

The energetics, evolution, and stellar depletion of ${}^6\text{Li}$ in the early Galaxy

N. Prantzos

Institut d'Astrophysique de Paris, 98bis Bd. Arago, 75104 Paris, France
e-mail: prantzos@iap.fr

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ABSTRACT

Motivated by the recent report of a high ${}^6\text{Li}$ “plateau” extending to low metallicities in Galactic halo stars, we study the energetics of an early production of ${}^6\text{Li}$ through the interaction of energetic particles with the interstellar medium. We then explore the potential of various candidate sources of pre-galactic energetic particles and show that, in general, they fail to satisfy the observational and theoretical requirements (especially if the ${}^6\text{Li}$ plateau is at a considerably higher level than observed). Successful candidates appear to be: supernova explosions with abnormally low metal yield; the massive black hole in the Galactic center (provided that it was formed early on and that it was then radiating much more efficiently than today); and, perhaps, an early accretion phase of supermassive black holes in galaxies. Assuming that ${}^6\text{Li}$ is indeed pre-galactic, we study the galactic evolution of the light isotopes ${}^7\text{Li}$, ${}^6\text{Li}$, and Be in a self-consistent way. We find that the existence of a ${}^6\text{Li}$ plateau is hard to justify, unless a fine-tuned and metallicity-dependent depletion mechanism of ${}^6\text{Li}$ in stellar envelopes is invoked. The depletion of ${}^6\text{Li}$ should be different, both in magnitude and in its metallicity dependence, than the depletion required to explain current observations of Li (mostly ${}^7\text{Li}$) in halo stars. If the recently reported ${}^6\text{Li}$ “plateau” is confirmed, our analysis suggests important implications for our understanding of the production, evolution, and stellar depletion of the Li isotopes.

Key words. stars: abundances – ISM: cosmic rays

1. Introduction

The idea that the light and fragile elements Li, Be and B are produced by the interaction of the energetic nuclei of galactic cosmic rays (CRs) with the nuclei of the interstellar medium (ISM) was introduced 35 years ago (Reeves et al. 1970; Meneguzzi et al. 1971, hereafter MAR). In those early works it was shown that, by taking into account the relevant spallation cross-sections and with plausible assumptions about the CR properties (injected and propagated spectra, intensities etc.; see Sect. 2) one can reproduce the abundances of those light elements observed in meteorites and in CRs, i.e. after $\sim 10^{10}$ yr of galactic evolution (see, e.g. Reeves 1994, for a review on LiBeB). However, the earliest evolution of the light element abundances was not considered in those works.

One of the major cosmological developments of the 1980s was the discovery of the Li plateau in low metallicity halo stars (Spite & Spite 1982). The unique behavior of that element, i.e. the constancy of the Li/H ratio with metallicity, strongly suggests a primordial origin. Its major isotope, ${}^7\text{Li}$, is indeed found to be produced in standard primordial nucleosynthesis calculations, at a level close to the one observed in halo stars (e.g. Lambert 2004, and references therein).

The other isotope of Li, ${}^6\text{Li}$, is produced in extreme low levels in Big Bang nucleosynthesis (${}^6\text{Li}/\text{H} < 10^{-14}$, e.g.

Serpico et al. 2004). Its only known source at present is non-thermal nucleosynthesis through the interaction of CRs with the ISM. Its abundance is expected to rise continuously during galactic evolution, similar to the one displayed by Be, another light element solely synthesized by CRs. Taking into account the observed abundance of Be in stars of metallicity $[\text{Fe}/\text{H}] \sim -3$ and the respective production cross-sections, one expects that the ${}^6\text{Li}/\text{H}$ ratio at such low metallicities would be considerably less than 10^{-12} .

The recent reports of the detection of ${}^6\text{Li}$ in halo stars (Asplund et al. 2004, 2005) give a new twist to the LiBeB saga. The reported ${}^6\text{Li}/\text{H}$ value at $[\text{Fe}/\text{H}] \sim -2.7$ is much larger than expected if standard galactic CRs are the only source of ${}^6\text{Li}$. This problem was already noticed by Ramaty et al. (2000) after preliminary reports of ${}^6\text{Li}$ detection in very low metallicity halo stars. Equally surprising is the report (Asplund et al. 2004, 2005) of a ${}^6\text{Li}$ plateau, at the level of ${}^6\text{Li}/\text{H} \sim 10^{-11}$ and in the metallicity range $-2.7 < [\text{Fe}/\text{H}] < -0.6$; such a plateau is reminiscent of the Spite Li plateau and suggests a pre-galactic origin for ${}^6\text{Li}$. It should be stressed, at this point, that the reality of the ${}^6\text{Li}$ plateau or even its absolute level, is not well established at present. However, a recent preliminary analysis of *SUBARU* data (Inoue et al. 2005) corroborates the findings of Asplund et al. (2005) for ${}^6\text{Li}$ in halo stars, although the derived abundance could be twice as small.

Those intriguing, albeit not yet fully established, observational results have already prompted a few ideas using a pre-galactic origin of that light isotope:

- 1) Primordial, non-standard production during Big Bang Nucleosynthesis (Jedamzik 2004): the decay/annihilation of some massive particle (e.g. neutralino) releases energetic nucleons/photons that produce ${}^3\text{He}$ or ${}^3\text{H}$ by spallation/photodisintegration of ${}^4\text{He}$, while subsequent fusion reactions between ${}^4\text{He}$ and ${}^3\text{He}$ or ${}^3\text{H}$ create ${}^6\text{Li}$. This scenario may have undesirable consequences on the abundances of other primordial nuclei (e.g. the $\text{D}/{}^3\text{He}$ ratio), as criticized by Ellis et al. (2005), and will not be discussed here.
- 2) Pre-galactic, by fusion reactions of ${}^4\text{He}$ nuclei, accelerated by the energy released during cosmic structure formation (Suzuki & Inoue 2002); in that case, CR energetics are decoupled from the energetics of supernovae (SN), the latter being at the origin of the failure of the conventional scenario (see Sect. 3.1).
- 3) Finally, Rollinde et al. (2004) postulated an early pre-galactic burst of CRs with appropriately tuned intensity in order to justify the reported level of early ${}^6\text{Li}$, but without considering potential sources or the corresponding energetics.

All scenarios of ${}^6\text{Li}$ production involving energetic particles are constrained by energy requirements: what is the source accelerating the energetic particles (EP) and is the provided energy sufficient to justify the reported abundance of ${}^6\text{Li}$ at very low metallicities? This is the main subject of this work. In Sect. 2 we evaluate the energy requirements for ${}^6\text{Li}$ production. In Sect. 3 we compare these requirements with the energy potential of various candidate sources of pre-galactic CR and show that, in general, they are hard to meet. Finally, in Sect. 4 we assume a pre-galactic ${}^6\text{Li}$ at the reported level and study the evolution of the light element abundances with a detailed model of galactic chemical evolution, coupled to CR propagation and nucleosynthesis. In agreement with previous works, we find that the existence of a ${}^6\text{Li}$ plateau is hard to justify, unless a fine-tuned metallicity-dependent depletion mechanism of ${}^6\text{Li}$ in stellar envelopes is invoked. All those results together cast some doubt, either on the reality of the reported ${}^6\text{Li}$ detection or on our understanding of ${}^6\text{Li}$ production and evolution.

2. Energy requirements for ${}^6\text{Li}$ production

The energy requirements for the production of light nuclei (Li, Be, B) through spallation of CNO nuclei have been thoroughly studied in Ramaty et al. (1997). Here a slightly different formulation of the problem is presented, based on the formalism of CR propagation developed in MAR.

