

COSMOLOGICAL COSMIC RAYS AND THE OBSERVED ⁶Li PLATEAU IN METAL POOR HALO STARS

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ABSTRACT

Very recent observations of the ⁶Li isotope in halo stars reveal a ⁶Li plateau about 1000 times above the predicted BBN abundance. We calculate the evolution of ⁶Li versus redshift generated from an initial burst of cosmological cosmic rays (CCRs) up to the formation of the Galaxy. We show that the pregalactic production of the ⁶Li isotope can account for the ⁶Li plateau observed in metal poor halo stars without additional overproduction of ⁷Li. The derived relation between the amplitude of the CCR energy spectra and the redshift of the initial CCR production puts constraints on the physics and history of the objects, such as pop III stars, responsible for these early cosmic rays. Consequently, we consider the evolution of ⁶Li in the Galaxy. Since ⁶Li is also produced in Galactic cosmic ray nucleosynthesis, we argue that halo stars with metallicities between [Fe/H] = -2 and -1, must be somewhat depleted in ⁶Li.

Subject headings: Cosmology - Cosmic rays - Big Bang Nucleosynthesis - Stars: abundances

1. INTRODUCTION

To account for the origin and evolution of lithium, beryllium and boron, we rely on our understanding of several very different aspects of nucleosynthesis, namely: Big Bang, non thermal, stellar nucleosynthesis, all of which must be correlated through cosmic and chemical evolution. These rare light nuclei are not generated in the normal course of stellar nucleosynthesis (except ⁷Li in the galactic disk) and are in fact destroyed in stellar interiors. This explains the relatively low abundance of these species. While a significant fraction of the observed ⁷Li is produced in the Big Bang, the Big Bang nucleosynthesis (BBN) production of ⁶Li, Be and B results in abundances which are orders of magnitude below that observed in halo stars. For example, BBN production of ⁶Li is dominated by the process D(α, γ)⁶Li. At the baryon density deduced from observations of the anisotropies of the Cosmic Microwave Background (CMB) radiation by WMAP (Spergel et al. 2003), its BBN value is ${}^6\text{Li}/\text{H} \simeq 10^{-14}$ (Thomas, Schramm, Olive, & Fields 1993; Vangioni-Flam et al. 1999). On the other hand the BBN mean value of the ⁷Li abundance is, according to Cyburt (2004) ${}^7\text{Li}/\text{H} = 4.27^{+1.02}_{-0.83} \times 10^{-10}$, according to Cuoco et al. (2004) ${}^7\text{Li}/\text{H} = 4.9^{+1.4}_{-1.2} \times 10^{-10}$, or according to Coc et al. (2004) ${}^7\text{Li}/\text{H} = 4.15^{+0.49}_{-0.45} \times 10^{-10}$. As such, the ⁷Li/⁶Li ratio in BBN is about 4×10^4 .

The very low abundances of the ⁶Li, ⁹Be and ^{10,11}B isotopes predicted by BBN theory imply that their most plausible production process was the interaction of Galactic Cosmic rays (GCRs) with the interstellar medium (for a review see Vangioni-Flam, Cassé, & Audouze 2000). Of these isotopes, ⁶Li is of particular interest because it has only recently been measured in halo stars (Smith, Lambert, & Nissen 1993;

Hobbs & Thorburn 1994, 1997; Smith, Lambert, & Nissen 1998; Cayrel et al. 1999; Nissen et al. 1999, 2000; Asplund et al. 2001, 2004b; Aoki et al. 2004) thus offering new constraints on the very early evolution of light elements (Steigman et al. 1993). Many studies have followed the evolution of ⁶Li in our Galaxy (see e.g. Fields & Olive 1999b; Vangioni-Flam et al. 1999). Of particular importance in this context is the $\alpha + \alpha$ reaction that leads to the synthesis of this isotope (as well as ⁷Li) and is efficient very early in the evolutionary history of the Galaxy.

Different scenarios have been discussed to explain the abundance of ⁶Li in metal-poor halo stars (MPHS). Suzuki & Inoue (2002) discussed the possibility of cosmic rays produced in shocks during the formation of the Galaxy, which was consistent with ⁶Li data available at that time. Jedamzik (2000) considers the decay of relic particles, during the epoch of the big bang nucleosynthesis, that can yield to a large primordial abundance of ⁶Li. Fields & Prodanović (2004) have studied in detail the lithium production in connection to gamma rays, using a formalism similar to ours but with a different point of view as far as the observational constraints are concerned (see Section 5.2).

Until recently, the abundance of ⁶Li had been observed in only a few MPHS with metallicity [Fe/H] larger than -2.3. New values of the ratio ⁶Li/⁷Li have been measured with UVES at the VLT-UT2 Kueyen ESO telescope, in halo stars with metallicity ranging from -2.7 to -0.5 (see Section 2). These observations indicate the presence of a plateau in ⁶Li/H $\simeq 10^{-11}$ which suggests a pregalactic origin for the formation of ⁶Li.

In this paper, we consider the synthesis of lithium due to the interaction of cosmological cosmic rays (CCRs), produced at an early epoch, with the intergalactic medium (Montmerle 1977a,b,c, and Section 3). As $\alpha + \alpha$ processes also produce ⁷Li, these models are constrained by the ⁷Li plateau observed in the same MPHS. This constraint is made more severe by the current discrepancy between the BBN predicted value of ⁷Li and the observational abundance. We demonstrate how this model can explain the recent observations and constrain

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the history of cosmological structure formation (Section 4) and the galactic evolution of ${}^6\text{Li}$ (Section 5.1). We compare these results with the expected evolution of ${}^6\text{Li}$ from GCR nucleosynthesis. Without the pregalactic production of ${}^6\text{Li}$, the latter model can not account for the elevated ${}^6\text{Li}$ abundances at very low metallicity. In contrast, models for which O/Fe increases at low metallicity are able to produce sufficient ${}^6\text{Li}$ at low metallicity, without pregalactic production. However, in this case, the bulk of the ${}^6\text{Li}$ data seen in higher metallicity stars must be argued to be depleted. The same is true for our model of CCR nucleosynthesis, but to a lesser extent. We argue that ${}^6\text{Li}$ data in stars with $[\text{Fe}/\text{H}] = -3$ to -4 will be required to distinguish between these scenarios. Our predictions will be compared to other work in Section 5.2 and our conclusions are given in Section 6.

2. OBSERVATIONAL AND NUCLEAR DATA

The determination of the ${}^6\text{Li}$ abundance in MPHS is extremely difficult and requires high resolution and high signal to noise spectra due to the tiny hyperfine splitting between the two lithium isotopes. The line splitting is only seen as the narrowly shifted lines are thermally broadened. Though the fits to the width of this feature are sensitive to the ${}^7\text{Li}/{}^6\text{Li}$ ratio, it is very difficult to obtain accurate measurements of the isotopic ratio. ${}^6\text{Li}$ can only be realistically expected to be observed in stars with high surface temperatures and at low metallicities of $[\text{Fe}/\text{H}] < -1.3$. Brown & Schramm (1988) determined that only in stars with surface temperatures greater than about 6300 K will ${}^6\text{Li}$ survive in the observable surface layers of the star. At metallicities $[\text{Fe}/\text{H}] \gtrsim -1.3$, even higher effective temperatures would be required to preserve ${}^6\text{Li}$.

