lithium isotopes.

Recently, major observational advances (Smith et al. 1993, Hobbs and Thorburn 1994, 1997) have yielded an estimate of the $^6$Li/$^7$Li ratio in a few very old stars in the halo of the Milky Way. Specifically, the lithium isotopic ratio has been measured in HD 84937, most recently by Cayrel et al. (1998) with a very good S/N ratio finding $^6$Li/$^7$Li $= 0.052 \pm 0.015$.
at [Fe/H] = -2.3, and by Smith et al. (1998) who found $^6\text{Li}/\text{Li} = 0.06 \pm 0.03$ at [Fe/H] = -2.2. Smith et al. (1998) have reported one other positive detection in BD $+26^\circ3578$ (=HD 338529) with $^6\text{Li}/\text{Li} = 0.05 \pm 0.04$ at [Fe/H] = -2.3. For the other halo stars examined, only upper limits are available. This is not surprising since i) above [Fe/H] = -1, the convection zone deepens and $^6\text{Li}$ reaches high temperatures and is therefore burnt, ii) at very low metallicity, the $^6\text{Li}/^7\text{Li}$ ratio is so small that it becomes heroic to try to separate the two lithium isotopes. More observations are required around [Fe/H] = -2 to improve the situation.

Provided the galactic $^6\text{Li}$ evolution can be followed through its nucleosynthetic mechanisms, these detections permit one to draw important conclusions on the depletion factor of both lithium isotopes in the stars of interest. Limits on the depletion factors allow in turn to get constraints on their primordial abundances.

In fact, non thermal lithium production occurs through well identified spallation and fusion processes (Read and Viola 1984) mainly fast O and alphas impinging on interstellar H and He, specifically in the early Galaxy (Vangioni-Flam et al 1998). Here, we study the evolution of the cumulated abundance of $^6\text{Li}$ in the ISM i) through a galactic evolutionary model (Vangioni-Flam et al. 1996, 1997, 1998), and ii) through an empirical (model independent) criterion based on the requirement that $^6\text{Li}$ evolution vs [Fe/H] is linear at least from [Fe/H] = -2.5 up to -1. In principle, the comparison between the calculated value of the $^6\text{Li}/\text{H}$ ratio in the ISM and that observed in the stellar envelope at a measured [Fe/H] leads to an estimate of the depletion factor of this isotope. This provides important constraints at the intersection of three different astrophysical domains, stellar evolution, non thermal nucleosynthesis and cosmological nucleosynthesis. In section 2 we develop the BBN and spallation production mechanisms of $^6\text{Li}$. In section 3, we study the general evolution of $^6\text{Li}$ using empirical and theoretical constraints and we derive i) the depletion factor of this isotope in stellar envelopes and ii) the range of $^6\text{Li}$ abundance in the very early galaxy to be compared to the primordial $^6\text{Li}$ abundance in relation to $^7\text{Li}$ from BBN. In section 4, we present the astrophysical and cosmological consequences of the $^6\text{Li}$ observations.

2. Production of $^6\text{Li}$ in the Big Bang and by spallation

2.1. Big Bang nucleosynthesis

The Big Bang production of $^6\text{Li}$ is dominated by the D ($\alpha$, $\gamma$) $^6\text{Li}$ reaction (Thomas et al. 1993, Schramm 1992, 1994, Nollet et al. 1997). No direct measurement of the
cross section of this reaction has been performed below 1 MeV. However, the Coulomb breakup technique (Kiener et al. 1991) provides an indirect estimate which is in qualitative agreement with the theoretical extrapolation at low energy of Mohr et al. (1994). 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 (Angulo et al. 1998). They conclude that the reaction rate based on the Mohr et al. (1994) S factor is the most relevant. This rate is similar to that of Caughlan and Fowler (1988), in the temperature range of cosmological interest. The two estimates agree to within a few percents. Following the recommendation of Kiener (1998, private communication) and Angulo et al. (1998) we adopt the Mohr estimate. Note that the upper limit given by Cecil et al. (1996) is much higher. This upper limit is indeed related to the bad sensitivity of the detector used (Kiener, private communication). Figure 1 shows the variation of the 6Li and 7Li abundances versus the baryon-to-photon ratio, η, calculated with our BBN model. Also shown are the 9Be, 10B and 11B abundances calculated with updated reactions rates, including the new 10B(p, α)7Be reaction (adopted from Rauscher and Raimann, 1997). Clearly, the calculated primordial Be and B abundances are negligibly small, much more so than 6Li and the observed abundances were not produced in BBN (Delbourgo-Salvador and Vangioni-Flam 1992).

