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LITHIUM ABUNDANCES IN THE SOLAR TWINS 16 Cyg A AND B AND THE SOLAR ANALOG α Cen A, CALIBRATION OF THE 6707 Å Li REGION LINELIST, AND IMPLICATIONS

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ABSTRACT

We present high resolution ($R\sim45{,}000$–$70{,}000$) and very high S/N ($\sim1{,}000$) spectroscopy of the Li I 6707 Å region in each component of the binary solar twins 16 Cyg A and B, the solar analog α Cen A, and α Cen B. Spectra of 16 Cyg were obtained with the University of Hawai'i 2.2-m, McDonald Observatory 2.1-m, and Keck 10-m telescopes and have been independently reduced. Comparison of spectral synthesis and the 16 Cyg data, and corresponding similarly obtained solar data, yields ^{7}Li abundances which show excellent concordance between the various data sets. Despite differing in $T_{\rm eff}$ by only 35–40 K, the Li abundances of 16 Cyg A and B differ by a factor of $\gtrsim4.5$. The solar photospheric abundance is intermediate to the two values. This intermediacy indicates that the Sun, whose highly depleted photospheric Li abundance is in gross conflict with standard stellar models, is not an isolated anomaly in its Li abundance evolution. A similar conclusion is reached via comparison of α Cen A and metal-rich Hyades dwarfs. The difference in the 16 Cyg components' abundances suggests, though does not directly establish, a slow (possibly rotationally-induced) mixing mechanism operating below the surface convection zone in these stars. Indeed, the Li abundance difference can be viewed as an analog to the Li abundance dispersion seen in cool stars of similar $T_{\rm eff}$ in open and globular clusters, and in Galactic field halo stars. It is possible, in principle anyway, that the low Li abundances of the Sun and 16 Cyg B with respect to 16 Cyg A may be related to the presence of a planetary companion; Li abundances of 47 UMa, and HD 114762 might further support such a connection between planets/disks, angular momentum evolution, and photospheric Li abundances. Due to a variety of uncertainties, however, any conclusions remain tenuous and speculative at this time. Finally, as an interesting aside, we show that current line list uncertainties in the λ6707 Li region suggest that claims of very small ^{6}Li/^{7}Li ratios ($\leqslant0.01$) inferred from analysis of the solar photospheric spectrum are overly optimistic—though not necessarily incorrect. © *1997 American Astronomical Society.* [S0004-6256(97)00805-4]

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1. INTRODUCTION

Measured ^{7}Li abundances in cool ($T_{\rm eff} \lesssim T_\odot$) dwarfs have long challenged the applicability of standard stellar models as regards light element abundance evolution in their interiors. Li is a particularly useful model diagnostic since the element is destroyed by (p,α) reactions at temperatures of a few million degrees at the base of the surface convection zone. Standard stellar models, which burn Li generally during the early pre-main-sequence (PMS) phase of evolution, are unable to account for a number of phenomena observed in cool stars, such as: (a) the dispersion of Li at fixed $T_{\rm eff}$ in open cluster dwarfs (Thorburn *et al.* 1993; Soderblom *et al.* 1993), (b) the larger Li abundances of sufficiently short-period tidally locked binaries in a variety of stellar populations (Ryan & Deliyannis 1995), and (c) barring Li enrichment in the past 5 Gyr, the apparent age-Li abundance dependence observed in open clusters (Boesgaard 1991; Deliyannis *et al.* 1994; though see also King 1997).

It has been known for decades that the Sun's photospheric Li abundance, depleted by over a factor of 100 relative to the meteoritic abundance, cannot be accounted for by standard solar models (Ahrens *et al.* 1992; Swenson & Faulkner 1992). This discrepancy has led to consideration of a variety of mechanisms which might explain the observed abundance and other aforementioned phenomena, e.g., mass loss (e.g., Boothroyd *et al.* 1991), turbulent diffusion (e.g., Lebreton & Maeder 1987), and enhanced convective overshoot (e.g., D'Antona & Mazzitelli 1984). A helpful constraint on additional mechanisms, which seek to explain the solar ^{7}Li abundance, comes from the solar ^{9}Be abundance. This is particularly true if the photospheric Be abundance has been depleted, even slightly, as some analyses (Chmielewski *et al.* 1975; King *et al.* 1997) have suggested.

Since meteorites provide us with the most secure estimate of the initial solar Li and Be abundances (Anders & Grevesse 1989), the Sun's light element depletion can be established more confidently than for other field stars. It is interesting to ask whether the discrepant solar Li, and possibly Be, abundance is related to the aforementioned phenomena observed in cool open cluster stars as well as to other, apparently distinct, trends seen in mid- to late-F field and open cluster stars. These trends include: (a) the well-known Li gap (Boesgaard & Tripicco 1986), and (b) stars (such as 110 Her) which show a sizable Be depletion, yet still retain some Li (Deliyannis 1995; Stephens *et al.* 1997). First, however, it is important to ascertain whether the present-day light element abundances of the Sun are typical of other similar stars. If not, then this may be a manifestation of other parameters at work or an indication that the Sun is an isolated anomaly which places little constraint on light element abundance evolution in similar stars.

The study of genuine solar analogs may be helpful in investigation of these issues. Two such candidates are found in the binary system 16 Cyg A and B, which has been studied by Friel *et al.* (1993) via high resolution, high S/N spectroscopy. Using an analysis differential to the Sun, they find that the two stars have $T_{\rm eff}$ differing by 25 K around the canonical solar value and an iron abundance only slightly (0.05 dex) larger the Sun's. Based on a comparison of chromospheric activity indicator lines, they conclude that the Sun and 16 Cyg are similar in age, with the latter perhaps slightly older. Friel *et al.* (1993) found that Li was present in 16 Cyg A in approximately solar abundance, but was "virtually absent" in their spectrum of 16 Cyg B. These authors also recognized that these Li abundances could provide important constraints for models of Li evolution in cool stars, but did not comment further on the issue.

Study of the Li abundances of the 16 Cyg system is particularly timely. Cochran *et al.* (1997) have recently reported the discovery of a $\geqslant$1.5 Jupiter-mass companion to 16 Cyg B from precision radial velocity observations. Given accumulating evidence of a connection between angular momentum transfer and stellar light element depletion, one might wonder if the presence of a planetary companion and/or circumstellar disk can influence (or be inferred from) photospheric Li abundances. While we can not hope to answer this question here, we are able to contribute the requisite precision Li abundances for two stars with planetary systems—16 Cyg B and the Sun. Here, we present Li abundances of 16 Cyg A and B, the metal-rich solar analog α Cen A, and the Sun. To minimize possible errors, the 16 Cyg and solar spectra were obtained with three different instruments and reduced independently. The implications of our results for models of Li evolution in cool stars are discussed.

2. OBSERVATIONS AND DATA REDUCTION

Since we expected the Li feature to be quite weak in these stars, of order 5 mÅ or less, special care was taken in the data acquisition, reduction, and analysis. It was important to employ rather high resolution (45,000 to 70,000) and very high S/N (of order 1,000). To check for possible systematic errors inherent in any single telescope/instrumentation combination and/or individual's analysis, we observed the 16 Cyg pair and the Sun (proxy) at three different telescopes: the University of Hawai'i (UH) 2.2-m, the McDonald 2.1-m, and the Keck I 10-m. Finally, the data from each telescope were reduced by a different individual. The observational details given below are summarized in Table 1, which lists the dates of observation, number of individual exposures, total exposure time, and total (per pixel) S/N achieved at each facility for each object.

2.1 UH 2.2-m Coude Spectra

We used the UH 2.2-m telescope, Coude spectrograph, and a Tek 2048×2048 CCD to obtain spectra of 16 Cyg A and B during the nights of 1993 October 5, 29, 30, and 31 (UT). The small slit width (~0.3″) used, while hampering throughput, yielded a resolution of $R \sim 70{,}000$ (as measured from the ~2.5 pixel FWHM of Th-Ar lamp lines) with a dispersion of 0.039 Å/pix. For 16 Cyg A, we obtained two exposures totaling 2520 s on October 5 and four exposures of 1800 s each on October 31. For 16 Cyg B, we obtained two exposures totaling 2903 s on October 5, four exposures of 1800 s each on October 29, and six exposures totaling 11,700 s on October 30. Two 600 s exposures of the day time sky were taken on October 5 and two 300 s exposures

TABLE 1. Observational summary.