As noted above, the previous sets of data on the lithium isotope ratio has been significantly expanded by Asplund et al. (2004b) (see also Lambert 2004) with the observations of 24 MPHS. Previously, only 3 stars with metallicity $[\text{Fe}/\text{H}] < -1.3$ showed net detections of ${}^6\text{Li}$ (Smith, Lambert, & Nissen 1993; Hobbs & Thorburn 1994, 1997; Smith, Lambert, & Nissen 1998; Cayrel et al. 1999; Nissen et al. 2000). The observed abundances of Li/H and ${}^6\text{Li}/\text{H}$ are displayed versus the metallicity, $[\text{Fe}/\text{H}]$, in Fig. 1. There are in addition several stars with metallicities in the range $[\text{Fe}/\text{H}] = -3$ to -0.5 for which only upper limits (not shown) to the ${}^6\text{Li}/{}^7\text{Li}$ ratio are available. Note that the ${}^6\text{Li}$ abundance at solar metallicity is plotted for both the meteoritic value (Lodders 2003) and the solar photospheric value (Asplund, Grevesse, & Sauval 2004). The latter is derived from the photospheric value of Li assuming the solar ratio ${}^7\text{Li}/{}^6\text{Li} = 12$ and therefore really represents an upper limit to the ${}^6\text{Li}$ photospheric abundance.

These new data at low metallicity reveal the existence of a plateau for ${}^6\text{Li}$, whose abundance is about 1000 times higher than that predicted by BBN. As such, another production mechanism which is capable of producing what appears to be an initial enrichment of ${}^6\text{Li}$ in the intergalactic medium is required. Here, we concentrate on the interaction of α particles present in CCRs produced at high redshift, with He at rest in the IGM, as a potential description of this pregalactic enrichment process. The abundances in higher metallicity stars will be discussed in Section 5.1.

Note that there is, however, considerable dispersion in the data, and as noted above, there are many stars for which there was no detectable ${}^6\text{Li}$, indicating that depletion may have played a role in the observed ${}^6\text{Li}$ abundance for stars in the

plateau as well. This is in contrast to the ${}^7\text{Li}$ plateau which shows very little dispersion and for which we expect the role of depletion to have been minor (Ryan et al. 2000).

Galactic production of lithium arises from the interaction of GCRs with the ISM via the $\alpha + \alpha$ reaction. This is a primary process which yields a logarithmic slope of 1 in the lithium abundance versus metallicity ($[\text{Fe}/\text{H}]$) relation as seen in Fig. 1. The amplitude for ${}^6\text{Li}$ production is constrained by the abundances of Be and B (see Section 5.1 for an additional discussion). As one can see, this model can not explain the elevated ${}^6\text{Li}$ abundances at low metallicity and requires some ${}^6\text{Li}$ depletion at higher metallicity (as will all of the models discussed here).

Recently, Mercer et al. (2001) have performed new measurements related to the $\alpha + \alpha$ reaction and provide a new fit for the production of ${}^6\text{Li}$ and ${}^7\text{Li}$. The calculated ${}^6\text{Li}$ abundances from the GCR process using the often applied Read & Viola (1984) cross sections and the fit at higher energy provided by Mercer et al. (2001) resulting in slightly less (30–50% at solar metallicity) ${}^6\text{Li}$ are compared in Fig. 1. In what follows, we use the most recent cross sections of Mercer et al. (2001).

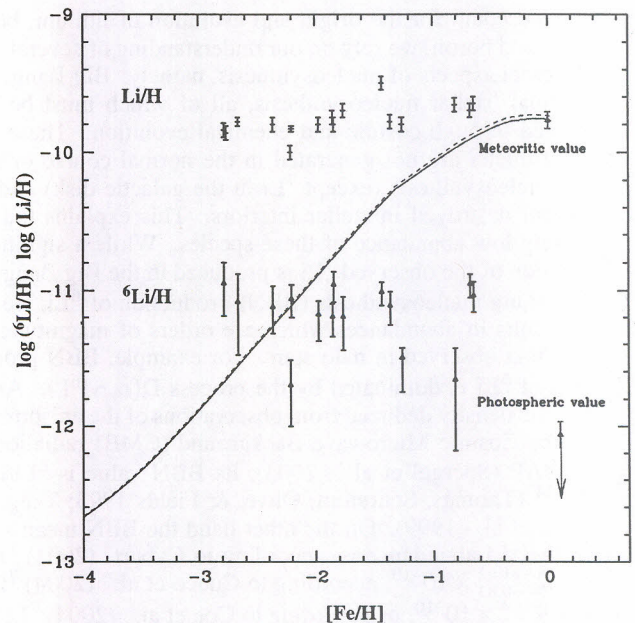


FIG. 1.— The evolution of ${}^6\text{Li}/\text{H}$ vs $[\text{Fe}/\text{H}]$. Here, the evolution of ${}^6\text{Li}/\text{H}$ is modeled by GCR nucleosynthesis alone. Predictions using cross sections from Mercer et al. (2001) (lower line) are reduced compared to those from Read & Viola (1984) (upper dashed line). The abundances of ${}^6\text{Li}$ in low metallicity stars reveal a plateau. The solar abundance of ${}^6\text{Li}$ from meteorites (Lodders 2003) and the upper limit to the solar photospheric abundance (Asplund, Grevesse, & Sauval 2004) are also shown.

3. CCR PRODUCTION OF LITHIUM IN THE IGM : FORMALISM

3.1. On the Existence of Cosmological Cosmic Rays

The existence and global properties of cosmic rays in the Galaxy are often related to supernova explosions and/or gamma-ray bursts, in massive stars. Motivated by the WMAP results indicating an early epoch of reionization, Daigne et

al. (2004) have developed models that include an early burst of massive stars with several possible mass ranges, capable of reionizing the intergalactic medium, while satisfying observational constraints on cosmic chemical evolution in pregalactic structures and in the intergalactic medium. In particular, Daigne et al. (2004) have demonstrated that the presence of massive stars ($M \sim 40\text{--}100 M_{\odot}$) is required at high redshift ($z \gtrsim 15\text{--}20$). This early population of stars (pop III) is able to reionize the intergalactic medium and generate a prompt initial enrichment (PIE) in metals. It is likely that particles will be accelerated within the same process.

