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Jeremy R. King
Clemson University, jking2@clemson.edu

Constantine P. Deliyannis
Yale University

Ann Merchant Boesgaard
University of Hawaii

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CONSTRAINTS ON THE ORIGIN OF THE REMARKABLE LITHIUM ABUNDANCE IN THE HALO STAR BD+23 3912

JEREMY R. KING[1]
Department of Astronomy, RLM Building 15.308, University of Texas, Austin, Texas 78712
Electronic mail: king@verdi.as.utexas.edu

CONSTANTINE P. DELIYANNIS[1,2]
Department of Astronomy, Center for Solar and Space Research, and Center for Theoretical Physics, Yale University,
P.O. Box 208101, New Haven, Connecticut 06520-8101
Electronic mail: con@athena.astro.yale.edu

ANN MERCHANT BOESGAARD[2]
Institute for Astronomy, University of Hawaii, 2680 Woodlawn Drive, Honolulu, Hawaii 96822
Electronic mail: boes@galileo.ifa.hawaii.edu

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ABSTRACT

The Li abundance of the halo star BD+23 3912 ([Fe/H]$=-1.5$) lies a factor of $2-3$ above the Spite plateau. This remarkable difference could reflect either less-than-average stellar Li depletion from a higher primordial Li abundance (as predicted by the Yale rotational stellar evolutionary models), which may have interesting implications for Big Bang nucleosynthesis, or the extraordinary action of Galactic Li production mechanisms. It is also possible that both processes have acted. We use our high resolution, high S/N Keck HIRES spectrum of BD+23 3912 to determine the s-process element abundances and ^{6}Li/^{7}Li ratio in this star. These values serve as signatures for two possible Li production scenarios: the ^{7}Be transport mechanism in AGB stars, and cosmic ray interactions with the ISM. The unremarkable abundances of Y, Zr, Ba, La, Nd, and Sm that we derive argue against a significant contribution to this star's excess Li from AGB production mechanisms carrying an s-process signature. Since halo subgiants like BD+23 3912 are expected to be particularly good ^{6}Li preservers, our conservative upper limit of ^{6}Li/^{7}Li≤ 0.15 (compared to $0.25-0.50$ expected from cosmic ray production) argues against cosmic ray + ISM interactions as the source for the excess Li, unless Li depletion from an even higher abundance has occurred with preferential ^{6}Li depletion. Highly speculative RGB production scenarios also seem unlikely given the normal Na and Al abundances we find and the normal C and O abundances determined by others. The totality of Li data on halo subgiants argues against possible diffusion scenarios, in which all such stars dredge up Li that diffused during the main sequence. While the high Li abundance in BD+23 3912 is consistent with that expected from Yale rotational models having a lower-than-average initial angular momentum, future observations of ν-process elements (particularly ^{11}B) produced in supernovae should provide additional constraints on any enrichment scenarios seeking to explain the large Li abundance of this interesting star. © *1996 American Astronomical Society.*

1. INTRODUCTION

Halo dwarfs and subgiants near the turnoff have long been known to display an approximately (but not completely, see below) uniform plateau of lithium (Li) abundances (Spite & Spite 1982). Figure 1 shows that the halo star BD +23 3912 is unusual in that its lithium (Li) abundance[3] lies approximately a factor of 2 above the Spite plateau.[4] There are at least two possible reasons for this, which we investigate here: (1) the initial abundances of halo stars were higher in general, and stellar processing has depleted them to current levels, but less depletion took place in this star, and (2) a source of Li production affected the material out of which this star formed, or contaminated its surface after it formed.

Figure 1 shows Li equivalent widths for: (a) plateau halo dwarfs as compiled and averaged in Ryan *et al.* (1996) (b)

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[1] Hubble Fellow.

[2] Visiting Astronomer, W. M. Keck Observatory, jointly operated by the California Institute of Technology and the University of California.

[3] Li abundances are given on a common logarithmic scale by number relative to hydrogen where hydrogen is 12. (i.e., $A(\mathrm{Li})=12+\log(N(\mathrm{Li})/N(\mathrm{H}))$). We also employ the usual notation $[a/b]$ to give the abundance ratio of element a to b by number on a logarithmic scale, relative to the solar abundance ratio.

[4] T_{eff} for subgiants and possible subgiants are those used in Fig. 4 of Deliyannis et al. (1995a), which are consistent with the T_{eff} scale of Thorburn (1994). A comparison of 70 stars in common (ignoring CS 22876−32, CS 29506−7, and G21−22 for reasons discussed in Ryan *et al.* 1996) shows that her temperatures are, on average, 16 K higher than those adopted by Ryan *et al.* 1996. For consistency, we have raised all T_{eff} values from Ryan *et al.* 1996 by 16 K in Fig. 1.

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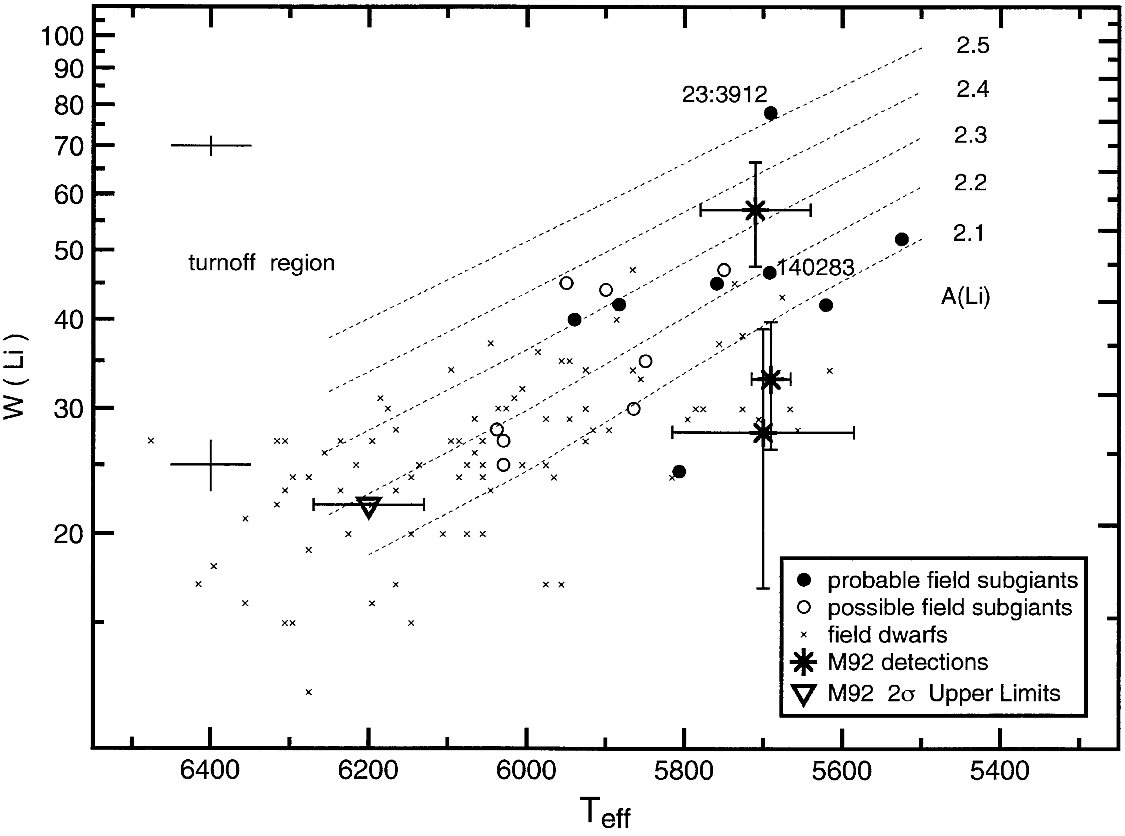

FIG. 1. Li equivalent widths for field plateau halo dwarfs (crosses) as compiled and averaged in Ryan *et al.* (1996), for subgiants (circles) as compiled and averaged similarly by us from the same sources listed in Ryan *et al.*, and for subgiants (asterisks and inverted triangle) in the globular cluster M92 recently observed by us on the same night as the data presented here for BD+23 3912. The subgiants plotted here are listed in Deliyannis *et al.* (1995). It becomes more difficult to distinguish between subgiants and dwarfs near the turnoff, so some of the hotter stars have only been assigned "possible subgiant" status (open circles vs filled circles for probable subgiants). 1σ errors in W(Li) and $T_{\rm eff}$ are explicitly shown for the M92 stars ($V=18$); for the field dwarfs and subgiants ($V\sim 8-12$) typical errors (~ 2 mÅ per star in W(Li), see Ryan *et al.* 1996, and ~ 50 K in $T_{\rm eff}$, see Deliyannis *et al.* 1995b) are shown to the left, at two different W(Li). Also shown are lines of constant Li abundance.

subgiants[5] we compiled and averaged similarly and (c) subgiants in the globular cluster M92 recently observed by us (Deliyannis *et al.* 1995a). For the subgiants BD+23 3912 and HD 140283, we show only our own Keck data acquired on the same night as the M92 observations. It is clear that BD+23 3912 has a higher Li abundance than any other plateau star. At similar $T_{\rm eff}$, its abundance is about a factor of two larger than that of other halo subgiants and a factor of 3 larger than dwarfs. Compared to stars right at the turnoff, its abundance is about a factor of 2 higher. If apparent Li differences at the turnoff are due to Galactic Li enrichment, then BD+23 3912 must be compared to the *lower* (less enriched) turnoff abundances– it is about a factor of 3 higher than those.

Evidence is mounting that one cannot merely equate a simple average of plateau Li abundances with the pristine, primordial Li abundance (hereafter, Li_p). Ryan *et al.* (1996) have applied multiple regression methods in a uniform reanalysis of all published halo plateau Li data. They (a) show that dwarfs exhibit a slight trend with $T_{\rm eff}$, (b) find evidence for a very slight trend of Li with Fe, and (c) find evidence that at least a few stars have clearly different Li abundances (see Ryan *et al.* for references to earlier suggestions of these trends and to opposing views). Additionally, a few stars are known that are very Li-deficient relative to the plateau (Thorburn 1992, 1994, and references therein). The Li-$T_{\rm eff}$ trend clearly shows that cooler *plateau* stars have less Li than turnoff stars. The Li−Fe trend could be due to Galactic Li enrichment, metallicity-dependent stellar Li depletion, or both. The severely Li depleted stars could reflect some process(es) that are active only in them or that are active in all stars (depleting the entire Li plateau, but having depleted them more extremely). Improved understanding of the observed substructure of the Spite plateau is clearly prerequisite to a confident determination of Li_p. The high Li abundance of BD+23 3912 might offer important clues in this regard.

We also note that, whereas it is not currently possible to distinguish between dwarf and subgiant Li abundances near the turnoff ($\sim$6300 K), subgiants seem to have (on average)

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[5] Evolutionary status has been determined on the basis of the c_0 Stromgren index and the diagrams of Schuster & Nissen (1989); for precision, we refer to any star evolved past the bluest point at the turnoff as a subgiant.

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slightly higher Li abundances than dwarfs near 5700 K (where dwarfs are more easily distinguished from subgiants, Fig. 1). This difference is consistent with (a) the preservation of Li to depths of order a few percent by mass and its manifestation at the surface as the subgiant convection deepens past the turnoff (e.g., Deliyannis *et al.* 1990) and (b) the observed trend of decreasing A(Li) with lower $T_{\rm eff}$ for dwarfs. The difference between subgiants and dwarfs at 5700 K indicates that discussions of halo Li abundances should separate dwarfs and subgiants, even on the plateau itself.