Telescope	R^{-1}	Object	Dates UT	Exp #	Time (s)	S/N
UH 2.2-m	70,000	16 Cyg A	5,31 Oct 1993	6	9720	515
Coude		16 Cyg B	5,29,30 Oct 1993	12	21803	755
		Sky/Moon	5,31 Oct 1993	4	1800	3000
		α Cen A	22 Jun 1994	8	690	1110
		α Cen B	22,23 Jun 1994	6	1690	1010
McD 2.1-m	60,000	16 Cyg A	9 Sep 1994	7	4900	1010
Sandiford		16 Cyg B	10 Sep 1994	7	4410	910
		Sky	8 Sep 1994	1	9	540
		γ Tau	10 Sep 1994	2	220	655
Keck 10-m	45,000	16 Cyg A	30 Jul 1994	2	120	750
HIRES		16 Cyg B	30 Jul 1994	3	300	1050
		Moon	30 Jul 1994	1	30	1500

of the Moon were taken on the night of October 31. We also obtained 6 exposures totaling 1690 s of α Cen B on the nights of 1994 June 22 and 23 (UT), and 8 exposures totaling 690 s of α Cen A on the night of 1994 June 22.

Numerous flat-field exposures and several Th-Ar exposures were acquired each night. The reductions were carried out by AS. Preliminary processing (overscan subtraction, trimming, calibration frame combining, etc.) was performed with standard IRAF routines. No bias frames were obtained; however, any residual bias or light contamination is removed prior to extraction by subtracting off the average of a block of pixels running parallel to the dispersion adjacent to, but removed from the wings of, the spectrum. Tracing, extraction, and dispersion correction were performed with routines in the IRAF KPNOCOUDE suite. The individual 1-d spectra of each object were then combined. Our estimates, based on Poisson statistics, of the S/N in the continuum of the 6707 Å region are 515, 755, 3000, 1010, and 1110 for 16 Cyg A, B, scattered/reflected solar spectrum, α Cen B, and α Cen A.

2.2 McDonald 2.1-m Echelle Spectra

Spectra of 16 Cyg A and B were obtained on the nights of 1994 September 9 and 10 (UT), respectively, using the Sandiford cassegrain echelle spectrograph (McCarthy *et al.* 1993) and a Reticon 1200×400 CCD on the McDonald Observatory 2.1-m telescope. The employed slit width (~1.0″) provided a resolution of $R\sim 60{,}000$ (~1.8 pixels) with a dispersion of 0.062 Å/pix near 6707 Å. Seven exposures of 700 s and 630 s each were acquired of 16 Cyg A and B, respectively. A 9 s exposure of the afternoon sky was obtained on September 8. Two 110 s exposures were also taken of the Hyades giant γ Tau on the same night that 16 Cyg B was observed.

Multiple bias frames and internal flat-field lamp exposures were obtained each night in addition to an internal Th-Ar lamp exposure. The reductions were carried out by KC. Preliminary processing (overscan and bias subtraction, trimming, combining multiple calibration frames) was carried out with standard IRAF routines. The flat fielding, order identification, tracing, scattered light corrections, extraction, and dispersion corrections were carried out within the IRAF echelle package. The individual, 1-d spectra of each object were then combined. The approximate, Poisson-based S/N values of the final spectra are 1010, 910, 540, and 655 for 16 Cyg A, B, the day-time sky, and γ Tau.

2.3 Keck 10-m HIRES Spectra

We observed 16 Cyg A and B during the night of 1994 July 30 (UT) using the HIRES echelle spectrograph (Vogt *et al.* 1994) and a Tek 2048×2048 CCD on the W. M. Keck 10-m telescope. The measured resolution is $R\sim 45{,}000$ (~3.4 pixels) with a dispersion of 0.044 Å/pix near 6707 Å. Two exposures of 60 s each were obtained for 16 Cyg A. Two 120 s and one 60 s exposure were obtained of 16 Cyg B. We also acquired a 30 s exposure of the Moon near dawn.

Multiple internal flat-field lamp exposures, bias frames, and an internal Th-Ar lamp spectrum were acquired during nightly engineering time. The reductions were carried out by JRK. Again, preliminary processing was carried out with standard IRAF routines. The flat fielding, order identification, tracing, and extractions were performed within the specialized suite of FIGARO echelle reduction routines, developed and modified by J. McCarthy and A. Tomaney, imported into the IRAF environment at the University of Texas. Scattered light corrections and dispersion solutions were determined and applied using the nominal IRAF echelle package routines. The individual 1-d spectra of 16 Cyg A and B were then coadded. The Poisson noise S/N estimates in the continuum of the 6707 Å region are 750, 1050, and 1500 for 16 Cyg A, B, and the Moon.

3. ABUNDANCE ANALYSIS

Because the 6707 Å Li features are relatively weak (a few mÅ) in our program objects and could be perturbed by neighboring weak atomic and molecular features, we carry out the Li abundance analysis via spectrum synthesis. Synthetic spectra were constructed from the line list described below using an updated version of the LTE analysis code MOOG (Sneden 1973). All model atmospheres were taken from the new $\alpha = l/H_p = 1.25$ grids of Kurucz (1992).

3.1 Parameters

Friel *et al.* (1993) determine parameters of 16 Cyg A and B relative to the Sun using their own high S/N, high resolution spectroscopy of these stars. While verifying the details of their results independently is of interest and will be pursued elsewhere, for the present purposes it is sufficient to rely mainly on their results. Based on comparison of Hα profiles, Friel *et al.* (1993) find $T_{\rm eff}=5785\pm25$ K and 5760 ± 20 K for 16 Cyg A and B on a scale where the solar $T_{\rm eff}=5770$ K. Using these temperatures, bolometric magnitudes based on CCD parallax measurements (see their Table 2), and masses from evolutionary tracks, they find that log $g=4.28\pm0.07$ and log $g=4.35\pm0.07$ for log $g_\odot=4.44$; these values agree with those inferred from ionization equilibrium. Although the gravity difference is not significant given the errors, they note that it would appear to be real given the stars' V magnitudes and other photometric data.

Gray (1995) has determined *relative* $T_{\rm eff}$ values for the 16 Cyg components using high precision line depth ratio measurements. His relative $T_{\rm eff}$ difference (50 K) between the A and B components is double that of Friel *et al.* (1993). We settle on a value intermediate to these determinations and take $T_{\rm eff}=5747$ K for 16 Cyg B. This somewhat lower value makes the slight gravity difference adopted above more likely. We assume a microturbulent velocity of 1.0 km/s for the Sun and 16 Cyg based on the absolute curve of growth analysis of Friel *et al.* (1993). Finally, Friel *et al.* (1993) conclude that [Fe/H]$=+0.05\pm0.06$ for both stars based on their analysis of various Fe I and Fe II lines and we adopt this abundance here.

For α Cen B, we use the parameters determined by Chmielewski *et al.* (1992)—namely, $T_{\rm eff}=5325\pm50$ K and log $g=4.58\pm0.02$. We use a microturbulent velocity of 0.7 km s^{-1} and have assumed the same scaling of abundances as their Fe determination [Fe/H]$=+0.24\pm0.02$ (based on both A and B), except for (a) the few odd-numbered elements found to be even slightly more enhanced by Furenlid *et al.* (1994); (b) Ce, for which we use the Furenlid *et al.* value; and (c) CN, which is determined from a feature in our spectrum.

We also adopt the parameters of Chmielewski *et al.* (1992) for α Cen A: $T_{\rm eff}=5800\pm20$ K and log $g=4.31\pm0.02$. A microturbulent velocity of 1.1 km s^{-1} was employed in the syntheses. As for α Cen B, we initially adopted [Fe/H]$=+0.24$ and scaled other elements similarly except for the cases noted above. During the analysis, however, the Fe lines in our spectrum consistently appeared slightly weaker than the synthesized features. Thus, we have taken [Fe/H]$=+0.18$ dex for our final results. The small 0.04 dex difference with the Chmielewski *et al.* (1992) value is within the mutual uncertainties, and does not affect our conclusions. The implied 0.08 dex difference with α Cen B could be due to unexpected uncertainties in the data, model atmosphere deficiences, parameter errors, abundance scale differences, a genuine difference, or a combination of these. For γ Tau, we use the parameters adopted by King & Hiltgen (1996)—an infrared flux method-based $T_{\rm eff}=4965$ K, a physical gravity of log $g=2.65$, and a literature-based microturbulence of 2.0 km s^{-1}. We have assumed scaling of all Hyades abundances except CNO and Ce by [M/H] $=+0.12$.

