DETAILED ABUNDANCES OF THE SOLAR TWINS 16 CYGNI A AND B: CONSTRAINING PLANET FORMATION MODELS*

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ABSTRACT

Results of a detailed abundance analysis of the solar twins 16 Cyg A and 16 Cyg B based on high-resolution, high signal-to-noise ratio echelle spectroscopy are presented. 16 Cyg B is known to host a giant planet while no planets have yet been detected around 16 Cyg A. Stellar parameters are derived directly from our high-quality spectra, and the stars are found to be physically similar, with $\Delta T_{\rm eff} = +43$ K, $\Delta \log g = -0.02$ dex, and $\Delta\xi = +0.10$ km s^{-1} (in the sense of A

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– B), consistent with previous findings. Abundances of 15 elements are derived and are found to be indistinguishable between the two stars. The abundances of each element differ by ≤ 0.026 dex, and the mean difference is $+0.003 \pm 0.015$ (σ) dex. Aside from Li, which has been previously shown to be depleted by a factor of at least 4.5 in 16 Cyg B relative to 16 Cyg A, the two stars appear to be chemically identical. The abundances of each star demonstrate a positive correlation with the condensation temperature of the elements (T_c); the slopes of the trends are also indistinguishable. In accordance with recent suggestions, the positive slopes of the [m/H]-T_c relations may imply that terrestrial planets have not formed around either 16 Cyg A or 16 Cyg B. The physical characteristics of the 16 Cyg system are discussed in terms of planet formation models, and plausible mechanisms that can account for the lack of detected planets around 16 Cyg A, the disparate Li abundances of 16 Cyg A and B, and the eccentricity of the planet 16 Cyg B b are suggested.

Subject headings: planetary systems:formation – stars:abundances – stars:atmospheres – stars:individual(16 Cyg A, 16 Cyg B)

1. INTRODUCTION

16 Cyg A and 16 Cyg B are a well known common proper-motion pair of solar-twin stars with spectral types G1.5V and G3V, respectively. Stellar parameters and [Fe/H] abundances of the pair have been derived by numerous groups (e.g., Gray 1994; Fernley et al. 1996; Fuhrmann et al. 1998; Laws & Gonzalez 2001; Takeda 2005), and the abundances of additional elements have been derived by others (e.g., Friel et al. 1993; King et al. 1997; Feltzing & Gustafsson 1998; Gonzalez 1998; Deliyannis et al. 2000; Takeda et al. 2001; Reddy et al. 2003; Galeev et al. 2004). In each study, 16 Cyg A and B have been found to be physically similar, with A being slightly hotter and having a slightly lower surface gravity than B, consistent with their spectral types. Differences in the derived stellar parameters in the sources listed above range from +25 to +62 K in $T_{\rm eff}$, -0.03 to -0.15 dex in $\log g$, and 0 to +0.05 dex in [Fe/H] (all comparisons herein are made in the sense of A $-$ B).

A defining property distinguishing the two stars is the designation of 16 Cyg B as a planet host. Cochran et al. (1997) reported the presence of a radial-velocity detected planet (16 Cyg B b) with $M \sin i = 1.5\ M_{\rm Jup}$ orbiting 16 Cyg B on an eccentric orbit ($e = 0.63$), but despite being monitored with the same temporal coverage, no planet was detected around 16 Cyg A. Continued radial-velocity monitoring has yielded no additional planet signatures for either star (D. Fischer, private communication). Imaging observations, however, do indicate that 16 Cyg A has a faint M dwarf binary companion with a separation of $\sim$ 3", corresponding to projected separation of $\sim$ 70 AU at the measured distance of the system ($\sim$ 22 pc; Hauser & Marcy 1999; Turner et al. 2001; Patience et al. 2002). Whether these two objects are gravitationally bound has yet to be determined firmly, but initial proper motion measurements do suggest that they are physically associated (Patience et al. 2002).