After acceleration cosmic ray nuclei obtain an *injection spectrum* $Q(E)$ as a function of energy E . While propagating through the ISM, they suffer various losses (ionization, nuclear reactions, and escape from the Galaxy, in the framework of the

leaky box model). The *propagated spectrum* $N(E)$ is assumed to reach *equilibrium* ($\partial N/\partial t = 0$) rapidly:

$$\frac{\partial N(E)}{\partial t} = Q(E) - \frac{\partial}{\partial E} [b(E)N(E)] - \frac{1}{\tau(E)}N(E) = 0 \quad (1)$$

where $b(E)$ represents ionization losses, and $\tau(E)$ is the effective timescale for losses through nuclear reactions and escape from the Galaxy:

$$\frac{1}{\tau} = \frac{1}{\tau_{\text{NUC}}} + \frac{1}{\tau_{\text{ESC}}} \sim \frac{1}{\tau_{\text{ESC}}} \quad (2)$$

The functions $b(E)$ and $\tau(E)$ are determined from basic physics and from the observed properties of the ISM (density, composition, ionization stage) and of the CR (abundance ratios of primary to secondary and of unstable to stable nuclei). For *primary* nuclei, like H, He, C, N, O (the abundances of which are little affected by their propagation through the interstellar medium), the solution of Eq. (1) is:

$$N(E) = \frac{1}{b(E)} \int_E^\infty Q(E') \exp\left[-\frac{R(E') - R(E)}{\Lambda}\right] dE', \quad (3)$$

where

$$R(E) = \int_0^E \frac{\rho v(E')}{b(E')} dE' \quad (4)$$

is the *ionization range*, with ρ the ISM mass density and $v(E)$ the particle velocity, while $\Lambda = \rho v \tau_{\text{ESC}}$ is the *escape length* from the Galaxy.

The resulting equilibrium spectrum can also be expressed in terms of the omnidirectional particle *flux* $\Phi(E) = N(E)v(E)$. That quantity is then folded with the relevant spallation cross-sections $\sigma(E)$ in order to calculate the yield of the LiBeB nuclei:

$$\frac{\partial y_k}{\partial t} = \sum_j y_j^{\text{ISM}} \sum_i \int_T^\infty \Phi_i^{\text{GCR}}(E) \sigma_{ij}^k(E) P_{ij}^k(E_C) dE. \quad (5)$$

In this expression, y_k is the abundance (by number) of the light nucleus k ($k = 1, \dots, 5$ for ${}^6\text{Li}$, ${}^7\text{Li}$, ${}^9\text{Be}$, ${}^{10}\text{B}$, ${}^{11}\text{B}$). The indices i and j run over the range $1, \dots, 5$ for H, ${}^4\text{He}$, ${}^{12}\text{C}$, ${}^{14}\text{N}$, and ${}^{16}\text{O}$. The cross sections $\sigma_{ij}^k(E)$ represent the probability of producing nucleus k through the interaction of nuclei i and j , and they have a threshold T . The quantities $P_{ij}^k(E_C)$ represent the fraction of light nuclei k that are produced at energy E_C and are incorporated in the ISM at time t . They are given by

$$P_{ij}^k(E_C) = \exp\left[-\frac{R_k(E_C)}{\Lambda}\right] \quad (6)$$

where $R_k(E)$ is the ionization range of nucleus k . The energy E_C is close to zero when a fast proton or alpha hits a CNO nucleus of the ISM (i.e. the resulting light nucleus is created at rest and $P \sim 1$), and $E_C = E$ when fast CNO nuclei are spallated by ISM protons and alphas (i.e. the resulting light nuclei inherit the same energy per nucleon). In the case of the fusion reaction $\alpha + \alpha \rightarrow {}^6\text{Li}$ ($i = j = 2$) the resulting Li nuclei are created with a velocity about half the one of the fast α particles, and $E_C = E/4$ (see Eq. (6) in MAR).

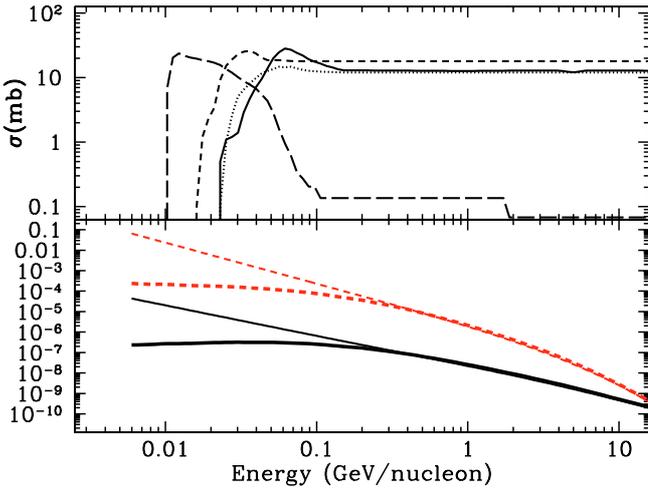


Fig. 1. *Top:* cross sections for the production of ${}^6\text{Li}$ from proton spallation of ${}^{12}\text{C}$ (dotted), ${}^{14}\text{N}$ (short dashed), ${}^{16}\text{O}$ (solid) and $\alpha + \alpha$ (long dashed); the recent measurements of Mercer et al. (2001) have been taken into account in the last curve. *Bottom:* energetic particle spectra adopted in this study; they correspond to Eqs. (8) (solid) and (9) with $s = 3$ and $E_0 = 10$ GeV/nucleon (dashed). In each case, the upper (thin) curve corresponds to the injection spectrum and the lower (thick) one to the equilibrium spectrum, propagated in a leaky box model with an escape length $\Lambda = 10$ g cm $^{-2}$. Normalization of the spectra is arbitrary.

The total power (energy per unit time) in accelerated particles is

$$\dot{W} = \frac{\partial W}{\partial t} = \sum_i A_i \int_0^\infty E Q_i dE, \quad (7)$$

where multiplication by the mass number A_i accounts for the fact that energy E is always expressed in units of energy/nucleon. Obviously, by dividing Eqs. (7) by (5) one obtains the energy of accelerated particles of a given composition that is required to produce one nucleus of species k . The result essentially depends on two factors: the form of the injection spectrum $Q(E)$ and the composition of that spectrum. The composition of the ISM is also involved, but it is always taken as equal to solar today, while its evolution is constrained well by observations of low-metallicity stars.

The CR equilibrium spectrum is known very poorly at low energies, precisely those that are important for Li production (in view of the relevant production cross sections, see Fig. 1, upper panel). The reason is the poorly understood modulation effects of the solar wind. Instead of using a demodulated spectrum (e.g. Ip & Axford 1985), in most studies of Li production, a theoretical injection spectrum is adopted and propagated in the Galaxy, in order to recover the equilibrium spectrum through Eq. (3). The form of the injection spectrum is motivated by theories of collisionless shock acceleration (e.g. Ellison & Ramaty 1985). Two popular spectra adopted in most studies in the field (Prantzos et al. 1993; Fields et al. 1994; Ramaty et al. 1997, 2000) are

$$Q(E) \propto \frac{E + E_p}{[E(E + 2E_p)]^{1.5}} \quad (8)$$

where $E_p = 938$ MeV is the proton rest mass-energy, and

$$Q(E) \propto \frac{p^{-s}}{\beta} \exp(-E/E_0) \quad (9)$$

where $\beta = v/c$ is the velocity expressed as a fraction of the light velocity, p the particle momentum per nucleon, the factor s is usually $2 < s < 3$ (in the case of strong shocks), and E_0 is a cut-off energy. In view of the form of the $\alpha + \alpha$ cross sections, one might think that a much steeper spectrum than those two may favor the energetics of ${}^6\text{Li}$ production. However, ionization losses increase as E^{-1} and are so important in the energy range of few tens of MeV/nucleon that steeper spectra lead to much larger energy demands. Even if the energy spectra of energetic particles in the early Galaxy or in the pre-galactic era are poorly known (see e.g. Gabici & Blasi 2003; Inoue et al. 2004), we feel that those adopted here represent the various possibilities reasonably well, at least as far as energetics is concerned (see below).

The adopted spectra appear in Fig. 1 (lower panel). The energetics of ${}^6\text{Li}$ production also depends on the adopted CR source composition. Today, that composition is very close to solar, once effects of propagation and various biases are taken into account (e.g. Wiedenbeck et al. 2001). Intuitively, it appears that the CR source composition should always follow the one of the interstellar medium. However, the observed linearity of Be vs. Fe in Galactic stars (e.g. Primas et al. 1999) strongly suggests that the CR composition varied little during the Galactic history; this was first suggested by Duncan et al. (1992) and convincingly demonstrated by Ramaty et al. (1997) on the basis of energetics arguments. Note that the composition of CRs in the early Galaxy affects the ${}^6\text{Li}$ energetics relatively little, since a large fraction of that isotope is produced by $\alpha + \alpha$ fusion reactions, especially at low metallicities (Steigman & Walker 1992).

