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

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ABSTRACT

Very recent observations of the $^6$Li isotope in halo stars reveal a $^6$Li plateau about 1000 times above the predicted big bang nucleosynthesis abundance. We calculate the evolution of $^6$Li versus redshift generated from an initial burst of cosmological cosmic rays (CCRs) up to the formation of the Galaxy. We show that the pre-Galactic production of the $^6$Li isotope can account for the $^6$Li plateau observed in metal-poor halo stars without additional overproduction of $^7$Li. 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 Population III stars, responsible for these early cosmic rays. Consequently, we consider the evolution of $^6$Li in the Galaxy. Since $^6$Li is also produced in Galactic cosmic-ray nucleosynthesis, we argue that halo stars with metallicities between $[\text{Fe}/\text{H}]=-2$ and $-1$ must be somewhat depleted in $^6$Li.

Subject headings: cosmic rays — cosmology: theory — early universe — nuclear reactions, nucleosynthesis, abundances — stars: abundances

Online material: color figures

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, nonthermal, and 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 $^7$Li in the Galactic disk) and are in fact destroyed in stellar interiors. This explains the relatively low abundances of these species. While a significant fraction of the observed $^7$Li is produced in the big bang, the big bang nucleosynthesis (BBN) production of $^6$Li, Be, and B results in abundances that are orders of magnitude below those observed in halo stars. For example, BBN production of $^6$Li is dominated by the process $\alpha + B$-$^6$Li. At the baryon density deduced from observations of the anisotropies of the cosmic microwave background radiation by the Wilkinson Microwave Anisotropy Probe (WMAP) (Spergel et al. 2003), its BBN value is $^6$Li/H $\approx 10^{-14}$ (Thomas et al. 1993; Vangioni-Flam et al. 1999). On the other hand the BBN mean value of the $^7$Li abundance is, according to Cyburt (2004), $^7$Li/H $= 4.27^{+0.09}_{-0.08} \times 10^{-10}$; according to Cucchi et al. (2004), $^7$Li/H $= 4.9^{+0.1}_{-0.1} \times 10^{-10}$; or according to Coe et al. (2004), $^7$Li/H $= 4.15^{+0.45}_{-0.43} \times 10^{-10}$. As such, the $^6$Li/$^7$Li ratio in BBN is about $4 \times 10^4$.

The very low abundances of the $^6$Li, $^9$Be, 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 (ISM) (for a review see Vangioni-Flam et al. 2000). Of these isotopes, $^6$Li is of particular interest because it has only recently been measured in halo stars (Smith et al. 1993, 1998; Hobbs & Thorburn 1994, 1997; Cayrel et al. 1999; Nissen et al. 1999, 2000; Asplund et al. 2001; M. Asplund et al. 2005, in preparation; 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 $^6$Li 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 $^7$Li) and is efficient very early in the evolutionary history of the Galaxy.

Different scenarios have been discussed to explain the abundance of $^6$Li in metal-poor halo stars (MPHSs). Suzuki & Inoue (2002) discussed the possibility of cosmic rays produced in shocks during the formation of the Galaxy, which was consistent with $^6$Li data available at that time. Jedamzik (2000) considers the decay of relic particles during the epoch of BBN, which can yield a large primordial abundance of $^6$Li. Fields & Prodanović (2004) have studied in detail the lithium production 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 § 5.2).

Until recently, the abundance of $^6$Li had been observed in only a few MPHSs with metallicities $[\text{Fe}/\text{H}]$ larger than $-2.3$. New values of the ratio $^7$Li/$^6$Li have been measured with the Ultraviolet and Visual Echelle Spectrograph (UVES) at the Very Large Telescope (VLT)-UT2 Kueyen European Southern Observatory (ESO) telescope, in halo stars with metallicity ranging from $-2.7$ to $-0.5$ (see § 2). These observations indicate the presence of a plateau in $^6$Li/H $\approx 10^{-11}$, which suggests a pre-Galactic origin for the formation of $^6$Li.

