The Evolution of $^6$Li in Standard Cosmic-Ray Nucleosynthesis

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ABSTRACT

We review the Galactic chemical evolution of $^6$Li and compare these results with recent observational determinations of the lithium isotopic ratio. In particular, we concentrate on so-called standard Galactic cosmic-ray nucleosynthesis in which Li, Be, and B are produced (predominantly) by the inelastic scattering of accelerated protons and $\alpha$’s off of CNO nuclei in the ambient interstellar medium. If O/Fe is constant at low metallicities, then the $^6$Li vs Fe/H evolution–as well as Be and B vs Fe/H–has difficulty in matching the observations. However, recent determinations of Population II oxygen abundances, as measured via OH lines, indicate that O/Fe increases at lower metallicity; if this trend is confirmed, then the $^6$Li evolution in a standard model of cosmic-ray nucleosynthesis is consistent with the data. We also show that another key indicator of $^6$LiBeB origin is the $^6$Li/Be ratio which also fits the available data if O/Fe is not constant at low metallicity. Finally we note that $^6$Li evolution in this scenario can strongly constrain the degree to which $^6$Li and $^7$Li are depleted in halo stars.

Subject headings: cosmic-rays – Galaxy : abundances – nuclear reactions, nucleosynthesis, abundances
1. Introduction

Both of the stable isotopes of lithium, $^6\text{Li}$ and $^7\text{Li}$, have a special nucleosynthetic status; however, their origins are quite different. The story of $^7\text{Li}$ is perhaps better-known, as this nuclide dominates by far the Li production in big bang. Starting in the 1980’s, observations of extreme Pop II stars (Spite & Spite 1982) revealed a constant Li abundance versus Fe, the “Spite plateau.” This discovery has been confirmed many times over, and demonstrates that Li is primordial. Furthermore, the mean value along the plateau, $\text{Li}/\text{H} = (1.6 \pm 0.1) \times 10^{-10}$ (Molaro, Primas & Bonifacio, 1995; Bonifacio & Molaro, 1996) agrees well with the inferred primordial values of the other light elements, in dramatic confirmation of big bang nucleosynthesis theory (Walker et al. 1991; Fields et al. 1996).

In Pop I stars, the Li abundance rises by factor of $\sim 10$ from its primordial level and various stellar production mechanisms have been suggested to explain this (e.g., Matteucci, d’Antona, & Timmes 1995). Here, we will focus on the Pop II behavior of both $^7\text{Li}$ and $^6\text{Li}$.

Unlike $^7\text{Li}$, the less abundant $^6\text{Li}$ has long been recognized as a nucleosynthetic “orphan”—along with Be and B, $^6\text{Li}$ is made neither in the the big bang nor in stars. That is, primordial nucleosynthesis does produces some $^6\text{Li}$, but the abundance is unobservably small ($\text{§}$3); moreover, stellar thermonuclear processes destroy $^6\text{Li}$, whose low binding energy renders this nucleus thermodynamically unfavorable. Thus, $^6\text{Li}$ can only be produced in Galactic, non-equilibrium processes. Just such a process was identified by Reeves, Fowler, & Hoyle (1970), in the form of Galactic cosmic ray interactions. Specifically, the propagation of cosmic rays (mostly protons and $\alpha$’s) through the interstellar medium (ISM) inevitably leads to spallation reactions on CNO nuclei (e.g., $p + O \rightarrow ^6\text{Li}$) and fusion reactions on interstellar He ($\alpha + \alpha \rightarrow ^6\text{Li}$). Furthermore, Reeves, Fowler, & Hoyle (1970) and Meneguzzi, Audouze, & Reeves (1971) showed that cosmic ray interactions do indeed yield solar system abundances of these nuclides over the lifetime of the Galaxy. This mechanism, the so-called “Standard GCR Nucleosynthesis” (GCRN), was thus seen to be viable. Although lingering questions remained (standard GCRN alone is unable to reproduce the solar $^7\text{Li}/^6\text{LiBeB}$ ratio, nor the $^{11}\text{B}/^{10}\text{B}$ ratio), this process was viewed as the conventional source of solar system $^6\text{LiBeB}$ until the late 1980’s.

