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Pop II ^{6}Li as a Probe of Nucleosynthesis and Stellar Structure and Evolution

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Abstract

We discuss the importance of Pop II ^{6}Li as a diagnostic for models of primordial nucleosynthesis, cosmic ray nucleosynthesis in the early Galaxy and the structure and evolution of metal-poor solar type stars. The observation of ^{6}Li in the sub-dwarf HD 84937 is shown to be consistent with the existing Pop II LiBeB data within the context of a simple three-component model: (1) Standard big bang nucleosynthesis + (2) Pop II cosmic ray nucleosynthesis + (3) standard (non-rotating) stellar LiBeB depletion. If this interpretation is correct, we predict a potentially detectable boron abundance for this star: $B/H \sim 2 \times 10^{-12}$. Subsequent Pop II LiBeB observations, and in particular further observations of Pop II ^{6}Li, are shown to be crucial to our understanding of the primordial and early-galactic creation and destruction mechanisms for light elements.

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It is widely recognized that the abundances of the isotopes of the light elements lithium, beryllium and boron contain valuable astrophysical information. The abundances and abundance ratios in stars of different ages, masses and metalicities provide constraints on:

- Primordial Nucleosynthesis
- Cosmic Ray Nucleosynthesis/Galactic Chemical Evolution
- Stellar Structure and Evolution

In particular, the LiBeB abundances inferred from observations of very metal-poor halo stars (Spite & Spite 1982a,b,1986; Rebolo *et al.* 1988; Ryan *et al.* 1990; Gilmore, Edvardsson & Nissen 1992; Ryan etal 1992; Gilmore *et al.* 1992; Duncan, Lambert & Lemke (1992)) have been used as a probe of primordial and early-Galaxy nucleosynthesis (Steigman and Walker 1992 (SW); Prantzos, Cassé & Vangioni-Flam 1993 (PCV); Olive & Schramm 1992 (OS); Walker *et al.* 1993 (WSSOF)). A key to the utility of the LiBeB data is that the production sites of these relatively fragile elements and their isotopes are limited. For example, in standard big bang nucleosynthesis (SBBN) only ^{7}Li is produced in an astrophysically interesting abundance. In stars and/or supernovae only ^{7}Li and B are - perhaps - produced significantly (Woosley *et al.* 1989; Brown *et al.* 1991). The relativel y small binding energy of the LiBeB isotopes requires that they be made in high energy - low density environments which are rare in cosmology and astrophysics. As a result, the major site for the origin of ^{6}Li, Be and perhaps significant amounts of Pop II ^{7}Li and B is believed to be cosmic ray nucleosynthesis (CRN). That is, the fusion/spallation reactions that occur when galactic cosmic rays collide with the nuclei of interstellar gas atoms (Reeves, Fowler & Hoyle 1970; Menneguzzi, Audouze & Reeves 1971; Walker, Mathe ws & Viola 1985; SW).

Even for LiBeB however, there are more unknown astrophysical quantities which enter into the abundance predictions than there are observables. For this reason it is often useful to consider abundance ratios so that - at some level - the astrophysical unknowns are reduced and some of the uncertainties are cancelled. In this manner it has been shown (SW; OS; WSSOF) that observations of LiBeB in Pop II halo stars are consistent - within the observational uncertainties and the theoretical simplifications - with SBBN, CRN, and standard models of standard LiBeB depletion. If indeed CRN is an important contributor to the Pop II LiBeB abundances, then certain predictions emerge for the isotope ratios. In particular Walker *et al.* (1993) noted that the observed Be and B abundances in metal-poor halos stars suggested that observable amounts of the very fragile isotope ^{6}Li would have been produced and, if not destroyed by nuclear burning (Brown & Schramm 1988; Deliyannis *et al.* 1989 (DDKKR); Deliyannis, Demarque & Kawaler 1990 (DDK)), might be observable in the warmer Pop II stars.

It is in this context that the observation of ^{6}Li in the halo star HD 84937 by Smith, Lambert and Nissen (1992) (SLN) assumes great importance. If this seminal result is confirmed and extended to other metal-poor halo stars, ^{6}Li will prove a crucial diagnostic for primordial nucleosynthesis, CRN and the structure and evolution of metal-poor solar type stars. It is the purpose of this *Letter* to review the context of the SLN observation and to explore the inferences which may be drawn from their data as well as from future observations of ^{6}Li in Pop II halo sta rs.