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 (IGM) (Montmerle 1977a, 1977b, 1977c, and § 3). As $\alpha + \alpha$ processes also produce $^6$Li, these models are constrained by the $^7$Li plateau observed in the same MPHSs. This constraint is made more severe by the current discrepancy between the BBN-predicted value of $^7$Li and the observational abundance. We demonstrate how this model can explain the recent observations and constrain the history of cosmological structure formation (§ 4) and the Galactic evolution of $^6$Li (§ 5.1). We compare these results with the expected evolution of $^6$Li from GCR nucleosynthesis. Without the
pre-Galactic production of $^6$Li, the latter model cannot account for the elevated $^6$Li abundances at very low metallicity. In contrast, models for which O/Fe increases at low metallicity are able to produce sufficient $^6$Li at low metallicity, without pre-Galactic production. However, in this case, the bulk of the $^6$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 $^6$Li data in stars with $[\text{Fe/H}] = -3$ to $-4$ will be required to distinguish between these scenarios. Our predictions are compared to other work in § 5.2, and our conclusions are given in § 6.

2. OBSERVATIONAL AND NUCLEAR DATA

The determination of the $^6$Li abundance in MPHs is extremely difficult and requires high-resolution and high signal-to-noise-ratio 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. Although the fits to the width of this feature are sensitive to the $^7$Li/$^6$Li ratio, it is very difficult to obtain accurate measurements of the isotopic ratio. The isotope $^6$Li can only be realistically expected to be observed in stars with surface temperatures and at low metallicities of $[\text{Fe/H}] < -1.3$. Brown & Schramm (1988) determined that only in stars with surface temperatures greater than about 6300 K will $^6$Li survive in the observable surface layers of the star. At metallicities $[\text{Fe/H}] \geq -1.3$, even higher effective temperatures would be required to preserve $^6$Li.

As noted above, the previous sets of data on the lithium isotope ratio have been significantly expanded by M. Asplund et al. (2005, in preparation; see also Lambert 2004) with the observations of 24 MPHs. Previously, only three stars with metallicities $[\text{Fe/H}] < -1.3$ showed net detections of $^6$Li (Smith et al. 1993, 1998; Hobbs & Thorburn 1994, 1997; Cayrel et al. 1999; Nissen et al. 2000). The observed abundances of $^6$Li/H and $^6$Li/H are displayed versus the metallicity, [Fe/H], in Figure 1. There are, in addition, several stars with metallicities in the range $[\text{Fe/H}] = -3$ to $-0.5$ for which only upper limits (not shown) to the $^7$Li/$^6$Li ratio are available. Note that the $^6$Li abundance at solar metallicity is plotted for both the meteoritic value (Lodders 2003) and the solar photospheric value (Asplund et al. 2004). The latter is derived from the photospheric value of Li assuming the solar ratio $^7$Li/$^6$Li = 12 and therefore really represents an upper limit to the $^6$Li photospheric abundance.

These new data at low metallicity reveal the existence of a plateau for $^6$Li, whose abundance is about 1000 times higher than that predicted by BBN. As such, another production mechanism that is capable of producing what appears to be an initial enrichment of $^6$Li in the intergalactic medium is required. Here, we concentrate on the interaction of $\alpha$-particles present in CCRs produced at high redshift, with He at rest in the IGM, as a potential description of this pre-Galactic enrichment process. The abundances in higher metallicity stars are discussed in § 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 $^6$Li, indicating that depletion may have played a role in the observed $^6$Li abundance for stars in the plateau as well. This is in contrast to the $^7$Li plateau, which shows very little dispersion and for which we expect the role of depletion to have been minor (Ryan et al. 2000).

The amplitude for $^6$Li production is constrained by the abundances of Be and B (see § 5.1 for an additional discussion). As one can see, this model can not explain the elevated $^6$Li abundances at low metallicity and requires some $^6$Li depletion at higher metallicity (as do all 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 $^6$Li and $^7$Li. The calculated $^6$Li abundances from the CCR 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) $^6$Li are compared in Figure 1. In what follows, we use the most recent cross sections of Mercer et al. (2001).