One possible explanation for the enhanced Li seen in BD +23 3912 is Li production, either recent or pre-stellar. If A($\mathrm{Li_p}$)$\sim$2.1, consistent with stellar models that ignore possible effects of rotation (Deliyannis *et al.* 1990; Proffitt & Michaud 1991), then Galactic Li production is needed to raise the Li abundance to Population I levels (the largest, presumably minimally depleted, Population I abundances found are generally $\sim$3.0$-$3.3, as measured in meteorites and young clusters; e.g., Anders & Grevesse 1989, Soderblom *et al.* 1993a, Cunha *et al.* 1995). At least three plausible Li production mechanisms exist: (a) $\alpha+\alpha$ production from, e.g., cosmic rays interacting with the ISM (Steigman & Walker 1992; Prantzos *et al.* 1993), (b) the neutrino process in Type II supernovae (Woosley *et al.* 1990; Timmes *et al.* 1995), and (c) the ^{7}Be transport process (Cameron & Fowler 1971) in asymptotic giant branch (AGB) stars. Li-rich AGB stars have been observed in the moderately metal-poor Small Magellanic Cloud (Smith & Lambert 1990) and a very Fe-poor, Li-rich CH subgiant has been observed in the field (Thorburn 1994, McWilliam *et al.* 1995). These stars are markedly overabundant in s-process elements, and we use this as one possible signature of the ^{7}Be transport mechanism.

Alternatively, stellar processing may have depleted less Li in BD+23 3912 from a significantly higher initial abundance for all halo stars. Evolutionary models which consider mixing related to instabilities triggered by angular momentum loss and transport (Deliyannis 1990; Pinsonneault *et al.* 1992; Chaboyer & Demarque 1994; hereafter, "Yale models") find Li depletion of order one dex, suggesting initial halo Li abundances similar to those in Pop I stars. Such a high primordial Li abundance has important cosmological implications—particularly for Big Bang nucleosynthesis (Deliyannis 1995; Deliyannis *et al.* 1995a). The Yale models predict a small Li abundance dispersion in halo stars resulting from differences in, e.g., initial angular momentum or age. In this picture, BD+23 3912 could have had less Li depletion if it formed with smaller than average initial angular momentum or if it is younger than an average halo star. Support for this possibility has been found in very young Orion nebula stars by Choi & Herbst (1996), who have discovered a small fraction of stars with much longer periods (15$-$21 d; 1 star has a $\sim$35 d period) than is typical (3$-$4 and 6$-$8 d).

In this paper, we attempt to distinguish between alternative explanations. By examining elemental abundances in BD+23 3912, we are able to search for signatures of Li production mechanisms associated with advanced stages of stellar evolution (such as the ^{7}Be-transport mechanism). We also place limits in the ^{6}Li content of BD+23 3912, which constrains cosmic ray production as a source for the excess Li in this star.

2. OBSERVATIONS AND DATA REDUCTION

Observations of BD+23 3912 were obtained on 1994 July 30 (UT) using the W. M. Keck telescope, HIRES echelle spectrograph (Vogt *et al.* 1994), and a Tektronix 2048^2 CCD. The spectra cover 4480 to 6770 Å with some gaps. The measured 3.1$-$3.2 pixel FWHM resolution element corresponds to $R\sim45000$. Additional details on the instrumentation and reduction are provided by Deliyannis *et al.* (1995a). The per-pixel S/N achieved in our 3 minute exposure ranges from $\sim$200 at 4500 Å to 325 at 6700 Å. Figure 2 shows different regions of our final spectrum with some features of interest marked.

3. RADIAL VELOCITY DETERMINATION

Few radial velocity estimates for BD+23 3912 have been published. We were only able to locate the three photographic-based values of Bond (1970). A modern measurement may be of future use in assessing (e.g.) binary status; we have made one using our spectrum, which was acquired on HJD 2449564.061. The radial velocity was determined from a cross correlation analysis using the `fxcor` routine in the `rv` IRAF package. As a template, we used a lunar reflectance spectrum which was acquired on the same night with the same instrumentation as for BD+23 3912. An apodized region from $\sim$5125 to 5200 Å (commonly used in stellar radial velocity studies) was filtered (with the various available `fxcor` options) in Fourier space to remove the highest and lowest data frequencies. The resulting cross correlation peak was then fit with Gaussians, parabolas, and Lorentzians to determine the velocity shifts.

There is excellent agreement (within $\sim$0.4 km s^{-1}) in the velocities derived with different choices of filter, region of the power spectrum filtered, and correlation peak fitting function. Because the present spectra were not taken with precision radial velocities in mind, no deliberate attempt was made to monitor instrumental drifts in the ensuing 2.5 hours between the BD+23 3912 and lunar exposures. We were able to assess these, however, by investigating the positions of numerous telluric $\mathrm{O_2}$ features near 6290 Å in both spectra. These consistently indicated a small shift of $\sim$1.1 km s^{-1}. Applying this shift and the appropriate diurnal, lunar, and annual velocity corrections, we find a radial velocity of -115.2 km s^{-1}. While the internal uncertainties ($\leq$1 km s^{-1}) would seem to allow such precision, the total (1σ level) uncertainties may approach 1.5$-$2.0 km s^{-1}. Our radial velocity is, fortuitously, in nearly exact agreement with the mean of Bond's (1970) three values.

4. ABUNDANCE ANALYSIS

4.1 Equivalent Width Data

We searched the literature (e.g., Gratton & Sneden 1994, McWilliam *et al.* 1995, various solar analyses) for *n*-capture element line lists. We were able to identify confidently eight

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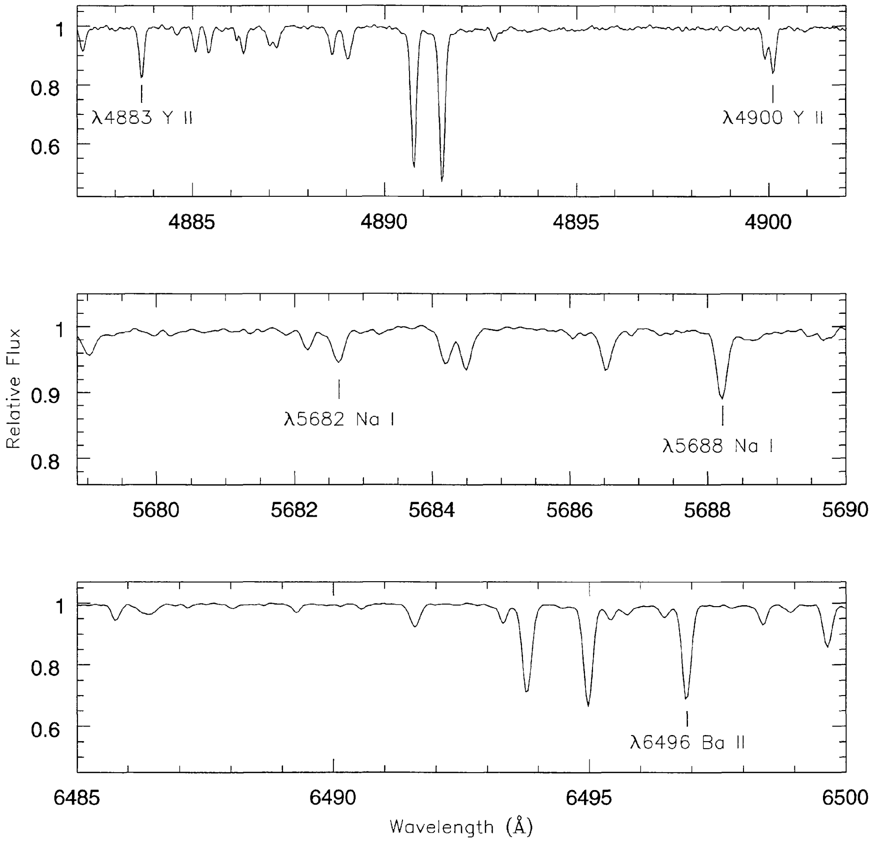

FIG. 2. Samples of our HIRES spectrum of BD+23 3912. The top panel shows a region containing two of the Y II lines used in the analysis. The middle panel shows two of the weak Na I lines. The bottom panel includes the Ba II line at 6496 Å used in our analysis.

Y II lines, 4 Ba II lines, and 1 Zr II line in our spectrum which are reliable for use in abundance determinations. These lines are listed in the second column of Table 1. Not listed are the λ5319.8 Nd II, λ4642.3 Sm II, λ4574.9 La II, and λ4522.6 Eu II lines which we use to derive abundance upper limits. We also measured abundances of the non-n-capture elements Na and Al using the neutral features listed in Table 1.

Equivalent widths were measured using various routines in the IRAF and SPECTRE (Fitzpatrick & Sneden 1987) packages. Solar equivalent widths were taken from literature measurements, our own high resolution ($R \sim 80{,}000$) daytime sky spectra obtained with the McDonald Observatory 2.7-m and 2D-Coude spectrograph (Tull *et al.* 1995) in January 1994, or from resampled and renormalized Kurucz *et al.* (1984) flux atlas data. Comparison of the multiple measurements indicates good agreement that is well within the uncertainties. We assessed uncertainties from the various repeated measures and a subjective estimate of the continuum location uncertainties. The resulting values are somewhat larger than those expected from limiting case photon-noise based estimates (e.g., Cayrel 1988), but are more appropriate. The solar and BD+23 3912 equivalent widths, their uncertainties, and the source of the solar measurements are given in Table 1.

4.2 Stellar Parameters

We take values of $T_{\rm eff}$, log g, and [Fe/H] for BD +23 3912 from Deliyannis *et al.* (1995b). Using numerous studies with high quality data, these authors derived self-consistent parameters (temperature, gravity, and [Fe/H]) based on the widely-used color$-T_{\rm eff}$ relation of Carney (1983) and that of King (1993), whose scale gives hotter temperatures. The $(b-y)$ color from Schuster & Nissen (1988) yielded a $T_{\rm eff}$ value for BD+23 3912 on both scales. The [Fe/H] values from literature studies were adjusted to reflect the differing $T_{\rm eff}$ choices and then averaged. Gravities derived from ionization balance analyses (e.g., Tomkin *et al.* 1992 for BD+23 3912) were adjusted to reflect the different Fe I abundances derived for the different choice of $T_{\rm eff}$ scale . We believe the subgiant status we assign to BD +23 3912 is secure since it is indicated by both the large Stromgren c_1 index and the ionization balance analysis of Tomkin *et al.* (1992). Here, we adopt the average (which is sufficient for our purposes) of the parameters from each scale. Namely, we take $T_{\rm eff}$= 5750 K, log g = 3.75, and [Fe/H]= −1.49; this $T_{\rm eff}$ value is very close to the recent infrared flux method determination of 5788 K by Alonso *et al.* (1996). The estimated 1σ level internal uncertainties (i.e., on a given $T_{\rm eff}$ scale) are ±40 K, ±0.10 dex in gravity, and

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TABLE 1. Equivalent width measurements.

Species	Wavelength (Å)	EW($\odot$) (mÅ)	σ (mÅ)	Ref.	EW(BD+23) (mÅ)	σ (mÅ)
Y II	4854.87	46.2	–	1	17.5	1.1
	4883.69	58.9	–	1	31.5	3.1
	4900.11	55.3	–	1	26.5	2.2
	5087.42	48.7	–	1	19.0	1.2
		47.3	–	2		
	5119.11	14.0	–	1	2.2	0.7
	5123.21	31.3	–	1	5.5	1.2
	5200.41	37.6	–	1	11.9	1.3
	5205.73	48.8	–	1	13.5	2.4
Ba II	4554.04	182.6	8.6	4	111.5	4.4
	5853.69	63.3	–	2	28.0	2.0
		64.1	1.7	5		
	6141.73	117.0	–	2	68.5	3.4
		121.1	3.9	5		
	6496.91	104.3	2.0	4	65.0	3.3
		101.1	3.7	5		
Zr II	4496.97	36.0	–	3	16.1	2.3
Al I	6696.03	38.2	2.7	5	2.5	0.9
Na I	5682.65	106.1	4.4	4	10.6	0.9
	5688.22	130.3	5.3	4	20.3	1.2
	6160.75	59.6	2.6	5	3.7	1.0
		58.6	–	2		
Li I	6707.83	–	–	–	78.0	0.9

References to TABLE 1

Hannaford *et al.* (1982), 2: Edvardsson *et al.* (1993), 3: Biemont *et al.* (1981), 4: measured from Kurucz *et al.* (1984) Solar flux atlas, 5: Measured from McDonald Observatory day sky spectra.