3.2 Atomic Linelist Data

Our 6707 Å linelist for the spectrum synthesis is taken from Hiltgen (1996). This latter linelist is based on that of Gilroy (1988) and has been augmented and modified with the atomic data from the new Kurucz line lists and CN features from Davis & Phillips (1963) and Jorgensen & Larsson (1990). CN features from the latter reference were only used if they could be identified in both the solar and an Arcturus spectrum. The atomic data for Li have been taken from Table 1 of Andersen *et al.* (1984). Because we are dealing with very weak features in the immediate Li I λ6707.8 region, it is useful to compare our linelist with those used by others in the study of cool stars having weak Li features. The linelist utilized by Lambert *et al.* (1993, hereafter LSH93) seems well-suited for such a comparison since these authors found that their linelist allowed for little if any Li to be present in Ba giants in contrast to previous reports of claimed detections.

Small adjustments (~0.15 dex) were first made to the gf values of the 6703.6, 6704.5, 6705.1, and 6710.3 Å Fe I features, which are useful in determining the broadening utilized in the synthesis, by forcing agreement between the Kurucz *et al.* (1984) solar flux atlas data and syntheses conducted assuming log N(Fe)$=7.52$. Next, adjustments to other lines outside the immediate λ6707.8 Li region were made using the K84 atlas and the abundances of Anders & Grevesse (1989). Valuable checks and ambiguity resolutions were provided by analogous syntheses of α Cen B and the Hyades giant γ Tau, which provide a baseline in $T_{\rm eff}$ and gravity. It should be cautioned, however, that possible systematic errors might limit the usefulness of these other stars in this procedure. While the α Cen B parameters seem to be fully consistent with those adopted here for 16 Cyg and the Sun (since the Chmielewski *et al.* α Cen analysis is very similar to that conducted by Friel *et al.* for 16 Cyg), this may not be the case for γ Tau. There may be systematic differences between the dwarf parameters and the infrared flux-based Hyades giant parameters. Larger deficiencies may exist in cool giant model atmospheres. Finally, there are the well known problems of discrepant spectroscopic and physical gravity scales for giants (Luck & Challener 1995), large variations in different investigators' derived C and N abundances for the Hyades giants, and the large systematic differences between Hyades giant- and dwarf-based metallicities sometimes seen (e.g., Griffin & Holweger 1989). We cannot hope to resolve these (perhaps related) long-standing problems here, so we have not considered constraints provided by γ Tau to be as stringent as from the solar atlas and α Cen B, though they do remain useful.

In the immediate Li region, there are a few features of particular interest in analyses of cool, Li-weak stars. The λ6707.82 (5,1) R1 64 CN feature falls right in the midst of the Li region. By synthesizing α Cen B assuming no Li (a reasonable assumption), we were led to increase the gf value of this feature in our initial list. The final value is 0.21 dex larger than that in the linelist of LSH93 and nearly identical

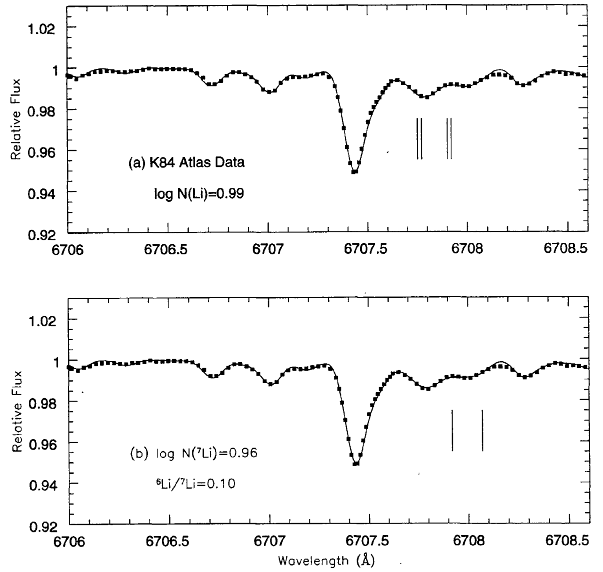

FIG. 1. (a) The K84 solar data (squares) vs a spectrum synthesis (line) conducted with our final linelist for a ^{7}Li abundance of log N(Li)=0.99 and no ^{6}Li. The vertical lines indicate the ^{7}Li components in the synthesis. (b) Same as above except the λ6708.07 V I and fictitious λ6708.00 Si I feature have had their gf values slightly altered. A synthesis with ^{6}Li/^{7}Li = 0.10 is seen in this case to be as plausible as the former synthesis with no ^{6}Li. For the sake of clarity of display, not all K84 atlas points encompassed by the range of the abscissa have been plotted.

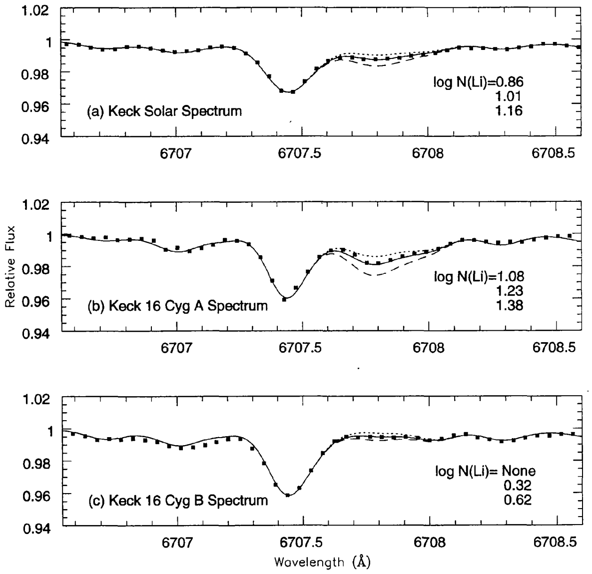

FIG. 2. (a) The Keck solar proxy spectrum (filled squares) vs synthetic spectra (lines) having Li abundances of log N(Li)=0.86, 1.01 (the best fit value), and 1.16. (b) The Keck spectrum of 16 Cyg A vs synthetic spectra having Li abundances of 1.08, 1.23, and 1.38. (c) The Keck spectrum of 16 Cyg B vs synthetic spectra having logarithmic Li abundances of $-\infty$, 0.32, and 0.62.

to that employed in the solar Li analysis of Muller *et al.* (1975, hereafter, MPD75). Similarly, we increased the gf value of the λ6707.740 Ce II feature suggested by LSH93 based on their syntheses of Ba giants. The gf increase, which improves agreement with the α Cen B spectrum but is not discordant with the solar spectrum, is again 0.21 dex. Synthesis of the Hyades giant indicates no deleterious effects from these mild enhancements. Indeed, the inferred LTE abundance, log N(Li)$\sim$1.05 is in excellent agreement with the recent determination of Luck & Challener (1995).

As noted by MPD75, the region around 6708.0 Å is more problematic. These authors suggested the presence of unidentified lines at 6708.025 Å and "beyond" 6708.087 Å in their solar spectra. Despite the improvements in atomic data, reflected in our larger line list, since the MPD75 study, comparison of our solar synthesis with the very high resolution and S/N K84 atlas data shows that these discrepancies still persist. It may be that the latter feature referred to by MPD75 is the ~6708.1 Å V I line. Wavelengths for this feature we found quoted in the literature range from 6708.07 to 6708.17 Å. Our spectra of α Cen B clearly suggested a value between 6708.05 and 6708.10 Å. We have assumed the wavelength, 6708.070 Å, used by LSH93 since this appears to reproduce their stars' much stronger V I feature well.

We followed MPD75 in accounting for the deficient absorption near 6708.0 Å using a fictitious 6.0 eV Si I line. A wavelength of 6708.00 Å, however, seemed preferable to their value. Coupled with the difference between our adopted V I wavelength and that probably inferred by MPD75, this may reflect a small (~0.02 Å) difference in wavelength scale. The gf values of the V I and Si I features were altered to sufficiently match the K84 spectrum. Happily, the final values provided a good fit to our α Cen B spectrum. Our spectrum of γ Tau suggests the V I gf value may be slightly too large, but we do not give this much weight in light of the uncertainties discussed above. Finally, the gf value of the 6707.64 Å Cr I feature was also slightly enhanced to improve agreement with the α Cen B spectrum. The final value is 0.14 dex larger than that in the linelist of LSH93. All of our slight line list modifications in the immediate Li I region lead to a more conservative linelist than used by LSH93 in the sense that less absorption could be ascribed to Li.