3. COSMOLOGICAL COSMIC RAY PRODUCTION OF LITHIUM IN THE IGM: FORMALISM

3.1. On the Existence of Cosmological Cosmic Rays

The existence and global properties of CRs in the Galaxy are often related to supernova (SN) 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 IGM, while satisfying observational constraints on cosmic chemical evolution in pre-Galactic structures and in the IGM. In particular, Daigne et al. (2004) have demonstrated that the presence of massive stars ($M > 40\, M_\odot$) is required at high redshift ($z \geq 15-20$). This early population of stars (Population III) is able to reionize the IGM 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 CRs, may also come from active (Stecker & Salamon 1996; Mukherjee & Chiang 1999) and normal (Pavlidou & Fields 2002) galaxies (see also Lemoine 2002). Depending on the strength of the magnetic fields in those
structures, CRs will be confined or will propagate into the IGM (e.g., Berezinsky et al. 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 IGM (Kang & Jones 2002; Miniati 2002; Keshet et al. 2003; Ryu et al. 2003). Finally, at ultrahigh energies, more exotic sources of CRs have also been studied (Bhattacharjee et al. 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 Population III stars, as discussed in Daigne et al. (2004) at a given redshift \( z_s \). Note that very little is known about the CR 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,

\[
\phi_\alpha(E) = 12.5FK_\alpha(E + E_0)(E + 2E_0)^{-(\gamma + 1)/2} \quad \text{cm}^{-2} \text{s}^{-1} \text{(GeV nucleon}^{-1})^{-1},
\]

which is the form expected from standard shock acceleration theory (Blandford & Eichler 1987). The expression \( F \) is a normalization factor that 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 MPGSS (see § 4). The term \( E \) is the kinetic energy per nucleon, \( E_0 = 939 \text{ MeV} \) 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 \( \alpha \)-particles with energy \( E \approx 10 \text{ MeV} \) nucleon\(^{-1}\).

### 3.2. Transport Function in an Expanding Universe

The initial burst of CCRs evolves in the framework of an expanding universe with a cosmological constant. If \( N(E, z) \) is the comoving number density (GeV nucleon\(^{-1}\)) of a given species at a given time, or redshift, and energy, we define \( N_{\text{H},1}(E, z) \equiv N(E, z)/n_\text{H}(z) \), the abundance by number with respect to the ambient gaseous hydrogen (in units of [GeV per nucleon]\(^{-1}\)). The evolution of \( N_{\text{H},1} \) is defined through the transport function

\[
\frac{\partial N_{\text{H},1}}{\partial t} + \frac{\partial}{\partial E}(bN_{\text{H},1})/T_D = Q_{\text{H},1}.
\]

The expression \( Q \) is a source function that accounts for particle sources of production, while \( T_D \) is the lifetime against destruction. The term \( b \) describes the energy losses due to expansion or ionization processes (GeV nucleon\(^{-1}\))\( \cdot \)\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 \( f(z) = (1 + z)^{-1} \). \( H_0 \)\(^{-1} \) (e.g., Wick et al. 2004). Other contributions to \( b \) or \( Q \) do not depend on the assumed cosmology and are given explicitly in M77.

Two important quantities, \( z^*(E, E', z) \) and \( E'(E, z) \), are used in this formalism. Given a particle (\( \alpha \)-lithium) with an energy \( E \) at a redshift \( z \), \( z^*(E, E', z) \) corresponds to the redshift at which this particle had an energy \( E' \). The energy \( E'(E, z) \) is the initial energy required if this particle was produced at the redshift of the burst, \( z_s \). In particular, \( z^*(E, E', z) = z_s \). The equation that defines \( z^* \) (eq. [A5], M77) is

\[
\frac{\partial z^*}{\partial t} = -B(E)f(z)\left(\frac{dz}{dt}\right)^{-1} \quad \text{and} \quad z^* = \frac{1}{B(E)f(z)}\int_0^t \frac{dE}{B(E')}\frac{dz}{dt} \quad \text{and} \quad B(E) = 0 \text{ when } \Omega_\Lambda = 0.
\]

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

### 3.3. The Cosmological Cosmic Ray Flux and the Lithium Abundance

The evolution of the CCR \( \alpha \)-particle energy spectrum is derived, using equation (A8) of M77 and the single-burst properties, as

\[
\Phi_{\alpha,1}(E, z) = \frac{\phi_\alpha(E)}{n_\text{H}} \beta \frac{\phi_\alpha(E')}{b(E, z)} \exp\left(-\frac{\xi}{E_s(z)}\right) \frac{1}{z_s} \frac{1}{dz/dt} E_{\text{inj}}(E, z) \theta(E - E_{\text{cut}}(z)),
\]

where \( \Phi_{\alpha,1}(E, z) \equiv \Phi_{\alpha}(E, z)/n_\text{H}(z) \) is the flux of \( \alpha \)-particles per comoving volume,

\[
\frac{\partial N_{\text{H},1}(E, z)}{\partial t} = \int b(E, z)f(z)\Phi_{\alpha,1}(E, z)E' dE',
\]

and \( \beta (\beta') \) is the velocity corresponding to energy \( E (E') \); \( \xi \) accounts for the destruction term (eq. [A9], M77).