The discussion of this section is summarized in Fig. 2, where the energy required to produce a ${}^6\text{Li}$ nucleus by EP hitting the ISM is displayed as a function of the evolving composition of the ISM, represented by $[\text{Fe}/\text{H}]$. It is assumed that the abundances of N and C in the ISM follow exactly the one of Fe, while the abundance of O evolves differently (O/Fe is 3 times solar for $[\text{Fe}/\text{H}] < -1$ and declines smoothly to its solar value for higher $[\text{Fe}/\text{H}]$); this assumption is based on the observed evolution of those elements. The momentum spectrum of Eq. (9) is more efficient than the energy spectrum of Eq. (8). Note that increasing the slope s of the momentum spectrum to higher values than the adopted value of $s = 3$ does not improve the energetics, because of the resulting high ionization losses¹. Thus, the two lowest curves in Fig. 2 are close to the maximum efficiency for ${}^6\text{Li}$ production. Pre-galactic CRs were obviously devoid of CNO nuclei, so the energy requirement for ${}^6\text{Li}$ production in the case of pure $\alpha + \alpha$ is $\varepsilon_6 \sim 16$ erg/nucleus. We shall adopt it as a canonical value in the following. (Note: Increasing

¹ See e.g. Fig. 8c in Ramaty et al. (1997), displaying clearly the effects of slope s and cut-off energy E_0 on the energetics of Be; increasing s (steeper spectra) increases dramatically the energetic requirements. A similar, albeit not so dramatic effect (in view of the large low energy $\alpha + \alpha$ cross sections) holds for ${}^6\text{Li}$.

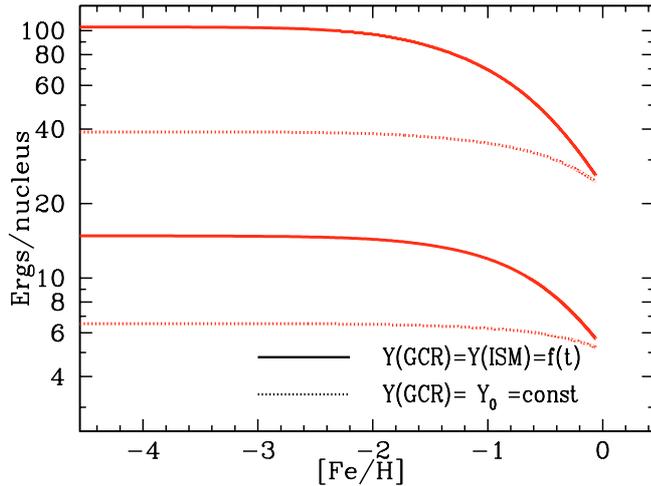


Fig. 2. Energy requirement for the production of ${}^6\text{Li}$, as a function of the metallicity of the ISM, expressed by $[\text{Fe}/\text{H}]$. The two upper curves correspond to the spectrum of Eq. (8) and the two lower ones to the spectrum of Eq. (9) with $s = 3$ and $E_0 = 10$ GeV/nucleon (see Fig. 1). The curves correspond to two different assumptions about the composition of the energetic particles (EP) that hit the ISM. The *solid curve* is obtained by assuming that the composition of EP always follows the one of the ISM, i.e. it varies with time. The *dotted curve* is obtained by assuming that the composition of EP is always the same and similar to the source composition of galactic CRs today. In the former case, ${}^6\text{Li}$ at low metallicities is produced almost exclusively by $\alpha + \alpha$ reactions.

the value of the escape length Λ_{ESC} from 10 g cm^{-2} adopted here to $100\text{--}200 \text{ g cm}^{-2}$ (i.e. assuming a more efficient confinement of the CRs, which could be the case in the early Galaxy) slightly improves the energetics of ${}^6\text{Li}$ production, by less than $\sim 40\%$; however, this small difference does not affect the conclusions of Sect. 3).

The tentative plateau value in the data of Asplund et al. (2005) is at $({}^6\text{Li}/\text{H})_{\text{PL}} \sim 10^{-11}$ (where *PL* stands for “plateau”). Taking the discussion on energetics into account, one sees that $\varepsilon_6 \sim 16$ erg in EP are required in order to produce 1 nucleus of ${}^6\text{Li}$ for every 10^{11} nuclei of the ISM; this energetic requirement can be expressed as

$$w_6 = \varepsilon_6 \left(\frac{{}^6\text{Li}}{\text{H}} \right)_{\text{PL}} \frac{1}{m_p} \sim 10^{14} \text{ erg g}^{-1} \quad (10)$$

where m_p is the proton mass. This means that $\sim 10^{14}$ erg of EP are required to pollute each gr of the ISM to the level of $({}^6\text{Li}/\text{H})_{\text{PL}} \sim 10^{-11}$ through $\alpha + \alpha$ reactions. We note that similar values are found in Reeves (2005), through a different evaluation. In the next section we explore the energetic potential of various CR sources and compare it to the requirement for early ${}^6\text{Li}$ production of Eq. (10). One should note, however, that if the true pregalactic ${}^6\text{Li}$ value is higher than 10^{-11} (see Sect. 4.2), the value of w_6 should be revised upwards accordingly.

3. Candidate sources for particle acceleration in the early Galaxy

3.1. Typical core collapse supernovae

Core collapse supernovae release a “canonical” energy of $E_{\text{SN}} \sim 1.5 \times 10^{51}$ erg, of which $\sim 10\text{--}20\%$ may accelerate CR particles, i.e. the efficiency of turning SN shock energy into EP is $f_{\text{SN}} \sim 0.1\text{--}0.2$. The efficiency value results from the total power of Galactic CR, estimated to $2 \times 10^{41} \text{ erg s}^{-1}$ (e.g. Longair 1992), and from the statistics of supernovae in the Milky Way (about 3–4 supernovae per century are expected on average, on the basis of observed SN frequencies in Milky Way type galaxies, e.g. Mannucci et al. 2005).

Taking Eq. (10) into account, one sees that a mass of the ISM $M_{\text{ISM}} = f_{\text{SN}} E_{\text{SN}}/w_6 \sim 10^3 M_{\odot}$ can be polluted by a single SN to the level of $({}^6\text{Li}/\text{H})_{\text{PL}} \sim 10^{-11}$. However, a “canonical” core-collapse SN, i.e. resulting from the explosion of a not too massive star, also ejects $M_{\text{Fe}} \sim 0.07 M_{\odot}$ of Fe, (e.g. Woosley & Weaver 1995) polluting the ISM to the level of

$$X_{\text{Fe}} = \frac{M_{\text{Fe}}}{M_{\text{ISM}}} \sim 5 \times 10^{-5} \frac{M_{\text{Fe}}}{0.07 M_{\odot}} \left(\frac{f_{\text{SN}}}{0.1} \right)^{-1} \frac{w_6}{10^{14} \text{ erg/g}} \left(\frac{E_{\text{SN}}}{1.5 \times 10^{51} \text{ erg}} \right)^{-1} \quad (11)$$

where X_{Fe} is the mass fraction of Fe. This corresponds to a metallicity $[\text{Fe}/\text{H}] \sim -1.4$ (adopting a solar mass fraction of $X_{\text{Fe},\odot} = 1.25 \times 10^{-3}$ for Fe, following Lodders 2003). Thus, “canonical” SN may indeed pollute the ISM to the level of ${}^6\text{Li}/\text{H} \sim 10^{-11}$, but only for metallicities as high as $[\text{Fe}/\text{H}] \sim -1.4$. At metallicities $[\text{Fe}/\text{H}] \sim -2.7$ (the lowest metallicity point in the data of Asplund et al. 2005), a simple scaling shows that the expected level of pollution is only ${}^6\text{Li}/\text{H} \sim 5 \times 10^{-13}$, i.e. a factor of ~ 20 below the observations. Note that this is a real upper limit to the level of ${}^6\text{Li}$ enrichment that can be obtained by a “canonical” supernova, because it is assumed that the EP accelerated by the supernova produce ${}^6\text{Li}$ only inside the matter that is enriched in Fe. In actual reality, those EP diffuse much further and produce ${}^6\text{Li}$ in a much larger region, but to a proportionally lower level (since the total number of ${}^6\text{Li}$ atoms is determined by the energy of the explosion and is a constant: $\sim M_{\text{ISM}} ({}^6\text{Li}/\text{H})_{\text{PL}}/m_p \sim 2 \times 10^{49}$ ${}^6\text{Li}$ atoms).