A comparison of a synthesis having log N(Li) = 0.99 and the K84 solar spectrum is shown in Fig. 1(a). Very good agreement is seen, which is not too surprising since this is largely, though not entirely, forced. This agreement also carries over to our lower resolution and S/N solar proxy spectra shown in Figs. 2(a), 3(a), and 4(a). An interesting aside concerns the ^{6}Li/^{7}Li ratio. Except for the brief discussion in Sec. *4.1*, we assume no contributions from ^{6}Li. MPD75 argued that their solar spectra and synthesis indicated ^{6}Li/^{7}Li$\leq$0.01. However, given the uncertainties concerning the unknown blending feature at 6708.0 Å, the precise wavelength of the 6708.1 Å V I feature, and other apparent remaining linelist deficiencies such as that evident near 6708.16 Å, it is not clear to us how firm this limit is. By slightly altering the gf values of only the Si I and V I features, we are easily able to accommodate ratios as large as ^{6}Li/^{7}Li = 0.10 as shown in Fig. 1(b). Isotopic ratios this large may have interesting implications, but we do not consider these here since additional improvements in the atomic data appear necessary to confidently derive them in solar type, high metallicity stars.

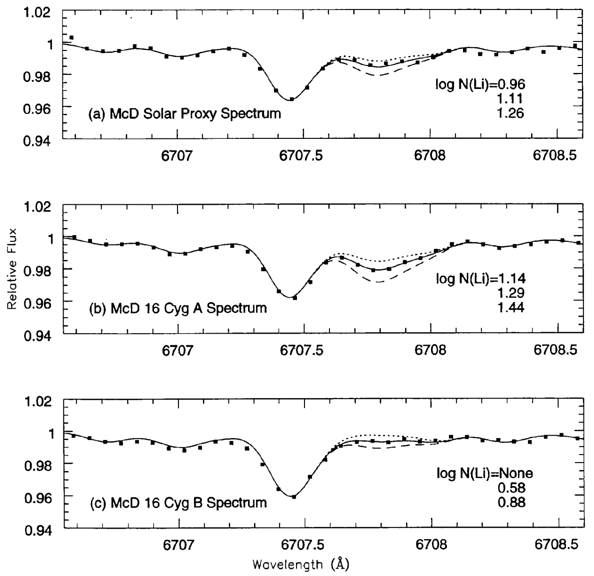

FIG. 3. (a) The McDonald Observatory 2.1-m echelle solar proxy spectrum vs syntheses with log N(Li)=0.96, 1.11, and 1.26. (b) The McDonald spectrum of 16 Cyg A vs syntheses with Li abundances 1.14, 1.29, and 1.44. (c) The McDonald spectrum of 16 Cyg B vs syntheses with Li abundances $-\infty$, 0.58, and 0.88.

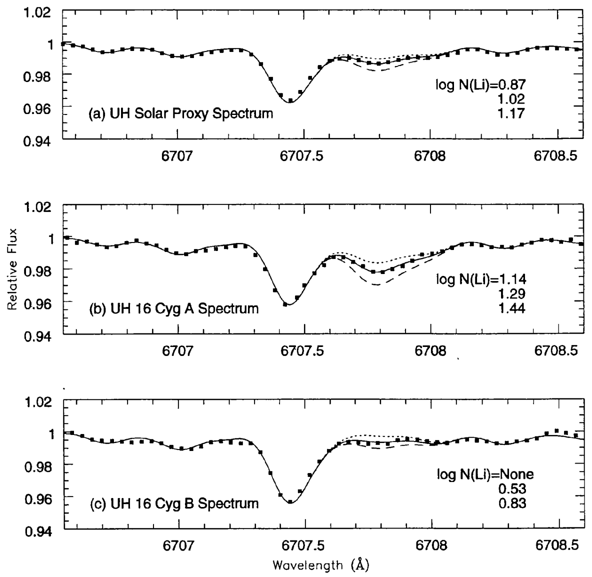

FIG. 4. (a) The UH 2.2-m coude solar proxy spectrum vs syntheses with log N(Li)=0.87, 1.02, and 1.17. (b) UH 2.2-m spectrum of 16 Cyg A vs synthetic spectra having Li abundances of 1.14, 1.29, and 1.44. (c) UH 2.2-m spectrum of 16 Cyg B vs synthetic spectra having Li abundances of $-\infty$, 0.53, and 0.83.

3.3 16 Cyg Li Abundance Determinations

3.3.1 Keck HIRES data

Figure 2(a) shows our Keck HIRES lunar reflectance spectrum and three syntheses of differing Li abundance conducted with the same final linelist as in Fig. 1(a) for the K84 atlas data. The best fit is found for log N(Li)=1.01. An F-test of reduced χ^2 values, computed from the data points surrounding the Li region, for syntheses of varying Li abundance suggests that the internal 1σ uncertainty (i.e., that of the fitting uncertainty due to noise in the data) is a scant 0.01 dex. Other external factors, such as the continuum level, slight wavelength errors, broadening uncertainty, and other factors, are the dominant sources of error. The external errors were estimated by redetermining the Li abundance after altering these various factors by plausible amounts. We estimate the total (negligible internal plus external) error to be ~0.07 dex. Here, for the Sun, we have assumed no uncertainty in the fundamental parameters. Additionally, we do not consider other external systematic errors (e.g., the Li gf values, model atmosphere deficiencies, etc.) for any of our program objects since these should not affect the derived *relative* abundances.

Figure 2(b) contains the Keck spectrum of 16 Cyg A and three syntheses of varying Li abundance. The initial syntheses of the λ6707.4 Fe+CN feature were seen to be slightly too broad on the red side of the profile. It was then noticed that the synthesis of the relatively clean λ6706.7 CN feature appeared to be too strong. Comparison of the observed spectra indicates that the CN feature is weaker than in the Sun and we have tentatively ascribed this behavior to a mild CN deficiency in 16 Cyg compared to the Sun. Keeping the C/N ratio at the solar value, we decreased both the C and N input abundances (to [C/H]= [N/H]=-0.07) until better agreement was seen between the synthetic and observed 6706.7 Å region, resulting in improved agreement between the red profile of the 6707.4 Å feature and the synthesis. The best fit abundance is found to be log N(Li)=1.23 with an internal error (described above) of ±0.03 dex. Total uncertainties (internal plus external plus those in the parameters) are estimated to be 0.08 dex.

The Keck spectrum of 16 Cyg B is displayed in Fig. 2(c). Here too (and in all the other 16 Cyg syntheses as well as those conducted for γ Tau and α Cen B) the CN was not fixed, but instead estimated from the 6706.7 Å feature (we find [C=N/H]=0.00). This allows differences in the CN abundance between the 16 Cyg A and B components and differences from data set to data set. This was done to treat each particular synthesis as an independent analysis in order to search for possible systematic differences and to yield independent checks on abundance uncertainties for features of similar strength to Li I λ6707.8. Comparison of the data and the synthesized spectra indicates that there is absorption in the Li region. Ascribing this absorption to Li is a different matter, however, and relies heavily on the adequacy of the linelist. The best fitting Li abundance is log N(Li)=0.32. The 3σ internal uncertainties in this value are $+0.12$ and $-\infty$ dex. The estimated 1σ errors including external/parameter uncertainties $+0.18$ dex and -0.30 dex.

3.3.2 McDonald echelle data

The solar proxy spectrum acquired with the McDonald Observatory 2.1-m cassegrain echelle spectrograph is displayed in Fig. 3(a) (solid points). Syntheses having three different Li abundance values are overplotted on the observed data. The best fitting Li abundance is log N(Li)

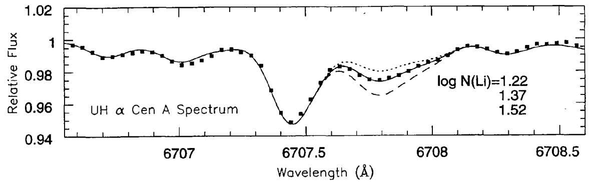

FIG. 5. UH 2.2-m spectrum of α Cen A (solid points) vs synthetic spectra (lines) having Li abundances of 1.22, 1.37 (our favored value), and 1.52.

$=1.11\pm0.06$ (internal 1σ level uncertainty). Combined internal and external uncertainties are estimated to be ±0.12 dex.

The McDonald spectrum of 16 Cyg A and analogous syntheses are shown in Fig. 3(b). The CN abundance determined from the 6706.7 Å feature and utilized in the overplotted syntheses was [C=N/H]$=-0.03$. The best fit Li abundance is found to be $\log N(\mathrm{Li})=1.29$ with an internal 1σ level uncertainty of ±0.02 dex. Total (internal, external, and parameter) uncertainties are estimated to be ±0.07 dex.