This simple picture of the origin of Li has met with several complications over the past decade or so. There is a nagging uncertainty as to whether or not the observed $^7\text{Li}$ abundance in the plateau stars is in fact representative of the primordial abundance or was partially depleted by non-standard stellar processes. In other words, does the Spite plateau measure the primordial Li abundance, or should one apply an upward correction to offset the effects of depletion? Stellar evolution models have predicted depletion factors which differ widely, ranging from essentially no depletion in standard models (for stars
with $T \gtrsim 5500$ K) to a large depletion (Deliyannis et al. 1990, Charbonnel et al. 1992). Depletion occurs when the base of the convection zone sinks down and is exposed to high temperatures, $\sim 2 \times 10^6$ K for $^7\text{Li}$ and $\sim 1.65 \times 10^6$ K for $^6\text{Li}$ (Brown & Schramm 1988). Indeed, in standard stellar models, the depletion of $^7\text{Li}$ is always accompanied by the depletion of $^6\text{Li}$ (though the converse is not necessarily true). Thus any observation of $^6\text{Li}$ has important consequences on the question of $^7\text{Li}$ depletion. The issue of depletion affects not only $^6\text{Li}$ and BBN, but also $^6\text{LiBeB}$ and their evolution; indeed, in this paper we will make use of this connection.

Another complication has emerged to apparently overthrow the picture of standard GCRN. Namely, measurements of Be and B in halo stars have shown that Be and B both have logarithmic slopes versus iron which are near 1. However, in standard GCRN, the rates of Be and B production depend on the CNO target abundances. This implies that Be and B should be “secondary,” with abundances which vary quadratically with metallicity; i.e., the Be and B log slopes should be 2 versus Fe. While neutrino-process nucleosynthesis (Woosley et al. 1990; Olive et al. 1994) can help explain the linearity of B vs Fe/H, it is the slope of [Be/H] vs. [Fe/H] which has focused the attention of modelers of cosmic-ray nucleosynthesis. For example, to explain the observed “primary” slope, new, metal-enriched cosmic ray components have been proposed as the dominant LiBeB nucleosynthesis agents in the early Galaxy (Cassé, Lehoucq, & Vangioni-Flam 1995; Ramaty, Kozlovsky, & Lingenfelter 1995; Vangioni-Flam et al. 1996; Vangioni-Flam et al. 1998a; Ramaty, Kozlovsky, Lingenfelter, & Reeves 1997).

In the last few years, key new observations have begun to address questions concerning the Galactic evolution and stellar depletion of the lithium isotopes, with the first observations of the $^6\text{Li}/^7\text{Li}$ ratio in a few very old halo stars (Smith et al. 1993, Hobbs and Thorburn 1994, 1997). The lithium isotopic ratio has been measured several times in HD 84937, and most recently by Cayrel et al. (1998). The weighted average of the available measurements yields $^6\text{Li}/\text{Li} = 0.054 \pm 0.011$ at $[\text{Fe/H}] \simeq -2.3$. Recently, Smith et al. (1998) have reported one other positive detection in BD 26°3578 with $^6\text{Li}/\text{Li} = 0.05 \pm 0.03$, at about the same metallicity. For the other halo stars examined, only upper limits are available. The rarity of $^6\text{Li}$ detection in halo stars is well-understood (Brown & Schramm 1988) in terms of $^6\text{Li}$ depletion in stellar atmospheres. Namely, $^6\text{Li}$ is rapidly burned at at relatively low temperatures. Thus, $^6\text{Li}$ survives only in halo stars with shallow convective zones and high effective temperatures, $T \gtrsim 6300$ K. The data bear out this picture: both $^6\text{Li}$ detections have been in hot halo stars, and only upper limits have been set in cooler stars.

Combined with the present ISM abundance of $^6\text{Li}$, the halo $^6\text{Li}$ measurements can be
an important tool for testing models of Galactic cosmic-ray nucleosynthesis. Here, we will restrict our attention to standard models in which accelerated protons and $\alpha$'s produced the LiBeB elements through spallation as well as $\alpha - \alpha$ fusion in the production of the lithium isotopes. We show that as in the case of the evolution of Be and B, the general accord between standard GCRN and the observational data depends crucially on the behavior of the O/Fe ratio in Pop II (Fields & Olive 1998). The model is described in detail below ($\S 3$); the basic idea is that for spallation production, the slope vs O (rather than Fe) is the better indicator of nucleosynthesis origin. If O/Fe is constant, this distinction is irrelevant. However, new O/Fe data for Pop II reveal an evolving O/Fe ratio; if true, then it follows that the Be and B slopes versus Fe are not equal to the respective slopes vs O. As pointed out by Fields & Olive (1998), if O/Fe does vary as suggested by Israelian et al (1998) and by Boesgaard et al. (1998), then GCRN-produced BeB can have a roughly “primary” slope versus Fe yet a secondary slope vs O. Within the observational errors, the LiBeB data vs O and Fe are consistent with a “neoclassical” or “revised standard” cosmic ray nucleosynthesis consisting of (1) GCRN which makes LiBeB, without additional metal-enriched cosmic rays, and (2) the $\nu$-process in SNe, required to fit the solar $^{11}\text{B}/^{10}\text{B}$ ratio as well as the different B and Be slopes in Pop II. As we show below, the effect of a varying O/Fe ratio, will also soften the slope of $^{6}\text{Li}/H$ vs. Fe/H, though to a lesser extent.