The situation may be even worse if the level of primordial ${}^7\text{Li}$ is as high as suggested by the WMAP data. Indeed, the baryonic density of the universe derived by observations of the cosmic microwave background corresponds to ${}^7\text{Li}/\text{H} \sim 4 \times 10^{-10}$, according to standard calculations of primordial nucleosynthesis (e.g. Serpico et al. 2004). That value is 2–3 times higher than the observed plateau of Li/H in the low metallicity stars of the Milky Way, and the discrepancy may be attributed to our presently poor understanding of Li depletion in stellar envelopes (e.g. Lambert 2004, and references therein). If that explanation is correct, an even greater depletion of the more fragile ${}^6\text{Li}$ is expected; the true value of ${}^6\text{Li}/\text{H}$ should then be at least 2–3 times higher than the one measured by Asplund et al. (2005), making the problem of its production by supernovae even worse.

3.2. Energetic (and/or low Fe yield) supernovae

The arguments of the previous section may not hold if the energetics of SN is decoupled from the Fe yield: if $(E_{\text{SN}}/M_{\text{Fe}}) \gg (1.5 \times 10^{51} \text{ erg}/0.07 M_{\odot})$, Eq. (11) shows that a high ${}^6\text{Li}/\text{H}$ could be obtained for a small $[\text{Fe}/\text{H}]$. Such a decoupling might be justified on both observational and theoretical grounds; however, as is usually the case, observations leave less room for optimism than does the theory.

Observations of extragalactic core collapse SN suggest a clear, but not exactly linear, correlation between M_{Fe} and E_{SN} , as shown in the review by Hamuy (2003). In Fig. 15 of that review, it can be seen that SN98bw, a type Ic supernova, may have ejected $0.5 M_{\odot}$ of Fe (i.e. 7 times the canonical value adopted here) for an energy of $2\text{--}5 \times 10^{52} \text{ erg}^2$, which is 15–30 times the canonical energy of core collapse supernovae³. If such events dominated in the early Galaxy, the discrepancy with the energetics of ${}^6\text{Li}$ production would be reduced to $\sim 4\text{--}9$ (the original discrepancy of a factor of 20 is reduced by a factor of 15–30 because of the increased energy, and again augmented by a factor of 7 due to the increased Fe yield). In their analysis, Nomoto et al. (2000) find that the progenitor mass of SN1998bw had $\sim 40 M_{\odot}$. One might think that such energetic supernovae with large $E_{\text{SN}}/M_{\text{Fe}}$ values would be common among massive stars of the so-called “hypernova” branch (e.g. Nomoto et al. 2005). However, although the energy of such explosions is indeed larger than the canonical value, the $E_{\text{SN}}/M_{\text{Fe}}$ value is not always large. Thus, in the case of SN1999as, again a type Ic supernova, the energy is estimated as $3 \times 10^{52} \text{ erg}$ (see e.g. Fig. 1 in Maeda & Nomoto 2003), but the Fe yield is also quite large, around $4 M_{\odot}$, so that the resulting $E_{\text{SN}}/M_{\text{Fe}}$ ratio is even lower than in the canonical case. Thus observations of energetic supernova in the nearby universe do not support $E_{\text{SN}}/M_{\text{Fe}}$ ratios large enough to explain the ${}^6\text{Li}/\text{H}$ plateau.

From the theoretical point of view, the relation between E_{SN} and M_{Fe} is impossible to derive at present, due to our very poor understanding of the explosion mechanism of core collapse supernovae (see e.g. Janka et al. 2003, for a review). In current 1D models of nucleosynthesis in supernovae, some assumptions have to be made about the way the shock wave induces explosive nucleosynthesis in the Si layers (see e.g. Limongi & Chieffi 2003); comparison with observations (e.g. SN1987A in the LMC, a $20 M_{\odot}$ star that ejected $0.07 M_{\odot}$ of Fe) may then help to fix some of the parameters of the model, e.g. the so-called “mass-cut”, the fiducial surface separating expanding material from material falling back to the compact object. Standard 1D calculations of that type usually produce a few $10^{-2}\text{--}10^{-1} M_{\odot}$ of Fe for a few $10^{50}\text{--}10^{51} \text{ erg}$ of kinetic energy,

² Iwamoto et al. (1998) derive an energy of $2\text{--}5 \times 10^{52} \text{ erg}$ for SN1998b, while in Maeda & Nomoto (2003) the derived value is $3 \times 10^{52} \text{ erg}$.

³ The large energy value of SN1998bw is derived by Iwamoto et al. (1998) under the assumption of spherical symmetry; however, it could be as low as only $3 \times 10^{51} \text{ erg}$, if that assumption is dropped and an ellipsoidal geometry for the ejecta is assumed, as suggested in Hoeflich et al. (1998).

at least for stars in the mass range $12\text{--}35 M_{\odot}$ (e.g. Thielemann et al. 1996; Woosley & Weaver 1996; Limongi & Chieffi 2003).

For larger stellar masses, in the range $30\text{--}100 M_{\odot}$, simulations suggest that collapse to a black hole should be the general outcome, either directly or after the formation of a weak shock (see Heger et al. 2003, for a review of the situation for 1D simulations with no rotation). Even if the shock is weak, the almost total absence of metals in the ejecta of such explosions makes them suitable candidates for the production of early ${}^6\text{Li}$, free of the problem of the associated production of Fe. Further support for that possibility comes from the very short lifetimes of such objects (less than a few million yrs) and their potentially large number in a zero-metallicity stellar generation: indeed, some theoretical arguments suggest that the stellar IMF at zero metallicity was considerably skewed towards massive stars, in the $100 M_{\odot}$ range (Nakamura & Umemura 2002). If such objects are at the origin of the observed early ${}^6\text{Li}/\text{H}$, one can easily evaluate their population in the Milky Way halo (with a rather large uncertainty, though).

As discussed in Sect. 3.1, the mass of the ISM that a normal SN may “pollute” to the level of the observed early ${}^6\text{Li}/\text{H}$ is $M_{\text{ISM}} \sim 10^3 M_{\odot}$. We assume here that each of these explosions leaves a black hole with mass $M_{\text{B}} \sim 50\text{--}100 M_{\odot}$. The stellar mass of the Galactic halo is $M_{\text{H}} \sim 2 \times 10^9 M_{\odot}$ (Bullock & Johnston 2005, and references therein), and this may well be (within an order of magnitude) the mass of the gas from which the halo was formed (see Fig. 1, right top panel, in Prantzos 2003). The number of black holes is then $N_{\text{B}} = M_{\text{H}}/M_{\text{ISM}} \sim 10^6$, and their total mass $N_{\text{B}} \times M_{\text{B}} \sim 10^8 M_{\odot}$, i.e. $\sim 10\%$ of the stellar halo mass. One immediately sees that only a “top-heavy” IMF can produce such a large fraction of massive stars, since in a normal IMF (i.e. Salpeter or Kroupa et al. 1993), only $\sim 1\%$ of the mass is in $50\text{--}100 M_{\odot}$ stars. Unfortunately, the required total mass in black holes is far below the microlensing detection limits of the MACHO or EROS2 experiments: EROS2 places an upper limit of $\sim 20\%$ on the fraction of the Milky Way’s *dark halo* which could be in the form of such objects (Tisserand, Ph.D. Thesis 2004, and private communication). For a $10^{12} M_{\odot}$ dark halo, this corresponds to $\sim 2 \times 10^{11} M_{\odot}$. Thus, the idea that early ${}^6\text{Li}$ is produced by mildly energetic stellar explosions of a first generation of (non-rotating) massive stars that lead to black holes and produce too few metals does not violate current constraints from microlensing experiments.