Gamma-ray emission, as well as cosmic rays, may also come from active (Stecker & Salamon 1993; Mukherjee & Chiang 1999) and normal (Pavlidou & Fields 2002) galaxies (see also Lemoine 2002). Depending on the strength of the magnetic fields in those structures, cosmic rays will be confined or will propagate into the intergalactic medium (e.g. Berezhinsky, Blasi & Ptuskin 1997; Zweibel 2003). In addition, recent numerical simulations have shown that the formation of large scale structures leads to accretion shocks in the baryonic gas, and thus to particle acceleration directly in the intergalactic medium (Kang & Jones 2002; Miniati 2002; Keshet et al. 2003; Ryu et al. 2003). Finally, at ultra-high energies, more exotic sources of cosmic rays have also been studied (Bhattacharjee, Hill & Schramm 1992; Sigl et al. 1999). Clearly, there are several viable mechanisms for the production of CCRs and just as clearly, there is a great deal of uncertainty surrounding their production.

In this paper, CCRs are assumed to be produced in a single burst correlated to a very early generation of pop III stars as discussed in Daigne et al. (2004) at a given redshift z_s . Note that very little is known about the cosmic ray injection spectra at these energies. Here, our formalism is directly derived from the work of Montmerle (1977a), hereafter M77. We briefly summarize this formalism and note explicitly our differences with this model. A power-law distribution in particle energy is adopted for the CR injection spectrum,

$$\phi_{\alpha}(E) = \mathcal{F} 12.5 K_{\alpha p} (E + E_0) \{E(E + 2E_0)\}^{-(\gamma+1)/2} \text{cm}^{-2} \text{s}^{-1} (\text{GeV per nucleon})^{-1}, \quad (1)$$

which is the form expected from standard shock acceleration theory (Blandford & Eichler 1987). \mathcal{F} is a normalization factor which is fixed by the value of the injection spectral index, chosen to be $\gamma = 3$ (Suzuki & Inoue 2002), and by z_s . It will ultimately be constrained by the observed abundance of ${}^6\text{Li}$ in the MPHS (see Section 4). E is the kinetic energy per nucleon, $E_0 = 939$ MeV is the nucleon rest mass energy and $K_{\alpha p} = 0.08$ is the abundance by number of ${}^4\text{He}/\text{H}$. Lithium production is sensitive to α 's with energy $E \approx 10$ MeV/n.

3.2. Transport function in an expanding universe

The initial burst of cosmological cosmic rays evolves in the framework of an expanding universe with a cosmological constant.

If $N_i(E, z)$ is the comoving number density per (GeV/n) of a given species at a given time or redshift, and energy, we define $N_{i,H}(E, z) \equiv N(E, z)/n_H(z)$, the abundance by number with respect to the ambient gaseous hydrogen (in units of $(\text{GeV/n})^{-1}$). The evolution of $N_{i,H}$ is defined through the transport function

$$\frac{\partial N_{i,H}}{\partial t} + \frac{\partial}{\partial E} (b N_{i,H}) + \frac{N_{i,H}}{T_D} = Q_{i,H}. \quad (2)$$

Q is a source function which accounts for different sources of particle production while T_D is the lifetime against destruction. b describes the energy losses due to expansion or ionization processes ($(\text{GeV/n}) \text{s}^{-1}$). The energy and time dependencies can be separated as $b(E, z) = -B(E)f(z)$. We can distinguish two cases depending on whether losses are dominated by expansion or by ionization. The general form for the redshift dependence, when expansion dominates is $f_E(z) = (1+z)^{-1} |dz/dt| H_0^{-1}$ (e.g. Wick, Dermer & Atoyan 2004). Other contributions to B or f , do not depend on the assumed cosmology and are given explicitly in M77.

Two important quantities, $z^*(E, E', z)$ and $E'_s(E, z)$ are used in this formalism. Given a particle (α or lithium) with an energy E at a redshift z , $z^*(E, E', z)$ corresponds to the redshift at which this particle had an energy E' . $E'_s(E, z)$ is the initial energy required if this particle was produced at the redshift of the burst, z_s . In particular, $z^*(E, E'_s, z) = z_s$. The equation that defines z^* (Eq. A5, M77) is $\partial z^*/\partial E = -[B(E)f(z) |dz/dt|]^{-1} (\partial z^*/\partial z)$. M77 gives analytical solutions for z^* when $\Omega_{\Lambda} = 0$. When $\Omega_{\Lambda} \neq 0$, it cannot be solved analytically when ionization dominates. Integration of this equation shows that $z^*(E, E'_s, z)$ is the solution of

$$\int_z^{z^*} dz'' f(z'') (|dz/dt|)_{z''} = \int_E^{E'_s} \frac{dE''}{B(E'')} \quad (3)$$

We solve this relation for z^* numerically whenever analytical solutions are not available.

3.3. The CCR flux and the lithium abundance

The evolution of the CCR α energy spectrum is derived, using Eq. A8 of M77 and the single burst properties, as

$$\Phi_{\alpha,H}(E, z) = \frac{\phi_{\alpha}(E)}{n_H^0} \frac{\beta}{\beta'} \frac{\phi_{\alpha}(E'_s)}{\phi_{\alpha}(E)} \left| \frac{dz}{dt} \right|_{z_s} \frac{\exp(-\xi)}{|b(E, z_s)|} \frac{1}{|\partial z^*/\partial E'|_{E'_s}} \quad (4)$$

where $\Phi_{\alpha,H}(E, z) \equiv \Phi_{\alpha}(E, z)/n_H(z)$ is the flux of α 's per comoving volume

$$\Phi_{\alpha,H}(E, z) = \beta N_{\alpha,H}(E, z) \quad (5)$$

and β (β') is the velocity corresponding to energy E (E'_s); ξ accounts for the destruction term (Eq. A9, M77).

The abundance by number of lithium ($l = {}^6\text{Li}$ or ${}^7\text{Li}$) of energy E , produced at a given redshift z , is computed from

$$\begin{aligned} \frac{\partial N_{l,H}(E, z)}{\partial t} &= \int \sigma_{\alpha\alpha \rightarrow l}(E, E') n_{\text{He}}(z) \Phi_{\alpha,H}(E', z) dE' \\ &= \sigma_l(E) K_{\alpha p} \Phi_{\alpha}(4E, z) [(\text{GeV/n})^{-1} \text{s}^{-1}], \quad (6) \end{aligned}$$

where $\sigma_{\alpha\alpha \rightarrow l}(E, E') = \sigma_l(E) \delta(E - E'/4)$. The cross sections used have been discussed in Section 2. Note that this equation does not take into account the destruction of lithium in the intergalactic medium. We show below that this is a reasonable approximation.

Furthermore, we want to compute the abundance of lithium in the gas that is present at the redshift of the formation of the Galaxy (see below). We assume that all the lithium produced will be thermalized in the protogalaxy before stars

form. Thus, the quantity that should be compared to the data is,

$$[l/H](z) = [l/H]_{\text{BBN}} + \int_{z^*}^z \int \frac{\partial N_{l,H}(E, z')}{\partial t} dE |dt/dz'| dz'. \quad (7)$$

where $[l/H]_{\text{BBN}}$ is the primordial abundance predicted by BBN.