It is important to note that while the revised standard GCRN is allowed by the present data, the uncertainties in the observations are large enough that primary models for BeB are also allowed. Fortunately, this ambiguity will not persist: the two classes of models give very different predictions for LiBeB and O/Fe evolution, and can thus be tested with more and better observations. As described in detail below, $^{6}\text{Li}$ evolution, and the $^{6}\text{Li}/\text{Be}$ ratio provide one of the best discriminators between the different scenarios. Below we will show in detail the prediction of the secondary (standard) model regarding $^{6}\text{Li}$, the current data, and suggest future observations. The evolution of $^{6}\text{Li}$ in a primary model of cosmic-ray nucleosynthesis is discussed in Vangioni-Flam et al. (1998b).

We also discuss the possibility of using this model to constrain the degree to which both Li isotopes are depleted in halo stars ($\S 4$). Following Steigman et al. (1993) and Lemoine et al. (1995), we compute the maximum difference between the initial predicted $^{6}\text{Li}$ and the observed $^{6}\text{Li}$, and find that little $^{6}\text{Li}$ depletion is allowed. That implies that the $^{7}\text{Li}$ depletion is at least as small and probably negligible, so that the observed Spite plateau value of Li/H should reflect the true primordial Li abundance.
2. The $^6\text{Li}$ Data

The determination of the $^6\text{Li}$ abundance in halo dwarf stars is extremely difficult and requires high resolution and high signal to noise spectra due to the tiny hyperfine splitting between the two lithium isotopes of $\sim 0.16 \text{ Å}$. The observational challenge arises in part because the line splitting is not seen as a distinct doublet, but rather the narrowly shifted lines are thermally broadened so that one sees only a single, anomalously wide absorption feature; fits to the width of this feature are sensitive to the $^7\text{Li}/^6\text{Li}$ ratio. The first indication of a positive result was reported by Andersen, Gustafsson, and Lambert (1984) in the star HD211998 with $^6\text{Li}/^7\text{Li} = 0.07$ (though they caution that the detection was not certain) consistent with the upper limit of 0.1 reported by Maurice, Spite, & Spite (1984). Given the relatively low surface temperature of this star, $T \simeq 5300 \text{ K}$, standard stellar models (e.g. Deliyannis, Demarque, & Kawaler, 1990) would predict that this star is severely depleted in $^6\text{Li}$. Indeed, the star is depleted in $^7\text{Li}$ ($[^7\text{Li}] \simeq 1.22$), thus lying well below the Spite plateau.

Table 1: Hot Halo Dwarf Stars

| Star     | Temperature (K) | [Fe/H] | [Li]            |
|----------|----------------|--------|-----------------|
| G 64-12  | 6356 ± 75      | -3.03  | 2.32 ± 0.07     | B               |
|          | 6468 ± 87      | -3.35  | 2.40 ± 0.07     | IRFM            |
| G 64-37  | 6364 ± 75      | -2.6   | 2.03 ± 0.07     | B               |
|          | 6432 ± 70      | -2.51  | 2.11 ± 0.06     | IRFM            |
| LP 608 62| 6435 ± 52      | -2.51  | 2.28 ± 0.06     | B               |
|          | 6313 ± 80      | -2.81  | 2.21 ± 0.08     | IRFM            |
| BD 9°2190| 6452 ± 60      | -2.05  | 2.20 ± 0.11     | B               |
|          | 6333 ± 89      | -2.89  | 2.15 ± 0.07     | IRFM            |
| BD 72°94 | 6347 ± 88      | -1.3   | –               | B               |
| BD 36°2165| 6349 ± 84    | -1.15  | –               | B               |
| HD 83769 | 6678 ± 97      | -2.66  | –               | IRFM            |
| HD 84937 | 6330 ± 83      | -2.49  | 2.27 ± 0.07     | IRFM            |
| BD 26°3578| 6310 ± 81     | -2.58  | 2.24 ± 0.06     | IRFM            |
| G 4-37   | 6337 ± 92      | -3.31  | 2.16 ± 0.08     | IRFM            |
| G 9-16   | 6776 ± 84      | -1.31  | –               | IRFM            |
| G 37-37  | 6304 ± 112     | -2.98  | –               | IRFM            |
| G 201-5  | 6328 ± 111     | -2.64  | 2.27 ± 0.09     | IRFM            |
| BD 20°3603| 6441 ± 76     | -2.05  | 2.41 ± 0.07     | IRFM            |
$^6$Li can only be realistically expected to be observed in stars with both high surface temperatures and at intermediate metallicities of [Fe/H] between about -2.5 and -1.3. Brown and 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 much lower than [Fe/H] $\sim$ -2.5, the $^6$Li abundance is expected to be lower due to the short timescales available for GCRN production. At metallicities [Fe/H] $\gtrsim$ -1.3, even higher effective temperatures would be required to preserve $^6$Li. In Table 1, we show the stellar parameters and $^7$Li abundances of a set of stars from with $T > 6300$ K from Molaro, Primas & Bonifacio (1995) who use the Balmer line method of Fuhrmann, Axer & Gehren (1994) for determining the surface temperatures (labeled B) and from Bonifacio & Molaro (1996) who use the Infrared Flux Method (IRFM) of Blackwell et al. (1990) and Alonso et al. (1996). Included in this set of stars is the well observed HD 84937. In an early report, Pilachowski, Hobbs, & De Young (1989) were able to determine an upper limit of $^6$Li/$^7$Li < 0.1 for this hot halo dwarf star. The $^7$Li abundance for BD $72^\circ$94 was determined by Rebolo, Molaro, & Beckman (1988) and by Pilachowski, Sneden, & Booth (1993) using other parameter choices to be [Li] = 2.22 ± 0.09.