The abundance by number of lithium \((0 = ^6\text{Li} \text{ or } ^7\text{Li})\) of energy \( E \), produced at a given redshift \( z \), is computed from

\[
\frac{dN_{\text{H},1}(E, z)}{dt} = \int \sigma_{\alpha,1}(E, E') n_\text{H}(z) \Phi_{\alpha,1}(E', z) dE',
\]

where \( \sigma_{\alpha,1}(E, E') = \sigma(E)\delta(E - E'/4) \). The cross sections used have been discussed in § 2. Note that this equation does not take into account the destruction of lithium in the IGM. 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 proto-Galaxy before stars form. Thus, the quantity that should be compared to the data is

\[
\left[\frac{\text{[Li]/[H]}_\text{BBN}}{\text{[Li]/[H]}_\text{BBN}}\right] = \frac{1}{[\text{[Li]/[H]}_\text{BBN}]} + \int z_s \frac{dz}{dz_s} \frac{dN_{\text{H},1}(E, z)N_{\text{H},1}(E, z)}{dt} dE,\]

where \([\text{[Li]/[H]}_\text{BBN}]\) 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,

\[
E_p(z) = \int E_{\text{cut}} \frac{\Phi_{\alpha}(E_p, z)}{K_{\alpha, p}} \frac{E_p}{\beta} dE_p,
\]

where \( E_{\text{cut}} \) = 10 MeV corresponds to the \( \alpha \)-particle energy cutoff (MeV per nucleon) for the \( \alpha + \alpha \to \text{Li} \) reaction.
Finally, we comment on the subsequent destruction of lithium. The differential rate of destruction (by protons) is equal to \( \sigma_D(E) N_H(Z) \bar{N}(E, \gamma) \beta(E) \) and is proportional to the lithium abundance. The cross section \( \sigma_D \) decreases rapidly with energy below 10 MeV nucleon\(^{-1}\) (see Fig. 2 of M77). Assuming a constant energy of 10 MeV nucleon\(^{-1}\), 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 and the \(^{6}\)Li and \(^{7}\)Li abundances predicted by BBN and observed in MPHSs have changed considerably. They have been updated here. Unless otherwise noted, we use the standard \( \Lambda \)CDM cosmology (Speyer et al. 2003) for which \( H_0 = 71 \) km s\(^{-1}\) Mpc\(^{-1}\), \( \Omega_m = 0.27 \), and \( \Omega_\Lambda = 0.73 \), with \( \Omega_\Lambda h^2 = 0.0224 \). The Hubble constant is defined as \( H(z) = H_0 \left[ 1 + (1 + z)^{\Omega_m \Omega_\Lambda} \right]^{1/2} \) and is fixed. In addition, the rate of production of \(^{6}\)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 (\( z_s \gtrsim z_{gal} \)), the \(^{6}\)Li abundance is almost constant for \( z \lesssim z_{gal} \).

Since the production rates of \(^{6}\)Li and \(^{7}\)Li are similar, the additional production of \(^{7}\)Li due to CCRs (\( \approx 10^{-11} \)) is negligible compared to the BBN primordial values (\( \approx \) a few times \( 10^{-10} \)). The evolution of the abundance of \(^{7}\)Li with redshift is shown in Figure 1 for \( z_s = 10, 30, \) and 100. In each case a \(^{6}\)Li plateau is produced. By construction, the abundance of \(^{7}\)Li at \( z = z_{gal} \) is fixed. In addition, the rate of production of \(^{6}\)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 (\( z_s \gtrsim z_{gal} \)), the \(^{6}\)Li abundance is almost constant for \( z \lesssim z_{gal} \).

The evolution of the abundance of \(^{6}\)Li with redshift is shown in Figure 2 for \( z_s = 10, 30, \) and 100. In each case a \(^{6}\)Li plateau is produced. By construction, the abundance of \(^{7}\)Li at \( z = z_{gal} \) is fixed. In addition, the rate of production of \(^{6}\)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 (\( z_s \gtrsim z_{gal} \)), the \(^{6}\)Li abundance is almost constant for \( z \lesssim z_{gal} \).