±0.16 dex in [Fe/H]. We also adopt a depth independent microturbulent velocity of $\xi = 1.6$ km s^{-1}. For the Sun, we use $\xi = 1.0$ km s^{-1}.

We emphasize that the inferred Li overabundance for BD +23 3912 is well-established independent of the adopted $T_{\rm eff}$ scale. This can be seen by a comparison in the $(b-y)$ versus Li equivalent width plane, which is independent of $T_{\rm eff}$ scale and details of the abundance analysis. Such a comparison is shown in Fig. 2 of Deliyannis *et al.* (1993), where mere inspection indicates the extraordinary Li line strength of this metal-poor star relative to others of similar color. This figure also indicates that the high Li abundance is independent of reddening assumptions. Indeed, any reddening for this star (we assumed none in the derivation of our $T_{\rm eff}$ values) would only increase the difference in the Li line strength/abundance relative to other stars of similar color/$T_{\rm eff}$.

The $T_{\rm eff}$ determinations for a given scale (which determines the overall scale of the Spite plateau Li abundance) also play little, if any, part in the large Li abundance inferred for BD+23 3912. This is evident from, e.g., a comparison to the halo star HD 140283, which we find to have similar parameters (except for its lower metallicity) as BD +23 3912, but whose Li abundance lies in the middle of the Spite plateau (see Fig. 1). The difference in the $T_{\rm eff}$ values (in the sense BD+23 3912 − HD 140283) are −1 and +7 K for the cooler C83 scale and the hotter K93 scale. These values are in very reasonable agreement with those derived from other color−$T_{\rm eff}$ relations by Pilachowski *et al.* (1993; −50 K) and Tomkin *et al.* (1992; −10 K) and with the infrared flux method results of Alonso *et al.* (1996; +97 K). We have also estimated the $T_{\rm eff}$ difference from $(B-V)$ photometry as in Deliyannis *et al.* (1995b), and taking into account metallicity dependency using the Yale isochrone color calibration; the resulting difference, +20 K, is in good accord with the above differences, also suggesting that the relative $(B-V)$ photometry is consistent with the $(b-y)$ photometry. If one regards the independent infrared flux method as a superior relative $T_{\rm eff}$ indicator to extant photometric calibrations, then the Li abundance of BD +23 3912 would be even larger relative to other Spite plateau stars such as HD 140283 than our $T_{\rm eff}$ estimates would indicate. Going in the other direction, the small ~50 K difference between our results and those of Pilachowski *et al.* (1993) pales in comparison to the 250 and 350 K $T_{\rm eff}$ adjustments (*relative to* other Spite plateau stars such as HD 140283) needed to force the BD+23 3912 Li abundance to match the largest and the more typical abundances on the Spite plateau (see Fig. 1).

One might wonder if the photometry for BD+23 3912 could be in error, thus causing an anomalously high Li content to be inferred in either the color−EW or $T_{\rm eff}$−abundance plane. In this case, significant photometric errors in both $(b-y)$ and $(B-V)$ would be required at the substantial level of 0.04−0.05 and 0.08−0.11 mag. Available evidence suggests otherwise. Schuster & Nissen's (1988) $b-y$ value, upon which our $T_{\rm eff}$ estimate is based, differs by only 0.01 mag from Bond's (1970) value. The Schuster & Nissen (1988) V magnitude also only differs by ≲0.01 mag from Bond's (1970) value, which (in turn) is only 0.01 mag different from that of Carney (1983). The

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TABLE 2. Abundance results

Species	Wavelength (Å)	χ (eV)	log gf	log $N(X)$ $\odot$	log $N(X)$ (BD+23)	$\pm\sigma$ (dex)
Y II	4854.87	0.99	−0.38	2.26	0.86	0.03
	4883.69	1.08	0.07	2.22	0.87	0.07
	4900.11	1.03	−0.09	2.24	0.87	0.05
	5087.42	1.08	−0.17	2.21	0.85	0.03
	5119.11	0.99	−1.36	2.36	0.84	0.12
	5123.21	0.99	−0.83	2.33	0.74	0.08
	5200.41	0.99	−0.57	2.21	0.84	0.04
	5205.73	1.03	−0.34	2.28	0.72	0.07
Ba II	4554.04	0.00	hfs	2.24	0.69	0.08
	5853.69	0.60	−1.01	2.30	0.75	0.05
	6141.73	0.70	−0.08	2.41	0.74	0.07
	6496.91	0.60	−0.37	2.36	0.81	0.07
Zr II	4496.97	0.71	−0.81	2.69	1.48	0.07
Al I	6696.03	3.14	−1.34	6.28	4.94	0.10
Na I	5682.65	2.10	−0.70	6.29	4.81	0.04
	5688.22	2.10	−0.45	6.27	4.88	0.04
	6160.75	2.10	−1.23	6.26	4.84	0.10
Li I	6707.83	0.00	hfs	–	2.56	0.07

photometry for this star, then, appears secure. In sum, the choice of $T_{\rm eff}$ scale and the uncertainties in reddening and photometry are unable to explain the relative Li overabundance seen in BD+23 3912. Rather, the abundance difference is real as can be deduced directly from the star's position in the color versus Li equivalent width plane.

4.3 Atomic Data

When possible, we adopted laboratory gf values and derive solar abundances for each line in order to minimize any uncertainty in the gf values. For Y II and Zr II we use the laboratory data of Hannaford *et al.* (1982) and Biemont *et al.* (1981), respectively. Data for the Ba II lines were taken from Beveridge & Sneden (1994) and McWilliam *et al.* (1995), who use NBS results (Wiese & Martin 1980). For the Al I 6696 Å line and three Na I lines, we adopt the Wiese & Martin (1980) gf values used by Beveridge & Sneden (1994); the Al value seems somewhat uncertain (see below). Oscillator strengths for the Nd II, Sm II, and La II lines were the experimental values of Maier & Whaling (1977), Biemont *et al.* (1989), and the solar value of Beveridge & Sneden (1994).

4.4 Procedure

Abundances were derived for all but two lines (see below) using the measured equivalent widths and the most recent version of the LTE analysis code MOOG (Sneden 1973). We employed the [M/H]$=-1.5$, $\alpha=l/H_p=1.25$ model atmosphere grids of Kurucz (1992) for both the BD+23 3912 and the Sun. Van der Waals broadening was handled in the manner of Unsold (1955). A large enhancement factor of 3.5 or $\Delta\log\ C_6\sim+1.37$ (typical of several analyses) was adopted for Ba. For the λ4554 Ba II line, calculations were carried out in the LTE analysis code RAI10 (courtesy of Dr. M. Spite), which can easily handle multiple fine structure components. MOOG was used to conduct spectrum synthesis of the λ4522.6 Eu II region.

5. RESULTS

Our derived abundances are shown in Table 2, which lists the wavelengths, excitation potentials, log gf values, absolute solar abundances (on the A(X) scale), absolute BD +23 3912 abundances, and the estimated errors due to the equivalent width uncertainties. The normalized abundances, [X/H] and [X/Fe] are given in the discussion below with other notes of interest for each element. The stellar equivalent width errors dominate over the solar ones in the internal relative (to the Sun) abundance uncertainties– typical errors are 0.07 dex. Uncertainties in the adopted parameters are comparable however. Reasonable 1σ estimates of ±100 K in $T_{\rm eff}$ and ±0.2 dex in log g lead to more realistic total errors of ∼0.15 dex in our final mean [X/Fe] values.

5.1 Yttrium

Gratton & Sneden (1994; GS94) note that hyperfine structure is negligible for Y II lines. We find a mean solar abundance of log ϵ(Y)$=2.26\pm0.06$ (s.d., the standard deviation of a single datum), which agrees well with the meteoritic value of 2.22 ± 0.02 listed by Grevesse & Anders (1989). For BD+23 3912, the mean of the eight individual Y II lines yields [Y/H]$=-1.44\pm0.10$ (s.d.), or [Y/Fe]$=+0.05$. The λ5123 and λ5205 abundances are somewhat lower than the others and indeed we had noted their equivalent widths during measurement due to possible asymmetries in the profiles and the proximity of a blending feature for the λ5205 line. Ignoring these two features gives a slightly larger abundance ([Y/H]$=-1.40\pm0.06$), with reduced scatter.

5.2 Barium

The 4554.04 Å resonance line of Ba II is affected by hyperfine structure, which needs to be considered. As noted above, we did this in the RAI10 package adopting the same linelist and gf values utilized by McWilliam *et al.* (1995). The 4934.1 Å Ba II feature was present in our spectra, but was not considered due to problematic blending concerns. A Fe I feature may affect the λ6496 abundance; we give this line's abundance half-weight, though the final results are identical regardless.

Though our solar abundance of log $\epsilon(\mathrm{Ba})=2.33\pm0.07$ (s.d.) is in agreement with the meteoritic value of 2.21 ± 0.03 to within the errors, we had hoped for better concordance. For BD+23 3912, we find a mean Ba abundance of $[\mathrm{Ba/H}]=-1.58\pm0.06$ (s.d.), where the dispersion is in accord with our estimated equivalent width errors. This abundance leads to $[\mathrm{Ba/Fe}]=-0.09$, but we note the sensitivity to ξ. An increase of 0.5 km s^{-1}, lowers the derived abundance ratio by ~0.17 dex. Thus, total 1σ uncertainties could approach 0.20 dex.

5.3 *Zirconium*

Our one Zr II line gives log $\epsilon(\mathrm{Zr})=2.69$ for the Sun. The uncertainty from the equivalent width measurement is estimated to be ±0.07 dex. The agreement with the meteoritic value given by Grevesse & Anders (1989), 2.61 ± 0.03, is good. For BD+23 3912, we find $[\mathrm{Zr/H}]=-1.21$, which gives $[\mathrm{Zr/Fe}]=+0.28$. As GS94 note, abundance determinations from ionized Zr features are desirable due to their insensitivity to ξ; a +0.5 km s^{-1} increase reduces our abundance by only 0.02 dex.

5.4 *Aluminum*

We could measure the 6696.03 Å Al I line in our spectra, but the neighboring 6698.67 Å feature was not apparent. We derived a solar Al abundance of 6.28 ± 0.05, where the uncertainty is that due to the equivalent width. Our value is not in such good agreement with the meteoritic result, 6.48 ± 0.02. The discrepancy does not seem to arise from our equivalent width since the Moore *et al.* (1966) atlas lists an even smaller value of 33 mÅ. Most likely, the discrepancy is rooted in the gf value. The implied ~0.20 dex error underscores the advantage in deriving self consistent solar abundances. For BD+23 3912 we find $[\mathrm{Al/H}]=-1.34\pm0.05$, which yields $[\mathrm{Al/Fe}]=+0.15$, with an equivalent width uncertainty of ±0.10 dex. Uncertainties due to log g and ξ are negligible.

5.5 *Sodium*

Our three Na I lines give a solar abundance of log $\epsilon(\mathrm{Na})=6.27\pm0.01$, which is in good agreement with the meteoritic value of 6.31 ± 0.03. For BD+23 3912, we find $[\mathrm{Na/H}]=-1.43\pm0.05$ (s.d.), or $[\mathrm{Na/Fe}]=+0.06$. Effects of varying log g and ξ are again negligible.