Friel et al. (1993) and subsequently King et al. (1997) found that 16 Cyg A and B differ in another fundamental way: their Li abundances. The photospheric Li abundance of 16 Cyg B is a factor $\geq$ 4.5 lower than that of 16 Cyg A. While both stars are depleted in Li relative to the Solar System's meteoritic value ($\log N(\mathrm{Li}) = 3.26$; Asplund et al. 2009), the Li abundance of 16 Cyg A ($\log N(\mathrm{Li}) = 1.27$) is slightly higher and that of 16 Cyg B is lower ($\log N(\mathrm{Li}) \leq 0.60$) than that of the Sun ($\log N_{\odot}(\mathrm{Li}) = 1.05$) (King et al. 1997). The difference in the Li abundances of 16 Cyg A and B cannot be explained by standard stellar models, which predict Li depletion is a function of stellar age, mass, and composition; empirical evidence suggests that an extra parameter is needed. King et al. (1997) argue that a slow mixing mechanism, possibly related to rotation, can account for the low absolute Li abundances of both stars, and they discuss a possible connection between Li depletion and planet formation as an explanation for the difference between the two. More recently, others have also argued that an extra parameter (beyond standard models) is needed to account for the observed Li abundances of solar-type stars (e.g., Pasquini et al. 2008). Deliyannis et al. (2000) note that the Li–T_{eff} trend could be quite steep for solar twins, consistent with the 16 Cyg A – Sun – 16 Cyg B pattern, so that even if initial angular momentum (J_{o}) and rotational history do play the role of the extra parameter, J_{o} need not be unreasonably different between A and B. Deliyannis et al. (2000) also found that the Be abundances of 16 Cyg A and B are the same within the measurement uncertainties, placing an additional constraint on the mechanism responsible for the disparate Li abundances.

In this Letter we present the results of a detailed abundance analysis of 15 elements of the solar twins 16 Cyg A (HR 7503, HD 186408, HIP 96895) and 16 Cyg B (HR 7504, HD 186427, HIP 96901) based on high-resolution echelle spectroscopy. The abundances allow us to constrain more fully the physical similarities of the two stars, and the implications for Li depletion and planet formation in this system are discussed.

2. DATA AND ANALYSIS

Abundances of 15 elements have been derived from high-resolution, high-signal-to-noise ratio (SNR) spectroscopy of 16 Cyg A and B obtained with the 10-m Keck I telescope and HIRES echelle spectrograph (UT 1994 July 30). The spectra are characterized by a nominal resolution of $R = \lambda/\Delta\lambda = 45,000$ and SNR at the continuum near λ6700 of 750 and 1050 for 16 Cyg A and 16 Cyg B, respectively. A solar spectrum (Moon) was also obtained and has a SNR of 1500 near λ6700. The data are the same as those used by King et al. (1997), in which the observations, calibration scheme, and data reduction are fully described.

An updated version of the LTE spectral analysis package MOOG (Sneden 1973) was used for the abundance analysis. All abundances are derived from equivalent width (EW) measurements of atomic lines and the measurements were made using the one-dimensional spectrum analysis package SPECTRE (Fitzpatrick & Sneden 1987). Carbon abundances are also derived by using the synthesis method to fit the observed spectra of two features (λ5086 and λ5135.6) of the C_2 Swan system. Stellar parameters were derived using excitation and ionization balance of Fe I and Fe II lines in the usual manner.

Our abundance and error analyses follow exactly those described in Schuler et al. (2011), where a more detailed description of the procedures can be found. Final abundances– given relative to solar abundances derived from our solar spectrum– stellar parameters, and uncertainties for 16 Cyg A and B are given in Table 1. The adopted line list, equivalent width measures, and line-by-line abundances of each element for the Sun, 16 Cyg A, and 16 Cyg B are provided in Table 2.

3. RESULTS & DISCUSSION

The stellar parameters shown in Table 1, we find 16 Cyg A and B to be physically similar, with A being slightly hotter and having a slightly lower surface gravity than B. The differences in parameters are $\Delta T_{\rm eff} = +43 \pm 45$ K, $\Delta \log g = -0.02 \pm 0.17$ dex, and $\Delta\xi = +0.10 \pm 0.11$ km s^{-1}. While the parameters are the same within the uncertainties, previous studies find consistently that 16 Cyg A is slightly hotter and has a lower surface gravity than 16 Cyg B, suggesting that the small parameter differences are real.