We begin by working within the context of the standard framework described in § 3, that is, a \( \Lambda \)CDM + WMAP cosmology. The shape of the CCR spectrum is given by equation (1), with \( \gamma = 3 \).

The evolution of the lithium abundance with redshift in our model is uniquely specified by the normalization constant \( F \) and the redshift of the CCR burst, \( z_r \).

Our CCR spectrum is constrained by (1) the Spite plateau (Spite & Spite 1982) for \(^{7}\)Li and (2) the hint of a \(^{6}\)Li plateau (M. Asplund et al. 2005, in preparation). The Spite plateau should correspond to the primordial value of the \(^{7}\)Li abundance. However, the observed \(^{7}\)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 \(^{7}\)Li plateau acts as a strong constraint in our model, since it forbids us from producing a non-negligible amount of \(^{7}\)Li. This constraint would be weakened if the observational value of \(^{7}\)Li were higher (see, e.g., Meléndez & Ramírez 2004), as the GCR component of \(^{7}\)Li would become more difficult to observe as the ratio of GCR-to-BBN-produced \(^{7}\)Li is diminished (Fields et al. 2005). Nevertheless, our model must produce a small quantity of this isotope compared to the BBN abundance. The abundance of \(^{6}\)Li observed at very low metallicity is assumed to trace the abundance in the IGM before the formation of the Galaxy. As mentioned above, our model must be able to reproduce this abundance at \( z = z_{gal} \).

The constraints on the \(^{6}\)Li abundance from the calculated BBN abundance at \( z \approx \infty \) and from its observed “pre-Galactic” value at \( z = z_{gal} \) specify a unique amplitude for the CCR energy spectrum, \( F \), for a given \( z_s \). Therefore, the normalization constant, \( F \), is determined by the choice of parameters (\( \Omega_\Lambda, \Omega_m, \gamma, z_s \)), under the constraint given by the initial and final \(^{6}\)Li abundances. The initial \(^{6}\)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 pre-Galactic component of \(^{7}\)Li.

4. CONSTRAINTS ON COSMOLOGICAL COSMIC RAY 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 MPHSs 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 pre-Galactic abundance, i.e., the predicted abundance at the redshift of the formation of the Galaxy. This may be justified by the presence of the \(^{6}\)Li plateau. We assume that the peak of the formation of the structures occurs at \( z_{gal} \approx 3 \) (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 IGM at \( z = z_{gal} \). We next define the procedure used to constrain the CCR burst parameters from the lithium observations.

4.1. Procedure

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 (\( F \)) using the same constraint on the “pre-Galactic” value \( [^{6}\text{Li}]_p = 0.8 \) at \( z = z_{gal} \). 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, which roughly 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 Figure 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, \( z_r \). At high energy, one can show that \( \Phi_{e, 18}(\gamma, z_s) \propto \phi_0(\gamma)(1 + z_s)(1 + z_{gal})^{(1 + z_{gal})^{3.3}} \). Thus, the required energy density at \( z = z_{gal} \) in the CCR is roughly proportional to \((1 + z_s)^{3.3}\). The CCR normalization also depends on the shape of the energy spectrum, \( \gamma \). A steeper spectrum (higher \( \gamma \)) favors the low-energy part of the spectrum, where the lithium production peaks. Thus, for a fixed amplitude \( F \), the abundance of \(^{6}\)Li will be higher for \( \gamma = 3 \) than for \( \gamma = 2 \). Conversely, for a fixed abundance, \( F \) 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 \(^{6}\)Li to set the amount of pre-Galactic \(^{7}\)Li production. Then assuming a given epoch for the formation of CCRs, the amplitude of the energy spectrum, \( F \), 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 \( 10^{-12.2} \).
The primordial abundance of \(^7\)Li is increased by less than 10% from \(C_0\) chosen to be 10. The initial abundances of the lithium isotopes are fixed according to BBN calculations. Dashed, and solid lines, respectively. The shape of the CCR energy spectrum is determined in order to reproduce the observed pre-Galactic \(^6\)Li abundance \(C_3\) is chosen to be 10, 30, and 100 and is represented by the dotted, \(C_0\) and of the ratio of \(^7\)Li/\(^6\)Li abundance \(C_13\) is 3. At this point, we assume only the primordial abundance of \(^7\)Li is increased by less than 10% from \(z_s\) to \(z_{gal}\). 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 for the 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 \(6.3 \times 10^{-13}\) ergs cm\(^{-3}\) 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 \(\mathcal{E}_p/(1 + z_s)^3\) and since \(\mathcal{E}_p\) increases slower than \((1 + z_s)^3\). It is interesting to note that CCRs were predicted to heat the IGM and thus avoid the problem of over-cooling in the IGM gas (Blanchard et al. 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 \(\gamma\)-parameter, and metal enrichment. Assuming the production of CCRs from galaxies at \(z = 10\), they obtained an initial luminosity of about \(1.6 \times 10^{-27}\) h ergs cm\(^{-3}\) s\(^{-1}\). Alternatively, from the amount of metals ejected by SNe, they place an upper limit on the CR energy density of \(10^{-14}\) ergs cm\(^{-3}\) 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 0.01 solar. Note that this is much larger than the resulting IGM metallicity where \(^6\)Li production occurs. At \(z = 10\) and at a metallicity of 0.01 solar, their limit is effectively relaxed to \(\mathcal{E}_p < 10^{-12}\) ergs cm\(^{-3}\).