Figure 3(c) displays the McDonald spectrum of 16 Cyg B. Here too, comparison of the data and the synthesis with no Li suggests that there is absorption in the Li region. A CN abundance of [C=N/H]$=+0.01$ is inferred from and used in the accompanying syntheses, which indicate a best fit value of $\log N(\mathrm{Li})=0.58$. The internal 1σ level abundance uncertainties are $-0.14/+0.08$ dex. We place our total uncertainty estimate at $-0.21/+0.14$ dex.

3.3.3 UH coude data

Figure 4(a) contains our UH 2.2-m coude solar proxy spectrum and syntheses of varying Li abundance. The best fitting Li abundance is $\log N(\mathrm{Li})=1.02$ with an internal uncertainty of ±0.02 dex. The total internal and external uncertainties are estimated to be ±0.06 dex.

Our UH coude spectrum of 16 Cyg A is shown in Fig. 4(b). The deduced CN abundance used in the displayed syntheses is [C=N/H]$=-0.02$. The Li abundance is determined to be $\log N(\mathrm{Li})=1.29$ with an internal uncertainty of ±0.03 dex. We estimate the total internal, external, and parameter uncertainties to be near ±0.06 dex.

Finally, Fig. 4(c) displays the UH coude spectrum of 16 Cyg B and corresponding syntheses having varying Li abundance. The CN abundances deduced here were [C=N/H]$=-0.01$). The best fitting Li abundance is found to be $\log N(\mathrm{Li})=0.53$ with internal 1σ uncertainties of $+0.08/-0.13$ dex. Total internal, external, and parameter errors are estimated to be $+0.16/-0.26$ dex.

3.4 α Cen A Li Abundance

Figure 5 displays our UH coude spectrum of α Cen A and syntheses for $\log N(\mathrm{Li})=1.22$, 1.37, and 1.52. The CN abundance inferred from the 6706.7 Å feature and used throughout the synthesis is [C=N/H]$=+0.22$. This carbon abundance is in excellent agreement with that, $+0.19$, found by Furenlid *et al.* Our best fit Li abundance is $\log N(\mathrm{Li})=1.37$ with internal and external 1σ level uncertainties of $\lesssim0.02$ and ~0.06 dex. This value is in good agreement with the determinations, $\log N(\mathrm{Li})=1.4$ and 1.28, of Chmielewski *et al.* (1992) and Soderblom & Dravins (1984).

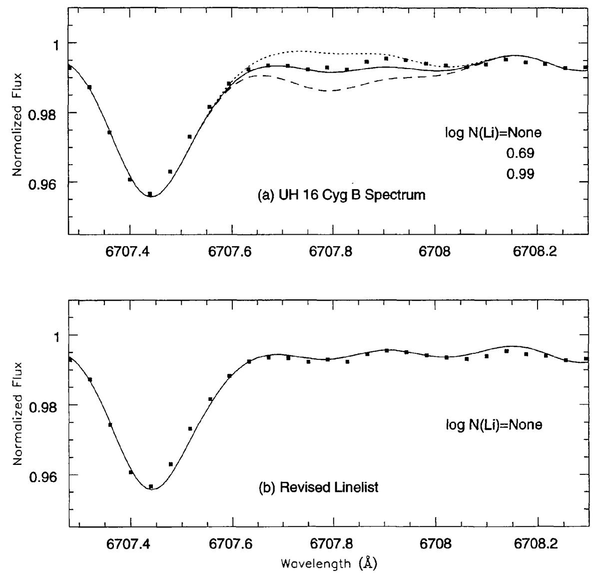

FIG. 6. (a) A magnified version of Fig. 4(c) showing our UH 2.2-m coude spectrum of 16 Cyg B vs several syntheses. An asymmetry between the synthesis and the observed points is apparent in the immediate 6707.8 Å Li I region. (b) The UH coude spectrum of 16 Cyg B vs a synthesis conducted with the trial Ce II, CN, and V I *gf* values described in Sec. *4.1* and having no Li. The asymmetry is now largely removed.

4. DISCUSSION

4.1 Li Region Linelist Revisited

Figure 6(a) is a magnified version of Fig. 4(c) and shows our highest resolution UH coude spectrum of 16 Cyg B and syntheses having no Li, a Li abundance (0.69) which reproduces the blue side of the immediate Li region, and an abundance 0.3 dex larger. This figure shows that the synthesis appears to be asymmetric with respect to the observed profile in the sense that abundances large enough to match the blue portion of the Li region are too strong in the red portion. Based on χ^2 tests, we find that the hypothesis that the asymmetry could be due to simple photon noise is rejected at the 93% confidence level. This borderline significance, coupled with other small and difficult to quantify uncertainties (e.g., those in the dispersion solution, the adequacy of the Gaussian functional form used in the synthetic spectrum broadening, and higher order effects in the continuum rectification) make it difficult to assess the import of the asymmetry. However, it is in the same sense noted by LSH93 in their analysis of Li-deficient Ba giants. Because of the interesting implications which follow from exploring the issue further, we do so now.

LSH93 ascribed their observed asymmetries to overestimated Li abundances caused by incomplete consideration of blending features. Following them, we ask if an improved fit for 16 Cyg B could be made assuming no Li content. Altering the $\log gf$ values of the 6707.740 Ce II, 6707.816 CN, and 6708.070 V I lines by $+1.08$, $+0.25$, and -0.10 dex

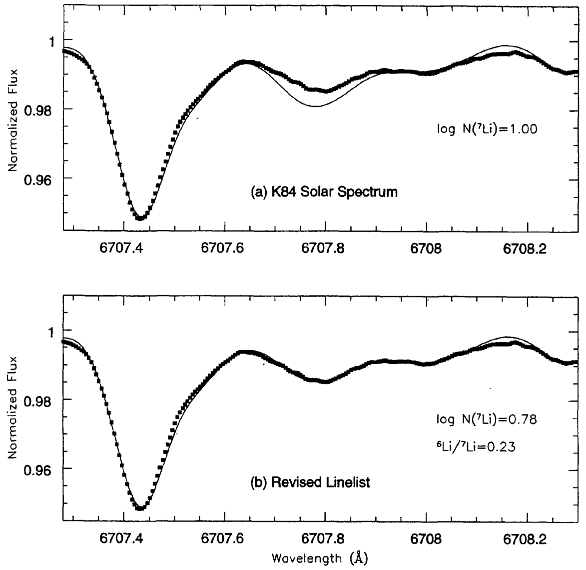

FIG. 7. (a) The K84 solar atlas data are shown vs a synthesis having $\log N(\mathrm{Li})=1.00$ and no ^{6}Li using the trial Ce II, CN, and V I *gf* values described in Sec. *4.1* and used in Fig. 6(b). An asymmetry between the 6707.7 Å and 6707.9 Å Li component regions is clear. (b) Same, except that a $^6\mathrm{Li}/^7\mathrm{Li}$ ratio of 0.23 is assumed and the synthesis is for a total Li abundance of $\log N(\mathrm{Li})=0.87$.

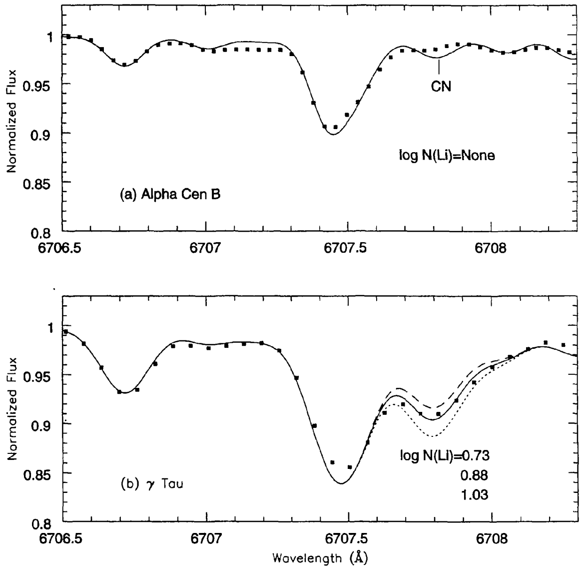

FIG. 8. (a) Our UH spectrum of α Cen B (solid points) is plotted with a synthesis assuming no Li content and utilizing the trial Ce II, CN, and V I *gf* values described in Sec. *4.1* and used in Fig. 6(b), 7(a), and 7(b). The 6707.82 Å CN feature in the synthesis appears to be too strong. (b) Our McDonald spectrum of the Hyades giant γ Tau vs a synthesis conducted using the trial Ce II, CN, and V I *gf* values. No gross discrepancies in the Li region are apparent and an abundance near $\log N(\mathrm{Li})=0.88$ is suggested.

with respect to the values in our final linelist produces the syntheses shown in Fig. 6(b). It can be seen that these trial *gf* values lead to a seemingly much improved match with the observed profile morphology over that in Figs. 4(c) and 6(a).