The [Fe/H] abundances are found to be indistinguishable within uncertainties, with Δ[Fe/H] $= +0.018 \pm 0.025$ (σ) dex, in agreement with previous studies. The difference in the Fe abundance, Δ[Fe/H], is the average of the line-by-line abundance differences of the Fe I and Fe II lines (difference of each individual line), as opposed to the difference in the mean abundances. Laws & Gonzalez (2001) carried out a differential Fe abundance analysis of 16 Cyg A and B and found A to be enhanced in Fe relative to B by 0.025 ± 0.009 dex. However, Takeda (2005) conducted a similar differential analysis and found the metallicities to be identical at a level of $\lesssim 0.01$ dex. Takeda also pointed out a possible systematic error in the analysis of Laws & Gonzalez (2001) that could account for the different results.

Abundances of the remaining elements derived here are also found to be indistinguishable, as seen in Table 1 and shown graphically in Figure 1. The abundance differences shown in Figure 1 are the means of the line-by-line differences for each element. The mean abundance difference of all elements is $+0.003 \pm 0.015$ (σ) dex, with no element abundance differing by more than 0.026 dex between the two stars.

Given the marked agreement in the abundances of 16 Cyg A and B for the 15 elements studied here, it seems likely that these two binary components are chemically identical save the factor of $\geq$ 4.5 difference in their Li abundances (King et al. 1997). The chemical homogeneity suggests that the Li abundance difference is not primordial but rather due to some physical process during the lifetime of the system. Laws & Gonzalez (2001) suggested that accretion of planetary material by A could explain its enhanced Li abundance relative to B. Baraffe & Chabrier (2010) have alternatively demonstrated that episodic accretion onto a young star can affect its internal structure and increase its core temperature, resulting in enhanced surface Li depletion. The similar chemical compositions of 16 Cyg A and B argues against any differential accretion onto either of the stars having occurred.

The disparate Li abundances of 16 Cyg A and B are more likely the result of rotationally-induced mixing and differences in angular momentum evolution. King et al. (1997) argue that non-standard slow mixing on the main sequence, possibly related to rotation, can account for the stars' low absolute Li abundances. The difference in the Li abundances of 16 Cyg A and B would then be due to differences in J_o and/or the rates of angular momentum loss. King et al. (1997) suggest that planet formation could affect the angular momentum evolution of the host star. Recent modeling efforts do indeed demonstrate the plausibility of this assertion (e.g., Bouvier 2008; Eggenberger et al. 2010). For instance, Bouvier (2008) shows that shear-induced turbulence due to core-envelope decoupling can result in enhanced Li depletion in solar-type stars and that stars with slow rotation rates on the zero-age main sequence (ZAMS) have longer core-envelope coupling timescales than fast rotators. Slow rotators are thus expected to deplete more Li than fast rotators. Bouvier further demonstrates that, compared to stars with short-lived circumstellar disks, stars with longer-lived disks will experience more angular momentum loss via magnetic star-disk interactions and will arrive on the ZAMS as more slowly rotating stars and thus have lower Li abundances.

This could explain, at least qualitatively, why two otherwise physically similar and chemically homogeneous stars such as 16 Cyg A and B could have significantly different Li abundances. Whereas the presence of a massive planet orbiting 16 Cyg B evidently requires a disk with a lifetime sufficient to form such a planet, the lack of a detected planet orbiting 16 Cyg A suggests that, if this star had a disk, its physical properties were such that planet formation was inhibited. Both observational (e.g., Jensen et al. 1996) and computational (e.g., Mayer et al. 2005) studies suggest disk structure and as a result planet formation are disrupted in binary systems with separations less than 100 AU. If the disk of 16 Cyg A was truncated by its M dwarf companion, determined to be at $\sim$ 70 AU, its shorter lifetime compared to the planet-forming disk of 16 Cyg B may have resulted in less Li destruction. While the lower Li abundance of 16 Cyg B relative to 16 Cyg A is consistent with this scenario, results of observational studies aimed at tying enhanced Li depletion to the presence of planets have not reached a consensus on the matter (e.g., Israelian et al. 2009; Ghezzi et al. 2010; Baumann et al. 2010). Nonetheless, the case of 16 Cyg A and B is intriguing as it may be an ideal system for further studies of the possible connection between binarity, planet formation, and Li depletion.