5.6 *Neodynium, Samarium, and Lanthanum Upper Limits*

Each of these elements demonstrated one possibly real feature (listed in the previous section) in our spectra. The measured equivalent widths, however, are near the noise limit, so we do not consider (even at a low confidence level) these features to be genuine. Also, at such low line strengths, there may be a bias at work such that the errors are skewed towards measuring higher equivalent width (i.e., random errors which decrease line strength—possibly pushing an "absorption" feature into "emission" in the extreme case—will result in features being disregarded in analysis while random errors which increase line strength will make a weak line more likely to be measurable and considered). Since we were curious about the upper limits we could derive, we assumed 3σ equivalent width upper limits based on the Cayrel (1988) formulation[6].

Using solar equivalent widths measured from the Kurucz *et al.* (1984) flux atlas (Nd and La) and from Biemont *et al.* (1989; Sm), we find solar abundances of 1.36 ± 0.03, 1.26, and 2.00 ± 0.04 for Nd, Sm, and La; again, the uncertainties are those from the equivalent widths. For Nd, agreement with the meteoritic value, 1.47 ± 0.01, is fair. Agreement with the Sm meteoritic abundance, 0.97 ± 0.01, is poor. Our La abundance is in serious conflict with the meteoritic value, 1.20 ± 0.01. Errors in the gf value may be the cause since our equivalent width (9.3 mÅ), admittedly uncertain given a strong neighboring Fe I line, agrees very well with the Moore *et al.* (1966) atlas value (9.5 mÅ). Our final upper limits for BD+23 3912 are $[\mathrm{Nd/Fe}]\lesssim+0.20$, $[\mathrm{Sm/Fe}]\lesssim+0.24$, and $[\mathrm{La/Fe}]\lesssim+0.19$.

5.7 *Europium Upper Limit*

The only line of Europium (a nearly pure r-process element) available in our spectra is the λ4522 Eu II feature. Unfortunately, the line is heavily blended in BD+23 3912, which is relatively metal-rich and of higher gravity compared to the metal-poor giants analyzed by McWilliam *et al.* (1995) using this feature. Using the McWilliam *et al.* linelist kindly provided by Dr. C. Sneden, we carried out spectrum synthesis of the Eu II region in order to see what limits could be placed on the abundance. While $[\mathrm{Eu/Fe}]\lesssim+0.6$ is consistent with the data, the uncertainties are such that we are only confident in stating $[\mathrm{Eu/Fe}]\lesssim+1.0$.

5.8 ^{6}*Li Analysis of BD+23 3912*

Our Keck spectrum includes the Li I 6707 Å region and we use this to constrain the ^{6}Li content in BD+23 3912 following the procedure of Smith *et al.* (1993a). We take as given the parameters adopted above. The measured Li equivalent width is then used to set the total Li abundance, giving log $N(\mathrm{Li})=2.56$ using the atomic data from Andersen *et al.* (1984). As the referee notes, their wavelengths are in excellent agreement with the recent measurement of Sansonetti *et al.* (1995). This abundance is then used to perform the synthesis of the line profiles.

Correction for radial velocity is carried out using measurements of Fe lines (and the λ6717 Ca I feature) in the Li and nearby orders for which precise wavelengths could be located. The empirical continuum fit was performed before the equivalent width measurement and was not altered for the ^{7}Li synthesis. Line broadening was characterized by smoothing with a Gaussian with a FWHM of 0.180 Å. This

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[6] In particular, we used $\sigma=1.5\times F/(\sqrt{n}\times S)$, where F is the FWHM of the line (or assumed FWHM for an upper limit), n is the number of pixels per FWHM, and S is the S/N per pixel.

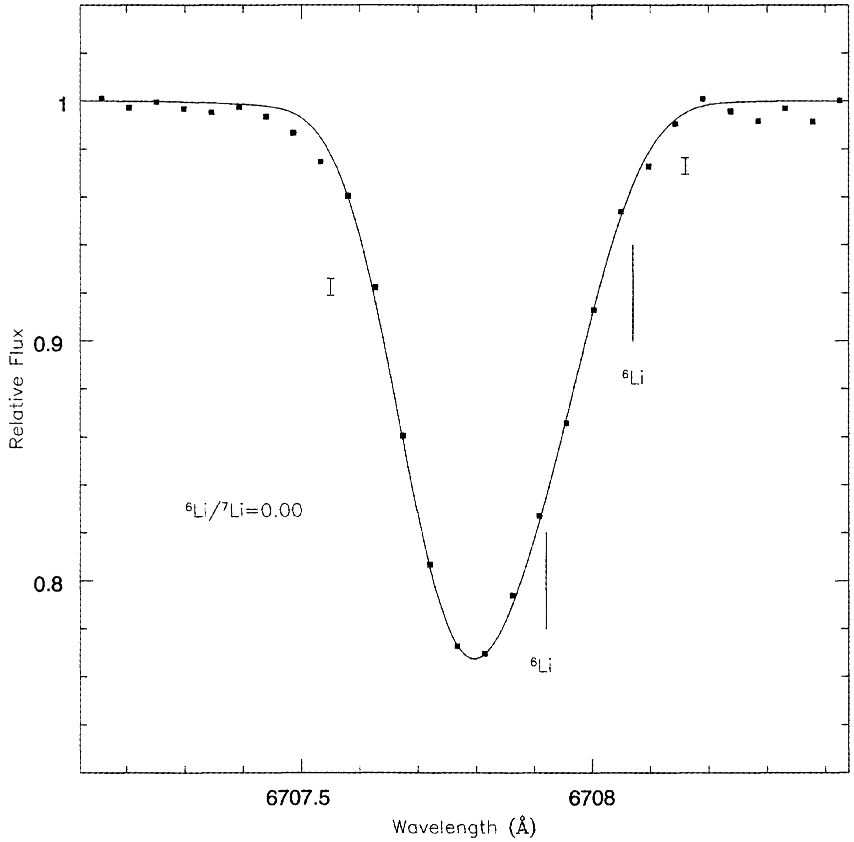

FIG. 3. The Li I line profile in BD+23 3912. The points are the observed data and the solid line is our synthetic spectrum for ^{6}Li/^{7}Li=0 for log N(Li) =2.56 computed with our favored wavelength shift and smoothing values. It is obvious that the zero ^{6}Li case provides a good fit to the data.

value was determined from a profile fit to the 6717 Å Ca I line (the 6162 Å line is judged to be too strong in our star to provide trustworthy constraints) and from measured FWHMs of weaker Fe lines; we believe the value to certainly be accurate to within ±0.015 Å. The estimated FWHM is larger than the instrumental resolution of 0.150 Å (at 6707 Å) measured from Th lines in comparison lamp spectra. Since we are unable to distinguish between the effects of rotation and Gaussian macroturbulence based on our data, we simply retain the Gaussian formulation.

The synthetic line profile (solid line) assuming no ^{6}Li is compared to the data (squares) in Fig. 3. The error bars show the expected photon noise error based on the *continuum* S/N. The positions of the ^{6}Li features (ignored in this case) are marked. The fit is quite satisfactory and it is immediately evident that very little ^{6}Li is present. Keeping the total Li content constant, we find ^{6}Li/^{7}Li ratios of 0.50 and 0.25 are easily ruled out. Even a ratio of 0.15 seems to be safely excluded by the data.

Following Smith *et al.* 1993a (e.g., their Fig. 14), we allowed the broadening, wavelength shift, and continuum normalization variables to float free in producing the closest match to the profile. The best-case results for a ^{6}Li/^{7}Li ratio of 0.15 are shown in Fig. 4. The wavelength shift (at 6707 Å) is larger by +0.007 Å relative to our best estimate used in Fig. 3. The data have been renormalized by multiplying by 1.001 relative to our initial continuum fit. Both of these adjustments are allowable within the errors. The red portion of the synthetic profile is clearly discordant with data. No further improvement could be made without *lowering* the Gaussian FWHM further; however, the value of 0.150 Å used in Fig. 4 is already *at* the instrumental limit so no further reduction seems possible.

A possible concern here is that the instrumental, macroturbulent, and any (small) rotational broadening is not well modeled by a Gaussian, a useful approximation which undoubtedly breaks down at some level. However, we do not believe this affects our results. First, in measuring the equivalent widths of features which are unblended and not strong lines (i.e., having dominant wings), we found that a Gaussian function provided an excellent "fit" to nearly all the lines profiles, which are dominated by instrumental and/or macroturbulent (and possibly small rotational) broadening in our data. Secondly, a finer comparison confirms this. Via direct integration, we measured the equivalent width of the λ6678 Fe I feature, a clean "case a" line in the compendium of Thevenin (1990). This measurement should be virtually independent of the line profile. Using the Thevenin (1990) atomic data, the abundance (also independent of the line profile) was determined from this equivalent width (53.6 mÅ) using MOOG. This abundance was then used to synthesize the line profile in the same exact fashion (i.e.,

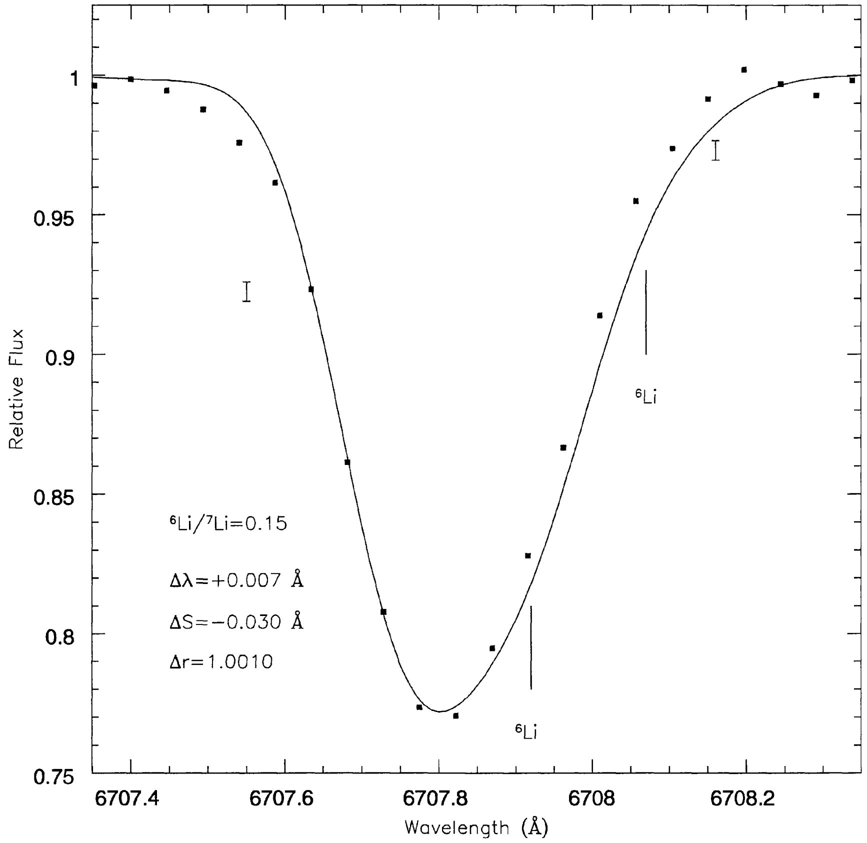

FIG. 4. The best case match for a ^{6}Li content of 15%. The wavelength, smoothing, and continuum normalization adjustments relative to our favored values used in Fig. 3 are indicated. It seems clear that even ^{6}Li/^{7}Li=0.15 is larger than the observations (filled squares) allow.

with the same broadening parameterization) as for the Li I features. The result is shown in Fig. 5, where outstanding agreement between the line profile and data can be seen. Thus, we believe it is clear that ^{6}Li/^{7}Li=0.15 is markedly inconsistent with the data. Slightly lower values can also probably be ruled out, but we prefer to be conservative here.