Figure 7(a) shows the K84 solar spectrum and a synthesis conducted using the trial Ce II, CN, and V I *gf* values from above. Here, an asymmetry in the opposite sense is seen. The ^{7}Li abundance (~1.00) reproducing the immediate red Li region is too strong in the immediate blue region. Reducing the Li abundance (~0.83) to reproduce the region containing the bluer ^{7}Li components causes the synthesis to be too weak in the red region. Such a discrepancy originally constrained the initial gf value adjustments employed in our final linelist discussed in Sec. *3.2*. In the absence of other free parameters, the discrepancy would suggest we have overenhanced the trial Ce II and CN oscillator strengths in this section's experiment.

However, as noted in Sec. *3.2*, another free parameter is the $^6\mathrm{Li}/^7\mathrm{Li}$ ratio, which we have assumed to be zero. Figure 7(b) shows that relaxing this assumption can lead to greatly improved agreement with the K84 solar spectrum. Here we have used the same trial Ce and CN *gf* enhancements as in in Fig. 7(a), but have assumed $^6\mathrm{Li}/^7\mathrm{Li} = 0.23$. Given the significant implications such a large ratio would have, it is interesting to see if our α Cen B and γ Tau spectra could rule out these trial Ce II and CN oscillator strength enhancements which permit the large Li isotope ratio in Fig. 7(b).

The UH coude spectrum and accompanying synthesis (assuming no Li) for α Cen B is shown in Fig. 8(a). The C and N abundances were kept in the solar ratio and varied to match the 6706.7 Å CN feature. A value of $[\mathrm{Ce/H}]=+0.09$ was assumed based on the results of Furenlid *et al.* (1994). The α Cen B spectrum in Fig. 8(a) suggests that the 6707.82 Å CN feature's small trial *gf* enhancement over that in our final linelist is too large. In contrast, the much larger trial enhancement of the 6707.74 Å Ce II feature seems allowable.

Figure 8(b) displays our McDonald echelle spectrum of γ Tau and three syntheses of varying Li abundance conducted with the trial Ce and CN enhancements. Based on the average Hyades giant results of Luck & Challener (1995), we have assumed a Ce abundance reproducing their value of $[\mathrm{Ce\ II/Fe\ II}]\sim-0.17$ and varied the C and N abundances to match the 6706.7 Å CN feature while maintaining their C/N ratio. Figure 8(b) does not suggest that either the CN or Ce II enhancements are out of line and a Li abundance near the displayed value of 0.88 is suggested. If, however, one utilizes a CN *gf* value which matches the α Cen B spectrum (which is a small 0.05 dex increase over the original value used in our final linelist discussed in Sec. *3.2*), then a Li abundance of 1.01 is needed to match the red portion of the broad blended 6707.8 Å profile. In this case, a reduction of the Ce II *gf* value is also needed so that the blue portion of the profile is not too deep. However, this value is still a substantial 0.94 dex larger than the original value adopted in Sec. *3.2* and 1.15 dex larger than the LSH93 value.

It may be that the truth concerning these matters lies somewhere in the middle. In particular, the very modest increase in the CN *gf* value allowed by α Cen B and the much larger increase in the Ce II value [which, however, is not as large as that used in Fig. 6(b)] may mean that a small amount of Li is present in 16 Cyg B. Given the various present uncertainties, it seems safest to consider our Li abundances as upper limits to this value; this does not affect any of the

TABLE 2. Li abundance summary.

Star	$T_{\rm eff}$ K	log g cgs	ϵ(Li) Keck	σ dex	ϵ(Li) McD	σ dex	ϵ(Li) UH	σ dex	ϵ(Li) Final	σ dex
16 Cyg A	5785	4.28	1.23	±0.08	1.29	±0.07	1.29	±0.06	1.27	±0.05
16 Cyg B	5747	4.35	0.32	$^{+0.18}_{-0.30}$	0.58	$^{+0.14}_{-0.21}$	0.53	$^{+0.16}_{-0.26}$	$\lesssim$0.60	⋯
Sun	5770	4.44	1.01	±0.07	1.11	±0.12	1.02	±0.06	1.05	±0.06
α Cen A	5800	4.31	⋯	⋯	⋯	⋯	1.37	±0.06	1.37	±0.06

conclusions we later reach. However, we take this opportunity to note that remaining uncertainties in the blending features in the Li region of the Sun (dominated by Ce II in the solar case) seem to make it difficult to exclude ^{6}Li/^{7}Li ratios even as large as ~0.15. While we are not advocating such values here and while there are other reasons for believing the ratio is significantly smaller, the current uncertainties suggest to us that claims of very small ($\leq$0.01) ratios based on current analyses of the solar photospheric spectrum may be optimistic. Finally, uncertainties in the blending features discussed above result in Hyades giant Li abundance uncertainties at the 0.10−0.15 dex level. The Li abundance in these stars are of particular interest in investigating mixing processes (beyond the standard model) in intermediate mass Pop I stars. Reducing this source of uncertainty (and others such as possible model atmosphere deficiencies, parameter uncertainties, and generally heterogeneous studies of earlier type dwarfs from which the initial Hyades cluster abundance is inferred) would be desirable in future attempts utilizing the Hyades giants' Li abundances to argue for or against nonstandard mixing in their interiors.

4.2 Final Li Abundances

The mean Li abundance of the Sun derived from our three separate data sets is log N(Li) = 1.05. The standard deviation is ±0.06 dex, though this has uncertain meaning for such a small sample size. However, this value does encompass the full range of the individual determinations and is comparable to the external errors in an individual determination, so we retain it as a reasonable estimate of the 1σ level uncertainty in the relative Li abundance. We reiterate that the errors in the absolute Li abundances could be larger due to uncertainties in, e.g., the Li gf values or model atmospheres. However, these should not affect the relative Li abundances, which are our main interest here, of the Sun and 16 Cyg. In order that comparison can be made with our choice of atmospheres and abundance software, we note that the above solar Li abundance corresponds to an equivalent width of 3.4 mÅ computed as a *single* transition in isolation from any other blending features.

The corresponding mean Li abundance of 16 Cyg A is log N(Li) = 1.27 (the computed equivalent width is 5.4 mÅ) with a standard deviation of ±0.04 dex. We increase this value slightly to ±0.05 dex to account for uncertainties, which are external to others in our analysis, in the stellar parameters (namely, $T_{\rm eff}$) relative to the Sun. Again, this value encompasses the full range of our values and is comparable to the external 1σ error in a single analysis, so is a reasonable indicator of the uncertainty in the relative Li abundance. An independent check of sorts is provided by the CN abundances inferred from the 6706.7 Å feature, which is of similar strength as Li. The standard deviation for 16 Cyg A is ±0.03 dex and the difference in the mean values of 16 Cyg A and B is 0.04 dex, consistent with the scatter seen in Li abundance.

The mean Li abundance of 16 Cyg B calculated from our three data sets is log N(Li) = 0.48 with a standard deviation of ±0.14. As discussed above, though, remaining uncertainties in the line list, the possible asymmetry observed in our highest resolution spectrum, and difficult to estimate small uncertainties in the data and analysis procedure prevent us from claiming a secure Li detection. Extremely high resolution ($R \gtrsim 150{,}000$), high S/N observations of 16 Cyg B and a range of calibrating stars may be useful in improving this situation. In the discussion of 16 Cyg B that follows, we take an upper limit of log N(Li) = 0.60 (corresponding to a computed equivalent width of 1.3 mÅ), which is slightly larger than the largest of our individual determinations. All of our Li abundance results for the Sun and solar analogs are summarized in Table 2.

4.3 Is the Sun Typical?

The above final Li abundances indicate that at least some solar analogs have Li abundances roughly a factor of two above (16 Cyg A and α Cen A) the solar photospheric value and at least nearly a factor of three below (16 Cyg B) the solar photospheric value. Regardless of whether 16 Cyg B contains no Li or has an abundance near our log N(Li)~0.6 upper limit, the solar photospheric abundance is close to the average of the 16 Cyg binary components'. Assuming that the 16 Cyg stars had an initial abundance similar (i.e., near-meteoritic) to the Sun, this suggests that the Sun is not somehow atypical compared to other similar cool stars in its Li abundance evolution. Since the Li abundance difference between the Sun and 16 Cyg A and between the Sun and α Cen A is much smaller than the discrepancy between the solar photospheric abundance and that predicted by evolutionary models, the 16 Cyg stars also argue against the adequacy of standard stellar models.