2.2. Spallation production

Aside from its marginal Big Bang origin, 6Li is a product of spallation operating through the α + α reaction and the collisional break up of C, N, O nuclei. Spallation agents are i) galactic cosmic rays (GCR), specifically acting in the galactic disk through p,α + He, CNO → 6Li, 7Li and ii) fast nuclei (α, C,O) produced and accelerated by SN II and fragmenting on H and He in the ISM, efficient in the halo phase as recently discussed by Vangioni-Flam et al. (1998). This Low Energy Component (LEC), distinct from standard GCR, is thought to be necessary due to an observed linear relationship between Be, B and [Fe/H], in metal poor halo stars (Duncan et al. 1992, 1997, Boesgaard and King 1993, Molaro et al. 1995, 1997, García-López et al. 1998 and references therein). Thus, the production rate is independent of the ISM metallicity , this is the definition of a primary product. 6Li itself is a primary product in both components due to the α + α reactions, though less efficient in the GCR case since the cross section is peaked around 10 MeV/n which is low compared to their average energy (about 1 GeV/n), whereas the mean energy of the LEC component corresponds to the maximum of the α + α cross section. Specifically,
the ratio of the $^6$Li production cross section averaged over the spectrum is about 50 times higher for the LEC than for GCR (using the spectrum given in Lemoine et al. 1998). In figure 2 which presents the $^6$Li/H evolution vs [Fe/H] (see below) it can be seen that the cumulated $^6$Li abundance is overwhelmed by the LEC, though the same nuclei are involved in the early Galaxy. Clearly the difference is due to the distinct spectral shapes.

In contrast, standard GCR predicts that BeB production rates depend both on the CNO abundance in the ISM at a given time and on the intensity of the cosmic-ray flux, itself assumed to be proportional of the SN II rate. Thus, the cumulated abundance of these light elements is proportional to the metallicity squared (secondary origin). Consequently, the observed linear behavior of Be and B is difficult to explain in terms of standard GCR (see also Lemoine et al. 1997).

A note of caution, however, since oxygen is the main progenitor of Be, the apparent linear relationship between Be and Fe could be misleading if O is not strictly proportional to Fe. Indeed, new observations about the O/H vs [Fe/H] correlation (Israelian et al. 1998 and Boesgaard et al. 1998b) lead to a slope less than 1, contrary to previous studies. So the Be-O relation would not be anymore linear but its slope would be about 1.5, leaving open the question of the primary and secondary origin of Be (Fields and Olive 1998a). Concerning Boron, as shown in Fields and Olive (1998a), neutrino spallation is necessary to fit the B-Fe relationship. In this case, a large if not diverging B/Be ratio is predicted below [Fe/H] = -2.5, whereas observations seem to show a quasi constant ratio down to very low metallicity. Moreover, it has to be shown that this pure standard GCR solution overcomes energetic difficulties (Ramaty et al. 1996, 1997, 1998).

Before ruling on models, we stress that there is a large dispersion in the [O/Fe] vs [Fe/H] observations. Mc Williams (1997) shows clearly this dispersion in his figure 3, which is a compilation of the available data until 1997, from [OI] results (Edvardsson et al. 1993, Spite and Spite 1991, Barbuy 1988, Kraft et al. 1991, Sneden et al. 1991, Shetrone 1996), from the OI triplet (Abia and Rebolo 1989, Tomkin et al. 1992 and from OH lines (Nissen et al. 1994, Bessell et al. 1991). Moreover, the [$\alpha$/Fe] vs [Fe/H] where $\alpha = Mg, Si, Ca, S, Ti$, (Cayrel 1996, Ryan, Norris and Beers 1996) show a plateau from about [Fe/H]= -4 to -1; on nucleosynthesis grounds, it would be surprising that oxygen would not follow this trend. Moreover, using all the published nucleosynthetic yields (Woosley and Weaver 1995, Thielemann, Nomoto and Hashimoto 1996) it seems impossible to fit the O/H vs [Fe/H] relation of Israeliian et al. (1998) and Boesgaard et al. (1998b) since the required oxygen yields is unrealistic. To come back to observations, these two papers contradict a large number of former works on the variation of the O/Fe ratio with metallicity. Both are best on high quality observations, but depends upon the same set of physical assumptions: same
empirical corrections of OH oscillator strengths derived from solar spectrum (Balachandran and Bell 1998), use of the O I IR triplet, for which no agreement between theory and observation exist for the sun itself (Kiselman and Nordlund 1995), etc... So a definitive statement on the variation of O/Fe with metallicity has also to explain why O/Fe ratios based on the [O I] line and Fe II lines, remarkably insensitive to departure to LTE and to the value of continuous opacity (Nissen and Edvardsson 1992) are wrong. Moreover, the situation could be even more complicated since a recent work (Thevenin and Idiard 1998) indicates that NLTE corrections for iron are needed for metal poor stars.

