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BERYLLIUM AND IRON ABUNDANCES OF THE SOLAR TWINS 16 CYGNI A AND B

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ABSTRACT

Red (signal-to-noise ratio of S/N ~ 1000 pixel^{-1}) and ultraviolet (S/N $\gtrsim$ 100 pixel^{-1}) Keck High Resolution Echelle Spectrograph (HIRES) spectra ($R \sim 45{,}000 = 3$ pixels) are used to derive the iron (Fe) and beryllium (Be) abundances in each of the solar twins 16 Cygni A and B. Self-consistent spectroscopic solutions yield, for 16 Cyg A and B, respectively, $T_{\rm eff} = 5795 \pm 20$ and 5760 ± 20 K, $\log g = 4.30 \pm 0.06$ and 4.40 ± 0.06, $\xi = 1.25 \pm 0.05$ and 1.12 ± 0.05 km s^{-1}, and [Fe/H] $= 0.04 \pm 0.02$ and 0.06 ± 0.02. If Fe is used as a surrogate for metallicity, this represents an average metallicity of 11% $\pm$ 5% above solar. These are in excellent agreement with other recent studies of this (wide) binary. Whereas it can be argued that no single study is conclusive, the consistent findings of these various studies offer compelling evidence that these stars have just barely supersolar metallicity, that 16 Cyg A is just hotter than the Sun, and that 16 Cyg B is just cooler. We have previously reported (based on Keck HIRES data) a difference in the lithium (Li) abundances of these stars of at least a factor of 4.5; for 16 Cyg A we detected a Li abundance of a factor of ~2 *above* solar, and for 16 Cyg B we placed a conservative upper limit of a factor of ~3 *below* solar. We detect Be in both stars and find that, if there is any difference between them, it must be much smaller—conservatively no more than 0.2 dex. Evidence suggests that solar-type stars deplete their surface Li abundance during the main sequence, a feat that the standard stellar evolution theory has, thus far, been unable to accomplish. Whatever physical mechanism depletes the surface Li abundance must create far less of a spread in the Be abundances than it does in the Li abundances. We find that our Li and Be results are consistent with the predictions of Yale models that include rotationally induced mixing driven by angular momentum loss. Our results provide no evidence for a small (~0.05 dex) enhancement in the ^{9}Be abundance of the A component relative to the B component expected if the stars' Li abundance difference was due to accretion of planetary material by the A component. Given the errors, however, neither are we able to firmly preclude such a signature.

Key words: binaries: general — circumstellar matter — planetary systems — stars: abundances — stars: evolution — stars: fundamental parameters — stars: individual (16 Cygni A, 16 Cygni B) — stars: late-type

1. INTRODUCTION

The binary system 16 Cygni comprises two early G dwarfs (the A component HR 7503 and the B component HR 7504), which have recently been the subject of great scrutiny. Cayrel de Strobel (1990) proposed that 16 Cyg B was one of only a few nearby genuine "solar twins." The spectroscopic analysis of Friel et al. (1993) confirmed that both components had a $T_{\rm eff}$ within ±20 K of the Sun and a metallicity only barely higher (+0.05 dex) than the Sun's. We shall therefore refer to these stars as solar twins.[3] These stars have become of greater interest because Cochran et al. (1997) have recently detected a $\gtrsim 1.5\ M_{\rm J}$ (Jupiter mass) companion to 16 Cyg B from precision radial velocity measures.

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[3] It has sometimes been suggested that the terms "solar twins" be reserved for stars that are not in any way measurably different from the Sun, the next most general category being solar analogs. However, this implies an unsettling degree of impermanency, as breakthroughs in technology can imply the sudden and sad demotion of the status of a star from solar twin to solar analog. Furthermore, in practice, the category of solar analogs encompasses, in our view, a rather broad range of spectral characteristics (F to K stars). Keeping in mind also that, like human twins, who—upon close examination—show subtle differences, we propose that 16 Cyg A and B are sufficiently similar to the Sun and to each other that they can be designated "solar twins."

King et al. (1997b) carried out detailed analysis of the Li I λ6707 region in the Sun and in 16 Cyg A and B. Despite the near-identical parameters—and, presumably, initial composition—of 16 Cyg A and 16 Cyg B, their current photospheric lithium (Li) abundances differ by a factor of ≳4.5. As King et al. (1997b) discuss, this represents a fundamental (and nontrivial) failure of standard stellar models, whose Li abundances are determined uniquely by mass, age, and composition. Li-abundance differences are also observed in otherwise identical solar-type stars in open clusters, as well. Notable examples include the young Pleiades (Soderblom et al. 1993b), the Hyades-age Praesepe (Soderblom et al. 1993a), and NGC 6633 (Jeffries 1997) clusters and the old M67 cluster (see, e.g., Deliyannis et al. 1994; Pasquini, Randich, & Pallavicini 1997; Jones, Fischer, & Soderblom 1999). Even the cluster with the tightest known Li-$T_{\rm eff}$ relation, the Hyades, shows *clear examples of* Li *dispersion* (Thorburn et al. 1993; see their Fig. 11).

These examples of Li dispersion are one part of an accumulating body of evidence revealing the incompleteness of standard stellar models. Other examples include (1) evidence for main-sequence Li depletion (see, e.g., Soderblom et al. 1993c; Jeffries 1997), (2) higher Li abundances often observed in short-period binaries of various stellar populations (Ryan & Deliyannis 1995), (3) the Li-$T_{\rm eff}$ morphology of and significant star-to-star scatter in the Li abundances of solar-age subgiants in the open cluster M67 (Deliyannis, King, & Boesgaard 1997), and (4) the correlated depletion of Li and beryllium (Be) observed in late F and early G stars (Deliyannis et al. 1998). All of these examples support the argument for the need to consider the action of additional physical mechanisms in low-mass stars, possibly slow mixing related to rotation.