6. DISCUSSION

6.1 Abundance Comparisons Between BD+23 3912 and Other Stars

The results of GS94 allow comparison of our n-capture abundances for BD+23 3912 with those of stars having similar metallicity. For Y at [Fe/H]=−1.5, their observed relation yields [Y/Fe]=−0.17, which agrees well with our value of +0.05 to within the errors (their uncertainties alone are 0.15−0.20 dex). They also find a mean value [Ba/Fe] =−0.08±0.10, which agrees almost exactly with our result of −0.09±0.15 for BD+23 3912.

GS94 find [Zr/Fe] of +0.20±0.14, which again agrees well with our BD+23 3912 abundance of +0.28. GS94 find very small scatter (probably due to correlation of abundance errors), ±0.05 dex, in the [Y/Zr] plateau value of −0.36 for [Fe/H]<−1.5. For BD+23 3912, we find [Y/Zr]=−0.23. Since our Zr abundance comes from a single line and since GS94's [Y/Zr] results may have slightly increasing slope for [Fe/H]≳−2.0, the difference is insignificant.

GS94's mean values for [Nd/Fe], [Sm/Fe], and [La/Fe] are +0.04±0.09, +0.14±0.11, and −0.11±0.11. Our upper limits of ≲+0.20, ≲+0.24, and ≲+0.19 are consistent with these. Any Nd or Sm overabundance is thus limited to

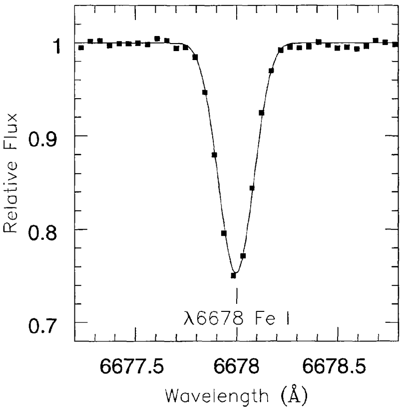

FIG. 5. Synthesis (line) of the clean λ6678 Fe I line in BD+23 3912 (points). The data are on the same wavelength and continuum scale as the λ6708 Li feature. The synthesis has been conducted with the same instrumental/macroturbulent broadening prescription (i.e., characterized by a Gaussian) as shown in Figs. 3 and 4 for Li; the abundance was fixed prior to the synthesis by the measured equivalent width. No departures, which would suggest our broadening prescription is inadequate, between the data and synthetic line profile are evident.

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about $\lesssim 0.15$ dex. The results for Eu are less interesting—our upper limit of [Eu/Fe]$< +1.0$ is significantly larger than GS94's mean result, $+0.29\pm0.11$.

Comparisons of the odd-Z element Na and Al abundances are a bit more difficult since the specter of large systematic errors has long haunted their determination. In recent years, higher quality data of weaker lines in the red and near-IR has resulted in clearer abundance trends for both elements (e.g., Francois 1986, Edvardsson *et al.* 1993). It is now seen that at [Fe/H]$=-1.5$, [Na/Fe]$\sim$ [Al/Fe]~0.0; this possibly indicates a modest (0.15 dex) decline from the abundances measured in more metal-rich ([Fe/H]~-1.0) stars. In any case, our results, [Na/Fe]$=+0.06$ and [Al/Fe]$=+0.15$, are consistent with the limited data, which show substantial scatter.

In sum, the abundance ratios for BD+23 3912 *are quite unremarkable*. Na and Al are perfectly normal with respect to other metal-poor stars that have been observed using the same transitions. The *n*-capture elements are also normal, though we are unable to rule out quite small ($\lesssim$0.15 dex) enhancements. We also note that the same conclusions are reached when we compare our abundance results for BD +23 3912 to data (of similar metallicity stars) from other literature studies compiled in Ryan *et al.* (1991; vis Magain 1987, 1989; Gratton & Sneden 1987, 1988; Gilroy *et al.* 1988; Peterson *et al.* 1990). We now consider the constraints these abundance ratios place on possible causes of the enhanced Li abundance seen in BD+23 3912.

6.2 The ^{7}Be Transport Mechanism

All known Li-rich metal-poor AGB stars have *s*-process element overabundances. In contrast, our *s*-process abundances in BD+23 3912 are normal, and we conclude that its Li overabundance is not a result of Li production carrying an *s*-process signature. We now explore these issues in additional detail. We begin, however, with a review of Li evolution prior to the AGB. Such an overview is prerequisite to interpreting Li on the AGB. While BD+23 3912 itself is certainly not an AGB star, we are seeking to explore scenarios in which the high Li abundance may have arisen from (a) mass transfer from a former AGB companion, or (b) BD +23 3912 being formed from material having been processed through the AGB evolutionary phase.

6.2.1 Brief overview of the surface Li evolution

In stellar interiors, Li is destroyed via (p,α) reactions at a temperature of only a few million degrees. As a result, by the time evolving stellar models reach the ZAMS, Li is preserved only in the outermost few percent (by mass) of the star. Depending on various factors that we shall not review here, stars on the ZAMS can still retain their initial or near-initial (early pre-main-sequence) surface Li abundance. The surface convection zone deepens on the subgiant and (first ascent) red giant branches (RGB) in Population I stellar models to the point where it occupies half or more of stellar mass; thus, the surface Li abundance is diluted by $1-2$ orders of magnitude, depending on various factors (Iben 1965, 1967; Michaud & Charbonneau 1990). By the time a star evolves to AGB, its surface Li abundance has been reduced significantly.

A study of hundreds of Population I red giants shows that this prediction generally defines the *upper* limit for the distribution of Li abundances (Brown *et al.* 1989). Li abundances extend at least $1-2$ orders of magnitude below this envelope, betraying the presence of additional Li depletion mechanisms at work either during the main sequence and/or on the giant branch. Field Population II subgiants (Pilachowski *et al.* 1993) exhibit a more orderly Li$-T_{\rm eff}$ relation, perhaps because their mass range is much more restricted than that of field Population I stars, even allowing for a significant age spread in the Galactic halo. The Pilachowski *et al.* (1993) data follow closely the predicted dilution curves of Deliyannis *et al.* (1990) from the turnoff (Spite plateau) abundance A(Li)~2.1 near $T_{\rm eff}\sim6300$ K to a diluted Li plateau abundance of ~1.0 between 5200 and 4900 K (see discussion in Deliyannis 1995; Ryan & Deliyannis 1995). Below 4900 K, A(Li) drops quickly, again indicating the action of additional Li depletion mechanisms prior to He-core ignition (see also Sec. *5.4*). Note that BD+23 3912 is slightly too hot for Li dilution to have begun (see Figs. 3a, 3b, and 3d of Ryan & Deliyannis 1995; BD+23 3912 is the star between 5600 and 5700 K that lies above the Spite plateau. Note the delineation of the Li dilution that occurs between 5500 and 5300 K.)[7]

6.2.2 The Li-rich SMC AGB stars

While the further evolved double-nuclear-shell AGB stars exhibit low Li abundances in accord with these trends, it has been known for a long time that a few super Li-rich (A(Li) $\geqslant3-4$) Population I giants do exist (e.g., McKellar 1940; Sanford 1944; Feast 1954; Torres-Peimbert & Wallerstein 1966; Boesgaard 1970; da Silva *et al.* 1995). Such super Li-rich stars are few, occurring with a frequency of order 1% − 2% for S stars and less for C stars (Catchpole & Feast 1976; Lloyd Evans & Catchpole 1989; Denn et al. 1991). Given that their Li abundances are even higher than currently supposed initial Pop I values, these rare objects must be synthesizing Li.

Theoretically, surface ^{7}Li can be enriched in red giants if ^{7}Be is produced in the deep interior through the $^3{\rm He}(\alpha,\gamma)$ ^{7}Be reaction, then quickly transported outward to avoid destruction via $^7{\rm Be}(p,\gamma)^8{\rm B}$, and converted to ^{7}Li through ($^7{\rm Be}(e^-,n)^7{\rm Li}$) electron capture in the cooler convection zone where ^{7}Li can survive (Cameron 1955). The required transport has been considered in early models of AGB stars

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[7] This assessment is an observational one, based on self-consistent comparison with other stars; hence, it is independent of the adopted $T_{\rm eff}$ scale, any change in which would affect all stars similarly. While the relative $T_{\rm eff}$ errors for BD+23 3912 seem insufficient (see Sec. *4.2*) to place BD +23 3912 in the region of observed certain dilution, the precise location of the onset of dilution defined by other stars is slightly uncertain (due to the paucity of data, possible metallicity effects, Li abundance uncertainties, etc.). It is therefore currently impossible to definitively exclude the possibility that BD+23 3912 could reside just over the boundary where dilution (of small magnitude) has begun. In this case, however, the (larger) Li abundance of this star when it resided on the (undiluted) Spite plateau proper would be even more discrepant than is currently inferred.

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with hot-bottom convective envelopes (Scalo *et al.* 1975), helium shell flashes (Cameron & Fowler 1971; Sackman *et al.* 1974; however, see Iben 1973,1975), and related nuclear plumes (Ulrich & Scalo 1972, Scalo & Ulrich 1973). Model improvements have led to improved agreement with observation, including the ability to create cool carbon stars at the observed (low) luminosities (Boothroyd *et al.* 1993). These models can also create super-Li rich stars, with at least partial success (see Plez *et al.* 1993). In principle, this ^{7}Li can then enrich the ISM through mass loss (Scalo 1976).

Of relevance here is the possibility of Li production in *metal-poor* evolved stars. Smith & Lambert (1989, 1990) found that oxygen-rich AGB stars (C/O$\leqslant$1, "S stars") of $4-8$ $M_\odot$ (or $-7 \leqslant M_{\rm bol} \leqslant -6$), having [Fe/H]$\sim -0.5$ (Plez *et al.* 1993), in the SMC are *all* Li-rich (N(Li)~ 3), though not super-Li rich. Lower mass (fainter) SMC AGB stars as well as brighter core-burning supergiants show no Li features. On the basis of ^{12}C/^{13}C ratios, which they find to be $5-9$ in four stars, Plez *et al.* (1993) argued that the Li-rich AGB stars have hot-bottom envelopes. By comparison, one supergiant had a ratio of ~ 25, consistent with an initial ratio of ~ 80 (the Sun's is 90) and dilution during first dredge-up. The lower ratios in the Li-rich ABG stars are consistent with CN-cycling at the base of the envelope (which can convert $^{12}{\rm C} \rightarrow {}^{13}{\rm C}$ until the equilibrium ratio ~ 4 is established); however, earlier stellar processing cannot be ruled out until the ratio is measured and found to be higher in lower luminosity AGB stars. Additional, but less secure, evidence of a hot-bottom envelope is the C abundance being depleted (presumably by CN-cycling), by about a factor of 3 relative to (uncertain) expectations, in the four Li-rich stars.

If a neutron source is operating, then n-capture elements can be produced via the *s*-process and transported outward convectively during a helium shell flash (thermal pulse) together with freshly synthesized ^{12}C from triple-α reactions. Subsequent re-establishment of the deep outer convection zone (third dredge-up) increases the surface s-process and ^{12}C abundances. After a sufficient number of shell flashes, one expects that M, MS, and S stars will become *s*-process rich SC and C carbon stars, though the SMC stars may temporarily remain O rich by transforming some of ^{12}C into O via CN-cycling at the base of the hot bottom envelope. The Li-rich SMC stars are indeed markedly *s*-process enhanced (Plez *et al.* 1993). Additionally, their ratio of heavy-to-light *s*-process abundances is significantly larger than the value at solar [Fe/H]; increasing [hs/ls] with declining [Fe/H] is also seen in Galactic CH and Ba stars [8] (e.g., Luck & Bond 1991; Smith *et al.* 1993b). Such signatures can be searched for in BD+23 3912.