To keep our discussion as self-contained as possible, we briefly outline the predictions of CRN (for further details see SW and WSSOF). Although our discussion is based on a simplified model for galactic chemical evolution, our predictions can be related to those of more complex mode ls (which have even more unknown functions of time and/or metalicity). In general, CRN depends on the time evolution of the ^{4}He and heavy element (CNO) abundances, on the evolution of the spectrum and overall normalization of the cosmic ray flux and on other evolutionary factors which are either unknown or poorly constrained. We choose to normalize to the present cosmic ray flux and have lumped all the uncertainties into the various "exposure times":

$$10^{12} y_A = \sum_{i,j} R_{ij}(A) \Delta t_{ij}. \qquad (1)$$

In (1), $y_A = N_A/N_H$ is the abundance of isotope A; $R_{ij}(A)$ are the "reduced" production rates of A in collisions of cosmic ray nucleus i with ISM nucleus j (i and j are summed over protons, ^{4}He, C, N and O in both the cosmic rays and interstellar gas). Without information on the evolution of cosmic ray fluxes and abundances, there are simply too many unknown functions of time on the right hand side of (1) to make much progress. We can exploit the data on the CNO abundances in halo dwarfs (Sneden, Lambert & Whitaker (1979); Barbuy & Erdelyi-Mendes (1988); Wheeler, Sneden & Truran (1989)) to adopt $[C/H] = [N/H] = [Fe/H]$ and $[O/Fe] \approx 0.5$ which relates the relative exposure times of C, N, and O nuclei and reduces the number of independent Δt_{ij} to two: Δt_α (for the Li producing $\alpha - \alpha$ fusion reactions) and Δt_{CNO} (for p, α and CNO spallation reactions). We also ignore any small variations in the ^{4}He abundance during Pop II nucleosynthesis. The ratio $\Delta t_{CNO}/\Delta t_\alpha$ is the time average - weighted by the cosmic ray flux - of the CNO abundances until the metalicity achieves the value of [Fe/H] observed for the star in question. Because of the weighting with cosmic ray flux (which may have been larger in the early Galaxy), Δt_α and Δt_{CNO} can be much larger than the actual time. In the case that the synthesis occurs in the ambient interstellar medium where the CNO abundances are monotonically increasing functions of time, $\Delta t_{CNO} \leq \Delta t_\alpha$ and the Be and B abundances, which depend on the integrated product of the cosmic ray flux and CNO densities, would be expected to show a quadratic dependence on the Fe abundance. However if Li, Be, and B are synthesized in supernova environments the CNO abundances are much larger during cosmic ray nucleosynthesis than the subsequently diluted abundances we observe in metal-poor halo stars (Feltzing & Gustafsson (1993)) In such situations $\Delta t_{CNO} \geq \Delta t_\alpha$ and the Be and B abundances would show a linear dependence on Fe/H. Observations show that Be and B in extreme Population

II dwarfs vary linearly with O which is supportive of the *in situ* production scenarios and suggests $\Delta t_{CNO} \gtrsim \Delta t_\alpha$. Note that the B/Be ratio expected from CRN is insensitive to the timescale ratio (WSSOF), but the relative yields of Li to either Be or B depend directly on $\Delta t_\alpha/\Delta t_{CNO}$. In the absence of a specific model, neither Δt_α nor Δt_{CNO} nor their ratio can be calculated; Steigman and Walker (1992), in their "zeroth order model" assumed $\Delta t_\alpha = \Delta t_{CNO}$. We must use observational data to constrain Δt_α and Δt_{CNO} if we are to use the LiBeB data from metal-poor halo stars.