At this point, it should be noted that the two most metal-poor stars of the Galaxy (as far as their Fe content is concerned) are at present HE 1326-2326 (a subgiant or main sequence star) and HE 0107-5240 (a red giant). They both exhibit low Fe abundances, $[\text{Fe}/\text{H}] \sim -5.2$, but quite large C/Fe and N/Fe ratios (around 10^4 times solar) and high ratios of Na/Fe, Mg/Fe and, rather surprisingly, Sr/Fe (around $10\text{--}100$ times solar), while other abundance ratios X/Fe are compatible with solar values (Frebel et al. 2005). These peculiar abundance patterns may indeed be explained (at least qualitatively) by “faint” SN, assuming that some mixing of the inner Fe peak nuclei with the exterior layers has occurred and that most of the Fe peak elements fall back onto the black hole. This mixing scheme, dictated on purely observational grounds, might correspond

to asymmetric explosions of rotating stars (e.g. Nomoto et al. 2005). One might think that such explosions also fulfill the requirements of “large energy and/or low Fe yield” explosions for early ${}^6\text{Li}$ production. However, no Li has been found in HE 1327-2326 and only an upper limit of ~ 0.5 times the Spite plateau value is given in Frebel et al. (2005); in all probability, ${}^6\text{Li}$ should also be absent from its atmosphere. Of course, one might argue that ${}^6\text{Li}$ was present during the star’s formation but subsequently depleted in its envelope. In any case, there is no observational proof at present that the supernovae responsible for the abundance pattern of the most metal poor Galactic stars were at the origin of the early ${}^6\text{Li}$ observed.

3.3. Shocks from cosmic structure formation

The currently popular scenario of hierarchical structure formation in the Universe suggests that large scale objects, such as galaxies and clusters, are formed from the merging of smaller subsystems, which are moving and virialised in the gravitational potential wells of dark matter haloes. During those mergers, shocks should develop in the gaseous component of the merging subsystems. The kinetic energy of those shocks from structure formation should be, on average,

$$E_{\text{SF}} = \frac{1}{2} M v_{\text{VIR}}^2 \quad (12)$$

where M is the mass of the baryonic gaseous component and the virial velocity is

$$v_{\text{VIR}} \sim \left(\frac{GM_{\text{DH}}}{R} \right)^{1/2} \sim 400 \left(\frac{M_{\text{DH}}}{10^{13} M_{\odot}} \right)^{1/4} \text{ km s}^{-1}, \quad (13)$$

G being the gravitational constant, M_{DH} the dark halo mass, and R the virial radius. The numerical values in Eq. (12) result from cosmological simulations of large-scale structure formation (Christophe Pichon, private communication). In the case of the Milky Way, the present-day dark halo mass is evaluated to $M_{\text{DH}} \sim 10^{12} M_{\odot}$ (Battaglia et al. 2005), leading to a virial velocity $v_{\text{VIR,MW}} \sim 220 \text{ km s}^{-1}$ today.

The energy of those shocks *per unit mass of gas* is $w_{\text{SF}} = 1/2 v_{\text{VIR}}^2$, and for the case of the Milky Way one gets $w_{\text{SF,MW}} \sim 2 \times 10^{14} \text{ erg g}^{-1}$. In order to satisfy the energetics requirement for ${}^6\text{Li}$ production of Eq. (10), the kinetic energy of shocks from the formation of the Milky Way should be converted to energetic particles with an efficiency of 50%, which is an extremely high value. Suzuki & Inoue (2002), who first suggested the idea that shocks from cosmological structure formation may be at the origin of early ${}^6\text{Li}$ production, assumed a higher value for M_{DH} ($3 \times 10^{12} M_{\odot}$) and found a reasonable acceleration efficiency of 15%. However, this estimate is overly optimistic, because it is based on the assumption that *the dark halo is fully formed before the first stars appear polluted by ${}^6\text{Li}$* . Taking the age of the low metallicity halo stars of the Milky Way into account (larger than 11 Gyr, corresponding to a redshift $z > 3$), such a hypothesis is extremely improbable. Indeed, a simple application of the Press-Schechter formalism (e.g. in the Appendix of van den Bosch 2002) shows that a dark halo of

$10^{12} M_{\odot}$ is only assembled at redshift $\sim 1.1-1.3$. In the earliest phases of our Galaxy, only much smaller dark haloes (less than $10^{10} M_{\odot}$) may have existed; the corresponding virial velocity being lower than 200 km s^{-1} , the resulting kinetic energy was too low to fulfill the energy requirement for ${}^6\text{Li}$ production.

One may, in fact, obtain an upper limit to that energy by noting that the mass of the baryonic halo today is $M_{\text{H}} \sim 2 \times 10^9 M_{\odot}$. Assuming a baryonic/dark matter ratio of 0.1, this corresponds to a dark matter halo of $2 \times 10^{10} M_{\odot}^4$ and to a corresponding virial velocity of $\sim 100 \text{ km s}^{-1}$ (from Eq. (13)). This leads to a total kinetic energy per unit mass of baryons of $\sim 0.5 \times 10^{14} \text{ erg g}^{-1}$ and, adopting a standard conversion efficiency to energetic particles ($f \sim 0.1$), one sees that no more than 5% of the observationally required w_6 value can be provided by that mechanism. Thus, shocks from early structure formation cannot be at the origin of early ${}^6\text{Li}$.

Note that, in the framework of the hierarchical structure formation paradigm, mergers occurred during a large fraction of the Galaxy’s history (e.g. Helmi et al. 2003). If the corresponding shocks accelerated EP, the proposed scenario cannot be characterized as “pre-galactic” and it would lead to a continuous rise of the ${}^6\text{Li}/\text{H}$ ratio, not to the observed “plateau”. A metallicity-dependent mechanism of ${}^6\text{Li}$ depletion inside stars should then also be introduced to account for the “plateau” (see also Sect. 4.2).

3.4. Accretion onto the Galactic black hole

Accretion onto black holes may have provided another energy source for particle acceleration in the early galactic (or pre-galactic) era. Both theory and observations suggest that a large fraction of the black hole mass-energy may be extracted in that case, either in the form of a jet or a wind; this fraction may be as large as $\eta \sim 0.1$.

The largest black hole in the vicinity of the Milky Way is the one laying in the Galactic center (GC). Its mass is estimated to $M_{\text{BH}} \sim 3 \times 10^6 M_{\odot}$ (Melia & Falcke 2001). The energy that could be released by accretion onto it is at most $E_{\text{BH}} = \eta M_{\text{BH}} c^2$, where c is the light velocity. Assuming a high value for the energy extraction efficiency ($\eta = 0.1$) and a typical value for the efficiency of conversion of that energy to energetic particles ($f = 0.1$) one finds that

$$E_{\text{BH}} \sim 5 \times 10^{58} \frac{\eta}{0.1} \frac{f}{0.1} \frac{M_{\text{BH}}}{3 \times 10^6 M_{\odot}} \text{ erg}. \quad (14)$$

Assuming that the black hole was already in place before the formation of the Milky Way’s halo, one finds that a mass of $E_{\text{BH}}/w_6 \sim 2 \times 10^{11} M_{\odot}$ could have been polluted to the level of the observed early ${}^6\text{Li}/\text{H}$. This is ~ 3 times larger than the total stellar mass of the Milky Way (around $6-7 \times 10^{10} M_{\odot}$, including the bulge), comparable to the total stellar mass of the Local Group, which is dominated by the Milky Way and Andromeda, and 100 times larger than the stellar mass of the

⁴ A recent work (Bullock & Johnston 2005), that studies the formation of Milky Way’s halo in a cosmological context confirms that the halo was indeed formed by the merging and tidal disruption of dwarf galaxies, mostly embedded in dark haloes of $\sim 10^{10} M_{\odot}$.

Galactic halo $M_{\text{H}} \sim 2 \times 10^9 M_{\odot}$. Thus, the Galactic center black hole apparently fulfills the energy requirement of Eq. (14) for early ${}^6\text{Li}$ production; however, this occurs only under extreme assumptions about 1) the time of its formation and 2) the efficiency of extracting its mass-energy.

The first of those points is, perhaps, not that crucial: observations of luminous quasars at high redshift (e.g. in the Sloan Digital Sky Survey, Fan et al. 2004) imply that massive black holes were already in place in the first billion years of the cosmic evolution. Similar conclusions are drawn in a recent study of the accretion history of supermassive black holes based on observations of the current population and accretion rates of those objects (Hopkins et al. 2005b).