The redshift evolution of ${}^6\text{Li}/\text{H}$ and ${}^7\text{Li}/\text{H}$ are the main results that will be compared to observations, and used to constrain the CCR proton energy density,

$$\mathcal{E}_p(z) = \int_{E_{\text{cut}}} [\Phi_\alpha(E_p, z)/K_{\alpha p}] E_p / \beta dE_p. \quad (8)$$

where $E_{\text{cut}} = 10$ MeV corresponds to the α energy cut-off (MeV/n) for the $\alpha + \alpha \rightarrow \text{Li}$ reaction.

Finally, we comment on the subsequent destruction of Lithium. The differential rate of destruction (by protons) is equal to $\sigma_D(E) n_H(z) N_{l,H}(E, z) \beta(E)$ and is proportional to the Lithium abundance. The cross section σ_D , decreases rapidly with energy below 10 MeV/n (see Fig. 2 of M77). Assuming a constant energy of 10 MeV/n we can derive an upper limit to the destruction process. We find that taking destruction into account increases the final proton energy density only up to 7% for $z_s = 100$ and has virtually no effect for $z_s \lesssim 50$.

3.4. Updated quantities

Since 1977, the cosmological parameters, the ${}^6\text{Li}$ and ${}^7\text{Li}$ abundances predicted by BBN and observed in MPHS have changed considerably. They have been updated here. Unless otherwise noted, we use the standard Λ CDM cosmology (Spergel et al. 2003) for which $H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.27$, $\Omega_\Lambda = 0.73$ with $\Omega_b h^2 = 0.0224$. The Hubble constant is defined as $H(z) = H_0 (\Omega_m (1+z)^3 + (1 - \Omega_m - \Omega_\Lambda)(1+z)^2 + \Omega_\Lambda)^{0.5}$ valid in a post-radiation dominated universe and we assume an equation of state parameter for the dark energy, $w = -1$. Finally, $dz/dt = -(1+z)H(z)$.

We use the recently calculated BBN abundances of lithium by Coc et al. (2004) and the observed ${}^6\text{Li}$ and ${}^7\text{Li}$ abundances in MPHS. From Fig. 1, we define the MPHS abundance for ${}^6\text{Li}$ as the value corresponding to the plateau, $[{}^6\text{Li}]_p = \log({}^6\text{Li}/\text{H}) + 12 = 0.8$.

4. CONSTRAINTS ON CCR PRODUCTION

The process described above occurs in the IGM, and modifies the abundance pattern of the medium that will later form the Galaxy. Observations of MPHS trace the evolution of the gas in the halo of the Galaxy at an early epoch at low metallicity. The observed abundance for the lowest metallicity is then assumed to be a pregalactic abundance, i.e. the predicted abundance at the redshift of the formation of the Galaxy. This may be justified by the presence of the ${}^6\text{Li}$ plateau. We will assume that the peak of the formation of the structures occurs at $z_{\text{gal}} \simeq 3$ (e.g. Fontana et al. 1999; Juneau et al. 2005; Hopkins 2004). Therefore, the abundance observed for the lowest metallicity stars must correspond to the abundance in the intergalactic medium at $z = z_{\text{gal}}$. We next define the procedure used to constrain the CCR burst parameters from the lithium observations.

4.1. Procedure

We begin by working within the context of the standard framework described in Section 3, that is a Λ CDM + WMAP cosmology. The shape of the CCR spectrum is given by Eq. 1, with $\gamma = 3$. Then, the evolution of the lithium abundance with redshift in our model is uniquely specified by the normalization constant \mathcal{F} and the redshift of the CCR burst, z_s .

Our CCR spectrum is constrained by (i) the Spite plateau (Spite & Spite 1982) for ${}^7\text{Li}$ and (ii) the hint for a ${}^6\text{Li}$ plateau (Asplund et al. 2004b). The Spite plateau should correspond to the primordial value of the ${}^7\text{Li}$ abundance. However, the observed ${}^7\text{Li}$ abundance is a factor of 2-3 lower than the calculated one (based on the WMAP baryon density). As a result of this discrepancy, the ${}^7\text{Li}$ plateau acts as a strong constraint in our model, since it forbids us to produce a non-negligible amount of ${}^7\text{Li}$. This constraint is weakened if the observational value of ${}^7\text{Li}$ were higher (see e.g. Meléndez & Ramírez 2004) as the GCR component of ${}^7\text{Li}$ would become more difficult to observe as the ratio of GCR to BBN produced ${}^7\text{Li}$ is diminished (Fields, Olive & Vangioni-Flam 2004). Nevertheless, our model must produce a small quantity of this isotope compared to the BBN abundance. The abundance of ${}^6\text{Li}$ observed at very low metallicity is assumed to trace the abundance in the intergalactic medium *before* the formation of the Galaxy. As mentioned above, our model must be able to reproduce this abundance at $z = z_{\text{gal}}$.

The constraints on the ${}^6\text{Li}$ abundance from the calculated BBN abundance at $z \sim \infty$ and from its observed 'pregalactic' value at $z = z_{\text{gal}}$ specify a unique amplitude for the CCR energy spectrum, \mathcal{F} , for a given z_s . Therefore, the normalization constant, \mathcal{F} , is determined by the choice of parameters $(\Omega_\Lambda, \Omega_m, \gamma, z_s)$, under the constraint given by the initial and final ${}^6\text{Li}$ abundances. The initial ${}^7\text{Li}$ abundance is fixed by the BBN. Then, for each set of parameters, we check that the model does not produce too large of an additional pregalactic component of ${}^7\text{Li}$.

4.2. The ${}^6\text{Li}$ plateau and the evolution of ${}^6\text{Li}$ versus redshift

The evolution of the abundance of ${}^6\text{Li}$ with redshift is shown in Fig. 2 for three values of $z_s = 10, 30$ and 100 . In each case a ${}^6\text{Li}$ plateau is produced. By construction, the abundance of ${}^6\text{Li}$ at $z = z_{\text{gal}}$ is fixed. In addition, the rate of production of ${}^6\text{Li}$ decreases rapidly soon after the initial burst. This was noted in M77 and corresponds to the dilution of the CCR flux with the expansion of the Universe. Unless the burst occurs just prior to the formation of the Galaxy (Section 5.1), the ${}^6\text{Li}$ abundance is almost constant for $z \lesssim z_{\text{gal}}$.

Since the production rates of ${}^6\text{Li}$ and ${}^7\text{Li}$ are similar, the additional production of ${}^7\text{Li}$ due to CCRs ($\simeq 10^{-11}$) is negligible compared to the BBN primordial values ($\simeq \text{a few} \times 10^{-10}$). Note that the predicted abundance in the Spite plateau is increased by only 6%, 8% or 10% for $z_s = 100, 30$ or 10 respectively. The ratio ${}^7\text{Li}/{}^6\text{Li}$ follows the same trend as ${}^6\text{Li}$ (upper panel of Fig. 2) and reaches a final value of about 60.