For example, if it is assumed that Be is synthesized only in CRN, then

$$y_{Be}^{CR} = [R_{CNO}(Be)\Delta t_{CNO}] \times 10^{-12}, \tag{2}$$

where $R_{CNO}(Be) = 3.4 \times 10^{[Fe/H]}$ and Δt_{CNO} is measured in Gyr. If Be is undepleted in Pop II stars, then $\Delta t_{CNO} = 10^{12} y_{Be}^{OBS}/R_{CNO}(Be)$. From the available data on metal-poor halo stars containing Be, the best fit to the data gives $12 + \log y_{Be}^{OBS} = 1.8 + 1.1[Fe/H]$. This is consistent within the observational uncertainties to a fit which is linear in [Fe/H] and gives $12 + \log y_{Be}^{OBS} \approx 1.6 + [Fe/H]$ (WSSOF; OS) so that

$$\Delta t_{CNO} \approx 11 \text{ Gyr}. \tag{3}$$

Note that, to the extent that the observed Be varies linearly with Fe/H, Δt_{CNO} is **independent** of metalicity. If we allow for depletion of Be so that $y_{Be}^{OBS} = D_9 y_{Be}^{CR}$ ($D_9 \leq 1$), then (3) would read $D_9 \Delta t_{CNO} \approx 11$ Gyr and therefore $\Delta t_{CNO} \gtrsim 11$ Gyr, the increase in exposure time due simply to the fact that more CRN Be must be made[1].

In the case of Li, both $\alpha - \alpha$ fusion reactions and CNO spallation contribute to the yield. For example, for ^{6}Li,

$$y_6^{CR} = [R_\alpha(6)\Delta t_\alpha + R_{CNO}(6)\Delta t_{CNO}] \times 10^{-12} \tag{4}$$

The spallation component can be scaled to that for Be:

$$R_{CNO}(6)\Delta t_{CNO} = \left(\frac{R_{CNO}(6)}{R_{CNO}(Be)}\right)\left(\frac{y_{Be}^{OBS}}{D_9}\right), \tag{5}$$

where $R_{CNO}(6)/R_{CNO}(Be) \approx 2.8$ (SW). For very metal-poor stars (*e.g.*, $[Fe/H] \lesssim -2$) this contribution to y_6^{OBS} is unobservable ($\lesssim 10^{-12}$). Thus, any ^{6}Li observed in Pop II stars must be made predominantly via $\alpha - \alpha$ fusion (SW):

$$y_6^{OBS} \approx (3.4 D_6 \Delta t_\alpha) \times 10^{-12}, \tag{6}$$

[1]Initially our discussion assumes that no significant ^{6}Li, Be, or B is made in the big bang. This is true for SBBN (Thomas *et al.* (1993b)) and inhomogeneous big bang nucleosynthesis (Thomas *et al.* (1993a); Terasawa and Sato (1993)). There are some models which may make significant primordial ^{6}Li (Dimopoulos *et al.* (1988)) - we discuss this at the end of this *Letter*.

where $D_6 \leq 1$ is the ^{6}Li depletion factor. Unfortunately, neither D_6 nor Δt_α is known independent of stellar models for ^{6}Li destruction and of models for cosmic ray evolution. In the "zeroth-order model", it is assumed that $\Delta t_\alpha = \Delta t_{CNO}$. In this case we would p redict that

$$y_6^{OBS} \approx 40\left(\frac{D_6}{D_9}\right) \times 10^{-12} \tag{7}$$

Finally we turn to ^{7}Li. In addition to stellar depletion ($D_7 \leq 1$) and CRN production, there is likely to be a significant big bang nucleosynthesis contribution to the observed Pop II abundance of ^{7}Li:

$$y_7^{OBS} \approx D_7[10^{12} y_7^{BBN} + 3.6\Delta t_\alpha] \times 10^{-12}, \tag{8}$$

where, as for ^{6}Li, the CNO spallation component of ^{7}Li CRN production may be ignored. For the warmer ($T_{eff} \gtrsim 5500$K), more metal-poor ($[Fe/H] \leq -1.3$) halo stars in the "Spite plateau", $10^{12} y_7^{OBS} = 120 \pm 12$ (Walker *et al.* (1991); OS). If D_7 and y_7^{BBN} were known independently, we could use y_7^{OBS} to infer Δt_α. However, in general eq. (8) has three unknowns and only one observable. This is where observations of ^{6}Li assume such a valuable role. If ^{6}Li and ^{7}Li are both observed, then

$$y_7^{BBN} \approx \frac{y_7^{OBS}}{D_7} - (1.1)\frac{y_6^{OBS}}{D_6}. \tag{9}$$