6.2.3 The Halo CH Subgiant CS 22898−27

Another interesting example of possible Li production in metal-poor stars is the CH subgiant CS 22898−27, a metal-poor star near the halo turnoff with $T_{\rm eff} \sim 6300$ K, which has a Li abundance about a factor of 2 above the Spite Li plateau (Thorburn 1994). CH subgiants are stars believed to have accreted a thick mantle of ^{12}C-rich and *s*-rich material produced in a companion that was formerly an AGB star (Luck & Bond 1991; Smith *et al.* 1993b). Indeed, CS 22898−27 has [Fe/H]$=-2.35$ but is *very* carbon rich ([C/Fe]$=1.91$) and *very* *s*-rich: [Sr/Fe]$=+0.97$, [Ba/Fe]$=+2.67$, [La/Fe] $=+2.49$, [Ce/Fe]$=+2.08$, and [Nd/Fe]$=+2.24$ (McWilliam *et al.* 1995). By comparison, halo field dwarfs at [Fe/H]~ -2.4 have [C/Fe]$\sim 0.1 \pm 0.2$, [Sr/Fe]$=+0.0 \pm 0.5$, [Ba/Fe]$=$[La/Fe]$=$[Ce/Fe]$\sim -0.5 \pm 0.5$, and [Nd/Fe] $\sim -0.2 \pm$ 0.3 (Tomkin *et al.* 1986; Gratton & Sneden 1994; and Ryan *et al.* 1991, and the references compiled therein). Additionally, the [hs/ls] ratio is high, >1.0 (here, heavy is Ba, La, Ce, Nd, and light is Sr). These properties are similar to those of the more Fe-rich SMC AGB stars, and are consistent with the idea that this star has been contaminated by or formed from ^{12}C-, s-, and Li-enriched material from an AGB star.

6.2.4 Comparison with BD+23 3912

The abundance results discussed in Sec. *5.1*indicate that BD+23 3912 is not *s*-process rich compared to field dwarfs and subgiants of similar metallicity ([Fe/H]~ -1.5, i.e., intermediate to the SMC AGB stars and CS 22898−27). Comparison of the heavy (here, Ba and Nd) and light (Y and Zr) *s*-process elements shows no significant enhancement in the [hs/ls] ratio for BD+23 3912 compared to the field stars of similar metallicity in GS94; the ratios [Ba/Zr]$=-0.37$ and [Nd/Y]<0.15 for BD+23 3912 agree well with the values of -0.28 and $+0.21$ for the GS94 field stars at [Fe/H] ~ -1.5. If anything, the value [Ba+Nd]/ [Y+Zr]<-0.22 for BD+23 3912 might be just slightly *lower* than the mean GS94 field star value of -0.07, though the significance is marginal.

Plez *et al.* 1993 find that the Li-rich SMC stars have Zr and Nd abundances $0.7-0.8$ dex higher than other stars in the SMC field. Their average Zr and Nd enrichment, [s/Fe] $\sim +0.5$, is consistent with that of Galactic S stars. Their [Nd/Zr] ratio of $\sim +0.6$ is significantly larger than the GS94 Galactic field stars (-0.16) and our value for BD +23 3912 of <-0.08. Thus, the Li-rich SMC star n-capture patterns are very different from those found in BD +23 3912.

The n-capture abundance patterns of CS 22898−27 are also very different from those in BD+23 3912. The former's [*s*/Fe] values for Ba, Nd, and La are two orders of magnitude larger than our values for BD+23 3912. Additionally, in CS 22898−27 [Eu/Fe]$=+2.04$, which is an order of magnitude larger than our upper limit. BD+23 3912 does not show any unusual abundances of *s*-processed material either present during the formation of the star or contaminating it later. Nor does it show any of the n-capture abundance signatures of the Li-rich SMC stars (which are more metal-rich than BD+23 3912) or the Li-rich CH subgiant CS 22898−27 (which is more metal-poor than BD +23 3912).

We conclude that *the Li overabundance in BD*

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[8] Larger [hs/ls] might be expected at subsolar metallicity if the neutron source is independent of [Fe/H] (Clayton 1988), and hence Plez *et al.* prefer the $^{13}{\rm C}(\alpha,n)^{16}{\rm O}$ source over $^{22}{\rm Ne}(\alpha,n)^{25}{\rm Mg}$, where ^{4}He burning results in $^{12}{\rm C}(p,\gamma)^{13}{\rm C}$ independent of metallicity.

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+23 3912 is not a result of Li production carrying an s-process signature.

6.3 *Non-Standard ^{7}Be Mechanisms: WZ Cas*

There does exist at least one Pop I example of an AGB star having produced Li without also producing *s*-process elements: WZ Cas. This cool ^{13}C-rich (J-type) carbon star has an extremely large Li abundance,[9] N(Li)$\sim$6 (Denn *et al.* 1991); this is markedly different from J stars in general, which have very low Li abundances (with range N(Li) $\sim -1.0\pm 0.5$) at a level similar to that of non-J carbon stars. Aside from low ^{12}C/^{13}C ratios near the CN-cycle equilibrium value of $3-4$, J-type carbon stars are also characterized by a lack of *s*-process overabundances, leading Denn *et al.* (1991) to speculate that J stars evolve differently from common carbon stars—perhaps experiencing a He-core flash of unusual severity (see also Dominy 1984) or He-shell flashes without activation of a neutron source.

Regardless, the ^{7}Be transport mechanism is likely responsible for the high Li in WZ Cas. Determination of the ^{12}C/^{13}C ratio in BD+23 3912 would be highly desirable. A normal ratio ($\sim$90 as in the Sun) would argue against contamination from processed material; ^{12}C-enriched carbon stars might also have high ^{12}C/^{13}C ratios near 90, but they are also s-rich while BD+23 3912 is not. A low ratio might be consistent with contamination from a metal-poor analog of the Li-rich J-type carbon star WZ Cas.

6.4 *Li Production in Pre-AGB Giants?*

Li abundances in field halo giants drop quickly below 4900 K (Pilachowski *et al.* 1993) to well below the maximum predicted diluted values (e.g., Ryan & Deliyannis 1995), suggesting that mixing is causing Li destruction, not production. The non-convective portions of such mixing are poorly understood and we wonder here if any Li production could result. Consider the possibility that thermal pulses of the hydrogen burning shell are causing the requisite mixing. While spherically symmetric models show the H-shell to be stable against such pulses, it is unknown whether rotation or other agents could render the H-shell unstable, possibly even resulting in asymmetric pulses which might then trigger the ^{7}Be transport mechanism. Similarly, one wonders whether an unusually strong or asymmetric He-core flash might result in surface ^{7}Li enrichment, possibly accompanied by mass loss which enriches the ISM.

A key issue here is the availability of the ^{3}He seed produced by $p-p$ chains during the main sequence. If mixing is the cause of halo giants attaining ^{12}C/^{13}C ratios near or at CN-cycle equilibrium values, then fragile ^{3}He nuclei will also be mixed and destroyed.[10] But whereas both Pop I and II low mass giants show low ^{12}C/^{13}C ratios, higher mass Pop I giants have ratios which agree with predictions of RGB dilution alone (Gilroy 1988). Hence, it may be that more massive Pop II giants are also better preservers of ^{3}He. Indeed, the creation of ^{7}Li in the SMC AGB stars implies an available supply of ^{3}He. However, these stars have less produced Li than the models predict, so perhaps the ^{3}He supply was depleted even in these more massive stars (see discussion of Plez *et al.* 1993).

Regardless, contamination of BD+23 3912 by ^{7}Li produced (quite speculatively) in low or high mass first ascent giants should have additional signatures. C,N,O, Na, and Al are known to evolve in globular cluster and/or field halo giants (see, e.g., Kraft 1994 for a recent review). For example: (a) the ^{12}C/^{13}C ratios drop in field halo subgiants and giants and in globular cluster giants down to values near or at the equilibrium value of $3-4$, (b) [C/Fe] in M92 drops from $\sim$0 at the turnoff to well below -1 up the giant branch, and (c) substantial O depletions are observed near the tips of some globular cluster RGB's, and are strongly correlated with N, Na, and Al enhancements. In some cases (e.g., M92) it is known that C+N+O=constant near the tip of the RGB and that Fe and *n* capture abundances show little or no variation near the RGB tip (Armosky *et al.* 1994), suggesting progressive nuclear processing via the CN and ON cycles and ^{20}Ne$-^{23}$Na chain and mixing (convective but also non-convective below the convection zone) to the surface.[11]

BD+23 3912 has normal C and O abundances compared to other halo dwarfs and subgiants of similar metallicity (e.g., Tomkin et al. 1992). As discussed earlier, our derived Na and Al abundances for BD+23 3912 are also normal for stars of this metallicity. *All of the elemental abundances (except Li) in* BD+23 3912 *that we have either examined ourselves or quoted from other studies are normal compared to other halo dwarfs/subgiants of similar metallicity, and show no evidence of contamination from material processed either on the RGB or AGB.* Determination of the N abundance and ^{12}C/^{13}C ratio in BD+23 3912 remains desirable, however.

6.5 *GCR Production of Li and the ^{6}Li/^{7}Li Ratio*

Models of cosmic rays interacting with the ISM produce Li. It has been supposed that, in the halo, such production would have been most efficient via $\alpha+\alpha$ reactions and may have made a significant contribution to a low Li$_p$ ($\sim$2.1; Steigman & Walker 1992). A key (and almost unique) feature of the GCR+ISM mechanism is that the amount of ^{6}Li produced is approximately equal to the ^{7}Li produced. This provides a potentially observable signature for the GCR+ISM mechanism.

Detection of ^{6}Li/^{7}Li$\sim$0.05 has been reported in one turnoff halo star (Smith *et al.* 1993a; Hobbs & Thorburn 1994) along with upper limits (some higher but also some *lower*) in other stars. However, the role of convection must be thoroughly understood before ^{6}Li can be reliably detected from small asymmetries (these and other concerns are discussed by Deliyannis *et al.* 1995b). Flares could possibly produce observable quantities of ^{6}Li in halo turnoff stars (Deliyannis & Malaney 1995), but in a subgiant like BD+23 3912, this

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[9] Non-LTE effects might reduce this value (Carlsson *et al.* 1994).

[10] Destruction of primordial ^{3}He in this manner may have implications for the D+^{3}He constraint on Big Bang nucleosynthesis (Deliyannis 1995, Wasserburg *et al.* 1995). Mixing on the giant branch could also imply a reduction in globular cluster age estimates from the ΔV method.

[11] The issue is still open as to whether some abundance variations might be primordial. In a few clusters, the evidence suggests at least some primordial variations, but generally favor has shifted toward mixing given the striking Na and Al evidence.

would have diluted long ago. The reason is that the surface spallated ^{6}Li would reside only in the surface convection zone, which in turnoff stars is orders of magnitude smaller (by mass fraction) than the ZAMS Li preservation regions. In the subgiant BD+23 3912, the convection zone is expected to have deepened quite significantly, and to be comparable to the (protostellar) Li preservation region (see also end of Sec. *5.2.1* and Fig. 3b in Ryan & Deliyannis 1995). Thus, any ^{6}Li seen in this star would likely be of protostellar origin. Preservation of protostellar ^{6}Li improves with increasing dwarf $T_{\rm eff}$, so subgiants are expected to be especially good preservers of protostellar ^{6}Li since they presumably recently evolved from the hottest turnoff temperatures.