Understanding the cause of the differential Li depletion in 16 Cyg A and B is not only important for improved knowledge of stellar interiors and mixing but may have cosmological implications as well, in terms of deriving and interpreting the level of the primordial Li abundance and testing models of big bang nucleosynthesis. Significant dispersions in Li at fixed $T_{\rm eff}$, possibly related to similar stellar Li depletion mechanisms, have been found in globular cluster stars (in M92, Deliyannis, Boesgaard, & King 1995 and Boesgaard et al. 1998a; in M13, Boesgaard et al. 1998b) and in the field (King, Deliyannis, & Boesgaard 1996). Also, the Sun (and, potentially, solar twins) is used as a fundamental calibrator of stellar models that explore the cause of Li depletion in low-mass stars (see, e.g., Pinsonneault, Kawaler, & Demarque 1990). An additional impetus for understanding Li depletion in the 16 Cyg system is the (somewhat speculative) possibility of a link between photospheric Li abundance and the presence of planetary systems mentioned by Cochran et al. (1997) and King et al. (1997b).

The recent studies of Deliyannis & Pinsonneault (1993), Stephens et al. (1997), and Deliyannis et al. (1998) underscore the great power in combining observations of both Li and Be in constraining models of the physical mechanism(s) responsible for stellar light-element depletion. The improved constraints arise from the fact that ^{7}Li and ^{9}Be are destroyed by protons at *different* temperatures in stellar interiors. Here, we present high-resolution spectroscopy of the Be II resonance doublet at 3130 Å in 16 Cyg A and B obtained with the Keck I Telescope. Our previous optical spectroscopy (King et al. 1997b) is first used to determine precise relative stellar parameters. In view of the factor of ≳4.5 difference in the Li abundances of these stars, the precise parameters are then used to derive Be abundances via spectrum syntheses, to see whether 16 Cyg A and B demonstrate any difference in their Be abundances. The implications of our results are discussed in § 4.

2. DATA

The optical spectroscopy of 16 Cyg A and B we employ for stellar parameter determination is that presented by King et al. (1997b), to which the reader is referred for fuller details. Briefly, the High Resolution Echelle Spectrograph (HIRES) spectrograph on the 10 m Keck I Telescope at the W. M. Keck Observatory was used to obtain high-resolution ($R \sim 45{,}000 = 3$ pixels) spectra with incomplete coverage from 4480 to 6760 Å. The Poisson-based signal-to-noise ratio (S/N) measured near 6700 Å is 750 and 1050 pixel^{-1} for 16 Cyg A and B, respectively. Samples of the spectra in wavelength regions containing Fe I and Fe II lines used in our analysis are shown in Figure 1.

We derive Be abundances from near-UV spectroscopy obtained with Keck HIRES on 1994 July 4 (UT) using the blue optics and a 2048 × 2048 Tektronix CCD, in the region of the Be II resonance doublet at 3130.42 and 3131.06 Å. The measured (3 pixel FWHM) resolution is again $R \sim 45{,}000$. Two 10 minute exposures of 16 Cyg A and three 10 minute exposures of 16 Cyg B yielded S/N of ∼110 and 115 pixel^{-1}, respectively, near the Be II lines. Multiple internal flat-field lamp, ThAr lamp, and bias-frame exposures were acquired during the night. After preliminary processing carried out with standard IRAF[4] tasks, flat-fielding, order identification, tracing, and one-dimensional extraction were performed using the specialized suite of FIGARO

[4] IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

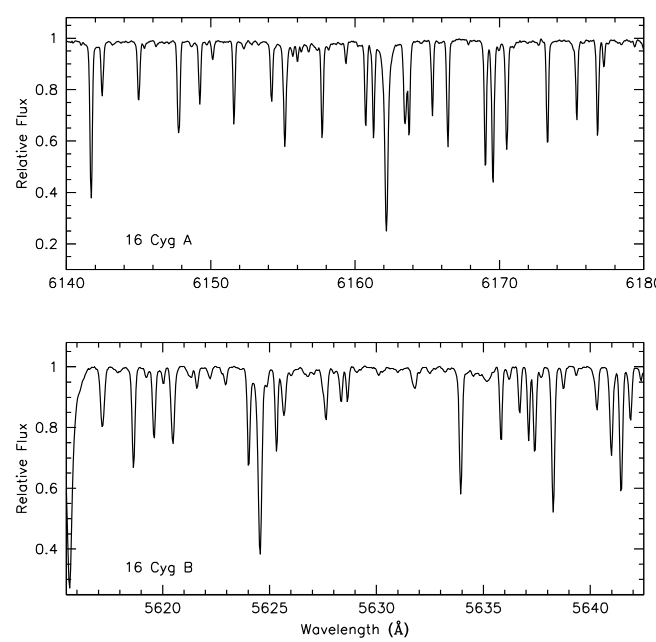

FIG. 1.—Samples of our optical spectra of 16 Cyg A (*top*) and 16 Cyg B (*bottom*).

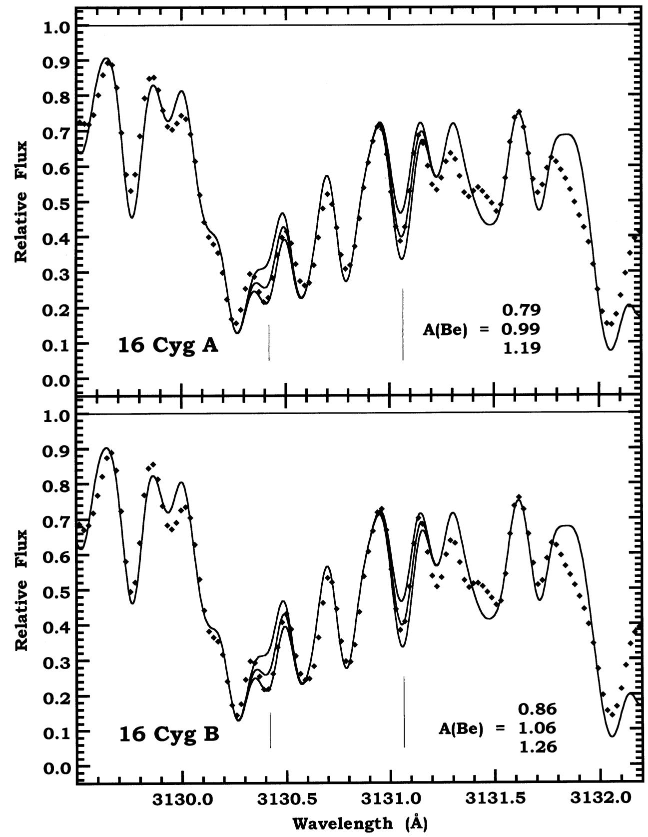

FIG. 2.—*Top*: Synthetic spectrum (*lines*) of varying Be abundances (*from top to bottom*) compared with our observed Keck spectrum (*points*) of 16 Cyg A. The vertical solid lines mark the positions of the Be II resonance features. *Bottom*: Synthetic spectrum compared with our Keck data for 16 Cyg B.