In the context of the above discussion, we now turn to the specific observations of ^{6}Li, ^{7}Li and Be in the metal-poor dwarf HD 84937 and to what they tell us about primordial and cosmic ray nucleosynthesis and stellar evolution. Smith, Lambert and Nissen (1993) have very recently found evidence for the presence of ^{6}Li in HD 84937. Since our comparisons are with the data of SLN, we adopt their values of $[Fe/H] = -2.4 \pm 0.2$ and $T_{eff} = 6090 \pm 100$K. For ^{6}Li they find $y_6^{OBS} = (6.6 \pm 2.6) \times 10^{-12}$ and for the total lithium, $y_{Li}^{OBS} = (132 \pm 17) \times 10^{-12}$ (which agrees very well with the world average value of $y_{Li}^{OBS} = (129 \pm 18) \times 10^{-12}$ for this star). For Be the observed upper limit (Ryan *et al.* 1992) is $y_{Be}^{OBS} < 0.14 \times 10^{-12}$ and there has been a preliminary detection of Be in this star at a value consistent with this upper limit (Duncan (1992)). To our knowledge B has not been detected in this star.

With allowance for possible Be-depletion, we may use (2) to bound Δt_{CNO},

$$D_9 \Delta t_{CNO} \lesssim 10 \text{ Gyr}. \tag{10}$$

The small abundance of Be implies negligible CNO-spallation contribution to the observed ^{6}Li abundance and thus we find

$$D_6 \Delta t_\alpha \approx 2 \pm 1 \text{ Gyr}. \tag{11}$$

In fact, since $D_6 \leq D_9$, the ratio of the cosmic ray exposure times must satisfy $\Delta t_\alpha / \Delta t_{CNO} \gtrsim 0.2 \pm 0.1$. This bound is a constraint on models which go beyond the "zeroth-order" approximations. On the other hand, if the zeroth-order model assumption ($\Delta t_{CNO} = \Delta t_\alpha$) is adopted, then we may constrain the relative depletions of ^{6}Li and Be:

$$\frac{D_6}{D_9} \gtrsim 0.2 \pm 0.1. \quad (12)$$

Although this result may be consistent with the predictions of the non-rotating Yale models (DDKKR; DDK; Deliyannis and Pinsonneault 1990 (DP)), it poses a severe challenge to the rotating models (a point we return to at the conclusion of this *Letter*).

For ^{7}Li, again ignoring the spallation contribution, $y_7^{OBS} = D_7 y_7^{BBN} + 1.1(D_7/D_6) y_6^{OBS}$ Unfortunately there are only two observables and three unknowns. If we ignore entirely the BBN contribution we can bound the relative depletions of ^{6}Li and ^{7}Li using the observations of lithium in HD 84937: $D_6/D_7 \gtrsim 0.01$ at 95% CL.

It should by now be clear that we are in a no-win situation - because we have three sources of unknowns (primordial and cosmic ray production and stellar depletion) and the observations of three nuclides (^{6}Li, ^{7}Li and Be), we will always have more unknowns than observations. We can however demonstrate the consistency of the following hypothesis: if we assume the depletions predicted by the non-rotating models (DDKKR; DDK; DP) along with the predictions of the "zeroth-order" cosmic ray model, we can use LiBeB observations to infer a primordial component of ^{7}Li which we then compare with the predictions of standard big bang nucleosynthesis (SBBN). In the following we will assume [Fe/H] $=-2.4$ and [O/Fe] $= 0.5$. Based on these assumptions, the zeroth order model predicts the following ratios: $^6\mathrm{Li}/^7\mathrm{Li} \simeq 0.9$; $^7\mathrm{Li}/Be \simeq 250$; and $B/Be \simeq 14$. The ingredients of our analysis are as follows:

1. The Be abundance of HD 84937 is $\leq 1.4 \times 10^{-13}$ relative to hydro gen.

   If we *assume* $D_9 = 1$ (as predicted by non-rotating models for metal-poo r stars with $T_{eff} \gtrsim 5000$K (DP), then we find that Δt_{CNO} is given by the upper limit in Eq. (10); $\Delta t_{CNO} \lesssim 10$ Gyr.

2. We next assume that $\Delta t_\alpha = \Delta t_{CNO}$ so that $y_6^{GCR} \leq 3.5 \times 10^{-11}$ and using the observed ^{6}Li we predict

   $$D_6 \geq 0.2 \pm 0.1.$$

3. The prediction of D_6 above is consistent, *albeit* only at $2-a$, with the depletion predicted by the Yale standard models (for a 16.5 Gyr, $Z = 10^{-4}$ star with T_{eff} between 6000K and 6200K they predict $0.02 \lesssim D_6 \lesssim 0.05$).[2] For this range of ^{6}Li depletion, no ^{7}Li depletion is predicted by the standard Yale models.