The second assumption is perhaps more difficult to justify, in view of the well-known (and poorly understood) inefficiency of the Galactic black hole for converting accreted matter into radiation. Indeed, the bolometric luminosity of Sgr A* is $\sim 10^5$ times lower than what is expected from the well-determined Bondi accretion rate of $\sim 10^{-5} M_{\odot}/\text{yr}$ (e.g. Feng et al. 2003, and references therein). If the same low efficiency characterised the GC black hole in its earliest life (i.e. if $\eta = 10^{-5}$ in Eq. (14)), and if we assume that the kinetic energy of the matter escaping the black hole (in the form of a jet or wind) is equivalent to the energy radiated by the black hole, then the corresponding energetic particles could enrich just the mass of a large globular cluster ($\sim 10^6 M_{\odot}$) with ${}^6\text{Li}$. Of course, one may assume that, for some reason, the efficiency of the GC black hole was much higher in its early youth, in which case the energetics of early ${}^6\text{Li}$ production could be satisfied. However, even in that case, it is difficult to imagine that cosmic rays accelerated from a single object could produce a uniform abundance of ${}^6\text{Li}$ over the whole Galactic volume (a radial gradient is rather expected).

The conclusion of this section is that, although promising in principle, the idea that accretion on the GC black hole is at the origin of early ${}^6\text{Li}$ encounters some serious difficulties.

3.5. Accretion onto supermassive black holes in the Universe

On a larger scale than the one of the Milky Way, accretion onto supermassive black holes may provide an important source of energy for particle acceleration in the Universe. Such objects are now routinely found in the centers of galaxies (see Ferrarese & Ford 2005, for a recent review). One may obtain a useful upper limit to their capacity to produce significant amounts of ${}^6\text{Li}$ by considering the following:

The present day cosmic density of those objects (in units of the critical density) is evaluated to $\Omega_{\text{SMBH}} = 4 \times 10^{-6}$, while the corresponding total baryon density is $\Omega_{\text{BAR}} = 4.5 \times 10^{-2}$ (Fukugita & Peebles 2004). As in the previous subsection, assuming that a fraction $\eta \sim 0.1$ of the black hole rest mass can be usefully extracted as mechanical/radiative energy, and that a fraction $f \sim 0.1$ of it can be used in accelerating particles, one

sees that the corresponding energy in such particles per unit baryon mass is:

$$\begin{aligned} w_{\text{SMBH}} &= \frac{\eta f \Omega_{\text{SMBH}} c^2}{\Omega_{\text{BAR}}} \\ &= 10^{15} \frac{\eta}{0.1} \frac{f}{0.1} \frac{\Omega_{\text{SMBH}}/\Omega_{\text{BAR}}}{10^{-4}} \text{ erg g}^{-1} \end{aligned} \quad (15)$$

i.e. $w_{\text{SMBH}} \sim 10 w_6$. It then appears that supermassive black holes should be able to provide the energy needed to produce early $({}^6\text{Li}/\text{H})_{\text{PL}}$, since the available energy per unit baryon mass is about ten times larger than required. However, one should again consider the meaning of those numbers. They imply that those supermassive black holes were fully formed and released the accreted energy *before the formation of the first stars of the Galactic halo*, i.e. at redshifts $z > 3$.

The recent study of Hopkins et al. (2005b), based on observations of the nearby supermassive black hole population, indeed suggests that the bulk of the supermassive black hole mass was accreted early on in a radiatively efficient accretion phase. However, it is not clear exactly when that happened. For instance, studies of the evolution of the quasar population suggest that the maximum in their number density in any luminosity interval was at redshift $z < 2$ (see e.g. Fig. 4 in Hopkins et al. 2005a). If this evolution also characterizes the formation history and accretion rate of supermassive black holes, then those sources cannot be at the origin of observed early ${}^6\text{Li}$.

4. Evolution of ${}^6\text{Li}$

In this section we *assume* that ${}^6\text{Li}$ was already present in the earliest moments of the formation of the Milky Way, at an abundance level at least as high as suggested by the observations of Asplund et al. (2005). We study its subsequent evolution with a detailed model of galactic chemical evolution, including its production by fusion of energetic alpha particles and spallation of CNO nuclei (see Sect. 4.2) in a self-consistent way; our aim is not to fully reassess the whole subject of LiBeB production (which is still poorly understood, despite the large amount of theoretical work devoted to it; see Prantzos 2004, for a short review) but rather to study the implications of a pre-galactic ${}^6\text{Li}$ component.

4.1. Pre-galactic ${}^6\text{Li}$: cosmic or just local?

At this point, a (quite useful) distinction should be made between the terms primordial, cosmic pre-galactic, and local pre-galactic.

The term *primordial* implies production of ${}^6\text{Li}$ in the early Universe, either during the period of Big Bang nucleosynthesis or shortly after, i.e. through the decay of an unstable (super-)particle e.g. Jedamzik (2004). The resulting abundance of ${}^6\text{Li}$ is then characteristic of the *total baryonic content* of the Universe, i.e. of the baryonic fraction Ω_{BAR} .

The term *cosmic pre-galactic* implies production of ${}^6\text{Li}$ prior to star or galaxy formation *everywhere* in the Universe; i.e. the resulting abundance of ${}^6\text{Li}$ is again characteristic of the *total baryonic content* of the Universe, so both the intergalactic medium (IGM) and the star-forming galaxies have the same

${}^6\text{Li}/\text{H}$ ratio. This is assumed in e.g. the scenario of Rollinde et al. (2005).

The term *local pre-galactic* implies that ${}^6\text{Li}$ has only (or mostly) polluted the baryonic gas that participates in galaxy formation and not at all the baryons of the intergalactic medium (or very little). This picture corresponds to the realistic case where accelerating sources and the energetic particles producing ${}^6\text{Li}$ are mostly confined inside the high density gas that decouples from the Hubble flow and forms galaxies. Indeed, except for the case of supermassive black holes, all the energy sources explored in Sect. 3 (including shocks from structure formation) belong to this class. Moreover, the magnetic field is much more intense within the dense gas surrounding such sources than in the rarefied IGM, and it certainly produces some local confinement, albeit to a degree that is very hard to evaluate at present (in view of our poor understanding of the origin and evolution of galactic magnetic fields).

The distinction between *cosmic* and *local* pre-galactic is important for reasons related to the energetics of ${}^6\text{Li}$ production. The local scenario requires less energy than the cosmic one, since in the former case only a fraction of the baryonic matter (the one participating in early galaxy formation) is involved. For instance, one can assume that only the $\sim 2 \times 10^9 M_\odot$ of the halo mass was polluted with $({}^6\text{Li}/\text{H})_{\text{PL}}$ early on; the $\sim 5 \times 10^{10} M_\odot$ of the Milky Way disk were accreted much later from the intergalactic medium and were enriched to much lower levels of ${}^6\text{Li}$ (produced from the small fraction of energetic particles that escaped confinement in the halo region).

4.2. Evolution of ${}^6\text{Li}$ and Be in the Milky Way

The evolution of the light isotopes ${}^6,7\text{Li}$, ${}^9\text{Be}$, ${}^{10,11}\text{B}$ is followed with a detailed model of the Milky Way's chemical evolution. The model, presented in Goswami & Prantzos (2000), satisfactorily reproduces all the major observational constraints in the solar neighborhood, and in particular, the metallicity distributions of halo and local disk stars. The only difference with that model is that the recent, metallicity dependent, massive star yields of Chieffi & Limongi (2003) are adopted here. They differ from those of Woosley & Weaver (1995), which were adopted in GP2000, in several respects, and in particular in the absence of neutrino-induced nucleosynthesis, so no primary ${}^{11}\text{B}$ and ${}^7\text{Li}$ are present in the CL2003 yields. However, the yields of C, N, O, and Fe, most important for following the overall metallicity and the evolution of light isotopes by spallation, display only small differences between the two sets (see Goswami & Prantzos 2000, for a comparison).