echelle reduction routines (developed and modified by J. McCarthy & A. Tomaney) imported into the IRAF environment. Scattered-light removal and dispersion corrections were determined and applied using the nominal routines in the IRAF echelle package. The individual one-dimensional spectra were then co-added. The final data can be seen in Figure 2 and are discussed in § 3.2.

3. ABUNDANCE ANALYSIS

3.1. *Stellar Parameters and Microturbulence Velocities*

The stellar parameters and microturbulent velocities for 16 Cyg A and B were derived by means of Fe I and Fe II lines in the red Keck spectra. The effective temperatures were obtained from the zero slope in the abundance versus excitation potential (EP) plane defined by the Fe I lines, while the surface gravities were estimated from the forced agreement between Fe I and Fe II average abundances—i.e., ionization balance. The microturbulent velocities were derived from the zero-slope condition in the abundances versus the measured equivalent width (EW) plane defined by the Fe I features. All three parameters ($T_{\rm eff}$, $\log g$, and microturbulence) were modified independently until a consistent solution was reached for the two stars. The iron (Fe) abundances were calculated in LTE by means of an updated version of the program MOOG (Sneden 1973). The model atmospheres adopted in the calculations were interpolated from R. L. Kurucz's (1992, private communication) grid of model atmospheres for solar metallicity and a depth-independent turbulent velocity of 2 km s^{-1}.

The selection of an appropriate sample of spectral lines is a crucial step in the spectroscopic determination of $T_{\rm eff}$ and $\log g$ since the accuracy of the equivalent width measurements and *gf*-values will influence the derivation of the stellar parameters, as well as the uncertainties involved. We selected a sample of unblended Fe lines for which there are accurate laboratory measurements of *gf*-values according to the critical evaluation in Lambert et al. (1996). Our sample of lines consists of 21 Fe I and four Fe II features, which are moderately strong (EWs ranging from approximately 20 to 90 mÅ) and which span a range in excitation potential sufficient to accurately estimate the stellar parameters for our two stars. The equivalent widths of the selected lines were measured with the IRAF data package by means of straight numerical integration. In Table 1, we present the selected Fe lines together with their excitation potentials, their adopted laboratory *gf*-values, and the measured equivalent widths for 16 Cyg A and B. Owing to the high resolution of our spectra and the very high S/N, the errors are dominated by effects other than photon noise (e.g., continuum placement), and we estimate the typical error to be of order ~1 mÅ.

Since the stars studied here are solar-type stars, it is instructive to analyze a solar spectrum in the same manner as 16 Cyg A and B, so that we can derive our results in reference to the Sun. To do this, we measured the equivalent widths of the same sample of Fe lines in the Kurucz et al. (1984) solar atlas in a similar manner as for 16 Cyg A and B; these equivalent widths are also presented in Table 1. We thus emphasize that for each line we have derived a solar abundance in the same manner as for both 16 Cyg components, and these so-derived abundances are used to normalize the stellar abundances. Hence, our abundances are essentially independent of the *gf*-values and perhaps other analysis details.

To search for a consistent solution of the stellar parameters for our stars, the following procedure was adopted: For a given value of the effective temperature and microturbulence, the slope was calculated (by linear least-squares fitting) in the run of EW versus Fe abundances and also in the run of EP versus Fe abundances. These calculations were repeated for a range in the values of effective temperature and microturbulence. The formal self-consistent parameter solution is that particular pair of (effective temperature, microturbulence) where both slopes are zero. Figures 3 and 4 show diagrams of the EW slope versus the EP slope, for several pairs of values of (effective temperature, microturbulence) at a given $\log g$: this provides a convenient way to illustrate the various possible solutions. The particular gravity values employed in these figures ($\log g = 4.30$ for 16 Cyg A and $\log g = 4.40$ for 16 Cyg B) represent the final ionization-based solutions; i.e., these gravity values bring the Fe I and Fe II abundances into agreement. The derived set of stellar parameters and Fe abundances are presented in Table 2.

Based on the measured equivalent widths, we find a consistent solution for the Sun with a Kurucz model calculated for $T_{\rm eff} = 5770$ K, $\log g = 4.40$, a microturbulence $\xi = 1.21$ km s^{-1}, and a mean Fe abundance of $\log \epsilon({\rm Fe}) = 7.46$ with a per line standard deviation of 0.05 dex (internal mean error of 0.01 dex). For 16 Cyg A and B we find $T_{\rm eff}$ values of 5795 and 5760 K, respectively. The relative temperature differences between the Sun and our solar analogs are there-