In the framework of the LEC model developed up to now, related physically to the acceleration of SN II ejecta in the superbubbles produced by the OB associations (Parizot, 1998 and Parizot et al. 1997), the linear relation between Be, B vs [Fe/H] is naturally obtained, leading to a quasi constant B/Be ratio, perhaps slightly affected by neutrino spallation (Vangioni-Flam et al. 1996) that generates $^{11}$B in agreement with the meteoritic $^{11}$B/$^{10}$B ratio. $^6$Li is also produced by this same physical process. In the next section we will specifically study the evolution of $^6$Li in the light of the new constraints set by its observation in Pop II stars.

3. Galactic evolution of $^6$Li

At a given time, when a star forms, it inherits the composition of the ISM at this particular moment. Is the atmospheric Li abundance preserved in the course of stellar evolution? Indeed, the depletion factor is still unknown in spite of many efforts to fix it (Chaboyer 1994, Vauclair and Charbonnel 1995, Deliyannis et al. 1996, Chaboyer 1998, Pinsonneault et al. 1998, Cayrel et al. 1999). In this context, it is necessary to compare the calculated and/or estimated $^6$Li/H in the ISM to the value measured in HD 84937 and BD +26°3578 to get the $^6$Li depletion factor at least in these stars, typical of all stars of the Spite’s plateau. The $^6$Li abundance observed in their atmosphere is necessarily equal or lower than that of the interstellar medium out of which these objects have formed since this isotope can only be depleted in stellar atmosphere due to proton capture. If there is no depletion in stars the observed points are located right on the evolutionary curves.

Aimed at evaluating this $^6$Li depletion factor in stars, we propose two procedures, the first is based on a well founded evolutionary model of light elements and the second is based on an empirical criterion which is model independent.

i) The Be and B evolution has been followed as a function of [Fe/H], relying on a model invoking fast nuclei ($\alpha$, C, O) originating from SN II within superbubbles, model
S1 (Bykov 1995, Parizot et al. 1997); here, only massive stars remain in the cavity (50 - 100 $M_\odot$) due to their short lifetime. They feed the cavity with C and O nuclei which are injected by winds and explosions and are accelerated in the low density gas by weak reflected shocks. In the early Galaxy, these extended acceleration sites would be sustained and filled essentially by SN II exploding in OB associations (Parizot et al. 1999). Later on, in the disk phase, Wolf Rayet stars would also participate, since the stellar winds intensify at increasing metallicities (Meynet et al. 1994).

The evolution of the $^6$Li abundance in the ISM as a function of time (or [Fe/H]) is calculated according to the same formalism and hypotheses than in Vangioni-Flam et al. (1998), and the progressive $^6$Li enrichment in the ISM is followed together with that of Be and B. A step forward relative to Vangioni-Flam et al. (1998) is to take into account the new constraints given by $^6$Li and $^9$Be observations in the two considered stars. Indeed, the high $^6$Li/$^9$Be ratio (20 - 80) at low metallicity (respective to the meteoritic value, about 6) leads us to consider a variation of the composition of the LEC. We invoke, to explain these preliminary observations, the fact that in the course of the evolution of the Galaxy the composition of the superbubble supplied by the most massive stars is O rich at the beginning and becomes progressively carbon rich due to the increasing contribution of massive mass loosing stars (Maeder 1992, Portinari et al. 1998). Thus the source composition of the LEC accelerated in these cavities changes as well, and in turn, the $^6$Li/$^9$Be ratio produced by its spallation, as shown in figures 3 and 4.