In a now seminal paper, Smith, Lambert, and Nissen (1993) reported the first detection of a small amount of $^6$Li in the halo dwarf HD 84937 at the level of $R = ^6$Li/($^6$Li + $^7$Li) = 0.05 ± 0.02. In a slightly cooler star, HD 19445, they found only an upper limit of $R < 0.02$. This observation was confirmed by Hobbs & Thorburn (1994, hereafter HT94) who found $^6$Li/$^7$Li = 0.07 ± 0.03 for HD 84937. HT94 observed 5 additional stars, only one of which is in Table 1, HD 338529 also known as BD 26$^\circ$3578, in which they found the upper limit $R < 0.1$. In their sample, they list BD $3^\circ$740 as a very hot star at 6400 K, however both the B and IRFM methods yield lower temperatures (6264 K and 6110 K respectively). In contrast, HT94 did report a positive detection in HD 201891 with $^6$Li/$^7$Li = 0.05 ± 0.02, in this relatively cool (5900 K) star. In Hobbs & Thorburn (1997, hereafter HT97), a reanalysis of HD 84937 yielded $^6$Li/$^7$Li = 0.08 ± 0.04 and converted the detection of $^6$Li in HD 201891 to an upper limit $R < 0.05$. In addition, HT97 found upper limits in 5 other cooler halo stars.

In more recent work, Smith et al. (1998) observe nine halo stars, three of which appear in Table 1. In two cases, HD 84937, and BD 26$^\circ$3578, they claim a positive detection for $^6$Li with $R = 0.06 \pm 0.03$ and $R = 0.05 \pm 0.03$ for the two stars respectively. In the third star, BD 20$^\circ$3603, $^6$Li was not detected and an upper limit $R < 0.02$ was established. In the remaining six stars, no $^6$Li was detected with certainty. In addition, it is interesting to note that Smith et al. (1998) confirm the small scatter in the $^7$Li abundances seen by Molaro et al. (1995), Spite et al. (1996), and Bonifacio & Molaro (1997), far below that expected if $^7$Li were depleted in these halo stars.
Recently, Cayrel et al. (1998) have performed new very high signal-to-noise measurements of HD 84937 and 2 other stars, BD 36°2165 and BD 42°2667, the former of which is hot enough to appear in Table 1. They report a very accurate determination of $^{6}\text{Li}/^{7}\text{Li} = 0.052 \pm 0.018$ in HD84937. The weighted mean of all measurements of the lithium isotopic ratio in HD 84937 is $^{6}\text{Li}/^{7}\text{Li} = 0.057 \pm 0.012$, corresponding to $R = 0.054 \pm 0.011$. Cayrel et al. (1998) also report a possible detection of $^{6}\text{Li}$ in the cooler of the other two stars but a lower S/N for this observation precludes a definite detection claim. BD 42°2667 was also observed by Smith et al. (1998) with no detection reported. In the third star, Cayrel et al. (1998) state that no $^{6}\text{Li}$ was detected.