4.3. Influence of the different parameters on the CCR amplitude

We next investigate the influence of the parameters of the model $(\Omega_\Lambda, \Omega_m; \gamma, z_s)$ on the required amplitude of the CCR flux (\mathcal{F}) using the same constraint on the 'pregalactic' value $[{}^6\text{Li}]_p = 0.8$ at $z = z_{\text{gal}}$. Results are given in Table 1. Note that, as mentioned above, the evolution of the lithium production is dominated by the dilution of the CCR flux that roughly

TABLE 1
CCR AMPLITUDE VERSUS INPUT PARAMETERS

z_s	$(\Omega_\Lambda, \Omega_m)$	γ	$\log(\mathcal{F})$	$\log(\mathcal{E}_p(z=z_s))$
100	(0.7, 0.3)	3.0	-4.6	-10.2
		2.0	-4.1	-9.4
		3.0	-4.6	-10.2
30	(0.7, 0.3)	2.0	-4.0	-9.3
		3.0	-4.4	-11.6
		2.0	-3.7	-10.6
10	(0.7, 0.3)	3.0	-4.1	-11.4
		2.0	-3.4	-10.3
		3.0	-3.5	-12.2
	(0.0, 1.0)	2.0	-2.7	-10.9
		3.0	-3.0	-11.8
		2.0	-2.3	-10.5

The redshift of the CCR burst (z_s), the cosmology, and the shape of the energy spectrum (γ) are varied. The amplitude of the CCR spectrum (\mathcal{F}) is determined in order to reproduce the observed 'pregalactic' ($z = z_{\text{gal}}$) abundance $[\text{}^6\text{Li}]_p = 0.8$ (Fig. 2). \mathcal{E}_p is the total initial energy density of protons in the CCRs (Eq. 8).

follows a $(1+z)^3$ law. Thus, the cosmological parameters and the shape of the energy spectrum have very little influence on the shape of the curves in Fig. 2. Only the amplitude of the initial CCR flux varies.

As one can see from the Table, our results are very sensitive to the redshift of the burst, z_s . At high energy, one can show that $\Phi_{\alpha, \text{H}}(E, z) \propto \phi_\alpha(E) \left(\frac{1+z}{1+z_s}\right)^{\gamma-1}$. Thus, the required energy density at $z = z_s$ in the CCR is roughly proportional to $(1+z_s)^{1.5}$. The CCR normalization also depends on the shape of the energy spectrum, γ . A steeper spectrum (higher γ) favors the low energy part of the spectrum, where the lithium production peaks. Thus, for a fixed amplitude \mathcal{F} , the abundance of ${}^6\text{Li}$ will be higher for $\gamma = 3$ than for $\gamma = 2$. Conversely, for a fixed abundance, \mathcal{F} must be lower for $\gamma = 3$. Finally, there is little dependence on the cosmological parameters, especially for large values of z_s .

We have used the observed plateau of ${}^6\text{Li}$ to set the amount of pregalactic ${}^6\text{Li}$ production. Then, assuming a given epoch for the formation of CCRs, the amplitude of the energy spectrum, \mathcal{F} , and the energy density are fixed (Table 1). The overall range of the proton energy density, \mathcal{E}_p at $z = z_s$ is $10^{-10.2}$ to $10^{-12.2}$, for WMAP concordance model when $\gamma = 3$ or $10^{-9.3}$ to $10^{-12.2}$ more generally. Yet, those CRs may also play a role in heating and ionizing the IGM at high redshift. In fact, when $z_s = 10$, the energy density of 6.3×10^{-13} ergs/cm³ is marginally consistent with the resulting temperature of the IGM today. At higher z_s , this constraint is far less important as the resulting IGM temperature scales as $\mathcal{E}_p/(1+z_s)^4$ and since \mathcal{E}_p increases slower than $(1+z_s)^4$. It is interesting to note that CCRs were predicted to heat the IGM and thus avoid the problem of overcooling in the IGM gas (Blanchard, Valls-Gabaud, & Mamon 1992). Furthermore, Nath & Biermann (1993) have put other constraints on the total luminosity of the CRs from the Gunn-Peterson optical depth at $z = 4.2$, the Compton y -parameter and metal enrichment. Assuming the production of CCRs from galaxies at $z = 10$, they obtained an initial luminosity of about 1.6×10^{-27} h ergs/cm³/s. Alternatively, from the amount of metals ejected by SN, they place an upper limit on the cosmic ray energy density of 10^{-14} ergs/cm³ at $z = 0$ and solar metallicity. At $z = 10$, the metallicity of the local ISM corresponding to the site of the CCR production is about

.01 solar. Note that this is much larger than the resulting IGM metallicity where ${}^6\text{Li}$ production occurs. At $z = 10$ and at a metallicity of 0.01 solar, their limit is effectively relaxed to $\mathcal{E}_p < 10^{-12}$ erg/cm³.

Thus, we see that the CCR production of ${}^6\text{Li}$ is capable of explaining the large abundance of ${}^6\text{Li}$ with negligible production of ${}^7\text{Li}$ (both relative to the BBN value). Sufficient ${}^6\text{Li}$ production is achieved by adjusting the flux of CCRs and depends primarily on the assumed redshift of the initial burst, z_s . Subsequently, the ${}^6\text{Li}$ abundance remains roughly constant until additional ${}^6\text{Li}$ is produced in the Galaxy through CGRs as we discuss in the next section.

5. DISCUSSION

5.1. Galactic evolution of ${}^6\text{Li}$

The above model for the CCR production can be thought of as a form of prompt initial enrichment if our Galaxy is formed hierarchically from previously evolved structures. CCRs produce ${}^6\text{Li}$ and a small amount (about a few % of the BBN value) of ${}^7\text{Li}$. Subsequently, the abundances of these element isotopes as well as all other element abundances are controlled by galactic chemical evolution. At this point, we assume only that the initial abundances in the gas in the Galaxy correspond to those in the IGM at $z = z_{\text{gal}}$.

It is certain that ${}^6\text{Li}$ will be produced in the ISM through GCR nucleosynthesis (described briefly below) as this is the primary mechanism for the production of ${}^9\text{Be}$ and ${}^{10}\text{B}$. These isotopes will not have been produced in any significant quantities as the IGM was initially devoid of C, N, and O needed for spallation processes. In contrast, the presence of primordial ${}^4\text{He}$ allows for the CCR production of Li.