A grid of stellar yields calculated at different metallicities has been released by Woosley and Weaver (1995). At very low metallicity, the composition of the U40B model of these authors is taken as representative of the matter accelerated in superbubbles. This LEC composition is propagated and the resulting isotopic ratios of light species are calculated (Parizot et al. 1999 in preparation). As the ISM metallicity increases, the source composition is taken variable. We adopt a spectrum of the form: $N(E) \, dE = kE^{-1.5} \exp(-E/E_o)$, with $E_o = 30$ MeV/n as previously (Vangioni-Flam et al. 1998). In figure 3, the behaviour of the $^6$Li/$^9$Be ratio versus C/O for three He/O ratios is shown. It is interesting to note that the He/O ratio in the ejecta and winds of massive stars varies much less than the C/O ratio in the course of the evolution. We see that as C/O increases the evolution going on, $^6$Li/$^9$Be decreases from about 20 to 6 (for He/O = 10). For comparison, we show in figure 4 the same diagram but with $E_o = 10$ MeV/n; the $^6$Li/$^9$Be ratio decreases more steeply starting from about 70 until 6. The related light element yields for $E_o = 30$ MeV/n at low C/O and at He/O = 10 corresponding to the early Galaxy, are in better agreement with the observational constraints.

These diagrams allow to derive the $^6$Li/$^9$Be ratio produced by the LEC primary
component for any composition and metallicity at any time. As a consequence, it is clear that in the disk phase this ratio will decrease, meaning that the production of $^6$Li per $^9$Be nucleus diminishes. So, to cover the $^6$Li disk evolution, the source composition has to be taken variable vs time, taking into account in details the variation of He, C, O in the source composition (Parizot et al. 1999). In this work, as a first approach, we include this variation, reducing the $^6$Li yield progressively (figure 3). Typically, in relation with U40B (Woosley and Weaver 1995): $\text{Li}/\text{Be} = 60$, $\text{B}/\text{Be} = 19$, $\text{Li}/^9\text{Be} = 20$ ending at present with $\text{Li}/^9\text{Be}$ at about 7. Note that the higher value of this last ratio obtained with $E_0 = 10$ MeV/n at low C/O, (about 70) corresponds to the upper observational value (Hobbs and Thorburn 1994). However, this extremely high Li production is quite inconsistent with other constraints, specifically with the global behaviour of Be. In this case, the model leads to $\text{Li}/\text{Be} = 271$ in the early Galaxy, which is too high.

The yields obtained with the truncated spectrum described above are injected in the galactic evolutionary model. We remind that the mass range of $\alpha$, C, O progenitors is 50 - 100 $M_\odot$ (Model S1) as implied by the superbubble scenario. For comparison we have extended the mass domain (10-100 $M_\odot$, Model S2) to see the effect of the enlargement of the stellar population involved as in Vangioni-Flam et al. (1998) using the Woosley and Weaver (1995) yields at low metallicity; this S2 model runs with a constant source composition contrary to S1 model since the dominant stars in this hypothesis have about 15 $M_\odot$, and in this case, they are not affected by mass loss at any metallicity.

Figure 2 presents the evolution of $^6$Li/H versus [Fe/H] for i) standard GCR ii) LEC from superbubbles for two mass ranges. The full line shows the behaviour of $^6$Li for model S1 (taking into account the variation of the source composition). The dotted line represents model S2. The HD 84937 and BD $+26^\circ3578$ measurements are plotted for confrontation. Though there are only two observational points, it is sufficient to draw important conclusions thanks to the good knowledge of the evolutionary process at work. As can be seen, at the metallicity of these stars, the quasi absence of $^6$Li depletion is demonstrated since models S1 and S2 go through the observational data. Note that standard GCR (Figure 2, dash-dotted line) assumed to have the same energy spectrum than observed presently (i.e. no strong excess at low energy, Lemoine et al. 1998) plays an insignificant role in the early evolution of $^6$Li and that cosmic ray alone cannot explain the amount of $^6$Li measured in these stars. This is not surprising because, as seen previously, the LEC production is much stronger than the GCR one (by a factor of about 50). Fields and Olive (1998b), on their side, fit the $^6$Li evolution into account, as mentionned above, the new O-Fe relation of Israelian et al. (1998). In this context, considering exclusively the standard GCR component, the slope of the relation $^6$Li/H vs [Fe/H] goes from 1 to about 0.6 leading to a good fit of all $^6$Li observations. In our case, the variation of the LEC component induces a flattening of
the $^6\text{Li}$ evolution in the disk phase, leading to the solar value.