3.1. Abundance Trends with Condensation Temperature of the Elements

The fact that no planet has heretofore been discovered around 16 Cyg A does not preclude the existence of a planet orbiting this star. However, the chemical composition of 16 Cyg A and B may place additional constraints on the existence of such a planet. Meléndez et al. (2009) have demonstrated that the Sun is deficient in refractory elements relative to volatile elements compared to a sample of solar twins. Moreover, the deficiencies are correlated with the condensation temperature of the elements ($T_{\rm c}$) such that the abundances of refractory elements ($T_{\rm c} \gtrsim$ 900 K) decrease with increasing $T_{\rm c}$. Meléndez et al. (2009) suggest that the abundance pattern is due to dust condensation and terrestrial planet formation in the proto-solar nebula. Follow-up studies (Ramírez et al. 2009, 2010) including larger samples of solar twins and analogs found that the abundance patterns of $\sim$ 85% of the stars analyzed differ from the Sun, i.e., they have increasing abundances of refractory elements as a function of $T_{\rm c}$. The authors speculate that the remaining $\sim$ 15% with flat or decreasing trends are potential terrestrial planet hosts.

We have recently extended the analysis of abundances versus $T_{\rm c}$ trends to a sample of 10 stars known to host giant planets (Schuler et al. 2011). The slopes of linear least-squares fits to the [m/H]-$T_{\rm c}$ trends were compared to similar slopes for a sample of 121 stars with and without known giant planets from Gonzalez et al. (2010); the distribution of slopes as a function of [Fe/H] for this larger sample was taken as the general trend arising from Galactic chemical evolution. Four of the 10 stars in our sample have very close-in giant planets (three at 0.05 AU) and are found to have positive slopes that fall above the general trend defined by the Gonzalez et al. data. These stars are speculated to have accreted refractory-rich planet material sometime during the evolution of their planetary systems. Abundance trends with $T_{\rm c}$ then may not only indicate the presence of terrestrial planets but also provide clues to the architecture of a planetary system and/or evolution thereof. The remaining six stars from Schuler et al. (2011) have negative slopes, possibly indicating the presence of terrestrial planets, but the slopes fall along the general trend of Galactic chemical evolution and thus may not be related to planet formation.

The abundances of 16 Cyg A and B are plotted versus $T_{\rm c}$ in Figure 2. Only the refractory elements ($T_{\rm c} \gtrsim 900$ K) are considered, because it is among these elements that the putative planet signature has been detected (Meléndez et al. 2009). The abundances are plotted against 50% $T_{\rm c}$ from Lodders (2003). Slopes of linear least-squares fits are positive and identical within the uncertainties: $m_{\rm A} = 5.77 \pm 2.08 \times 10^{-5}$ dex K^{-1} and $m_{\rm B} = 4.42 \pm 1.94 \times 10^{-5}$ dex K^{-1} for 16 Cyg A and 16 Cyg B, respectively.

Positive slopes in the [m/H]-$T_{\rm c}$ relations for 16 Cyg A and B, in the interpretation of Ramírez et al. (2009), imply that these solar twins are not terrestrial planet hosts. Continued RV monitoring have failed to yield additional planet signatures for either 16 Cyg A and B, but the sensitivity of the ground-based RV observations may not be sufficient to detect small terrestrial planets. Wittenmyer et al. (2007b) investigated the likelihood that additional planets could survive in the 16 Cyg B system given the large eccentricity of 16 Cyg B b. Using test-particle simulations, they found that particles only remained in stable orbits inside 0.3 AU, leaving open the possibility that short period planets may exist in this system. However, combining the numerical simulations with RV monitoring data, planets with masses $M \sin i \gtrsim 2$ Neptune mass with periods of less than about 100 days (roughly corresponding to $a = 0.3$ AU) can be excluded at the 99% confidence level.