Cosmic rays produced in the early Galaxy will invariably interact with the existing ISM. In standard GCR nucleosynthesis (Reeves, Fowler, & Hoyle 1970) LiBeB nuclei are produced by spallation when protons and α s in the cosmic rays impinge on ISM C, N, or O. LiBeB is also produced when CNO in the cosmic rays are spalled by ISM protons and α s. As such, spallation requires heavy elements ('metals') to be present in either the cosmic rays or the ISM. In addition, $\alpha + \alpha$ fusion reactions between cosmic rays and the ISM lead to the production of the lithium isotopes. Indeed, these were precisely the types of process considered above in our model of CCR nucleosynthesis. Note that ${}^7\text{Li}$ and ${}^{11}\text{B}$ also receive contributions from the ν -process (Woosley et al. 1990; Olive et al. 1994; Vangioni-Flam et al. 1996), but these will not be important for our present discussion.

As in the case of CCR nucleosynthesis, α fusion in GCR nucleosynthesis is a primary process in contrast to the production of Be and B in standard models. The spallation of ISM CNO is a secondary process so these abundances scale as the square of a metallicity tracer such as O or Fe if $[\text{O}/\text{Fe}]$ is constant at low values of $[\text{Fe}/\text{H}]$. Motivated by the observational fact that the log of the Be and B abundances appear to scale linearly with $[\text{Fe}/\text{H}]$ it has been proposed that the bulk of cosmic rays are not accelerated in the general ISM, but rather in the metal-rich interiors of superbubbles (Cassé, Lehoucq, & Vangioni-Flam 1995; Parizot & Drury 1999), specifically at low metallicity. Because the superbubble composition is enriched in metals, any cosmic rays which are accelerated in superbubble interiors would have a composition which is both metal-rich and time-independent. The low-energy component of the hard energy spectra associated with superbubbles re-

sults in the primary production of Be and B. We refer to this process as LEC. In general both the LEC and standard GCR nucleosynthesis are responsible for the observed LiBeB abundances.

In Fig. 1, we display the GCR production of ${}^6\text{Li}$ in the absence of the prompt initial enrichment produced by CCR nucleosynthesis. Here, we have normalized the flux of galactic cosmic rays so as to correctly reproduce the solar value of Be/H. The overall flux is the only parameter available in GCR nucleosynthesis, and as a consequence the abundances of ${}^{10}\text{B}$ and ${}^6\text{Li}$ are predictions of the model (recall that the ${}^{11}\text{B}$ and ${}^7\text{Li}$ receive an additional contribution from the ν -process). As expected the logarithmic slope of [Li] versus [Fe/H] is 1 (Fields & Olive 1999b; Vangioni-Flam et al. 1999).

In Fig. 3 we show the evolution of ${}^6\text{Li}$ vs [Fe/H] when both CCR and LEC processes are included. As one can see in Figure 3, without the initial enrichment of ${}^6\text{Li}$ due to CCRs, the evolution of ${}^6\text{Li}$ resembles that of standard GCRs. In this case, the ${}^6\text{Li}$ abundance begins at very low values and rises with a slope of unity until late times. This model alone can not explain the observational data. At low [Fe/H] ($\lesssim -2$), the observed ${}^6\text{Li}$ abundance is too high to be accounted for by standard CGR + LEC nucleosynthesis.

In addition, to explain the data at higher [Fe/H] ($\gtrsim -2$), one must argue that depletion has lowered the abundance of ${}^6\text{Li}$. This is perhaps reasonable as the depth of the convection zone is increased at higher metallicity for a fixed surface temperature. We note that many of the stars observed only reveal upper limits to the ${}^6\text{Li}$ abundance. That is, in roughly 15 examples of stars with similar temperatures and metallicities as those shown, no ${}^6\text{Li}$ was detected. The lack of ${}^6\text{Li}$ in some stars, coupled with the dispersion seen in the data may also indicate that some depletion of ${}^6\text{Li}$ has occurred in some of these stars. Indeed, the difference between the solar photospheric and meteoritic values corresponds to a destruction of ${}^6\text{Li}$ of at least a factor of about 200. In this model, we would argue that the destruction of ${}^6\text{Li}$ is negligible at [Fe/H] $\lesssim -2$ where the calculation from galactic processes cross the plateau.

We also show in Fig. 3 the evolution of ${}^6\text{Li}$ when the prompt enrichment due to CCRs is included. In this case, the data at low [Fe/H] is nicely modeled but depletion is still required to explain the data at higher metallicity. At present, the evidence for the plateau hinges on the abundances in only a few stars at low metallicity. However the two models shown in Fig. 3 can be distinguished by future observations of ${}^6\text{Li}$ at metallicities [Fe/H] < -2.7 which would establish the role of CCR nucleosynthesis as a mechanism for the early production of ${}^6\text{Li}$. As mentioned above, a prompt initial enrichment (PIE) in heavy elements is also expected in the intergalactic medium, especially within this Pop III stars scenario. However, the initial mass fraction of iron may be of the order of $X(\text{Fe}) = 10^{-7}$ (Daigne et al. 2004) and thus do not modify the curves in Fig. 1 and Fig. 3, for [Fe/H] $\gtrsim -4$. Thus, models with a ${}^6\text{Li}$ plateau are not affected by the iron PIE generated by pop III stars.

The GCR nucleosynthesis models described above were based on the assumption that [O/Fe] was constant at low [Fe/H]. That is, we can use the iron abundance to trace the evolution of the LiBeB elements. However some data show that [O/Fe] increases with decreasing [Fe/H] (Israelian, García-López, & Rebolo 1998; Boesgaard et al. 1999; Is-

raelian et al. 2001). As a consequence, the evolution of Be and B may appear to be primary with respect to [Fe/H], but in fact is secondary with respect to [O/H] (Fields & Olive 1999a). In reality, the data show that with the respect to [O/H], BeB have admixtures of primary and secondary components. That is, the slope for $\log(\text{BeB}/\text{H})$ vs. [O/H] is between 1 and 2 (Fields et al. 2000; King 2001).

In Fig. 4, we show the resulting evolution of ${}^6\text{Li}$ when the slope of [O/Fe] vs. [Fe/H] is taken to be -0.45 (cf. Fields et al. 2000; Fields, Olive & Vangioni-Flam 2004). For a slope larger than -0.45, a prompt initial enrichment is not required since the galactic production of ${}^6\text{Li}$ would already exceed the abundance observed in all stars. However, within such a model, the destruction rate of ${}^6\text{Li}$ must be non-negligible for metallicities as low as [Fe/H] ≈ -3 . In Fig. 1 and Fig. 3, the slope was chosen to be 0 corresponding to constant [O/Fe].

Before concluding this part of the discussion, we note that the dispersion in the data may be due to irregular production rather than depletion. Due to the dilution of the CCR flux, the production of lithium saturates soon after the initial burst (Fig. 2) at $z = z_s$. However, if this burst does not occur at a redshift much larger than z_{gal} , the abundance of lithium can still increase. Fig. 5 shows the expected variation of the ${}^6\text{Li}$ and ${}^7\text{Li}$ abundances from $z = 0$ to 3. If the IGM can pollute the Galaxy (e.g. through the merging of satellites, see e.g. Navarro 2004) at $z < z_{\text{gal}}$, the abundance pattern in stars that form later may reflect this dispersion. For our choice of $z_{\text{gal}} = 3$, the late production of Li may constrain the redshift of the CCR burst to be greater than about 5-6.