[2]Depletion of ^{6}Li in stellar models without rotation is a strong function of T_{eff} (Deliyannis 1990; DDKKR; DDK), and in fact $D_6 \gtrsim 0.1$ when $T_{eff} \gtrsim 6300K$, a value consist ent (within errors) with other observations of HD 84937.

4. Armed with $D_7 = 1$ and the prediction for y_7^{GCR} of $\lesssim 37 \times 10^{-12}$ from the "zeroth-order" model we now can infer the primordial component of ^{7}Li:

$$y_7^{BBN} \gtrsim (0.9 \pm 0.2) \times 10^{-10}$$

The ^{7}Li abundance predicted by SBBN, such that the predicted yields of D, ^{3}He and ^{4}He agree with their inferred primordial abundances, falls in the range $0.8 \times 10^{-10} \lesssim y_7^{SBBN} \lesssim 2 \times 10^{-10}$ (Walker *et al.* (1991)). Our result also is in good agreement with the BBN abundance extracted by Olive and Schramm (OS): $y_7^{BBN} = (1.0 \pm 0.2) \times 10^{-10}$.

This agreement between the inferred primordial abundance and that predicted by SBBN completes our "consistency check". The observation of ^{6}Li in HD 84937 is completely consistent with the predictions of SBBN, "zeroth-order" cosmic ray nucleosynthesis and the standard model of Li and Be depletion. Furthermore the above analysis allows us to estimate[3] the boron abundance in this star, $y_{10+11} \approx 2 \times 10^{-12}$. This is to be compared with the recent HST observation (Duncan, Lambert and Lemke 1992) of B in HD 1402 83: $B/H \sim 8 \times 10^{-13}$.

We caution the reader however that our consistency check requires assumptions about the cosmic ray synthesis of Li and Be as well as a measured Be abundance. The specific numbers (and ratios in some cases) can be sensitive to the assumptions of the model. For example, if we use the averages of all observations of HD 84937 ([Fe/H] = −2.2 and [O/F e] = 0.6), the timescale Δt_{CNO} would be reduced to only 5.5 Gyr and the ^{7}Li/Be ratio drops to 135 (note that the ratios of ^{6}Li to ^{7}Li and B/Be are robust). Though we would then predict a smaller CRN component of ^{7}Li(2×10^{-11}), we would also require less depletion of ^{6}Li (by about a factor of 2). As we have discussed in this *Letter*, further observations of ^{6}Li in metal-poor halo stars are crucial to our understanding of the evolutionary details of LiBeB synthesis in the early Galax y.

Important constraints on Li depletion are provided by the Brown and Schramm (1988) depletion arguments, which examine the rates of thermonuclear ^{6,7}Li burning at the base of the convection zone. The Brown and Schramm discussion points out that the ratio of thermonuclear (p, α) reaction rates for Li destruction are significantly different at fixed temperature, with $\beta = \langle\sigma_6 v\rangle/\langle\sigma_7 v\rangle \simeq 100$, approximately constant over appropriate stellar temperatures. This disparity in the rates means that during any nuclear burning process, ^{6}Li is much more readily destroyed than ^{7}Li: $D_6/D_7 \simeq D_7^{\beta-1}$. In the context of the present discussion, the Brown and Schramm result shows that if the depletion occurs by thermonuclear burning at the base of the convective zone, then given the lower bound $D_6/D_7 \gtrsim 0.01$, we have $D_7 \simeq 1$. Furthermore, if such burning

[3]Note that throughout this paper we have assumed the spectral index of the cosmic ray spec trum to be the same in the early Galaxy as it is today. Relaxing this assumption (as well as allowing the CNO composition to vary) allows B/Be to vary by 50% from its zeroth-order value of 14 (WSSOF). We have not included this uncertainty in our prediction of the B abundance based on the observation of *li*.

takes place, D_6 is a strong function of the temperature at the base of the convective zone, which must then be carefully tuned to give depletion significantly different from 0 or 1. The above constraints are avoided, however, if instead of nuclear burning, there is depletion through dilution or diffusion processes which mix material from the outer shells deep into the stellar interior where *all* Li is destroyed. In such a case the bound on D_6/D_7 may allow for significant ^{7}Li depletion.