Thus, we see that the CCR production of \(^6\)Li is capable of explaining the large abundance of \(^6\)Li with negligible production of \(^7\)Li (both relative to the BBN value). Sufficient \(^6\)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 \(^6\)Li abundance remains roughly constant until additional \(^6\)Li is produced in the Galaxy through GCRs, as we discuss in § 5.

5. DISCUSSION

5.1. Galactic Evolution of \(^6\)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 \(^6\)Li and a small amount (about a few percent of the BBN value) of \(^7\)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 the C, N, and O needed for spallation processes. In contrast, the presence of primordial $^4\text{He}$ allows for the CCR production of Li.

CRs produced in the early Galaxy will invariably interact with the existing ISM. In standard GCR nucleosynthesis (Reeves et al. 1970) LiBeB nuclei are produced by spallation when protons and $\alpha$-particles in the CRs impinge on ISM C, N, or O. LiBeB is also produced when CNO in the CRs are spallated by ISM protons and $\alpha$-particles. As such, spallation requires heavy elements ("metals") to be present in either the CRs or the ISM. In addition, $\alpha + \alpha$ fusion reactions between CRs 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 $\nu$-process (Woosley et al. 1990; Olive et al. 1994; Vangioni-Flam et al. 1996), but these are not important for our present discussion.

As in the case of CCR nucleosynthesis, $\alpha$-particle 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 $[\text{O/Fe}]$ is constant at low values of $[\text{Fe/H}]$. Motivated by the observational fact that the log of the Be and B abundances appear to scale linearly with $[\text{Fe/H}]$, it has been proposed that the bulk of CRs are not accelerated in the general ISM but rather in the metal-rich interiors of superbubbles (Cassé et al. 1995; Parizot & Drury 1999), specifically at low metallicity. Because the superbubble composition is enriched in metals, any CRs that are accelerated in superbubble interiors would have a composition that would be both metal-rich and time-independent. The low-energy component of the hard-energy spectra associated with superbubbles results in the primary production of Be and B. We refer to this process as LEC. In general both the LEC and standard GCR nucleosynthesis are responsible for the observed LiBeB abundances.

In Figure 1, we display the GCR production of $^6\text{Li}$ in the absence of the PIE produced by CCR nucleosynthesis. Here, we have normalized the flux of GCRs 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 $\nu$-process.) As expected, the logarithmic slope of $[\text{Li}]$ versus $[\text{Fe/H}]$ is 1 (Fields & Olive 1999b; Vangioni-Flam et al. 1999).

In Figure 2 we show the evolution of $^6\text{Li}$ versus $[\text{He/H}]$ 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 cannot explain the observational data. At low $[\text{Fe/H}] \lesssim -2$, the observed $^6\text{Li}$ abundance is too high to be accounted for by standard CCR + LEC nucleosynthesis.

In addition, to explain the data at higher $[\text{Fe/H}] \gtrsim -2$, 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 $[\text{Fe/H}] \lesssim -2$, where the calculation from Galactic processes cross the plateau.