3. The Production of $^{6}\text{Li}$

While primordial $^{7}\text{Li}$ is produced at observable levels, $^{6}\text{Li}$ production is orders of magnitude smaller (Thomas et al. 1993; Delbourgo-Salvador & Vangioni-Flam 1994). For values of the baryon-to-photon ratio $\eta$ consistent with $^{4}\text{He}$ and $^{7}\text{Li}$, $\eta = (1.8 - 5) \times 10^{-10}$ (see e.g. Fields et al. 1996), $^{6}\text{Li}$ lies in the range $^{6}\text{Li}/\text{H} \approx (1.5 - 7.5) \times 10^{-14}$, far below the levels measured in halo stars ($\sim 8 \times 10^{-12}$). One thus infers that Li in halo stars should be dominated by the primordial component of $^{7}\text{Li}$, and the data is completely consistent with this expectation. Furthermore, it follows that the $^{6}\text{Li}$ observed in Pop II is due to Galactic processes. The BBN production of $^{6}\text{Li}$ was recently reinvestigated in Nollett et al. (1997) comparing several measurements of the important D ($\alpha$, $\gamma$) $^{6}\text{Li}$ reaction. By and large they found similar results to those in Thomas et al. (1993), showing that the uncertainty in this reaction could allow for perhaps a factor 2 more $^{6}\text{Li}$.

As noted in the introduction, there have been several models advanced to explain Pop II $^{6}\text{Li}$ as well as Be and B; all of these involve spallation/fusion of accelerated particles. In this paper we focus on the case for standard GCRN as the source of Pop II $^{6}\text{Li}$, in the picture of Fields & Olive (1998), which includes both GCRN and the $\nu$-process. In contrast to “primary” models (at least in their simplest forms), different $^{6}\text{Li}$BeB nuclides have strongly different evolution in standard GCRN. Namely, in Pop II the Li isotopes and $^{11}\text{B}$ ($\approx \text{B}$) are mostly primary, due to $\alpha + \alpha$ interactions and $\nu$-process, respectively. On the other hand, $^{9}\text{Be}$ and $^{10}\text{B}$ are secondary (versus oxygen). Consequently, the ratios of primary to secondary nuclides—e.g., B/Be, $^{6}\text{Li}$/Be, and $^{11}\text{B}/^{10}\text{B}$—all vary strongly with metallicity and are good tests if measured accurately. We note however, that the Li/Be ratio is highly model dependent as shown in Fields, Olive, & Schramm (1994).

The GCRN model is described in detail elsewhere (Fields & Olive 1998); here, we only summarize essential cosmic ray inputs: (1) Galactic cosmic rays are assumed to
be accelerated with the (time-varying) composition of the ambient ISM. Consequently, interactions between cosmic ray $p, \alpha$ particles and interstellar HeCNO dominate the LiBeB production. (2) The injection energy spectrum is that measured for the present cosmic rays $\propto (E + m_p)^{-2.7}$; thus the cosmic rays are essentially relativistic, with no large flux increase at low energies. (3) The cosmic ray flux strength is scaled to the SN rate. On the basis of this model, production rates are computed. The (time-integrated) LiBeB outputs are normalized to the solar $^6$Li, Be, and $^{10}$B abundances, the isotopes that are of exclusively GCR origin. We adopt the solar abundances and isotopic ratios of Anders & Grevesse (1989) for all but elemental B, which is taken from the more recent determination of Zhai & Shaw (1994). The scaling factor effectively measures the average Galactic flux today, and is calculated from an unweighted average of the each of the scalings for $^6$Li, Be, and $^{10}$B.

To follow the LiBeB evolution in detail, the production rates are incorporated into a simple Galactic chemical evolution code. Closed and open box models are both able to give good results; here, we will adopt a closed box for simplicity. The model has an initial mass function $\propto m^{-2.65}$, and uses supernova yields due to Woosley & Weaver (1995). In this model, O/Fe indeed varies in Pop II. However, with the Woosley & Weaver (1995) yields, the model cannot reproduce a slope for O/Fe vs. Fe/H as steep as that observed by Israeli et al. (1998) and Boesgaard et al. (1998). Since the O-Fe behavior is crucial, and the Fe yields are the more uncertain (due to, e.g., the dependence on the Type II supernova mass cut as well as the inclusion of Type Ia supernova yields) we use the O trends as calculated in the model, but scale Fe from the O outputs and the observed O/Fe logarithmic slope. For comparison, we will present results from a model with the naive scaling Fe $\propto$ O, to show the effect of variations in the Pop II slope of O/Fe. In both cases, we use the observed Pop I relation $[O/Fe] \approx -0.5[Fe/H]$ over the range $[Fe/H] > -1$.

4. Galactic evolution of $^6$Li

Before presenting model results, some discussion is in order regarding how to compare the theory with the data. Since stellar $^6$Li abundances may have suffered some depletion, the observed $^6$Li represents a firm a lower limit on the initial abundance. For an evolution model to be acceptable, it must therefore predict a $^6$Li abundance which lies at or above the observed levels (within errors). If a model is viable by these criteria, then the difference

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1 Note that Chiappini, Matteucci, Beers, & Nomoto (1998) also find a changing O/Fe in Pop II. Their results are roughly consistent with ours when using the Woosley & Weaver (1995) yields, and they indeed find a a steeper [O/Fe] variation when using the Thielemann, Nomoto, & Hashimoto (1996) yields.
between the theory and the data quantifies the possible depletion.