TABLE 1

MEASURED EQUIVALENT WIDTHS

ID	λ (Å)	χ (eV)	*gf*	EW (mÅ) 16 Cyg A	16 Cyg B	Sun
Fe I	5242.491	3.634	1.072E−01	90	90	85
	5253.030	2.278	1.622E−04	20	20	18
	5288.525	3.694	3.090E−02	60	61	57
	5321.108	4.434	6.457E−02	43	43	39
	5618.633	4.209	5.495E−02	53	52	50
	5638.262	4.220	1.905E−01	81	81	77
	5679.023	4.651	1.698E−01	62	62	60
	5814.808	4.283	1.514E−02	24	26	22
	5852.219	4.548	6.607E−02	44	45	41
	5916.247	2.453	1.023E−03	57	59	54
	5934.655	3.928	9.550E−02	77	79	77
	6027.051	4.076	8.128E−02	69	68	64
	6151.616	2.176	5.129E−04	54	53	50
	6165.364	4.142	3.388E−02	49	51	46
	6173.340	2.223	1.318E−03	72	71	69
	6322.691	2.588	3.715E−03	78	79	74
	6593.871	2.437	3.802E−03	90	88	84
	6733.151	4.637	3.715E−02	31	31	28
	6750.149	2.424	2.399E−03	77	77	75
	6752.705	4.638	6.310E−02	38	39	38
Fe II	5234.619	3.221	5.754E−03	89	87	81
	5414.046	3.221	2.399E−04	32	29	26
	5425.247	3.199	6.166E−04	49	45	41
	6149.246	3.889	1.905E−03	41	39	34

fore +25 K for 16 Cyg A and −10 K for 16 Cyg B. Inspection of the final Fe abundances presented in Table 2 shows that 16 Cyg A and B are slightly overabundant relative to the Sun: [Fe/H] = +0.04 and +0.06, respectively.

We can estimate the uncertainties in the derived T_{eff} values and microturbulent velocities by considering the errors in the calculated slopes obtained from the excitation potentials and equivalent widths. Given uncertainties in the per line abundances of 0.05 dex (corresponding to the standard deviations) and the standard formula for calculating the errors in slopes as in Taylor (1982), we estimate that the internal relative errors in our derived effective temperatures are of the order of ±20 K, while the errors in the derived microturbulent velocities are roughly 0.05 km s^{-1}. The uncertainties in the derived surface gravities can be estimated by exploring the range of solutions in the plane of the calculated slopes if we accept a difference in the mean Fe I and Fe II abundances (again assuming per line uncertainties of 0.05 dex). This imparts an uncertainty in log g of 0.06 dex and a corresponding difference in T_{eff} and microturbulence of 20 K and 0.05 km s^{-1}, which are identical to the values

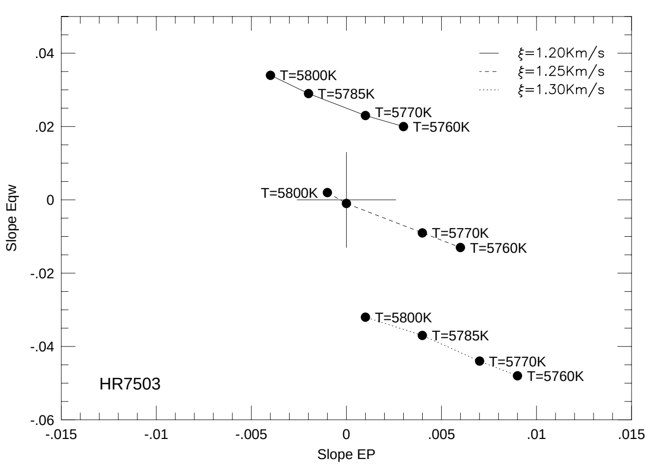

FIG. 3.—The slope of reduced equivalent widths (log EW/λ) vs. log ϵ(Fe I) plotted against the slope of excitation potentials (in electron volts) vs. log ϵ(Fe I) for a range of model effective temperatures and microturbulences at log g = 4.30 for 16 Cyg A. A formal solution is represented by the zero slopes, and this point is shown with error bars representing the formal statistical uncertainties in the respective slopes. The best solution is obtained for T_{eff} = 5795 K and ξ = 1.25 km s^{-1} with log g = 4.30; this gravity is that which brings the abundances of Fe I and Fe II into agreement.

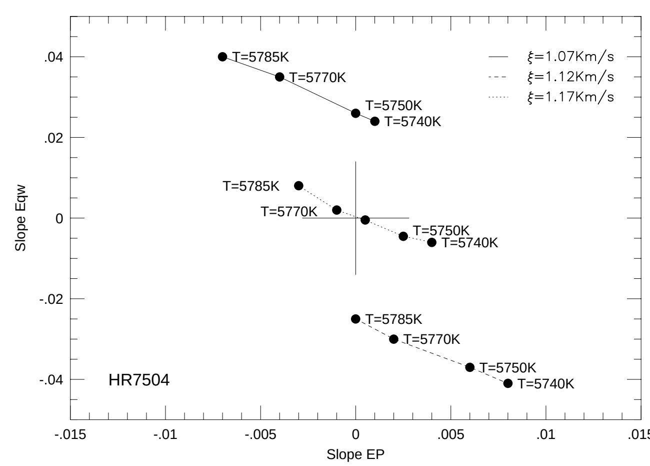

FIG. 4.—Same as Fig. 1, but for 16 Cyg B. The formal solution in this case is obtained for a model atmosphere with T_{eff} = 5760 K, ξ = 1.12 km s^{-1}, and log g = 4.40.

TABLE 2

STELLAR PARAMETERS AND ABUNDANCES

Star	T_{eff} (K)	log g (cgs)	ξ (km s^{-1})	[Fe/H]	log N(Be)	log N(Li)[a]
16 Cyg A......	5795	4.30	1.25	0.04	0.99	1.27
16 Cyg B......	5760	4.40	1.12	0.06	1.06	$\lesssim$0.60
Sun	5770	4.40	1.21	7.46[b]	1.12	1.05

[a] From King et al. 1997b.
[b] "Fe" scale for the Sun.

estimated from the formal uncertainties in the calculated slopes.

To summarize, we find, for 16 Cyg A and B, respectively, $T_{eff} = 5795 \pm 20$ and 5760 ± 20 K, $\log g = 4.30 \pm 0.06$ and 4.40 ± 0.06, $\xi = 1.25 \pm 0.05$ and 1.12 ± 0.05 km s^{-1}, and [Fe/H] $= 0.04 \pm 0.02$ (estimated mean relative error) and 0.06 ± 0.02.

Simple inspection of the equivalent widths in Table 1 indicates that the similar 16 Cyg components have similar Fe abundances. Indeed, the final Fe abundances presented in Table 2 ([Fe/H] = 0.04 and 0.06 for 16 Cyg A and B, respectively), differ by only 5%, though the equivalent widths themselves differ, on average, by much less, simply because of the conspiracy of the slight differences in the derived parameters. (This conspiracy also accounts for the differences in the Fe II equivalent widths being a bit larger than those for the Fe I line strengths.) The Fe abundances of both components are just slightly (12%) overabundant relative to the Sun.