The production of the light isotopes is followed as in Prantzos et al. (1993), i.e. using the formalism presented in Sect. 2 and, in particular, the momentum injection spectrum of Eq. (9). A major difference with Prantzos et al. (1993) is the adopted normalization procedure for the light element abundances: instead of normalizing the model Be abundance 4.5 Gyr ago to its solar value (and scaling all other abundances of light elements accordingly) we assume here that a fraction

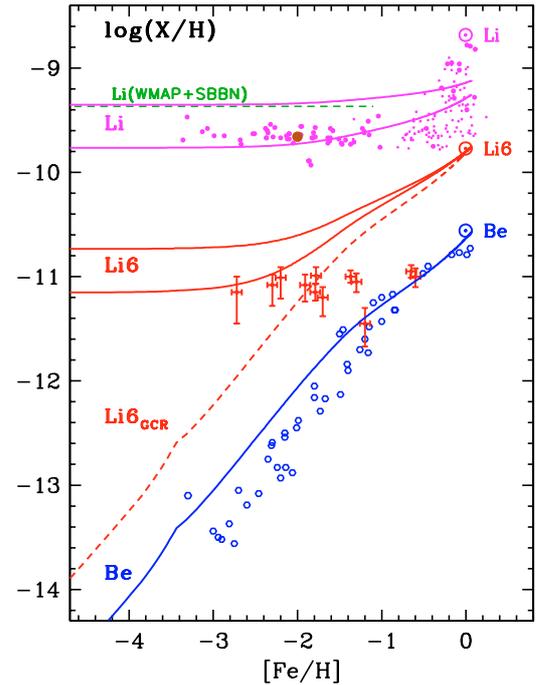


Fig. 3. Evolution of total Li, ${}^6\text{Li}$, and Be in the Milky Way. Observations for Li are: at low metallicities from Melendez & Ramirez (2004, *small dots*) and from Bonifacio et al. (2002, *large dot*); and at high metallicities from Chen et al. (2001, *small dots*) and Boesgaard & King (1993, *large dots*). At high metallicities, only values of $\text{Li}/\text{H} > -9.8$ are plotted, to avoid confusion with ${}^6\text{Li}$ values. Observations for Be (*open symbols*) are from Garcia-Lopez et al. (1998) and Primas et al. (1999). Observations for ${}^6\text{Li}$ (*with error bars*) are from Asplund et al. (2005, and references therein). The Li abundance corresponding to the baryonic density of the Universe derived by WMAP is indicated as *dashed horizontal line*. The curves correspond to a simple chemical evolution model with metallicity dependent stellar yields, GCR composition *assumed primary* (to reproduce the Be observations) and GCR spectra given by Eq. (9) with $s = 3$. The contribution of the GCR component of ${}^6\text{Li}$ is indicated by a *dashed curve*. The primordial ${}^7\text{Li}$ is assumed to be either low (at the level of the plateau of Charbonnel & Primas 2005, slightly lower than derived by Melendez & Ramirez 2004) or high (at the level of WMAP); only production by GCR is considered for Li7, i.e. no stellar source. Similarly, the pre-galactic ${}^6\text{Li}$ is assumed to be either “low” (at the level observed by Asplund et al. 2005), or “high” (by 0. \sim 0.4 dex, for consistency with assumed high Li value, which implies depletion of ${}^6\text{Li}$ in the stellar envelopes by at least that value).

$f_{\text{SN}} = 0.1$ of the kinetic energy $E_{\text{KIN}} = 1.5 \times 10^{51}$ erg of each SN is used to accelerate CR particles, i.e.

$$\dot{W} = f_{\text{SN}} E_{\text{KIN}} R_{\text{SN}} \quad (16)$$

where \dot{W} is given by Eq. (7) and R_{SN} is the SN rate (number of SN per unit of time) given by the model. As shown by Ramaty et al. (1997), this procedure is the only one that guarantees consistency between the energetics of CRs and SN. Another difference with Prantzos et al. (1993) is that the light isotopes are *assumed* to be produced as primaries by CR, i.e. that the CR composition does not vary with time. This is, indeed, the only way to reproduce the observed linearity between Be and Fe (see Fig. 3), since secondary production fails energetically

at low metallicities. Even the total SN energy turned into CR is not sufficient to produce the required number of Be atoms, as convincingly argued by Ramaty et al. (1997). It should be noted though that the reason for such $\sim\text{const.}$ CR composition has not been satisfactorily explained up to now (see Prantzos 2004, for a short critical assessment).

The results of our calculation concerning the evolution of Be, ${}^6\text{Li}$, and total Li, appear in Fig. 3. We adopt a pre-galactic Li value that is either “low”, i.e. at the level of the low-metallicity Li plateau reported by Charbonnel & Primas (2005), or “high”, i.e. at the level suggested by WMAP data plus Standard Big Bang Nucleosynthesis. In the latter case, currently observed Li in halo stars has been depleted by about 0.4 dex. Similarly, and for consistency, a “low” and a “high” value are adopted for pregalactic ${}^6\text{Li}$, respectively ${}^6\text{Li}/\text{H} = 10^{-11}$ (at the level of the “plateau” reported by Asplund et al. 2005) and 0.4 dex higher (assuming its depletion has been equal to the one of total Li). Note that the latter value corresponds to the minimal possible amount of ${}^6\text{Li}$ depletion, since this isotope is more fragile than ${}^7\text{Li}$ and should be more depleted (see Table 6 in Asplund et al. 2005; based on calculations by Richard et al. 2005). It can be seen that:

- the evolution of Be is satisfactorily reproduced; both its solar value and the slope of Be vs. Fe are reproduced with the energy normalization of Eq. (15). We stress, however, that the slope is “naturally” produced only under the assumption of a time invariant CR composition (as suggested first by Duncan et al. 1992), which has no sound theoretical justification at present;
- the CR component of ${}^6\text{Li}$ is sufficient to produce the solar value of that isotope (as already found analytically in MAR) but fails to reproduce the lowest metallicity value reported by Asplund et al. (2005) by a factor of ~ 10 (compared to the factor of 20, which was analytically derived in Sect. 3.1);
- assuming that the ${}^6\text{Li}$ plateau is real and extends to metallicities as high as $[\text{Fe}/\text{H}] = -0.6$, one sees that the CR component of ${}^6\text{Li}$ alone (dotted curve in Fig. 3) crosses that plateau value slightly earlier (around $[\text{Fe}/\text{H}] = -1.8$). A depletion mechanism *depending on metallicity* should be introduced to justify a plateau in the range $-1.8 < [\text{Fe}/\text{H}] < -0.6$ (see also Rollinde et al. 2005). When the assumed pre-galactic ${}^6\text{Li}$ component is also taken into account (either “low” or “high”), the ${}^6\text{Li}$ abundance curve leaves the plateau value even earlier, around $[\text{Fe}/\text{H}] = -2.4$.

A mechanism that depletes ${}^6\text{Li}$ in the stellar envelope with a metallicity dependent efficiency is, perhaps, not all that hard to find. Indeed, it is well known that convection sets in more easily in stellar envelopes with higher opacity, that is, higher metallicity. More metallic stars have deeper convective envelopes, which could bring ${}^6\text{Li}$ to higher temperatures and destroy it more efficiently. However, it is much harder to imagine that such a mechanism preserves the putative ${}^6\text{Li}$ plateau value *exactly*. Also, note that depletion of total Li is mandatory when one assumes a high primordial Li abundance (as suggested by WMAP, see Fig. 3) in order to bring that value to the observed plateau level of Li; here the depletion mechanism is metallicity