Lastly we turn to depletion in the Yale models with rotation (Deliyannis 1990; PDD; DP). As we have already mentioned, the ratio of the relative depletion of ^{6}Li to Be is a crucial diagnostic for stellar models. Our argument is a simple one based on the "zeroth-order" cosmic ray model,the observation of ^{6}Li and the observed upper bound to the Be abundance in HD 84937. For the Yale rotational models (we use the isochrones labeled "J0" for ages of 10 to 20 Gyr), $D_9 \approx 0.6 \pm 0.1$ (DP). From Eq. (11) we see that this implies that $D_6 \gtrsim 0.10 \pm 0.05$ for these sam e models. **We know of no rotational depletion models (for any temperature or any age between 10 and 20 Gyr) with $D_6 \geq 0.007$.**

Can such a large ^{6}Li depletion be reconciled with other LiBeB data? From the Yale rotational models (J0) of 16.5 Gyr stars with $Z = 10^{-4}$, and $6000K \lesssim T_{eff} \lesssim 6200K$: $D_7 \approx 0.15$ and $D_9 \approx 0.6$ and $0.0004 \lesssim D_6 \lesssim 0.001$ (Deliyannis 1990; PDD; DP). Using these predicted depletions and the SLN data for HD 84937, the inferred pre-stellar abundances are:

$$y_6^{PopII} = (6.6 \pm 2.6) \times 10^{-9} \left(\frac{10^{-3}}{D_6}\right),$$

$$y_7^{PopII} = (8.4 \pm 1.1) \times 10^{-10} \left(\frac{0.15}{D_7}\right),$$

and

$$y_9^{PopII} \lesssim (2.3 \times 10^{-13}) \left(\frac{0.6}{D_9}\right).$$

These should be compared to the solar system abundances (Grevesse & Anders 1989): $y_{6\odot} = 1.5 \times 10^{-10}$, $y_{7\odot} = 1.9 \times 10^{-9}$ and $y_{9\odot} = 2.6 \times 10^{-11}$. Thus the Pop II ($[Fe/H] \approx -2.4$) abundances inferred from the data and the Yale rotational models require that while Be increases by some two orders of magnitude from Pop II to Pop I, ^{6}Li must *decrease* by one to two orders of magnitude. Further, the Pop II 6/7 ratio must decrease by two orders of magnitude from $(y_6/y_7)_{PopII} \gtrsim 8 \pm 3$ to $(y_6/y_7)_\odot = 0.08$. Although the inferred high Pop II ^{6}Li to ^{7}Li ratio may seem to lend suppor t to the late decaying particle nucleosynthesis model of Dimopoulos *et al.* (1990), the very high Pop II ^{6}Li abundance is a challenge to that model. Furthermore , it is hard to see how ^{6}Li could decrease by such a large factor without a comparable - or larger - decrease in the Pop II (BBN) abundance of deuterium which has no significant galactic production source. Using the recent HST data of Linsky *et al.* (1992), the Yale rotational models would require an enormous BBN deuterium abundance

$$y_2^{BBN} \gtrsim y_2^{PopI}(y_6^{PopII}/y_6^{PopI}) \gtrsim 7 \pm 3 \times 10^{-4} \tag{13}$$

Our conclusion is that the single measurement of ^{6}Li in the Pop II star dwarf HD 84937 is completely consistent, when viewed in context with other Pop II LiBeB abundances, with the predictions of a three-component model:

1. Primordial ^{7}Li production as predicted by standard big bang nucleosynth esis.
2. LiBeB production in the early Galaxy by Pop II cosmic ray nucleosynthesis.
3. LiBeB depletion by metal-poor stars with little or no rotation.

Models with additional parameters above and beyond those contained in our simple three-component model do not seem to fit the available data as easily. Indeed, as we have shown, under certain assumptions about the evolutionary history of the early Galaxy, measurements of Pop II ^{6}Li along with other LiBeB nuclides pose a severe test for stellar depletion models with rotation in conjuction with non-standard models of nucleosynthesis. Additional observations of Pop II ^{6}Li (along with other Pop II LiBeB nuclides) are crucial to our understanding of primordial and early Galaxy nucleosynthesis and to the understanding of stellar structure and evolution of metal-poor solar type stars.

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