3.2. *Comparison with Other Results*

These results are in excellent agreement with previous work. Friel et al. (1993) determine T_{eff} values of 5785 ± 25 and 5760 ± 20 K for 16 Cyg A and B, respectively, assuming a solar T_{eff} (5770 K) identical to our value. Gray (1994) determined 5796 ± 6 and 5746 ± 6 K from spectral line-depth ratios. The zero point of Gray's (1994) values depends on that of calibrating photometric relations. Regardless, all these spectroscopic determinations consistently suggest a $\sim$35 K T_{eff} difference; this difference is identical to that directly inferred from the photometric T_{eff} estimates from Table 3 of Gray (1994).

Similarly, our Fe abundances of 16 Cyg A and B of [Fe/H] $= 0.04 \pm 0.02$ and 0.06 ± 0.02, respectively, are in excellent agreement with the Fe I–based values of 0.06 $\pm$ 0.04 and 0.02 ± 0.04 derived by Friel et al. (1993), as well as the spectroscopic values of [Fe/H] $= 0.11 \pm 0.06$ and 0.06 ± 0.06 derived by Gonzalez (1998). In addition, work in preparation by one of us (A. M. B.) finds [Fe/H] = 0.06 ± 0.02 and 0.02 ± 0.02 for the A and B components based on analysis of Fe I lines in high-resolution and high-S/N spectra obtained at the Canada-France-Hawaii Telescope. All these studies consistently indicate these solar analogs have mildly supersolar Fe abundances.

Our spectroscopic gravities ($\log g = 4.30 \pm 0.06$ and 4.40 ± 0.06 for 16 Cyg A and B, respectively) based on Fe ionization balance are in fine agreement with the ionization balance–based values 4.20 ± 0.05 and 4.35 ± 0.05 determined by Gonzalez (1998). These gravities are also in accord with those, 4.28 ± 0.07 and 4.35 ± 0.07, estimated by Friel et al. (1993) from ground-based CCD parallax estimates, their T_{eff} values, and theoretical stellar models. They also note that these independent gravity estimates are essentially identical to the results of their Fe ionization-balance analysis. It is thus comforting to note that the ground-based parallax of 47 mas they adopt is in excellent agreement with the new precise *Hipparcos* values of 46.3 and 46.7 ($\pm$0.5) mas for the A and B components, respectively. These results consistently suggest a 0.1 dex gravity difference between the A and B components and, as noted by Friel et al. (1993), the slightly more evolved state of both the 16 Cyg components relative to the Sun.

3.3. ^{9}Be *Abundance Determination*

Be abundances for 16 Cyg A and B were derived via LTE spectrum synthesis carried out in MOOG based on the Mn II λ3131.015–enhanced line list calibrated to the solar spectrum and discussed by King, Deliyannis, & Boesgaard (1997a). We employed the stellar parameters derived above and the same model atmospheres employed there. In the synthetic calculations, all metals, except Be, were enhanced by +0.05 dex relative to solar.

The observed spectra (*points*) are plotted with the synthetic spectra (*lines*) of varying Be abundance in Figure 2 for 16 Cyg A and B. Abundances were determined from the cleaner, redder Be II feature at 3131.06 Å, though the bluer, heavily contaminated Be II feature at 3131.42 Å provides a valuable check on the stars' relative Be abundances. The best-fit Be abundances so derived are $A(\mathrm{Be}) = 0.99 \pm 0.08$ for 16 Cyg A and 1.06 ± 0.08 for 16 Cyg B and are reported in Table 2. These (1 σ) uncertainties are estimates of the *relative* uncertainties, which are dominated by those in $\log g$, photon statistics, and continuum-normalization errors.

García López & Pérez de Taoro (1998) report Be abundances for 16 Cyg A and B of $A(\mathrm{Be}) = 1.10 \pm 0.17$ and 1.30 ± 0.17, respectively. They achieved resolutions of 33,000–50,000 and S/N of 15–35. Their abundances for the two components agree with each other, and in view of the various uncertainties (King et al. 1997a), there is also satisfactory agreement with our results, as well.

4. DISCUSSION

4.1. *Stellar Depletion*

The mean 16 Cyg Be abundance of about $A(\mathrm{Be}) = 1.03$ is within 0.1 dex of the similarly derived solar abundance of King et al. (1997a). More interesting is that our best-fit Be abundances of the individual 16 Cyg A and B components are the same to within the relative error of 0.08 dex. Given the relative uncertainties, their genuine Be abundances must conservatively differ by no more than 0.2 dex. This difference pales in comparison with the factor of $\gtrsim$4–5 ($\sim$0.65

dex) difference in their individual Li abundances. This difference can be used to investigate the mechanism of differential Li depletion (or enrichment, see below) that has acted in these stars.

Interestingly, the standard stellar evolution theory would predict identical (and undepleted) abundances for 16 Cyg A and B; however, it has already been established that the standard theory fails to predict the severity of the Li depletions in these stars and in the Sun, and the large difference in A(Li) between the two stars. Most importantly, over the past three decades, even as the input physics have improved considerably, a robust prediction of the standard theory has been that solar analogs deplete their Li only during the pre–main sequence. In sharp contrast to this prediction, open clusters show that solar analogs deplete Li during the main sequence. It is thus necessary to identify a physical mechanism(s), not incorporated into the standard theory, that depletes Li during the main sequence. The only viable mechanisms identified so far involve processes, perhaps driven by rotation, that mix material slowly over the lifetime of the star in the radiative layers below the convection zone. The present results place limits on the efficiency and effective depth of such mixing: while over 0.7 dex of relative Li depletion between A and B is required, the relative depletion of Be must be no more than 0.2 dex (and perhaps less).