5.2. Comparison with previous work

Suzuki & Inoue (2002) consider a model where cosmic rays generated by structure formation, during the process of Galaxy formation, produce ${}^6\text{Li}$ in the course of the evolution of the Galaxy. In their model, much of the ${}^6\text{Li}$ is produced early and therefore they also predict a ${}^6\text{Li}$ plateau which extends down to at most [Fe/H] ≈ -3 . The characteristics of the plateau depend on the history of structure formation. If this process occurs early enough in the formation of the Galaxy, model I of Suzuki & Inoue (2002) is consistent with the new observations (see their Fig. 1). Once again, observations of ${}^6\text{Li}$ at metallicities between -3 and -4 can distinguish between this model and the one we have presented here for which the plateau is predicted to extend to much lower metallicities. Furthermore, within the model of Suzuki & Inoue (2002), the exact evolution of the ${}^6\text{Li}$ abundance can be linked to the mean azimuthal rotation velocity of MPHSSs. Consequently, they predict larger dispersion among the observed ${}^6\text{Li}$ abundances, together with a correlation between the ${}^6\text{Li}$ abundance and the rotation velocity. This could also help distinguish between galactic $\alpha + \alpha$ GCR production from the early $\alpha + \alpha$ CCR production considered in this paper.

The work by Fields & Prodanović (2004) uses a similar formalism to that described above, though redshift evolution is not formally taken into account. However, their main focus is on the lithium-gamma ray connection in relation to the solar ${}^6\text{Li}$ abundance. Under this assumption, they claim that, if CCR interactions account for all of the ${}^6\text{Li}$ production, it will also account for all of the observed extragalactic gamma-ray background (EGRB). In this paper, we claim that CCRs

must produce a pregalactic ${}^6\text{Li}$ abundance, that is about 10 times smaller than the solar abundance since most of the ${}^6\text{Li}$ in stars at solar metallicity is produced during galactic evolution (Fig. 1). Hence, we would argue that it should produce only 10% of the total EGRB (from their Eq. 13), which is consistent with theoretical predictions (e.g. Berezhinsky, Blasi & Ptuskin 1997; Colafrancesco & Blasi 1998; Miniati 2002). Prodanović & Fields (2004) argue that the observation of Li in high-velocity clouds may help establish the necessity of an early source of Li.

Finally, we note that Jedamzik (2000, 2004a,b) considers the very early production of ${}^6\text{Li}$ during BBN from decay (Jedamzik 2000, 2004a) or annihilation (Jedamzik 2004a,b) of relic particles. Naturally, this model will also predict the existence of an elevated plateau.

6. CONCLUSION

The existence of the Spite plateau for ${}^7\text{Li}$ indicates that low metallicity halo stars are representative of the primordial BBN abundance, although the discrepancy with predictions based on WMAP results is still an issue (Asplund et al. 1999; Cyburt, Fields, & Olive 2004; Coc et al. 2004; Lambert 2004; Ryan & Elliot 2004). On the other hand, the hint for a plateau in ${}^6\text{Li}$ at very low metallicity, and at a higher abundance than predicted in standard BBN (by a factor of 1000), requires an additional process that produces ${}^6\text{Li}$ in a pregalactic phase. The process studied in this paper involves the interaction of α particles present in early cosmological cosmic rays with primordial Helium present in the intergalactic medium. We have shown that it is possible to produce sufficient quantities of ${}^6\text{Li}$,

without the additional over-production of ${}^7\text{Li}$.

The early production of ${}^6\text{Li}$ will be present in the gas that forms the Galaxy at $z = z_{\text{gal}}$ and provides a simple explanation for the existence of the observed ${}^6\text{Li}$ plateau in MPHs. The level of the ${}^6\text{Li}$ plateau may provide a strong constraint on the z_s - \mathcal{F} plane for the initial burst of CCRs, and hence on its total energy. However, the existence of this plateau needs to be confirmed with additional observations of ${}^6\text{Li}$ in stars with metallicities lower than -3. If the ${}^6\text{Li}$ plateau persists down to lower metallicities, it could confirm the predictions of this model and distinguish the physical processes occurring during Galaxy formation.

In a forthcoming paper, we will go further than the single burst approximation. The CCR production could be related to the formation and chemical evolution of pop III stars (Daigne et al. 2004). The influence of this process in the production of other elements, such as Be, B and D, will also be studied.

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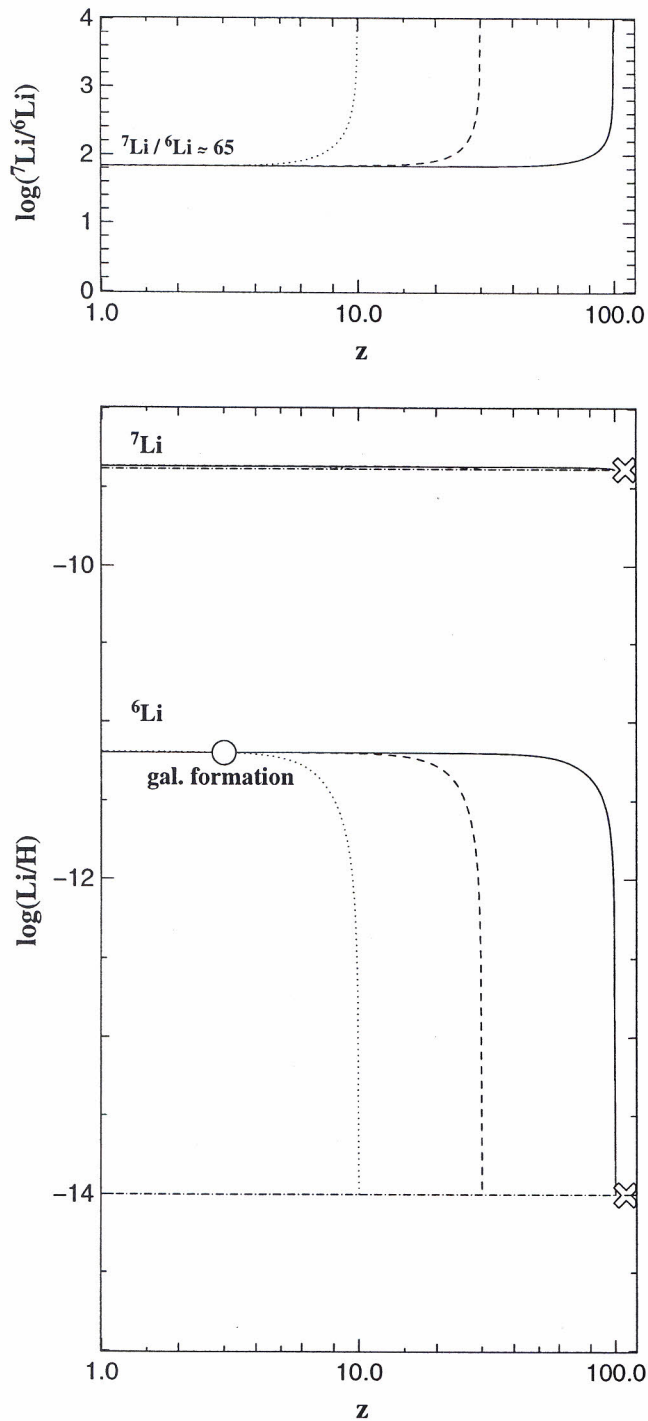