If we assume that all enhanced Li in BD+23 3912 comes from GCR+ISM reactions and that the star is overabundant in Li by a factor of 2, then 25% should be in the form of ^{6}Li. If, instead, the star is overabundant by a factor of 3 (compared to lower Li abundance *turnoff* stars), then nearly 50% of its Li should be ^{6}Li. Exploring a very low ^{6}Li content would also be highly desirable, but requires higher resolution ($R \geq 100{,}000$) and S/N ($\sim 400-500$) since ^{6}Li would appear as a slight asymmetry superimposed on stronger ^{7}Li features. Our derived low value for the upper limit on the ^{6}Li/^{7}Li ratio in BD+23 3912 implies that either (a) the extra Li observed did not originate in cosmic ray interactions, in which case an alternate Li source must be found or (b) the surface Li in this star has been depleted from a higher initial abundance, with ^{6}Li depleted preferentially. Such depletion is certainly possible within the context of the Yale rotational models.

In deciphering the signature of mechanisms that affect Li, it can be of crucial importance to consider simultaneously other light element tracers. Of relevance here may be our recent study of the evolution of beryllium in the Galactic halo (Deliyannis *et al.* 1995b), in which we find that the Be-Fe slope changes from shallower at higher (halo) metallicity to steeper at lower metallicity. The only published models that fit the data are ones where cosmic rays interact with CNO in the ISM to produce Be, where characteristics of the halo (e.g., mass outflow) are taken into account (Ryan *et al.* 1992; Prantzos *et al.* 1993). The Prantzos *et al.* models are quite detailed in that they satisfy a number of important constraints; they also produce both ^{6}Li and ^{7}Li at a level higher than what is observed in the Spite plateau. Thus, simultaneously taking into account the Be data, the high Li abundance in BD+23 3912, and the low Li isotope ratio in this star, it is possible that (a) halo stars formed with a significantly higher Li abundance than what is observed today in the Spite plateau, (b) a significant or perhaps even dominant component of this Li was cosmic-ray produced and thus rich in ^{6}Li, and (c) slow mixing such as that in the Yale models has significantly depleted the initial Li abundance–the ^{6}Li isotope preferentially. This scenario can accommodate a wide range for the primordial ^{7}Li component.

6.6 Microscopic Diffusion

Deliyannis *et al.* (1990) modeled Li and He diffusion in halo stars and devised observational tests to search for the effects of diffusion in these stars: (a) the efficiency of diffusion increases with stellar mass, so the Li$-T_{\rm eff}$ relation should show a downward slope toward the turnoff, (b) most of the Li diffused from the surface convection zone of turnoff stars should reappear when the stars evolve further and their convection zones deepen and dredge up the diffused Li (Fig. 17 of Deliyannis *et al.* 1990), and (c) while ^{6}Li diffuses at a similar rate as ^{7}Li, the size of their Li preservation regions differ, possibly leading to isotope ratios in a subgiant like BD+23 3912 which may be of order half that at the turnoff.

On the basis of (b), Pilachowski *et al.* 1993 suggested that the high Li abundance in BD+23 3912 might reflect dredged-up Li that was previously diffused. However, we find that the overall evidence suggests otherwise. First, if anything, Li increases slightly with $T_{\rm eff}$ (Thorburn 1994; Ryan *et al.* 1996), contradicting item a. Second, with relation to item b, (if diffusion alone is acting in the context of standard, non-rotational models) all stars should dredge up their diffused Li, not just BD+23 3912. By contrast, other subgiants of similar $T_{\rm eff}$, such as HD 140283, show lower Li abundances; our observations of Li in otherwise apparently identical subgiants in the globular cluster M92, and of similar $T_{\rm eff}$ as BD+23 3912, also show a dispersion (see the next section). This is more consistent with the predictions of rotational mixing, not diffusion. Finally, related to item (c), the low Li isotope ratio marginally argues against diffusion, although a lower ratio than we present here would make the case stronger. We must emphasize that the lack of evidence for diffusion does *not* necessarily indicate that diffusion has not occurred, but rather it could be that some other mechanism (e.g., rotational mixing) dominates over diffusion in affecting the evolution of the Li abundances.

6.7 Supernova production of Li

Models of core-collapse (Type II) supernovae suggest that ^{7}Li can be produced via the neutrino process in sufficient quantities to account for about a quarter to a half of the Population I abundance (Woosley *et al.* 1990; Timmes *et al.* 1995). Evidence of such Li production has not yet been found. However, if the extra Li in BD+23 3912 is due to Type II SN production, then perhaps this star is also overabundant in other elements created via the neutrino process, such as ^{11}B or fluorine. It would be highly desirable to observe such neutrino-process signatures in BD+23 3912.

6.8 Lithium Dispersions in the Old Metal-Poor Globular Cluster M92 and Other Coeval Stellar Populations

Searching for Li abundance dispersions in stellar clusters (i.e., samples of presumably uniform age) provides a complementary means to test for Li enrichment and/or stellar Li depletion. Deliyannis *et al.* (1995a) have recently reported that one subgiant (#18) in M92 shows a Li abundance that is about a factor of two higher than two otherwise apparently identical subgiants (#21 and #46). It seems, then, that Li dispersion in halo stars may not be confined to just the field—it is apparently seen in one of the oldest and most metal-poor globulars. Li dispersion is also commonly seen in direct comparisons of sufficiently high quality spectra of otherwise identical stars in open clusters such as the Pleiades and Praesepe (Soderblom *et al.* 1993a,1993b) and the Hyades (Thorburn *et al.* 1993).

The M92 subgiants' cluster membership provides some interesting constraints. While the M92 stars are much too faint to use ^{6}Li as a tracer of cosmic ray Li production, their similar age and spatial history argues against the GCR + ISM mechanism, (which requires Gyr age differences to be plausible) as the source of the extra Li in M92 #18. If rotational mixing from a higher initial Li abundance is responsible, then something other than age (e.g., initial angular momentum) must be the relevant parameter. Coupled with the apparently identical measurements of several Fe and Ba features in their M92 spectra, Deliyannis *et al.* (1995a) argued against all three major Li production mechanisms in M92 and concluded that different degrees of stellar Li depletion in M92 subgiants from a higher initial abundance was a more likely scenario, although it was not possible to rule out all exotic possibilities.

6.9 Comment on CS 22898−27

Finally, we consider the Li-rich (Thorburn 1994 quotes ~2.6) halo CH subgiant CS 22898−27 near the halo turnoff (~6300 K). It is tempting to conclude that this star's excess Li (relative to the Spite plateau) originated in accreted material from a companion that was (formerly) a (rare) Li-rich AGB star, and thus provides a signature for Li enrichment from a (low) primordial Li abundance near the level of the Spite plateau. However, such a conclusion would be premature. Information about the initial Li abundance of this star may have been lost prior to accretion, and so CS 22898 −27 tells us nothing about whether Li_p was high or low.

For example, evidence has been presented that CH subgiants have accreted a thick mantle of ABG processed material and will evolve to become (first ascent) Ba giants (Luck & Bond 1991; Smith *et al.* 1993b). If CS 22898−27 has indeed accreted such a thick mantle, then the pre-accretion star was likely of sufficiently low mass ($<0.6\ M_\odot$) to have quickly destroyed its Li to well below the Spite plateau level—regardless of whether Li_p was significantly higher than the Spite plateau value (as suggested by rotational mixing models) or not (as suggested by standard stellar models). If, instead, CS 22898−27 accreted only a little material from an AGB companion, then interpretation becomes considerably more difficult. We reiterate that, without further information, the Li abundance of CS 22898−27 is ineffective at distinguishing between a high or low primordial Li abundance.

7. SUMMARY AND CONCLUSIONS

The halo subgiant BD+23 3912 ([Fe/H]=−1.5) has a Li abundance that is higher than other halo subgiants belonging to the Spite plateau by about a factor of 2, or a factor of 3 relative to turnoff stars. This extra Li may be due to (1) less Li depletion (from a higher initial abundance) than has occurred for most Spite plateau stars, (2) extraordinary Li enrichment of its pre-stellar material, or (3) later contamination. Other possibilities or a combination of those listed may also have occurred. At least three plausible Li production mechanisms exist: (a) the ^{7}Be transport process in asymptotic giant branch (AGB) stars, (b) $\alpha+\alpha$ production from, e.g., cosmic rays interacting with the ISM, and (c) the neutrino process in Type II supernovae. In this paper, we have searched for signatures of Li production mechanisms which might be responsible for the extra Li in BD+23 3912.

Whereas there is currently no evidence that supernovae actually produce Li, some evidence does exist for cosmic ray Li production. Direct evidence exists for Li-producing AGB stars in the form of the SMC intermediate metallicity AGB stars exhibiting Li abundances near 3.0 (Smith & Lambert 1990) and a very Fe-poor CH subgiant near the halo turnoff with a Li abundance about a factor of 2 above the Spite plateau (Thorburn 1994). Both of these classes of stars also show very large surface enrichment of *s*-process elements (Plez *et al.* 1993; McWilliam *et al.* 1995) and have high heavy-to-light *s*-process element ratios.

Using our Keck spectrum of BD+23 3912, we have derived this star's abundances of the *s*-process elements Y, Zr, and Ba. We have found these abundances and the heavy-to-light *s*-process abundance ratio to be completely normal with respect to halo dwarfs and subgiants of similar metallicity. Our upper limits for the Nd, Sm, and La abundances are also consistent with those in field halo stars (as is our weak upper limit for the *r*-process element Eu). It is thus unlikely that BD+23 3912 formed out of or was later contaminated (e.g., from a companion) by any kind of material rich in *s*-process elements (Li-rich or not). Thus, it is unlikely that a Li- and *s*-process element rich AGB star is responsible for the high Li abundance of BD+23 3912.

At least one example of a cool Population I J-type (i.e., very low ^{12}C/^{13}C) carbon star is known that is Li-rich (WZ Cas), but BD+23 3912 has both normal C and O (Tomkin *et al.* 1992). The highly speculative hypothesis that Li could be synthesized on the red giant branch (RGB), where evolution of at least some of the ^{12}C/^{13}C, C, N, O, Na, and Al abundances is observed, seems an unlikely explanation for the excess Li in BD+23 3912 given the normal Na and Al abundances we derive in this star and the normal C and O abundances found by others. Determination of the ^{12}C/^{13}C ratio and N abundance of BD+23 3912 would be desirable to further constrain unusual sorts of contamination by material (Li-rich or not) processed on the RGB or AGB.

If the GCR + ISM mechanism has produced the extra Li seen in BD+23 3912, then one expects about half the spallated Li to be in the form of ^{6}Li. Depending on whether Spite plateau dwarfs or subgiants are assumed to contain the unaltered primordial Li abundance (Li_p), 25% − 50% of the total Li should be in the form of ^{6}Li. However, our data yield a conservative upper limit of $^6\mathrm{Li}/^7\mathrm{Li}\leq 0.15$ in this star. Hence, either the surface Li abundance has been depleted (with ^{6}Li depleted preferentially) from a higher initial abundance or the observed excess Li in BD+23 3912 did not originate in cosmic ray + ISM interactions.

It should be noted that there are difficulties with Galactic Li enrichment scenarios. Plez *et al.* (1993) argue that the SMC Li-rich AGB stars contain much less Li than required to enrich the Galaxy to levels of $A(\mathrm{Li})\sim 3.0-3.3$. The

D'Antona & Matteucci (1993) models reproduce the meteoritic abundance 4.5 Gyr ago, but then continue producing Li to a current level ~ 3.6; however, most young clusters and field stars show maximum abundances near or slightly less than the meteoritic value (3.3). While future observations of ^{11}B and other ν-process tracers may indicate whether supernovae have contributed to the excess Li in BD+23 3912, the supernovae ν-process apparently can only produce 25% − 50% of the present-day Li abundance (Timmes *et al.* 1995). Similarly, it is believed that GCR+ISM spallation production cannot produce enough Li either; however, halo outflow models (Prantzos *et al.* 1993) produce more Li than previous models, and recently observed high ISM ^{6}Li/^{7}Li ratios (Lemoine *et al.* 1995) are consistent with spallation. While it seems that none of these sources alone can account for the present-day Li abundance, perhaps they can when added together.