The physical process(es) responsible for the large eccentricities characteristic of many of the known extrasolar planets, including 16 Cyg B b, is currently not well constrained. Planet-disk interactions have been investigated, but simulations generally result in the dampening of orbital eccentricities and do not reproduce the observed planet eccentricity distribution (e.g., Bitsch & Kley 2010). An alternative explanation is dynamical instabilities resulting from planet-planet scattering. Simulations of multi-planet systems can produce planets with highly eccentric orbits, and more importantly, they can reproduce the observed extrasolar planet eccentricity distribution (e.g., Ford & Rasio 2008; Raymond et al. 2009). For 16 Cyg B b, 16 Cyg A may be the culprit. Secular interactions with a distant stellar companion have been shown to produce long-period oscillations in the eccentricities of a planet orbiting the companion binary star (the so called Kozai mechanism; Takeda & Rasio 2005). Holman et al. (1997) and Mazeh et al. (1997) have independently demonstrated that such a mechanism is plausibly responsible for the large eccentricity of 16 Cyg B b.

A possible consequence of induced eccentricity enhancement is the ejection of disk or planet material in the inner region of the system, disrupting terrestrial planet formation.

Simulations testing the effects of giant planets with eccentric orbits on the formation of terrestrial planets generally show a near complete clearing out of inner planetary material and thus no terrestrial planet formation (e.g., Veras & Armitage 2005; Raymond et al. 2011). In particular, Raymond et al. (2011) reported that in simulations in which a giant planet scattered to a minimum periastron distance of < 1.3 AU, all of the terrestrial material in those systems was destroyed. Extending this result to 16 Cyg B b, the periastron of which is $r_{\rm p} = 0.52$ AU based on the most recently derived orbital parameters ($e = 0.689$ and $a = 1.68$ AU; Wittenmyer et al. 2007a), no terrestrial planet material would be expected to have survived around 16 Cyg B. This is consistent with the implication of the positive slopes in the [m/H]-$T_{\rm c}$ relations for 16 Cyg A and B.

4. Conclusions

We have presented the results of a detailed abundance analysis of the solar twins 16 Cyg A and B, the second of which is host to a giant planet. Aside from a factor of ~ 4.5 difference in Li abundances, the two stars are found to be otherwise chemically identical based on the 15 elements considered. Slopes in the [m/H]-$T_{\rm c}$ relations are also statistically identical and are another indication that 16 Cyg A and B are chemically homogeneous. The stark consistency of the compositions of these stars suggest that the physical process(es) responsible for the enhanced Li depletion in B did not alter the abundances of other elements. This argues against any kind of accretion related mechanism and supports differences in internal mixing efficiencies possibly related to different angular momentum evolutions as the most likely explanation for the disparate Li abundances. Enhanced Li depletion in B can be plausibly tied to the presence of its giant planet, as predicted by rotational stellar evolution models; however, the mixed observational results regarding Li abundances of planet host stars cloud this issue. More work is clearly required to understand how star-disk interactions and/or planet formation does or does not increase Li depletion in planet host stars.

The chemical homogeneity of 16 Cyg A and B, combined with the heretofore lack of detected planets around 16 Cyg A, further suggests that the planet formation process did not affect the bulk composition of 16 Cyg B. Since the discovery that stars with giant planets tend to be more metal-rich than stars without known planets (Gonzalez 1997, 1998; Santos et al. 2004; Fischer & Valenti 2005), countless abundance studies of host stars have aimed to identify possible chemical vestiges of the planet formation process. As described above, Li may be one of these. As for the overall metallicity of planet hosts, the result for 16 Cyg A and B adds to the considerable evidence indicating that the planet-metallicity correlation for stars with giant planets is intrinsic in nature and does not arise from processes, such as accretion of solid-body material, associated with the formation and evolution of giant planets. Furthermore, it appears that the abundances of individual elements heavier than Li (with the possible exception of Be and B, the abundances of which can also be depleted by internal mixing mechanisms, depending on the depth and efficiency of the mixing; Deliyannis et al. 1998; Boesgaard et al. 2005) are also not affected by planet formation, at least in systems like 16 Cyg B.