We encourage theoretical studies that take advantage of these constraints. For now, we compare our results and the Yale stellar models with rotation, which predict main-sequence Li depletion. In these models, angular momentum is lost from the surface, in accordance with the observed spin-down of stars in clusters of different ages. Angular momentum loss results in the triggering of instabilities, which in turn causes (generally slow) mixing and depletion of Li. These models also predict Li dispersions in otherwise identical stars: a star that formed with a higher initial angular momentum (J_0) will deplete more Li. This prediction can be tested against our results. Specifically, the question is, can two models with the required minimal spread in Li [ΔA(Li) $\gtrsim$ 0.7 dex] meet the tight Be constraint [ΔA(Be) $\lesssim$ 0.2 dex]?

Before addressing this question, it is necessary to take into account the small difference in effective temperature between the two stars. The 16 Cyg system is at least as old as the Sun, and if we use the comparably aged cluster M67 as a guide, the Li-$T_{\rm eff}$ trend is rather steep near 5770 K. Thus, part of the difference in Li between 16 Cyg A and B may be due to this steep Li-$T_{\rm eff}$ trend (which, itself, is likely created by the mechanism[s] causing main-sequence Li depletion), and the rest may be a result of parameter(s) of this mechanism(s) causing Li dispersions in otherwise identical stars. (In the case of the Yale models, the parameter is J_0.) The degree of steepness of the Li-$T_{\rm eff}$ trend renders estimation of its effect on 16 Cyg A and B somewhat uncertain. Undaunted, we estimate the effect to be perhaps as large as 0.3–0.5 dex (Deliyannis et al. 1994; Pasquini et al. 1997; Jones et al. 1999; see Appendix for more details). This leaves approximately $\gtrsim$0.3 dex in Li to be created by the dispersion-inducing mechanism. The corresponding Be dispersion in the Yale models is $\gtrsim$0.1 dex, depending on the detailed choice of parameters (Deliyannis & Pinsonneault 1997; for example, their pair of 4 Gyr isochrones shows that near 5800 K, increasing v(initial) from 10 to 30 km s^{-1} implies increasing the Li depletion by 0.55 dex and the Be depletion by 0.17 dex). This is consistent with the constraints in this paper. The Yale models have a smaller Be dispersion as compared with Li dispersion for two reasons: (1) the surface convection zone is a larger fraction of the Li preservation region, as compared with Be preservation region, and (2) the efficiency of slow mixing increases outward. The first reason implies that slow mixing has to work harder (and over a larger area) to deplete Be as compared with Li. The second reason implies that the (nonconvective) Li-containing region is mixed more easily, on average, than is the larger (nonconvective) Be-containing region. To enable a better comparison, it would be desirable to refine our knowledge of the Li-$T_{\rm eff}$ trend in old clusters like M67 and NGC 188 with numerous high-quality Li data.

4.2. *Planets and Accretion*

As summarized in the recent study of Gonzalez, Wallerstein, & Saar (1999), spectroscopic analyses of stars harboring planetary mass companions indicate that the stellar parents are metal rich ([Fe/H] = 0.2 on average). They note two potential explanations for this. The first is bias, in that formation of rocky planets or cores is promoted in a high-metal environment. The second is that the parent stars have accreted metallic circumstellar material, resulting in increased photospheric abundances. It must be emphasized that the timing of such accretion and the detailed stellar structure of the central star are of great importance in the viability of such a scenario. In particular, if the accretion occurs at very early times or in very low mass or highly evolved stars, any impact on photospheric abundances may be obliterated by dilution of the accreted material in the convective envelope.

Assuming such constraints can be met, what is the relevance of accretion to light-element abundances in 16 Cyg? Given the significantly larger Li abundance of 16 Cyg A relative to 16 Cyg B and (in contrast to 16 Cyg B) the lack of a detected planetary companion around 16 Cyg A, Gonzalez (1998) proposed that the Li abundance difference might be due to 16 Cyg A ingesting an orbiting planet, thus raising its photospheric Li abundance. Indeed, some three decades ago, Alexander (1967) suggested such an accretion scenario to account for some (high) stellar Li abundances. Given solar system chondritic abundances and Jupiter's composition, Gonzalez's (1998) calculations indicate that ingestion of $\sim$0.25 M_J of gas-giant material or a couple terrestrial masses of chondritic material could provide the needed Li enhancement to account for the abundance difference between 16 Cyg A and B.

A key point is that such Li enhancement would *not* be accompanied by significant Fe enhancement (Δ[Fe/H] $\sim$ 0.01 dex). This is simply because of the fact that the chondritic Li-to-Fe ratio is some $\sim$2.5 orders of magnitude higher than the (current) solar photospheric ratio. Unfortunately, the present ^{9}Be abundances and their uncertainties do not permit a rigorous test of the accretion-ingestion hypothesis since the chondritic Be-to-Fe ratio is relatively similar to the photospheric value. Even in a slightly exaggerated solarlike case assuming a photospheric Be abundance 0.5 dex below chondritic, the increase in Be abundance accompanying a putative 0.7 dex Li increase in 16 Cyg A via accretion would only be $\sim$0.05 dex.

Such a small difference is well within our relative abundance errors. Our Be abundances thus provide no evidence for accretion in 16 Cyg A relative to 16 Cyg B; however, they are not able to exclude it. Gonzalez (1998) calls attention to the fact that extant studies of 16 Cyg find slightly higher [Fe/H] values in component A. However, this is *not* seen in our data, though the uncertainties in all of the individual studies do not allow any definitive conclusions to be drawn. In a similar spirit, we would simply note that both our study and that of García López & Pérez de Taoro (1998) find higher Be abundances in the B component. If real, which we doubt given the uncertainties, such a difference conflicts with speculative accretion signatures from the Fe abundances derived in other studies.

In their comparison of Li and Be abundances in planet-harboring and apparently single stars, García López & Pérez de Taoro (1998) note the odd position of 16 Cyg B in the Be versus Li abundance plane. However, if we take the Be abundances at face value, our Be abundance is some 0.24 dex lower than theirs. (Note that our 1 σ error range of 1.06 ± 0.08 overlaps their 1 σ range of 1.30 ± 0.17, so formally our values are in agreement.) If, once again, we take our Be abundance at face value, our value results in a rather unremarkable location for 16 Cyg B in Figure 3 of García López & Pérez de Taoro (1998).