FIG. 2.— Redshift evolution of the ^6Li and ^7Li abundances in the intergalactic medium (lower panel), and of the ratio of $^7\text{Li}/^6\text{Li}$ abundance (upper panel). The redshift of the initial CCR burst z_s is chosen to be 10, 30 and 100 and is represented by the dotted, dashed and solid lines respectively. The shape of the CCR energy spectrum is fixed by $\gamma = 3$ and a ΛCDM cosmology (Spergel et al. 2003) is assumed. The initial abundances of the lithium isotopes are fixed according to BBN calculations (crosses and horizontal dot-dashed lines) while the abundance of ^6Li is chosen to be $10^{-11.2}$ at the redshift of the formation of the Galaxy, $z_{\text{gal}} = 3$ (circle). These choices fix the amplitude of the CCR flux (see Section 4.1). We find that the primordial abundance of ^7Li is increased by less than 10% from z_s to z_{gal} .

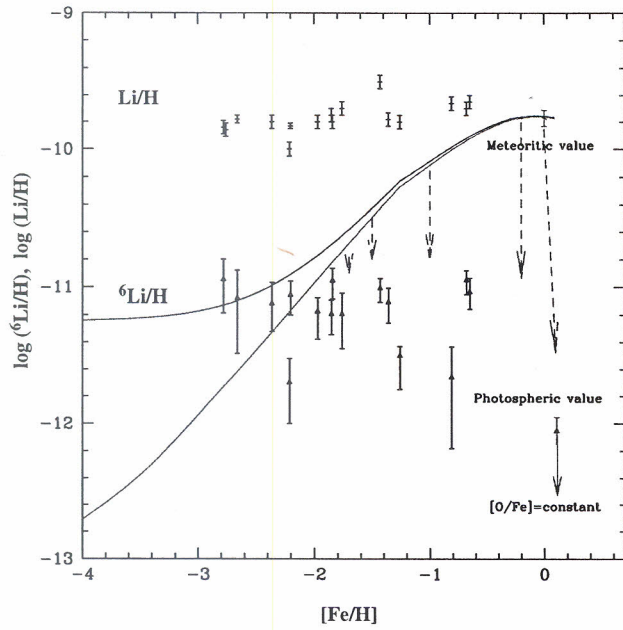


FIG. 3.— As in Fig. 1, the evolution of ${}^6\text{Li}/\text{H}$ vs $[\text{Fe}/\text{H}]$. In this case the evolution of ${}^6\text{Li}/\text{H}$ is modeled by GCR nucleosynthesis with the inclusion of the LEC (lower line). Also shown is the case where a prompt initial enrichment is produced by CCRs in the intergalactic medium (upper line). This model can explain the observed ${}^6\text{Li}$ plateau at low metallicity. The potential depletion of ${}^6\text{Li}$ is indicated by the dashed arrows.

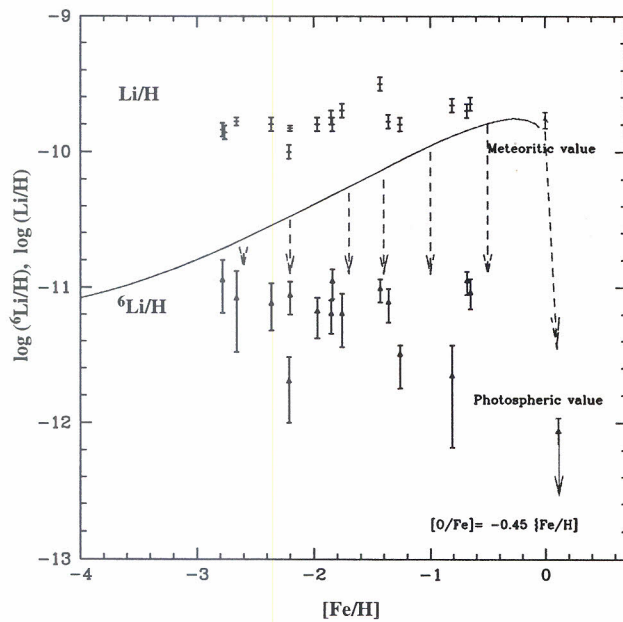


FIG. 4.— The evolution of ${}^6\text{Li}/\text{H}$ vs $[\text{Fe}/\text{H}]$. Here, $[\text{O}/\text{Fe}]$ is assumed to scale with $[\text{Fe}/\text{H}]$. We use the maximum slope of the relation that does not require a pre-galactic process (see text for details). However, the amount of destruction required is much higher, and must be present at metallicity as low as -3.

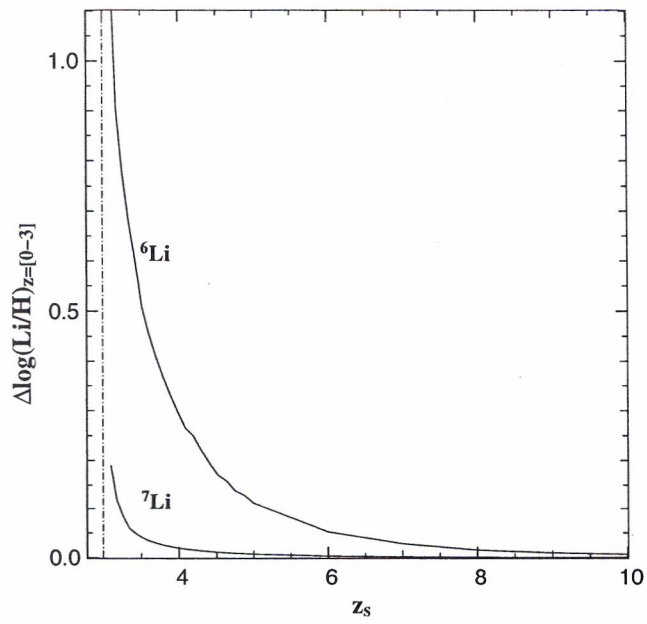


FIG. 5.— Predicted dispersion in the ${}^6\text{Li}$ and ${}^7\text{Li}$ abundances from $z = 0$ to 3 as a function of z_s . Note that by construction, z_s must be greater than the redshift of formation of the Galaxy, $z_{\text{gal}} = 3$ (vertical line).