The physical characteristics of 16 Cygni make it an ideal system to test and constrain planet formation models. Most tellingly, the conditions necessary for planet formation apparently were present for 16 Cyg B but not 16 Cyg A, despite their physical and chemical similarities. We have discussed empirical and computational results that can possibly account for the observed characteristics of the system, including the lack of a detected planet around 16 Cyg A, the enhanced Li depletion of 16 Cyg B, and the eccentricity of the planet 16 Cyg B b, and that imply that neither 16 Cyg A nor 16 Cyg B is a terrestrial planet host. Future efforts that can combine all of these attributes into a single model will represent a significant achievement in understanding the formation and evolution of planetary systems.

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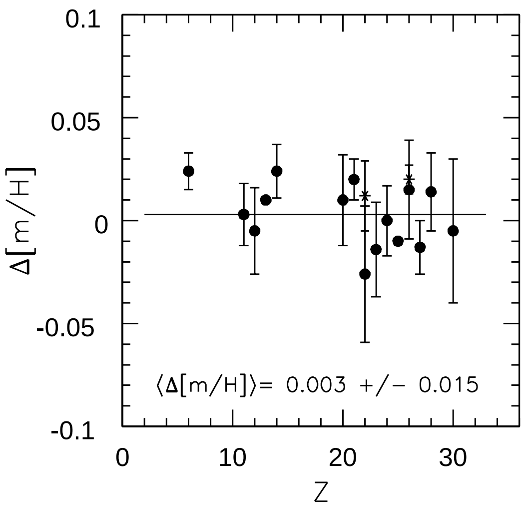

Fig. 1.— Abundance differences between 16 Cyg A and 16 Cyg B plotted against atomic number (Z). The six-pointed stars represent the abundances of Ti II and Fe II. The abundance difference for each element is the mean of the line-by-line abundance differences and is thus independent of the solar abundances; error bars are the standard deviations of the means. The solid line is drawn at Δ[m/H] = 0.003, the mean abundance difference of all elements.

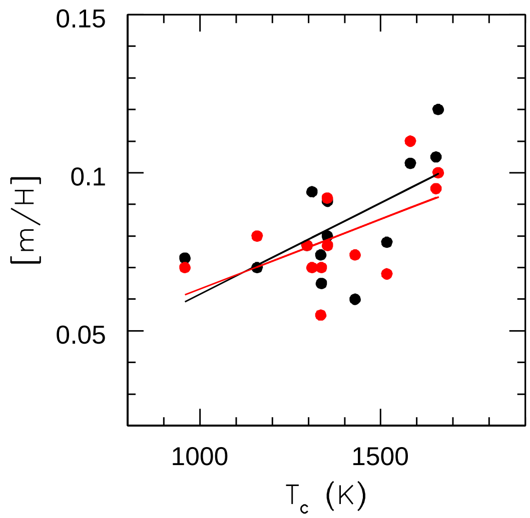

Fig. 2.— Relative abundances as a function of condensation temperature of the elements. Abundances of 16 Cyg A and B are plotted as black and red points, respectively. The solid lines are linear least-squares fits to the data and have positive slopes that are indistinguishable: $m_{\rm A} = 5.77 \pm 2.08 \times 10^{-5}$ dex K^{-1} and $m_{\rm B} = 4.42 \pm 1.94 \times 10^{-5}$ dex K^{-1} for A (black) and B (red), respectively.