Finally, we note that planetary companions may be relevant to the Li and Be abundances of parent stars via mechanisms other than accretion. As suggested by Cochran et al. (1997) and King et al. (1997b), differing circumstellar environments may lead to different initial stellar angular momenta or subsequent angular momentum evolution in otherwise similar stars. In such a scenario, planetary companions or circumstellar disks might be specific mechanisms that control these important parameters, and their star-to-star variations, in the Yale rotational models. Whether this is the case or not will require a considerably expanded sample of planet-bearing stars and their detailed abundances in order that various important characteristics (in stellar mass, age, composition, planetary mass, and planetary orbit) can be considered in isolation. As noted by King et al. (1997b), logical starting points are genuine solar twins.

5. SUMMARY AND CONCLUSIONS

We have presented high-resolution ($R \sim 45{,}000$) and high-S/N (1000, 100) optical and near-UV Keck HIRES spectroscopy of the solar twins 16 Cyg A and B and have used these data to derive their parameters, metallicities, and ^{9}Be abundances. From a fine analysis of optical Fe I and Fe II lines we find the following: $T_{\rm eff} = 5795 \pm 20$ and 5760 ± 20 K, $\log g = 4.30 \pm 0.06$ and 4.40 ± 0.06, and $\xi = 1.25 \pm 0.05$ and 1.12 ± 0.05 km s^{-1} for the A and B components, respectively. We derive iron abundances of $[\rm Fe/H] = 0.04 \pm 0.02$ (mean error) and $[\rm Fe/H] = 0.06 \pm 0.02$. Our parameters and metallicities are in excellent agreement with other studies, given the (generally small) uncertainties, and suggest that the A and B components are ~ 20 K hotter and cooler than the Sun, have a slightly larger ($\sim 12\%$) metallicity than the Sun and are slightly more evolved relative to the Sun.

These parameters are then used to derive the ^{9}Be abundances of the A and B components from spectrum synthesis. We find $A(\rm Be) = 0.99 \pm 0.08$ and $A(\rm Be) = 1.06 \pm 0.08$, respectively. Given the moderate uncertainties, these are in satisfactory agreement with the results from lower S/N spectroscopy obtained by García López & Pérez de Taoro (1998). These authors called attention to the apparently unique position that 16 Cyg B occupies in the Be versus Li plane; our results, however, result in a rather unremarkable location. Our mean 16 Cyg Be abundance of $A(\rm Be) \sim 1.03$ is within 0.1 dex of the similarly derived solar photospheric abundance value of King et al. (1997a).

The components' ^{9}Be abundance estimates are equal to within our relative uncertainty of 0.08 dex. Given the uncertainties, their genuine Be abundances are expected to differ by no more than 0.2 dex. Such a difference is substantially less than the 0.7 dex difference in their Li abundances and provides clues about stellar depletion and/or enrichment processes acting in these stars. For example, as noted in King et al. (1997b), the marked difference between the components' relative Li and Be abundances is inconsistent with expectations of diffusion. In particular, we find that the small spread in Be abundances compared with the significant spread in Li abundances is consistent with the predictions of Yale stellar models that include rotationally induced mixing driven by angular momentum loss.

If the ~ 0.7 dex Li abundance differences in the 16 Cyg components are due to ingestion of planetary material by 16 Cyg A, this component would be expected to exhibit only slightly higher abundances of Fe ($\Delta[\rm Fe/H] \sim 0.01$ dex) and ^{9}Be ($\Delta A(\rm Be) \sim 0.05$ dex). In contrast, our Fe and ^{9}Be abundances are slightly larger in the B component, though not significantly so given the uncertainties. Thus, they cannot rigorously exclude a planetary accretion hypothesis. As has been noted before, the absence or presence of planetary companions/material may influence the stellar Li abundances by simply providing a specific mechanism via which differential angular momentum evolution occurs in otherwise similar stars. Continued study of photospheric abundances in planetary companions around bona fide solar twins and continued identification of such planetary companions are needed to explore this possibility in detail.

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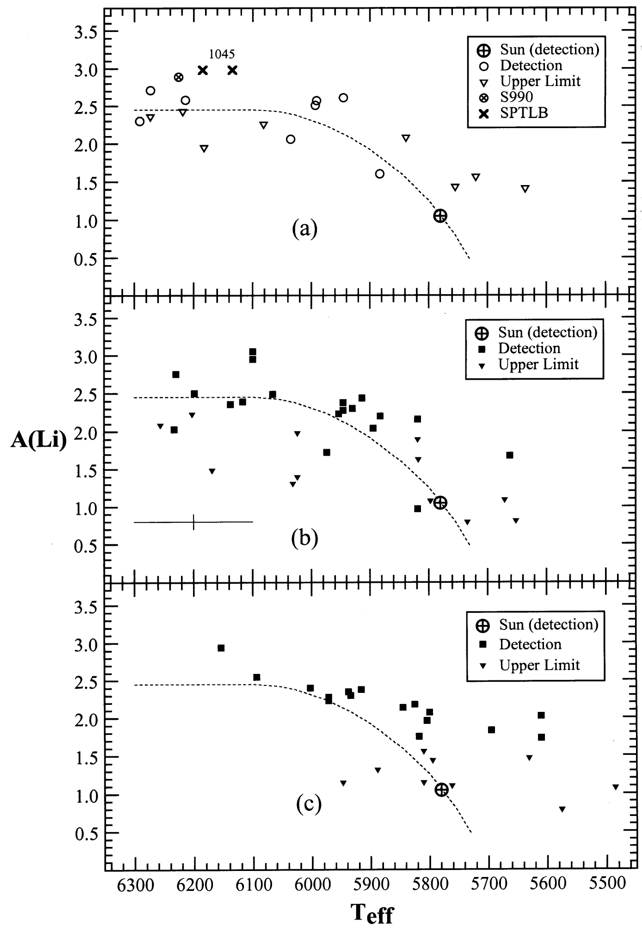

FIG. 5.—Lithium abundances in M67 and in the Sun, as measured by and/or compiled in (*a*) Deliyannis et al. (1994), (*b*) Pasquini et al. (1997), and (*c*) Jones et al. (1999). The slope at the Sun is steep, roughly 1–1.5 dex per 100 K, though it is rather poorly defined (see text).