Model results for $^6\text{Li}$ vs Fe appear in Figure 1, for $[\text{O}/\text{Fe}]-[\text{Fe}/\text{H}]$ Pop II slope $\omega_{\text{O}/\text{Fe}} = -0.31$ (the proposed GCRN model) and $\omega_{\text{O}/\text{Fe}} = 0$ for comparison. We see that GCRN does quite well in reproducing both solar and Pop II $^6\text{Li}$ when O/Fe is allowed to evolve in Pop II. On the other hand, if O/Fe is constant, then the $^6\text{Li}$-Fe slope is steeper and the model underproduces the Pop II $^6\text{Li}$. Clearly, the O/Fe behavior in Pop II is crucial to determine accurately. Note that because of the large uncertainty in $[\text{Fe}/\text{H}]$ for BD 26$^d$3578, this star does not at this time provide a stringent constraint.

Another test of the GCRN model is to compare primary versus secondary nuclides, e.g., $^6\text{Li}/\text{Be}$. Figure 2 plots $^6\text{Li}/\text{Be}$ and $^6\text{Li}/\text{B}$ vs Fe for the two O/Fe models. We see that while the model with changing O/Fe is consistent with $^6\text{Li}/\text{Be}$ for solar and Pop II metallicities, the uncertainty in the data do not sufficiently discriminate between this and the model with constant Pop II O/Fe. However, in purely primary models (with constant O/Fe), one expects $^6\text{Li}/\text{Be}$ to be approximately constant with respect to $[\text{Fe}/\text{H}]$ in Pop II, and that is clearly disfavored by the data, albeit there is only one star with both $^6\text{Li}$ and Be determined. While there is no positive detection of B/$^6\text{Li}$ in a halo star, the figure makes clear that this ratio is also a good test of the model. In Pop II, both B $\approx 11^B$ and $^6\text{Li}$ are dominated by primary processes ($\nu$-process and $\alpha+\alpha$, respectively), and thus the $^6\text{Li}/\text{B}$ ratio changes much less strongly than does $^6\text{Li}/\text{Be}$. Note that in our scenario, $^6\text{Li}$ and Be are pure cosmic ray products. Consequently, the $^6\text{Li}/\text{Be}$ curve is a particularly clean prediction of the model, free of any normalization between different sources; indeed, even the normalization of the present-day cosmic ray flux strength drops out as a common factor. By contrast, the B/$^6\text{Li}$ ratio does depend on the relative normalization between the GCRN and $\nu$-process yields (which is fixed so that $11^B/10^B$ equals the solar ratio 4.05 at $[\text{Fe}/\text{H}] = 0$).

The results shown above indicate that the standard cosmic-ray origin for $^6\text{LiBeB}$ is in fact consistent with the data. This is contrary to the conclusions of Smith, Lambert & Nissen (1998), who concluded that on the basis of the solar ratio of $^6\text{Li}/\text{Be}_\odot = 5.9$ and the value of this ratio for HD84937, $^6\text{Li}/\text{Be} \simeq 80 \gg ^6\text{Li}/\text{Be}_\odot$, an additional source of $^6\text{Li}$ was necessary. This conclusion assumes the observed linear evolution of $[\text{Be}/\text{H}]$ vs. $[\text{Fe}/\text{H}]$ and the expected linear evolution of $^6\text{Li}$ as a primary element due to $\alpha - \alpha$ fusion. In this case one would expect the $^6\text{Li}/\text{Be}$ ratio to be constant, which from a simple examination of Figure 2 is clearly not the case. In standard GCRN (with constant O/Fe at low metallicities), $^9\text{Be}$ is a secondary isotope, and given the linearity of $[^6\text{Li}]$, one should expect that $^6\text{Li}/\text{Be}$ is inversely proportional to Fe/H (i.e., to have a log slope of -1). However, if we take $[\text{O}/\text{Fe}] = \omega_{\text{O}/\text{Fe}}[\text{Fe}/\text{H}]$, then we would expect up to an additive constant (Fields &
Olive 1998)

\[ [\text{Be}] = 2(1 + \omega_{\text{O}/\text{Fe}}) [\text{Fe}/\text{H}] \] (1)

and

\[ [^6\text{Li}] = (1 + \omega_{\text{O}/\text{Fe}}) [\text{Fe}/\text{H}] \] (2)

so that

\[ \frac{[^6\text{Li}]}{[\text{Be}]} = -(1 + \omega_{\text{O}/\text{Fe}}) [\text{Fe}/\text{H}] \] (3)

Now for the Israeliian et al. (1998) value of \( \omega_{\text{O}/\text{Fe}} = -0.31 \), we would predict a dependence which is consistent with the data as shown in Figure 4. (The Boesgaard et al. (1998) value is very similar, \( \omega_{\text{O}/\text{Fe}} = -0.35 \).) While the case for a nonzero O/Fe Pop II slope has not been conclusively made, it is nevertheless striking that the reported \( \omega_{\text{O}/\text{Fe}} \) can explain all of the observed \(^6\text{Li}, \text{Be}, \) and B evolution within a simple (and canonical!) model.