Table 1. Stellar Parameters & Abundances

Parameter[a]	16 Cyg A	16 Cyg B
$T_{\rm eff}$ (K)	5796 $\pm$34	5753 $\pm$30
$\log g$ (cgs)	4.38 $\pm$0.12	4.40 $\pm$0.12
ξ (km s^{-1})	1.45 $\pm$0.07	1.35 $\pm$0.08
[Fe/H] ...	+0.07 $\pm$0.01[b] $\pm$0.05[c]	+0.05 $\pm$0.01 $\pm$ 0.05
[C/H]	+0.10 $\pm$0.03 $\pm$ 0.05	+0.08 $\pm$0.03 $\pm$ 0.05
[Na/H] ..	+0.07 $\pm$0.00 $\pm$ 0.03	+0.07 $\pm$0.00 $\pm$ 0.03
[Mg/H] ..	+0.07 $\pm$0.04 $\pm$ 0.05	+0.07 $\pm$0.04 $\pm$ 0.03
[Al/H] ...	+0.11 $\pm$0.02 $\pm$ 0.03	+0.10 $\pm$0.02 $\pm$ 0.03
[Si/H] ...	+0.09 $\pm$0.01 $\pm$ 0.01	+0.07 $\pm$0.01 $\pm$ 0.01
[Ca/H] ..	+0.08 $\pm$0.01 $\pm$ 0.04	+0.07 $\pm$0.01 $\pm$ 0.04
[Sc/H] ...	+0.12 $\pm$0.01 $\pm$ 0.07	+0.10 $\pm$0.01 $\pm$ 0.07
[Ti/H] ...	+0.10 $\pm$0.01 $\pm$ 0.07	+0.11 $\pm$0.01 $\pm$ 0.07
[V/H]	+0.06 $\pm$0.02 $\pm$ 0.04	+0.07 $\pm$0.02 $\pm$ 0.04
[Cr/H] ...	+0.08 $\pm$0.02 $\pm$ 0.04	+0.08 $\pm$0.02 $\pm$ 0.03
[Mn/H] ..	+0.07 $\pm$0.03 $\pm$ 0.04	+0.08 $\pm$0.03 $\pm$ 0.04
[Co/H] ..	+0.08 $\pm$0.02 $\pm$ 0.04	+0.09 $\pm$0.02 $\pm$ 0.03
[Ni/H] ...	+0.09 $\pm$0.01 $\pm$ 0.02	+0.08 $\pm$0.01 $\pm$ 0.02
[Zn/H] ...	+0.10 $\pm$0.02 $\pm$ 0.04	+0.10 $\pm$0.02 $\pm$ 0.03

[a] Adopted solar parameters: $T_{\rm eff} = 5777$ K, $\log g = 4.44$, and $\xi = 1.38$ km s^{-1}.

[b] σ_{μ}

[c] σ_{Total}– quadratic sum of σ_{μ} and uncertainties due to uncertainties in $T_{\rm eff}$, $\log g$, and ξ.

Table 2. Lines Measured, Equivalent Widths, and Abundances

	λ	χ				16 Cyg A		16 Cyg B	
Ion	(Å)	(eV)	log gf	$EW_{\odot}$	$\log N_{\odot}$	EW	$\log N$	EW	$\log N$
C I	5052.17	7.68	-1.304	31.8	8.43	39.6	8.56	37.0	8.54
	5380.34	7.68	-1.615	19.8	8.46	25.0	8.58	22.7	8.55
	6587.61	8.54	-1.021	13.5	8.41	18.5	8.57	16.7	8.54
Na I	5682.63	2.10	-0.700	105.0	6.21	109.7	6.29	110.2	6.27
	6154.23	2.10	-1.560	38.4	6.29	42.7	6.36	44.5	6.37
	6160.75	2.10	-1.260	58.1	6.26	62.9	6.33	64.2	6.33
Mg I	4730.03	4.35	-2.523	74.1	7.91	80.0	8.00	80.3	7.99
	5711.09	4.35	-1.833	104.3	7.60	106.7	7.64	108.6	7.66

Note. — Table 2 is published in its entirety in the electronic edition of The Astrophysical Journal Letters. A portion is shown here for guidance regarding its form and content.