We also show in Figure 3 the evolution of $^6\text{Li}$ when the prompt enrichment due to CCRs is included. In this case, the data at low $[\text{Fe/H}]$ are 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 Figure 3 can be distinguished by future observations of $^6\text{Li}$ at metallicities $[\text{Fe/H}] < -2.7$, which would establish the role of CCR nucleosynthesis as a mechanism for the early production of $^6\text{Li}$. As mentioned above, a PIE in heavy elements is also expected in the IGM, especially within this Population 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 does not modify the curves in Figures 1 and 3, for $[\text{Fe/H}] \gtrsim -4$. Thus, models with a $^6\text{Li}$ plateau are not affected by the iron PIE generated by Population III stars.

The GCR nucleosynthesis models described above were based on the assumption that $[\text{O/Fe}]$ was constant at low $[\text{Fe/H}]$. That is, we can use the iron abundance to trace the evolution of the LiBeB elements. However, some data show that $[\text{O/Fe}]$ increases with decreasing $[\text{Fe/H}]$ (Israelian et al. 1998, 2001; Boesgaard et al. 1999). As a consequence, the evolution of Be and B may appear to be primary with respect to $[\text{Fe/H}]$ but in fact is secondary with respect to $[\text{O/H}]$ (Fields & Olive 1999a). In reality,
the data show that with respect to [O/H], BeB have admixtures of primary and secondary components. That is, the slope for log (BeB/H) versus [O/H] is between 1 and 2 (Fields et al. 2000; King 2001).

In Figure 4, we show the resulting evolution of $^6$Li when the slope of [O/Fe] versus [Fe/H] is taken to be $-0.45$ (cf. Fields et al. 2000, 2005). For a slope larger than $-0.45$, a prompt initial enrichment is not required since the Galactic production of $^6$Li would already exceed the abundance observed in all stars. However, within such a model, the destruction rate of $^6$Li must be nonnegligible for metallicities as low as [Fe/H] $\approx -3$. In Figures 1 and 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 $z = z_r$. However, if this burst does not occur at a redshift much larger than $z_{gal}$, the abundance of lithium can still increase. Figure 5 shows the expected variation of the $^6$Li and $^7$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 $z < z_{gal}$, the abundance pattern in stars that form later may reflect this dispersion. For our choice of $z_{gal} = 3$, 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 in which CRs generated by structure formation, during the process of galaxy formation, produce $^6$Li in the course of the evolution of the Galaxy. In their model, much of the $^6$Li is produced early, and therefore they also predict a $^6$Li plateau that extends down to, at most, [Fe/H] $\approx -3$. 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 $^6$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 $^6$Li abundance can be linked to the mean azimuthal rotation velocity of MPHSs. Consequently, they predict larger dispersion among the observed $^6$Li abundances, together with a correlation between the $^6$Li abundance and the rotation velocity. This could also help distinguish between $\alpha + \alpha$ CCR 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, although redshift evolution is not formally taken into account. However, their main focus is on the lithium–gamma-ray connection in relation to the solar $^6$Li abundance. Under this assumption, they claim that if CCR interactions account for all of the $^6$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 pre-Galactic $^6$Li abundance, that is, about 10 times smaller than the solar abundance, since most of the $^6$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., Berezinsky et al. 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, 2004b) considers the very early production of $^6$Li during BBN from decay (Jedamzik 2000, 2004a) or annihilation (Jedamzik 2004a, 2004b) of relic particles. Naturally, this model will also predict the existence of an elevated plateau.
6. CONCLUSION

The existence of the Spite plateau for $^6$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 et al. 2004; Coc et al. 2004; Lambert 2004; Ryan & Elliot 2004). On the other hand, the hint for a plateau in $^6$Li at very low metallicity, and at a higher abundance than predicted in standard BBN (by a factor of 1000), requires an additional process that produces $^6$Li in a pre-Galactic phase. The process studied in this paper involves the interaction of $\alpha$-particles present in early cosmological CRs with primordial helium present in the IGM. We have shown that it is possible to produce sufficient quantities of $^6$Li, without the additional overproduction of $^7$Li.

The early production of $^6$Li will be present in the gas that forms the Galaxy at $z = \frac{1}{10}$ and provides a simple explanation for the existence of the observed $^6$Li plateau in MHPSSs. The level of the $^6$Li plateau may provide a strong constraint on the $\zeta/\nu$ plane for the initial burst of CRs and hence on its total energy. However, the existence of this plateau needs to be confirmed with additional observations of $^6$Li in stars with metallicities lower than $\sim 3$. If the $^6$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 Population 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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