Direct comparison between the Sun and α Cen A is more difficult due to their differing mass (~1.1 $M_\odot$ for α Cen A; Soderblom & Dravins 1984; Demarque *et al.* 1986) and metallicity. A comparison to the metal-rich Hyades stars indicates that the α Cen A Li abundance is a factor of ~13 lower than Hyades stars of similar $T_{\rm eff}$. The mass tracks and Hyades data in Fig. 1 of Swenson *et al.* (1994) indicate an α Cen A Li abundance lower by a factor of ~5 with respect to 1.1 $M_\odot$ Hyades stars. While detailed modeling relying on observational data to provide the needed surface and interior opacities would be beneficial in such a comparison, the opacity variations shown in the models of Fig. 1 of Swenson *et al.* (1994) suggest to us that a factor only as large as ~1.5 might be explained by abundance differences. Thus, if the initial Li abundance of α Cen A was not significantly less than that of the Hyades, its current Li abundance also argues against the adequacy of standard stellar models, which do not deplete significant amounts of Li during the main sequence in 1.1 $M_\odot$ stars like α Cen A.

4.4 Li Abundance Difference of 16 Cyg A and B

Our final estimates in Sec. *4.2* indicate that 16 Cyg A and B differ in Li abundance by at least a factor of ~4.5. This result confirms the apparent difference noted by Friel *et al.* (1993). A more robust conclusion can be reached from this significant difference in Li abundance than can be reached using the (albeit reasonable) assumption of near-meteoritic initial Li abundance. Given the similar parameters of these two stars, such a large Li abundance difference, which is evident from mere visual inspection of the spectra, can not be understood in terms of standard model processes (namely PMS burning and possible subgiant dilution) which affect photospheric Li abundances. Hence, the difference in Li abundances of 16 Cyg A and B alone also argues against the adequacy of standard models in explaining the Li abundance evolution of cool Pop I solar-type stars.

4.5 Stellar Models with Additional Physics

The dispersion in the Li abundances of 16 Cyg A and B, their low absolute Li abundances, the low photospheric Li abundances of α Cen A and the Sun, and the probable mild solar Be depletion (King *et al.* 1997) can at least be qualitatively explained by slow-mixing mechanisms—possibly those involving rotationally-induced mixing. In stellar models which include rotation (e.g., Pinsonneault *et al.* 1990), the Li abundance difference between 16 Cyg A and B would be due, in part, to differences in their initial angular momenta and/or differences in their rate of angular momentum loss.

At the $T_{\rm eff}$ of 16 Cyg A and B, the predicted effects of diffusion (e.g., Michaud & Charbonneau 1991) on Li and Be abundances are similar and small ($\lesssim$0.1 dex). We have obtained spectra of the 3130 Å Be features in 16 Cyg A and B with the Keck HIRES spectrograph. A preliminary inspection of these shows that any possible small Be abundance difference that may exist between the two binary components does not approach the factor of $\gtrsim$4.5 exhibited by Li as would be expected if diffusion were the cause.

Scenarios invoking mass loss to explain the 16 Cyg Li abundance differences and the low absolute Li abundances of the Sun and 16 Cyg are more difficult to rule out directly. However, using open cluster observations of G dwarfs akin to 16 Cyg A and B and the Sun *et al.* (1992) note some severe complications for a mass-loss mechanism. In broader terms of identifying a single mechanism which might account for a wide range of observed light element abundance patterns, the existence of Pop I F stars having significant Be depletions but small amounts of observable Li (Deliyannis 1995; Stephens *et al.* 1997) would argue against mass loss for these hotter objects. Based on the totality of the evidence, we suggest that the light element abundance patterns of 16 Cyg A and B, α Cen A, and the Sun are suggestive of a slow mixing mechanism, which can accommodate (a) the low absolute solar, 16 Cyg, and α Cen A Li abundances, (b) a significant Li abundance spread but much smaller Be abundance spread in the 16 Cyg components, and (c) a small amount of remaining Li in the solar photosphere despite possibly (mildly) depleted solar Be.

Evidence exists which supports the idea that this slow mixing is related to rotation. In particular, Li abundances in cool short-period tidally locked binaries strongly argue for the inclusion of rotation in stellar models (Ryan & Deliyannis 1995). The Yale rotational evolutionary models combined with tidal circularization calculations (e.g., Zahn & Bouchet 1989) predict that synchronized binaries having sufficiently large age and sufficiently small period should show larger Li abundances than similar single stars. As reviewed by Ryan & Deliyannis (1995), these predictions seem to be verified by Li abundances observed in cool dwarf/subgiant short-period binaries in a variety of stellar populations such as the Pleiades, the Hyades, M67, intermediate metallicity stars, as well as metal-poor halo stars.

This agreement between observation and theoretical prediction supports the need to consider stellar models which include the effects of slow (possibly rotationally-induced) mixing in cool solar-type stars. An additional attractive feature of such rotational models is the ability to simultaneously account for a number of apparently distinct observed phenomena (Deliyannis 1995): the well-known Li dip in Pop I F dwarfs, the presence of detectable Li in Be-depleted F dwarfs, the very low solar Li abundance (and likely mildly depleted Be abundance), the gross morphology of the G- and K-dwarf Li abundance-$T_{\rm eff}$ relation in open clusters, and the observed dispersion in Li abundances of cool open cluster dwarfs of similar $T_{\rm eff}$. We may now add to this list the observed Li abundances of the solar analogs 16 Cyg A and B and α Cen A.

It must also be acknowledged that it would be surprising if the Yale (or any) stellar models are wholly complete in their description of real stars. As has been noted (e.g., the discussion in Sec. 2 of Martin & Claret 1996), given the implicit assumption of uniform composition, standard stellar models and the Yale models are unable to account for the dispersion of Li abundances in cool stars of the Pleiades and, perhaps, IC 2602 (the preliminary results of Randich *et al.* 1996).[5] However, the relevance of these data for our analysis is unclear for the following reasons. First, this scatter is seen in stars of significantly lower mass ($\lesssim 0.8 M_\odot$, $T_{\rm eff} \lesssim 5250$

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[5] The α Per cluster also has been thought to display significant dispersion. However, the abundance revisions in Balachandran *et al.* (1996, BLS) lead them to conclude that there no longer remain any Li-deficient stars for $T_{\rm eff} \gtrsim 5500$ K; the star He 600, with a low Li abundance of 2.00 in the original BLS work, was determined to be a non-member by Stauffer *et al.* (1993). Cunha *et al.* (1995) and King (1992) discuss the possibility of dispersion in (and between) the Orion Ic/Id and Ib associations, but membership there remains problematic.

K) than the Sun and 16 Cyg. Second, Martin and Claret themselves note the substantial year-to-year Li equivalent width differences, also suggested by Patterer *et al.* (1993) on shorter time scales, for at least some weak T Tauri stars, and suggest that such behavior might be occurring in the Pleiades as well (and, one might presume, IC 2602). Such apparent Li line strength variations could conceivably contribute to an illusory Li abundance spread. Nevertheless, it is possible that physics not yet incorporated in the Yale prescription may be responsible for the discordant Li abundances of cool Pleiades dwarfs. For example, circumstellar disks (and lack thereof) may influence the angular momentum evolution of cluster stars differently—thus resulting in different mixing histories. Other examples may be angular momentum transfer by gravity waves (e.g., Zahn *et al.* 1997) or the effect of rotation on stellar structure and/or surface temperature (Martin & Claret 1996).

4.6 Photospheric Li and Planetary Companions

An interesting result of our work is that the Sun and 16 Cyg B, both with planetary systems, have significantly lower Li abundances than 16 Cyg A. Indeed, the sequence of Li abundances seems to follow that of the planetary system mass estimates. While this certainly may be mere coincidence, it may in principle be possible for planets or associated circumstellar disks to affect a parent star's initial angular momentum and/or its subsequent evolution (e.g., the comments of Butler *et al.* 1997 concerning tidal synchronization in the HR 5185 system) and thus induce or inhibit internal mixing resulting in Li depletion. Determining whether this is responsible for the above Li abundance pattern will require fuller knowledge of important details such as the mass of the planetary systems and/or precursor disks, the timescale of planet formation and/or disk dissipation, the specifics of angular momentum transfer mechanisms, and variations in the stars' initial Li abundances.