The data as shown in the figures and compared to the models do not take into account any depletion of \(^6\text{Li}. \) To be sure, there is still a great deal of uncertainty in the amount of depletion for both \(^6\text{Li} \) and \(^7\text{Li} \) as well as the relative depletion factor, \( D_6/D_7 \) (Chaboyer 1994, Vauclair and Charbonnel 1995, Deliyannis et al. 1996, Chaboyer 1998, Pinsonneault et al. 1992, Pinsonneault et al. 1998). In the remainder of this paper we examine to what extent, the data (present or future) can tell us about the degree to which the lithium isotopes have been depleted and hence the implications for the primordial abundance of \(^7\text{Li}. \) In addition, we will show that future data on the lithium isotopic ratio may go a long way in resolving some of the key uncertainties in GCRN.

The observed lithium abundance can be expressed as

\[ \text{Li}_{\text{Obs}} = D_7(7\text{Li}_{\text{BB}} + 7\text{Li}_{\text{CR}}) + D_6(6\text{Li}_{\text{BB}} + 6\text{Li}_{\text{CR}}) \] (4)

where the \( D_{6,7} < 1 \) are the \(^6,7\text{Li} \) depletion factors. Ignoring the depletion factors for the moment, we see that lithium (and in particular \(^7\text{Li} \)) has two components, due to big bang and cosmic ray production. In principle, given a model of cosmic-ray nucleosynthesis, one could use the observed Be abundances in halo stars along with the model predictions of Be/Li and \(^6\text{Li}/7\text{Li} \) to extract a cosmic-ray contribution to \(^7\text{Li} \) and through (4) the big bang abundance of \(^7\text{Li} \) (Walker et al. 1993, Olive & Schramm 1992). Unfortunately this procedure is very model-dependent since Li/Be can vary between 10 and \( \sim 300 \) depending on the details of the cosmic-ray sources and propagation—e.g., source spectra shapes, escape pathlength magnitude and energy dependence, and kinematics (Fields, Olive & Schramm 1994) On the other hand, the \(^6\text{Li}/7\text{Li} \) ratio is a relatively model-independent prediction of cosmic-ray nucleosynthesis. With more data, one could use this model-independence to great advantage, as follows. Given enough \(^6\text{Li} \) Pop II data, one could use the observed
$^6$Li evolution (1) to infer $^7$Li$_{CR}$ and thus $^7$Li$_{BB}$, and (2) to measure $^6$Li/Be and thereby constrain in more detail the nature of early Galactic cosmic rays.

In standard stellar models, Brown & Schramm (1988) have argued that $D_6 \sim D_7^\beta$ with $\beta \approx 60$. Clearly in this case any observable depletion of $^7$Li would amount to the total depletion of $^6$Li. Hence the observation of $^7$Li in HD84937 has served as a basis to limit the total amount of $^7$Li depletion (Steigman et al. 1993, Lemoine et al. 1997, Pinsonneault et al. 1998). There are however, many models based on diffusion and/or rotation which call for the depletion $^6$Li and $^7$Li even in hot stars. The weakest constraint comes from assuming that depletion occurs entirely due to mixing, so the destruction of the Li isotopes is the same despite the greater fragility of $^6$Li. Because $^6$Li/$^7$Li $\sim 1$ in cosmic-ray nucleosynthesis, the observation of $^6$Li does exclude any model with extremely large $^6$Li depletion on the basis of the Spite plateau for $^7$Li up to $[\text{Fe/H}] = -1.3$ (Pinsonneault et al. 1998, Smith et al. 1998). However, barring an alternative source for the production of $^6$Li, the data are in fact much more restrictive. At the 2$\sigma$ level, the model used to produce the evolutionary curve in Figure I, would only allow a depletion of $^6$Li by 0.15 dex ($D_6 > 0.7$); since $D_7 \geq D_6$, this is also a lower limit to $D_7$. We note that with improved data on BeB as well, and knowing that $D_B \geq D_{Be} \geq D_7 \geq D_6$, one can further limit the degree of depletion in the lighter isotopes.