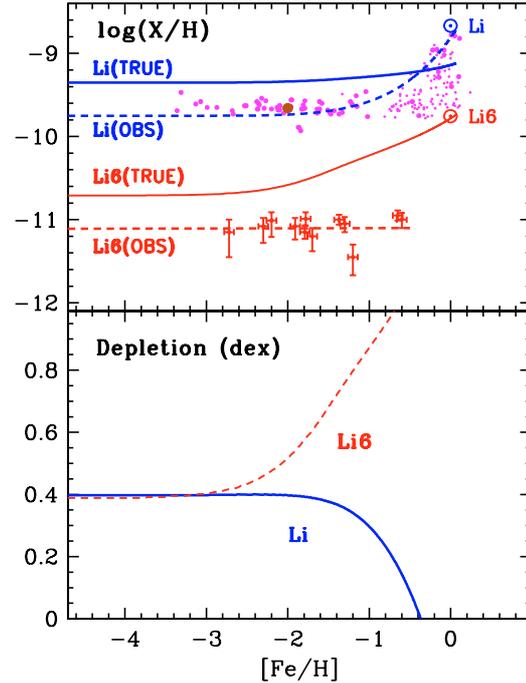


Fig. 4. *Upper panel:* evolution of Li and ${}^6\text{Li}$, observations vs theoretical estimates. Data points are as in Fig. 3. *Dashed* curves corresponding to observations are: for ${}^6\text{Li}$, at the plateau level suggested by Asplund et al. (2004, 2005, and references therein), for metallicities lower than $[\text{Fe}/\text{H}] = -0.6$; and for Li, the plateau value of Charbonnel & Primas (2005) for halo stars, plus the upper envelope of the data points for higher metallicities (of course, there is no unique way to draw that envelope, especially because of the lack of data in the region around $[\text{Fe}/\text{H}] = -1$). *Solid* curves corresponding to the “true” run of the abundances (as expected from theoretical considerations) are the upper curves of Fig. 3 for both Li and ${}^6\text{Li}$. Note, however, that no late stellar production is considered for Li; consequently, the corresponding curve underestimates the “true” Li abundance in disk stars. *Lower panel:* corresponding depletion that Li and ${}^6\text{Li}$ have suffered in stellar envelopes. Depletion of ${}^6\text{Li}$ at the lowest metallicities is assumed to be equal to depletion of Li (i.e. the difference of ~ 0.35 dex between values found by WMAP data analysis and by Charbonnel & Primas 2005), which is the minimum possible value for ${}^6\text{Li}$ depletion in view of the greater fragility of ${}^6\text{Li}$.

independent for halo stars, but it also has to maintain a plateau value, without significant dispersion (see Lambert 2004; and Charbonnel & Primas 2005).

Assuming that both Li and ${}^6\text{Li}$ have been equally depleted from their pre-galactic values in the atmospheres of the lowest metallicity stars and that the observed plateau values are those given by Charbonnel & Primas (2005) for Li and by Asplund et al. (2005) for ${}^6\text{Li}$, one can quantitatively trace the evolution of the stellar depletion of those elements, which is required to keep their abundances within the observed levels. This is done in Fig. 4. For total Li, the “observed” abundance level is situated at the plateau value for halo stars plus the upper envelope of the data for disk stars (the sparseness of data around $[\text{Fe}/\text{H}] = -1$ making a precise definition of the transition metallicity difficult). As can be seen in the lower panel of Fig. 4, the depletion of ${}^6\text{Li}$ has to be increasing with metallicity in order to preserve the observed plateau, from the original

depletion value of ~ 0.4 dex to almost its double at $[\text{Fe}/\text{H}] = -1.2$, and to about three times a higher value at $[\text{Fe}/\text{H}] = -0.6$. On the other hand, depletion of Li has to remain essentially constant in halo stars, but necessarily to decrease with metallicity at some point. This is even truer if it is confirmed that the Li abundances in halo stars do not form a real plateau but increase slightly with metallicity (e.g. Ryan et al. 1999; Boesgaard et al. 2005; Asplund et al. 2005; Charbonnel & Primas 2005).

Stated in a different way, Fig. 4 suggests that standard CRs play an important early role in the case of ${}^6\text{Li}$, but not in the case of the much more abundant ${}^7\text{Li}$; the primordial component dominates the abundance of the latter in halo stars. In order to cancel the effect of the CR contribution and to keep ${}^6\text{Li}$ at the level of the observed “plateau”, stellar depletion has to be progressively greater in the case of ${}^6\text{Li}$. In the case of Li, a metallicity independent depletion (or slowly decreasing with metallicity) has to be invoked, to bring the primordial (WMAP) value and observed plateau values into agreement. Whether a realistic stellar environment can indeed produce such a differential (and fine-tuned to preserve the plateau values) depletion, remains to be discovered.

5. Summary

In this work, we reassess the problem of ${}^6\text{Li}$ evolution in the Milky Way, motivated by the recently reported existence of a “plateau”-like behavior of its isotopic abundance in old and metal poor halo stars (Asplund et al. 2005).

At first, we calculate the energy requirements for ${}^6\text{Li}$ production through fusion and spallation reactions, during the propagation of energetic particles in the ISM. We show that, even under most favorable conditions (i.e. steep CR spectra), it takes at least 10^{14} erg g^{-1} to justify the reported value of $({}^6\text{Li}/\text{H})_{\text{PL}} \sim 10^{-11}$ (10^{14} erg in accelerated particles for each g of the ISM).

We proceed then by examining the energy performances of various candidate acceleration sources that may have operated in the early Galaxy: normal core collapse SN, atypical SN (energetic and/or having a low Fe yield), shocks from cosmic structure formation (an interesting suggestion of Suzuki & Inoue 2002), and the supermassive black hole lying in the Galactic Center. We find that:

- Normal SN producing $\sim 0.07 M_{\odot}$ of Fe could satisfy the energetics, but they should also simultaneously enrich the ISM to a level of $[\text{Fe}/\text{H}] \sim -1.4$; they fail to produce the earliest reported ${}^6\text{Li}$ value (at $[\text{Fe}/\text{H}] \sim -2.7$) by a factor of ~ 10 .
- Energetic SN with low Fe yield could certainly satisfy all the ${}^6\text{Li}$ constraints; we note, however, that most energetic SN observed today (sometimes called “hypernovae”) have rather high Fe yields and, despite their high energy, they fail for the same reason as normal SN.
- Shocks from structure formation are not powerful enough, since in the early times of Galaxy formation, the masses of the assembling dark haloes were still quite small and the corresponding virial velocities insufficient; in the most optimistic case (towards the end of halo formation), derived

energies are lower than required by a large factor (on the order of 20, i.e. they fail by a factor larger than normal SN).

- The Galactic black hole satisfies the energy requirements, assuming that a) it is formed to a large extent even before the metal poor stars of the halo (perhaps not an unreasonable assumption); and b) its efficiency in converting accretion energy into accelerated particles was then much higher than its present-day notorious inefficiency in turning accretion energy into radiation.
- Supermassive black holes in galaxies could pollute the total baryonic content of the Universe with $({}^6\text{Li}/\text{H})_{\text{PL}}$, provided that they were mostly formed before the formation of the very low-metallicity halo stars. This requirement is not compatible with recent ideas about the quasar luminosity evolution (Hopkins et al. 2005a), suggesting that the peak in the number density of those objects occurred at redshift $z < 2$.

We note that, in the case of early ${}^6\text{Li}$, a useful distinction should be made between *cosmic* and *local* pre-galactic values. The former implies pollution of the total baryonic content of the Universe, where the latter only concerns the baryons assembled in galaxies; obviously, the energy requirements are easier to fulfill in the latter case than in the former.

Finally, we study the evolution of the light elements with a full-scale galactic chemical evolution model, which satisfies all the major observational constraints. We assume momentum CR spectra, time-independent CR composition, a pre-galactic Li value either “low” (at the level reported by Charbonnel & Primas 2005) or “high” (WMAP value) and a pre-galactic ${}^6\text{Li}$ value again either “low” (at the level reported by Asplund et al. 2005) or “high” (by ~ 0.4 dex, minimal amount of depletion to be consistent with the assumption of “high” Li).

The model reproduces the observed linearity between Be and Fe abundances “by construction”. The associated production of ${}^6\text{Li}$ by CR is found to “break” the reported ${}^6\text{Li}$ plateau as early as $[\text{Fe}/\text{H}] = -2.4$. A fine-tuned and metallicity-dependent mechanism of ${}^6\text{Li}$ depletion in stellar envelopes would then be required in order to preserve the plateau value. We quantitatively evaluate the amount of required stellar depletion, and show that in the case of ${}^6\text{Li}$, it should increase with metallicity, while for Li it should roughly be metallicity-independent (or even decreasing with metallicity).

In summary, the present study suggests that 1) the energy requirements for large early ${}^6\text{Li}$ production are very constraining and hard to fulfill by the currently suggested sources; and that 2) contrary to the case of Li, the reported presence of a ${}^6\text{Li}$ plateau in halo stars is “threatened” by the production of ${}^6\text{Li}$ by ordinary CRs (the same that produce the observed Be) and requires some “fine-tuning”. In view of these implications, an unambiguous determination of the presence of ${}^6\text{Li}$ in halo stars (absolute abundance values and reality of the plateau) is urgently required. In that respect, we note that Inoue et al. (2005) recently report tentative detection of ${}^6\text{Li}$ in halo stars, at a level roughly compatible with the one reported by Asplund et al. (2005).

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