Besides noting that this is a fertile field for future theoretical and observational efforts, several other notes should be made concerning other alleged planetary systems (51 Peg, 47 UMa, HD 114762, 70 Vir, and τ Boo) detected by radial velocity observations. While all of these stars might fairly be referred to as "solar-type" in some contexts, only 47 UMa and 51 Peg are likely "solar analogs" based on, e.g., the temperatures, gravities, metallicities, and ages of Edvardsson *et al.* (1993). Francois *et al.* (1996) report a Li abundance of $\log N(\mathrm{Li})=1.16$ from their high resolution spectroscopy of 51 Peg. This low abundance is consistent with the low values of the 16 Cyg stars and the Sun. Interestingly, the refined 51 Peg planetary companion mass estimate of Francois *et al.* (1996) leads to a declining sequence of Li abundance with increasing inferred planetary companion mass for the four stars 16 Cyg A, 51 Peg, the Sun, and 16 Cyg B. For 47 UMa, Duncan (1981) finds $\log N(\mathrm{Li})<1.70$, which is not inconsistent with the abundances of 16 Cyg B and the Sun, but a modern measurement is highly desirable; as shown here, lowering this upper limit by an order of magnitude is possible. HD 114762 has a solar-like temperature and gravity, but is metal-poor ($[\mathrm{Fe/H}]\sim-0.8$); both Rebolo *et al.* (1988) and Lambert *et al.* (1991) (from which the noted parameters come) find $\log N(\mathrm{Li})\sim1.9$. This abundance is some ~0.2 dex *lower* than that found in most more metal-poor (but otherwise similar) stars on the Spite plateau—suggesting Li depletion in this moderately metal-poor star (see also the intermediate-metallicity stars in Fig. 2 of Ryan & Deliyannis 1995).

According to Duncan (1981), the near-solar metallicity star 70 Vir displays a Li abundance (1.12) nearly identical to the Sun's. However, literature studies indicate this star is an evolved cool ($\sim$5500 K) subgiant, which complicates interpretation of its Li abundance and any connection with a planetary companion. Finally, Butler *et al.* (1997) identify τ Boo as a hot (6450 K), little evolved ($\log g\sim4.3$), rather metal-rich ($[\mathrm{Fe/H}]\sim+0.3$) star forming an apparently tidally-locked short-period (3.3 d) nearly circular ($e=0.02$) system with a $\geqslant3.8$ Jupiter mass companion. The data of Boesgaard & Lavery (1986; a misprint in their Table 2 identifies this star as HR 5183 instead of HR 5185) indicate that HR 5185 is severely depleted both in Li and Be. This is not surprising since the star is located in the middle of the well-known F-star Li gap. Although the short-period tidally locked nature of stars in a variety of stellar populations are often seen to be related with inhibited Li depletion (Ryan & Deliyannis 1995; Barrado y Navascues 1997), the critical period drops sharply as a function of mass in late F stars; it is thus possible that this binary could not achieve the early PMS synchronization that would help prevent subsequent Li and Be destruction.

In sum, the data are too few at this point to establish a connection between alleged planetary companions and photospheric Li abundances. Any relation would depend on a variety of uncertain factors (e.g., masses, time scales, angular momentum transport) which need theoretical and observational clarification. An illustration of the complexities involved is that, as alluded to in this discussion, it is possible that planetary companions could *both* inhibit and foster Li depletion in different systems. Given the alleged detection of companions already for the Sun, 16 Cyg B, and 47 UMa, a good observational starting point might be identification of planetary systems around and the determination of the light element abundances of genuine solar analogs of similar metallicity, age, mass, temperature, and gravity. In this way, the number of free parameters in investigating a connection between Li abundance evolution and disks/planets can be reduced; of course, such systems would also make excellent candidates for follow-up focused SETI studies.

5. SUMMARY AND CONCLUSIONS

We have presented high resolution ($45{,}000\lesssim R\lesssim70{,}000$) and high S/N (generally 500–1,000) spectra of the binary solar twins 16 Cyg A and B, the solar analog α Cen A, α Cen B, the Hyades giant γ Tau, and the Sun. To check on the possibility of instrument- or individual-dependent systematic errors, the 16 Cyg data were acquired with three different telescope/spectrograph systems and have been independently reduced by three of us. Even though the Li line strengths are only of order 5 mÅ or less, the resulting spectra are in excellent agreement with each other. We have used our γ Tau and α Cen B data and the Kurucz *et al.* (1984) solar flux atlas to calibrate a linelist for the λ6707 Li I region.

Despite improvements in the atomic data since the seminal solar photospheric Li analysis of Muller *et al.* (1975), an unknown blending feature near 6708.00 Å seems to persist. The feature seems to be well modeled by their prescription of a fictitious high excitation neutral Si feature. Since laboratory data is not available for the majority of features in the λ6707.8 Li I region, there still remain uncertainties due to the stellar calibration and possible model atmosphere deficiencies. These uncertainties lead us to believe that very low limits on the solar ^{6}Li/^{7}Li photospheric ratio may be optimistic, though not necessarily incorrect. The linelist uncertainties alone may also have a non-negligible impact on Li abundance determinations in the Hyades giants, which (in principle anyway) offer useful diagnostics of diffusion, mass loss, and non-convective mixing in intermediate mass Pop I stars.

We proceed with our solar, 16 Cyg, and α Cen A analyses maintaining the usual assumption of negligible ^{6}Li. As summarized in Table 2, we find values of $\log N(\text{Li}) = 1.05\pm0.06$, 1.27 ± 0.05, ≤ 0.60, and 1.37 ± 0.06 for the Sun, 16 Cyg A, 16 Cyg B, and α Cen A, respectively, where the errors are conservative relative errors. The absolute abundances could have larger errors due to, e.g., model atmosphere deficiencies, small NLTE effects, etc., but these should not affect the relative abundances, which are our main concern here; these possible external errors (possibly as large as of order 0.2 dex) pale in comparison to the discrepancy (of order 1.8 dex) between the predicted and observed solar photospheric Li depletion. Taken at face value, the comparison of our three datasets with spectrum synthesis suggests a 16 Cyg B Li abundance of $\log N(\text{Li}) = 0.48$; given various uncertainties, however, we can only place the indicated upper limit on its Li abundance.

The solar photospheric Li abundance is very close to the mean of the 16 Cyg components'. If these latter stars had an initial Li abundance similar to the Sun's (i.e., near the meteoritic value of ~3.3), then this suggests that the Sun is not an isolated anomaly in its Li abundance evolution and argues for the inclusion of additional physics in stellar models of solar-type stars. The same conclusion is reached in comparing the Li abundances of α Cen A and Hyades dwarfs. Confirming the observation of Friel *et al.* (1993), we find that the Li abundance of the two 16 Cyg components differs by a factor of ~4.5 or greater despite differing in T_{eff} by only ~35−40 K. This abundance difference also cannot be understood in terms of purely standard stellar evolution.

The low Li abundances of the Sun and our solar analogs, the dispersion in Li abundance of the 16 Cyg components, and the probable mild solar Be depletion despite apparently lingering solar Li can all be explained by slow-mixing mechanisms. It is predicted that diffusion has a small (0.1 dex) and similar effect on Li and Be abundances in stars like 16 Cyg A and B. Their inferred large Li depletions (like the Sun's) and small (if not zero) Be abundance difference argue against a diffusion mechanism. Observations of open cluster cool dwarfs similar to the Sun argue against a mass loss scenario; open cluster stars also show a dispersion in Li (at fixed T_{eff}) which is consistent with rotationally-induced (slow) mixing. Additionally, if the well-known Li depletion in mid- to late-F Pop I dwarfs is caused by the same mechanism giving rise to the low Li abundances and Li abundance dispersion in cool dwarfs, then the observations of Be-depleted F dwarfs still retaining a small amount of Li would rule out mass loss.

The slow mixing we identify may be related to rotation. Indeed, observations of Li in cool short-period tidally locked binaries in a variety of stellar populations strongly support this hypothesis. In the context of the Yale rotational evolutionary models, the Li abundance difference in the 16 Cyg components could be due to differing initial angular momenta and rates of angular momentum transport. While likely incomplete, these models also can at least qualitatively account for a number of aforementioned phenomena such as the low solar and 16 Cyg Li abundances, the probable mild solar Be depletion, and the remarkable Li depletion in Pop I F dwarfs. This varied support for these models also lends support to their prediction that the open cluster Li plateau gets depleted with age (Deliyannis *et al.* 1994) and that, quite analogously, the halo star Spite Li plateau has also been depleted from a higher primordial (Big Bang) abundance. Finally, given the recent detection of a planetary companion to 16 Cyg B, the possible connection between Li abundance evolution and planets/disks has been discussed. While some interesting notes are made, no conclusions can be drawn at this time. This area presents a number of theoretical and observational opportunities which will need to be seized to establish any such connection; particularly helpful would be study of solar analogs with planetary companions.

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