At very low metallicity, $[\text{Fe/H} = -4$, which corresponds to the onset of the star formation in the Galaxy, models S1 and S2 differ substantially, for example by about 1 dex at $[\text{Fe/H}] = -4$. These two cases lead to a range of very early $^6\text{Li}$ abundance of $5.6 \times 10^{-14}$ to $3.1 \times 10^{-12}$, to be compared with the BBN calculations. It is interesting to see that the theoretical description of the $^6\text{Li}$ evolution in the early galaxy on the basis of the fast nuclei spallation is essentially consistent within a factor of 2 with the observations of the two stars, which is indicative of low destruction of $^6\text{Li}$, if any.

ii) In a second approach, independently of the galactic evolutionary model, one can derive an absolute upper limit of $^6\text{Li}$ depletion in HD 84937 and BD $+26^\circ3578$, using the following arguments a) the evolutionary curve of $^6\text{Li}$ versus $[\text{Fe/H}]$ is linear at least down $[\text{Fe/H}] = -3$, b) the maximum value of the Spite's plateau ending at about $[\text{Fe/H}=-1.3]$ is $2.5 \times 10^{-10}$ (see figure 2, horizontal thick line) (Spite 1997). Above this metallicity, which corresponds to the transition between the halo phase and the disk one, the Li abundance is rising, reaching $2.10^{-9}$ at solar metallicity (Anders and Grevesse 1989). Thus, typically, spallative Li (thick full line, slope 1) cannot be higher than $2.5 \times 10^{-10}$ at $[\text{Fe/H}] = -1.3$ to avoid crossing the Spite's plateau which corresponds to a maximum $^6\text{Li}/^{12}\text{C} = 10^{-10}$, since almost all spallation models lead to $^7\text{Li}/^6\text{Li}$ of about 1.5. This is an absolute upper limit of the $^6\text{Li}$ production in the halo of the Galaxy. Indeed, the same kind of argument has been used to limit the theoretical yields of $^7\text{Li}$ synthesized by neutrino spallation in SN II, in the early Galaxy (Vangioni-Flam et al. 1996). The deduced maximum $^6\text{Li}$ curve (Figure 2, long and short dashed thick line) passes again across the error bar of the observed points. This indicates, independently of any model, that $^6\text{Li}$ is essentially intact in the envelope of HD84937 and BD $+26^\circ3578$, provided the $^6\text{Li}/^7\text{Li}$ vs $[\text{Fe/H}]$ evolution is linear. Boesgaard et al. (1998a) advocate a larger dispersion of the Spite's plateau (full range of a factor of 3); in this case, the maximum depletion factor of $^6\text{Li}$ is about 2.

We can conclude that the $^6\text{Li}$ observed in HD84937 and BD $+26^\circ3578$ is in good agreement to the values expected from low energy spallation production; thus, there is little room for stellar destruction. Hence, $^7\text{Li}$ which is more solid than $^6\text{Li}$, is even less depleted. This result, besides the flatness and the small dispersion of the plateau is a new strong argument to consider the average Li/H of the Spite’s plateau as the primordial one.

Finally, for a primordial $^7\text{Li}$ value of $1.6 \times 10^{-10}$ we deduce $^6\text{Li}/^7\text{Li} = 3-6 \times 10^{-14}$ which is consistent with the range deduced by both empirical and theoretical methods. This corresponds to $\eta = (1.8 \text{ to } 3.8) \times 10^{-10}$ . These results are in agreement with other independent studies (Fields et al. 1996). It is gratifying to see that the $^6\text{Li}$ evolution can be followed consistently from the standard Big Bang up to now. Thus, a pregalactic production
through the $\alpha + \alpha$ reaction is not required.