Further constraints on $D_7$ become available if we adopt a model which relates $^6$Li and $^7$Li depletion. E.g., if we use $\log D_6 = -0.19 + 1.94 \log D_7$ as discussed in Pinsonneault et al. (1998), the data in the context of the given model would not allow for any depletion of $^7$Li. Of course there is uncertainty in the model as well. Using the Balmer line stellar parameters, we found (Fields & Olive 1998) $\omega_{\text{O}/\text{Fe}} = -0.46 \pm 0.15$. Using the value of -0.46, we determine that at the 2$\sigma$ (with respect to the $^6$Li data) that $\log D_6 > -0.32$ and would still limit $\log D_7 > -0.07$. Even under what most would assume is an extreme O/Fe dependence of $\omega_{\text{O}/\text{Fe}} = -0.61$, $^6$Li depletion is limited to by a factor of 3.5 and corresponds to an upper limit on the depletion of $^7$Li by 0.2 dex. This is compatible with the upper limit in Lemoine et al. (1997) though the argument is substantially different.

It should be clear at this point, that improved (≡ more) data on $^6$Li in halo stars can have a dramatic impact on our understanding of cosmic-ray nucleosynthesis and the primordial abundance of $^7$Li. Coupled with improved data on the O/Fe ratio in these stars, we would be able to critically examine these models on the basis of their predictions of $^6$Li and $^9$Be.
5. Conclusion

We have considered the evolution of $^6$Li in context of standard Galactic cosmic ray nucleosynthesis. In this scenario, $^6$Li and $^7$Li have a primary origin, due to the dominance of $\alpha + \alpha$ in Pop II, while Be and $^{10}$B are secondary (with $^{11}$B primary due to the neutrino process). $^6$Li thus provides an excellent diagnostic of LiBeB origin, both by itself and in ratio to Be and B. We find that if O/Fe has a changing slope in Pop II, as suggested by Israeli et al. (1998) and Boesgaard et al. (1998), then standard GCRN provides a good fit to $^6$Li/H and $^6$Li/Be for both Pop II and solar data. On the other hand, a model with constant O/Fe in Pop II does poorly, illustrating the need to determine the O/Fe trend accurately.

Given the evolution scheme proposed here, one can constrain both $^6$Li and $^7$Li depletion in halo stars. The predictions here are in good agreement with the observed $^6$Li data, uncorrected for depletion; it follows that in our model, the $^6$Li depletion cannot be very large: the abundance is reduced by a factor of 3.5 at the extreme, and more likely a factor of $< 2$. Using the model discussed in Pinsonneault et al. (1998), this leads to an upper limit on $^7$Li depletion of 0.2 dex.

It is interesting to note the robustness of our conclusions regarding $^6$Li evolutionary constraints Pop II Li depletion. As noted above, the GCRN model is not the only possible scenario for LiBeB production allowed by the current data. A class of sharply different scenarios is also viable, in which all of LiBeB are primary products through new mechanisms in addition to the standard GCRN. The $^6$Li evolution in one such model is considered in detail by Vangioni-Flam et al. (1998b), in an analysis very similar to our own. Interestingly, the two very different models get similarly strong constraints. Thus the basic conclusion is quite robust that viable LiBeB evolution models imply small $^6$Li depletion.

We wish to re-emphasize the utility of, and need for, more and better observations of $^6$Li, Be, and B in Pop II. The ambiguity of the putative “primary” versus “standard GCRN” scenarios can be resolved with careful observations, which will also pave the way for sharper tests of Li depletion, a better knowledge of the primordial Li abundance, and a better understanding of early Galactic cosmic rays.

Finally, as this volume celebrates the life and science of David Schramm, it is particularly fitting to point out his major role in the study of LiBeB origin and evolution. A single example of his impact is the prescient work of Reeves, Audouze, Fowler, & Schramm (1973), which sweepingly laid out a paradigm for the origin of the light elements. The LiBeB origin proposed by Reeves et al. combined contributions from primordial $^7$Li, cosmic-ray-produced $^6$Li, Be, and $^{10}$B, and an additional stellar $^7$Li and $^{11}$B source. This
basic picture has served as the starting point for all subsequent work in the field, including
the model presented here.

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Fig. 1.— The $^6$Li evolution as a function of [Fe/H]. *Solid line:* the “revised standard” GCRN model. Here Fe is scaled from the calculated O to fit the observed [O/Fe]–[Fe/H] slope. *Dashed line:* the GCRN model with Fe $\propto$ O in POP II. The error bars on the points are 2 sigma errors, and the spread in the points connected by lines show the uncertainty due to stellar parameter choices.
Fig. 2.— The evolution of the $^{6}\text{Li}/\text{Be}$ and $^{6}\text{Li}/\text{B}$ ratios. Models are as in Figure 1. The error bars on the points are 2 sigma errors, and the spread in the points connected by lines show the uncertainty due to stellar parameter choices.