Alternatively, Li_p may have been at or near the present-day abundance, and significant stellar Li depletion has occurred in halo stars. Even in this case, Li production may have *also* occurred in one of two ways: either this produced amount (for example A(Li) near 3.0) was comparable to the primordial value (for example, A(Li) near 3.0) and the sum produced the present day abundance, or else the produced quantity was negligible if the primordial abundance was sufficiently high to begin with. We also note that (contrary to conclusions drawn by others) in the context of the rotational Yale models, which suggest significant halo star Li depletion, it is still possible to accommodate the claimed detections of ^{6}Li in some halo stars (Deliyannis *et al.* 1995b).

Moreover, these models are able to explain a great number of apparently distinct phenomena in both Pop I and Pop II stars in a unifying manner. Particularly important in this regard is the analogy of the Pop I Li peak to the (Pop II) Spite plateau and the Li abundances observed in (a variety of) short period tidally locked binary systems (see Boesgaard 1991 and Deliyannis 1995 for a full discussion of these various phenomena). Since the high Li_p value suggested by the rotational stellar models would have implications for the interpretation of Big Bang cosmology, it is obviously important to test observationally models of Galactic Li production and possibly important stellar physics that is excluded in the simpler standard models. The metal poor star BD +23 3912, with its strikingly high Li abundance, provides a rather opportune laboratory for such investigations.

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REFERENCES

Alonso, A., Arribas, S., & Martinez-Roger, C. 1996, A&AS, 117, 227
Anders, E., & Grevesse, N. 1989, Geochim.Cosmochim.Acta, 53, 197
Andersen, J., Gustafsson, B., & Lambert, D. L. 1984, A&A, 136, 65
Armosky, B. J., Sneden, C., Langer, G. E., & Kraft, R. P. 1994, AJ, 108, 1364
Beveridge, C. R., & Sneden, C. 1994, AJ, 108, 285
Biemont, E., Grevesse, N., Hannaford, P., & Lowe, R. M. 1981, ApJ, 248, 867
Biemont, E., Grevesse, N., Hannaford, P., & Lowe, R. M. 1989, A&A, 222, 307
Boesgaard, A. M. 1970, ApJ, 161, 1003
Boesgaard, A. M. 1991, ApJ, 370 L95
Bond, H. E. 1970, ApJS, 22, 117
Boothroyd, A. I., Sackmann, I.-J., & Ahern, S. C. 1993, ApJ, 416, 762
Brown, J. A., Sneden, C., Lambert, D. L., & Dutchover, E. 1989, ApJS, 71, 293
Cameron, A. G. W. 1955, ApJ, 121, 144
Cameron, A. G. W., & Fowler, W. A. 1971, ApJ, 164, 111
Carlsson, M., Rutten, R. J., Bruls, J. H. M. J., & Shchukina, N. G. 1994, A&A, 288, 860
Carney, B. W. 1983, AJ, 88, 610
Catchpole, R. M., & Feast, M. W. 1976, MNRAS, 175, 501
Cayrel, R. 1988, in The Impact of Very High S/N Spectroscopy on Stellar Physics, edited by G. Cayrel de Strobel and M. Spite (Kluwer, Dordrecth), p. 345
Choi, P. I., & Herbst, W. 1996, AJ, 111, 283
Chaboyer, B., & Demarque, P. 1994, ApJ, 433, 510
Clayton, D. D. 1988, MNRAS, 234, 1
Cunha, K., Smith, V. V., & Lambert, D. L. 1995, ApJ, 452, 634
D'Antona, F. & Matteucci, F. 1993, A&A, 248, 62
da Silva, L., de la Reza, R., & Barbuy, B. 1995, ApJ, 448, L41
Deliyannis, C. P. 1990, Ph. D. dissertation, Yale University
Deliyannis, C. P., Demarque, P., & Kawaler, S. D. 1990, ApJS, 73, 21
Deliyannis, C. P., Pinsonneault, M. H., & Duncan, D. K. 1993, ApJ, 414, 740
Deliyannis, C. P. 1995, in The Light Element Abundances, edited by P. Crane (Springer, Berlin), p. 395
Deliyannis, C. P., Boesgaard, A. M., & King, J. R. 1995a, ApJ, 452, L13
Deliyannis, C. P., Boesgaard, A. M., King, J. R., & Duncan, D. K. 1995b, AJ, submitted
Deliyannis, C. P., & Malaney, R. A. 1995, ApJ, 453, 810
Denn, G. R., Luck, E. R., & Lambert, D. L. 1991, ApJ, 377, 657
Dominy, J. F. 1984, ApJS, 55, 27
Edvardsson, B., Andersen, J., Gustafsson, B., Lambert, D. L., Nissen, P. E., & Tomkin, J. 1993, A&A, 275, 101
Feast, M. W. 1954, Mem. Soc. Roy. Sci. Lifflge, 14, 413
Fitzpatrick, M. J., & Sneden, C. 1987, BAAS, 19, 1129
Francois, P. 1986, A&A, 160, 264
Gilroy, K. K., Sneden, C., Pilachowski, C. A., & Cowan, J. J. 1988, ApJ, 327, 298
Gilroy, K. K. 1988, ApJ, 347, 835
Gratton, R. G., & Sneden, C. 1987, A&A, 178, 179
Gratton, R. G., & Sneden, C. 1988, A&A, 204, 193
Gratton, R. G., & Sneden, C. 1994, A&A, 287, 927 (GS94)
Grevesse, N., & Anders, E. 1989, in Cosmic Abundances of Matter, edited by C. J. Waddington (AIP, New York), p. 1
Hannaford, P., Lowe, R. M., Grevesse, N., Biemont, E., & Whaling, W. 1982, ApJ, 261, 736
Hobbs, L. M., & Thorburn, J. A. 1994, ApJ, 428, L25
Iben, I. 1965, ApJ, 142, 1447

1996AJ....112.2839K

Iben, I. 1967, ApJ, 147, 650
Iben, I. 1973, ApJ, 185, 209.
Iben, I. 1975, ApJ, 196, 175
King, J. R. 1993, AJ, 106, 1206
Kraft, R. P. 1994, PASP, 106, 553
Kurucz, R. L., Furenlid, I., Brault, J., & Testerman, L. 1984, Solar Flux Atlas from 296 to 1300 nm, NSO Atlas No. 1
Kurucz, R. L. 1992 (private communication)
Lemoine, M., Ferlet, R., & Vidal-Madjar, A. 1995, A&A, 298, 879
Lloyd Evans, T., & Catchpole, R. M. 1989, MNRAS, 237, 219
Luck, E. R., & Bond, H. E. 1991, ApJS, 77, 515
Magain, P. 1987, A&A, 179, 176
Magain, P. 1989, A&A, 209, 211
Maier, R. S., & Whaling, W. 1977, J. Quant. Spec. Radiat. Trans., 18, 501
McKellar, A. 1940, PASP, 52, 407
McWilliam, A., Preston, G., Sneden, C., & Searle, L. 1995, AJ, 109, 2757
Michaud, G., & Charbonneau, P. 1990, Space Sci. Rev., 57, 1
Moore, C. E., Minnaert, M. G. J., & Houtgast, J. 1966, The Solar Spectrum from 2935 Å to 8770 Å, NBS Monograph 61
Peterson, R. C., Kurucz, R. L., & Carney, B. W. 1990, ApJ, 350, 173
Pilachowski, C. A., Sneden, C., & Booth, J. 1993, ApJ, 407, 699
Pinsonneault, M. H., Deliyannis, C. P., & Demarque, P. 1992, ApJS, 78, 181
Plez, B., Smith, V. V., & Lambert, D. L. 1993, ApJ, 418, 812
Prantzos, N., Casse, M., & Vangioni-Flam, E. 1993, ApJ, 403, 630
Proffitt, C. R., & Michaud, 1991, ApJ, 371, 584
Ryan, S. G., Norris, J. E., & Bessell, M. S. 1991, AJ, 102, 303
Ryan, S. G., Norris, J. E., Bessell, M. S., & Deliyannis, C. P. 1992, ApJ, 388, 184
Ryan, S. G., & Deliyannis, C. P. 1995, ApJ, 453, 819
Ryan, S. G., Beers, T., Deliyannis, C. P., & Thorburn, J. A. 1996, ApJ, 458, 543
Sackmann, I.-J., Smith, R. L., & Despain, K. H. 1974, ApJ, 187, 555
Sanford, R. A. 1944, ApJ, 99, 145
Sansonetti, C. J., Richou, B., Engleman, Jr., R., & Radziemski, L. J. 1995, Phys. Rev. A, 52, 2682
Scalo, J. M. 1976, ApJ, 206, 795
Scalo, J. M., & Ulrich, R. K 1973, ApJ, 183, 151
Scalo, J. M., Despain, K. H., & Ulrich, R. K. 1975, ApJ, 196, 805
Schuster, W. J., & Nissen, P. E. 1988, A&AS, 73, 225
Schuster, W. J., & Nissen, P. E. 1989, A&A, 222, 69
Smith, V. V., & Lambert, D. L. 1989, ApJ, 345, L75
Smith, V. V., & Lambert, D. L. 1990, ApJ, 361, L69
Smith, V. V., Lambert, D. L., & Nissen, P. E. 1993a, ApJ, 408, 262
Smith, V. V., Coleman, H., & Lambert, D. L. 1993b, ApJ, 417, 287
Sneden, C. 1973, ApJ, 184, 839
Soderblom, D. R., Jones, B. F., Balachandran, S., Stauffer, J. R., Duncan, D., Fedele, S., & Hudon, J. D. 1993a, AJ, 106, 1059
Soderblom, D. R., Fedele, S. B., Jones, B. F., Stauffer, J. R., & Prosser, C. F. 1993b, AJ, 106, 1080
Spite, F., & Spite, M. 1982, A&A, 115, 357
Steigman, G., & Walker, T. P., 1992, ApJ, 385, L13
Thevenin, F. 1990, A&AS, 82, 179
Thorburn, J. A. 1992, ApJ, 399, L83
Thorburn, J. A., Hobbs, L. M., Deliyannis, C. P., & Pinsonneault, M. H. 1993, ApJ, 415, 150
Thorburn, J. A. 1994, ApJ, 421, 318
Timmes, F. X., Woosley, S. E., & Weaver, T. A. 1995, ApJS, 98, 617
Tomkin, J., Sneden, C., & Lambert, D. L. 1986, ApJ, 302, 415
Tomkin, J., Lemke, M., Lambert, D. L., & Sneden, C. 1992, AJ, 104, 1568
Torres-Peimbert, S., & Wallerstein, G. 1966, ApJ, 146, 724
Tull, R. G., MacQueen, P. J., Sneden, C., & Lambert, D. L. 1995, PASP, 107, 251
Ulrich, R. K., & Scalo, J. M. 1972, ApJ, 176, L37
Unsold, A. 1955, Physik der Sternatmospharen, 2nd ed., (Springer, Berlin)
Vogt, S. S., *et al.* 1994, Proc. Soc. Photo-Optical Instr. Eng., 2198, 362
Wasserburg, G. J., Boothroyd, A. I., & Sackman, I.-J. 1995, ApJ, 447, L37
Wiese, W. L., & Martin, G. A. 1980, Wavelengths and Transition Probabilities for Atoms and Atomic Ions: Part II, NGS- NSRDS, No. 68
Woosley, S. E. Hartmann, D. H., Hoffman, R. D., & Haxton, W. C. 1990, ApJ, 356, 272

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