4. Conclusion

Thanks to the refined observations (Cayrel et al. 1998, Smith et al. 1998) of the $^{6}\text{Li}/^{7}\text{Li}$ ratio in two halo stars HD 84937, BD $+26^\circ3578$ and considering the galactic evolution of $^{6}\text{Li}$ driven by spallation, we arrive to the following conclusions: i) $^{6}\text{Li}$ and $^{7}\text{Li}$ are not significantly depleted in the atmosphere of halo stars, consequently, this is a new and strong argument in favor of the primordial status of the Spite’s plateau. ii) the model of Lithium-Beryllium-Boron evolution induced by fast nuclei from SN II distinct from the classical GCR is consistent, since we can explain the whole evolution of $^{6}\text{Li}$ from BB to now including the Be, B evolution. However, another alternative has been developed on the basis of a new O/H vs Fe/H relationship (Fields and Olive 1998a,b) who propose a solution based on standard GCR alone. Moreover, the new observational constraints on $^{6}\text{Li}/^{9}\text{Be}$ ratio in Pop II stars have been integrated. The fit of all the data on the light elements leads to adopt a $^{6}\text{Li}/^{9}\text{Be}$ ratio of about 20 in the early galactic evolution. A consistent scenario has been proposed on the basis of shock acceleration of nuclei in superbubbles the composition of which is oxygen rich in the halo phase and becomes progressively carbon rich iii) it is possible to set a range ($5.6\times10^{-14}$ to $3.1\times10^{-13}$) of the $^{6}\text{Li}$ abundance in the very early galaxy, which can be compared favorably to the $^{6}\text{Li}$ from BBN. Consequently, a pregalactic $\alpha + \alpha$ production of $^{6}\text{Li}$ is not required. iv) Considering both Li isotopes we get $1.8\times10^{-10} < \eta_{i} < 3.8\times10^{-10}$ in agreement with independent estimates based on deuterium and helium-4. In conclusion, the addition of $^{6}\text{Li}$ to the other light isotopes allows to confort the general picture of the cosmological nucleosynthesis followed by spallation processes.

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Figure Captions

Figure 1:

BBN of $^6$Li, $^7$Li, $^9$Be, $^{10}$B, $^{11}$B. The abundance of light isotopes by number is presented
versus the baryon/photon ratio (the $\eta$ parameter).

For the reaction $^{10}$B (p,α) $^7$Be, two different rates have been used. Full line (Caughlan
and Fowler 1988) and dashed line (Rauscher and Raimann 1997).

Figure 2:

Rise of the $^6$Li abundance from the birth of the Galaxy up to now.

The logarithm of the abundance by number of lithium isotopes is shown against the
$[\text{Fe/H}] = (\log(\text{Fe/H})^*/\log(\text{Fe/H}) M_\odot)$. HD 84937 observation is from Cayrel et al. (1998)
and BD +26°3578 is from Smith et al. (1998) (squares). Error bars are taken as 0.2 dex for
$[\text{Fe/H}]$, (+0.23, -0.19) dex for $^6$Li/H of HD 84937, and 0.2 dex for $^6$Li/H of BD +26°3578.
The corresponding Li/H for these stars are indicated by triangles. The meteoritic value is from Anders and Grevesse (1989).

- full line: galactic evolution of $^6$Li for model S1 (mass range: 50 - 100 $M_\odot$)
- dotted line: galactic evolution of $^6$Li for model S2 (10-100 $M_\odot$)
- dot-dashed line: galactic evolution of $^6$Li for standard GCR.

Thick lines:
1. horizontal full line: upper limit of the Spite’s plateau (Li/H)
2. Slope 1 full line: upper limit of the spallative $^7$Li plus $^6$Li evolution consistent with the upper limit of the Spite’s plateau.
3. Slope 1 dashed line: maximum $^6$Li evolution deduced from previous curve (knowing that $^7$Li/$^6$Li = 1.5 in spallative processes).

**Figure 3:**

The $^6$Li/$^9$Be ratio as a function of C/O for He/O = 1, 10, 50 for $E_0 = 30$ MeV/n.

The source abundances are from model U40B (Woosley and Weaver 1995).

**Figure 4:**

Same as figure 3 but for $E_0 = 10$ MeV/n.
$^{6}\text{Li}/^{9}\text{Be}$ (production ratio)

$E_0 = 30$ MeV/n

He/O = 50
He/O = 10
He/O = 1
$\frac{^6\text{Li}}{^9\text{Be}}$ (production ratio)

\begin{align*}
E_0 &= 10 \text{ MeV/n} \\
\text{He/O} &= 50 \\
\text{He/O} &= 10 \\
\text{He/O} &= 1 \\
\text{C/O (source composition)} &= 0.1 \sim 10
\end{align*}