APPENDIX

In this appendix, we describe how we estimated the slope of the Li-$T_{\rm eff}$ relation for solar twins in M67. Li data for M67 are shown from Deliyannis et al. (1994) in Figure 5*a*, Pasquini et al. (1997) in Figure 5*b*, and Jones et al. (1999) in Figure 5*c*. Also shown in all three panels is Deliyannis et al.'s (1994) by-eye "guestimate" of where the mean trend lies (*dotted line*). In Figure 5*a*, the slope of the tangent at the Sun is 1.3 dex per 100 K. Given the paucity of data and the inherent lack of information that an upper limit provides about the true abundance of the star, this slope is clearly uncertain. Nevertheless, the dotted line provides an adequate fit to the data in Figure 5*b*. If one focuses attention on the region 5700–5950 K, one could conceivably argue that the fit ought to be a bit flatter at higher $T_{\rm eff}$ and a bit steeper at lower $T_{\rm eff}$, resulting in a larger value for the slope. However, the scatter both above and below this temperature range confuses the issue; for example, one can also argue for a shallower slope. (Note, though, that a shallower slope might place the Sun below the trend; how then, would this shallower slope relate to the 16 Cyg pair, if at all?) Suffice it to say that the slope remains rather uncertain. Finally, Figure 5*c* confuses the issue further. Once again, a steeper slope can be argued for if one focuses on the immediate vicinity of the solar temperature, but the scatter at both higher and lower temperatures renders this assessment uncertain. This particular issue, and also the question of how normal the Sun is compared with solar twins in M67, could greatly benefit from study of a significantly larger number of M67 stars with higher quality data. In the meantime, we guestimate that the value of the slope can easily be as high as about 1–1.5 dex per 100 K.

REFERENCES

Alexander, J. B. 1967, Observatory, 87, 238
Boesgaard, A. M., Deliyannis, C. P., Stephens, A., & King, J. R. 1998a, ApJ, 493, 206
Boesgaard, A. M., Stephens, A., King, J. R., & Deliyannis, C. P. 1998b, BAAS, 29, 1352
Cayrel de Strobel, G. 1990, in New Windows to the Universe, ed. F. Sánchez & M. Vásquez (Cambridge: Cambridge Univ. Press), 195
Cochran, W. D., Hatzes, A. P., Butler, R. P., & Marcy, G. W. 1997, ApJ, 483, 457
Deliyannis, C. P., Boesgaard, A. M., & King, J. R. 1995, ApJ, 452, L13
Deliyannis, C. P., Boesgaard, A. M., Stephens, A., King, J. R., Vogt, S. S., & Keane, M. J. 1998, ApJ, 498, L147
Deliyannis, C. P., King, J. R., & Boesgaard, A. M. 1997, in Wide-Field Spectroscopy, ed. E. Kontizas et al. (Dordrecht: Kluwer), 201
Deliyannis, C. P., King, J. R., Boesgaard, A. M., & Ryan, S. G. 1994, ApJ, 434, L71
Deliyannis, C. P., & Pinsonneault, M. H. 1993, in ASP Conf. Ser. 40, Inside the Stars, ed. W. W. Weiss & A. Baglin (IAU Coll. 137) (San Francisco: ASP), 174
———. 1997, ApJ, 488, 836
Friel, E., Cayrel de Strobel, G., Chmielewski, Y., Spite, M., Lèbre, A., & Bentolila, C. 1993, A&A, 274, 825
García López, R. J., & Pérez de Taoro, M. R. 1998, A&A, 334, 599
Gonzalez, G. 1998, A&A, 334, 221
Gonzalez, G., Wallerstein, G., & Saar, S. H. 1999, ApJ, 511, L111
Gray, D. F. 1994, PASP, 106, 1248
Jeffries, R. D. 1997, MNRAS, 292, 177
Jones, B. F., Fischer, D., & Soderblom, D. R. 1999, AJ, 117, 330
King, J. R., Deliyannis, C. P., & Boesgaard, A. M. 1996, AJ, 112, 2839
———. 1997a, ApJ, 478, 778
King, J. R., Deliyannis, C. P., Hiltgen, D. D., Stephens, A., Cunha, K., & Boesgaard, A. M. 1997b, AJ, 113, 1871
Kurucz, R. L., Furenlid, I., Brault, J., & Testerman, L. 1984, Solar Flux Atlas from 296 to 1300 nm (Sunspot, NM: Natl. Sol. Obs.)
Lambert, D. L., Heath, J. E., Lemke, M., & Drake, J. 1996, ApJS, 103, 183
Pasquini, L., Randich, S., & Pallavicini, R. 1997, A&A, 325, 535
Pinsonneault, M., Kawaler, S. D., & Demarque, P. 1990, ApJS, 74, 501
Ryan, S. G., & Deliyannis, C. P. 1995, ApJ, 453, 819
Sneden, C. 1973, ApJ, 184, 839
Soderblom, D. R., Fedele, S. B., Jones, B. F., Stauffer, J. R., & Prosser, C. F. 1993a, AJ, 106, 1080
Soderblom, D. R., Jones, B. F., Balachandran, S., Stauffer, J. R., Duncan, D. K., Fedele, S. B., & Hudon, J. D. 1993b, AJ, 106, 1059
Soderblom, D. R., Pilachowski, C. A., Fedele, S. B., & Jones, B. F. 1993c, AJ, 105, 2299
Stephens, A., Boesgaard, A. M., King, J. R., & Deliyannis, C. P. 1997, ApJ, 491, 339
Taylor, J. R. 1982, An Introduction to Error Analysis, (Mill Valley, CA: Univ. Sci. Books)
Thorburn, J. A., Hobbs, L. M., Deliyannis, C. P., & Pinsonneault, M. H. 1993, ApJ, 415, 150