A DIFFERENTIAL SPECTROSCOPIC ANALYSIS OF 16 CYgni A AND B

CHRIS LAWS AND GUILLERMO GONZALEZ

Astronomy Department, University of Washington, P.O. Box 351580, Seattle, WA 98195; laws@astro.washington.edu, gonzalez@astro.washington.edu

Received 2000 September 27; accepted 2001 January 18

ABSTRACT

We utilize high-resolution, high signal-to-noise spectra to perform a differential analysis of Fe abundances in the common proper-motion pair 16 Cyg A and B. We confirm that both stars are slightly metal-rich compared to the Sun, and we show for the first time that the primary is enhanced in Fe relative to the secondary by a significant amount. We find $\Delta[\text{Fe/H}] = 0.025 \pm 0.009$. This tends to support a "self-pollution" scenario, though lack of a complete understanding of small primordial metallicity variations among binaries and open cluster members prevents a definitive conclusion.

Subject headings: planetary systems — stars: abundances — stars: chemically peculiar — stars: individual (HD 186408, HD 186427)

On-line material: machine-readable table

1. INTRODUCTION

The nearby common proper-motion pair 16 Cyg A and B (HD 186408 and HD 186427, respectively) has been of particular interest to stellar astronomers for a number of reasons. In their physical characteristics, they are both very similar to the Sun and as such have been labeled "solar twins" or "solar analogs" (Friel et al. 1993). Like any human twins, however, these two stars clearly cannot be exactly similar to the Sun or even to each other, and it is their differences that have generated the most recent interest. Most notably, radial velocity studies have revealed that 16 Cyg B harbors a planetary mass companion, while 16 Cyg A apparently does not (Cochran et al. 1997). This remarkable observation has itself been invoked by some to explain other unexpected chemical differences between these two stars (Cochran et al. 1997; King et al. 1997; Gonzalez 1998, hereafter G98): their Li abundances differ by a factor of 5 or more (Deliyannis et al. 2000, hereafter D00), while studies of the Fe abundance of this pair have consistently suggested that 16 Cyg A may be slightly more metal-rich ($\sim 0.05$ dex) than its companion (G98). How are these differences achieved in such otherwise similar stars, which share a presumably common primordial environment? To what level can dynamic interactions with a planetary system affect abundances in a stellar photosphere?

Unfortunately, with the exception of lithium, the small differences in line depths between these two stars combined with the relatively large uncertainties in abundance determinations to date have prevented any conclusive statements from being made about deviations between 16 Cyg A and B with regard to any other element, including iron (G98; D00); within the uncertainties, the measured chemical differences are all effectively zero. The primary goal of this work is to utilize a new differential line abundance analysis method to constrain better the relative [Fe/H] values between 16 Cyg A and B. Such a method, as shown by Langer et al. (1998), eliminates nontrivial uncertainties in oscillator strengths, or $gf$-values. Further, we utilize a more extensive Fe line list covering a wider range in lower excitation potential ($\chi_l$) than previously published studies. In §2 we describe our observations and the data reduction, in §3 we describe our analysis methods and present results, and in §4 we discuss their significance.

2. OBSERVATIONS

Our intentions from the start have been to perform a very careful spectroscopic analysis of 16 Cyg A and B, optimized for differential analysis. We determined at the outset to make every effort to minimize any systematic differences that might arise as a result of variations in our observations, reductions, and subsequent analyses of each star. With this goal in mind, we obtained optical spectra of 16 Cyg A and B within 30 minutes of each other on 1999 December 22 with the McDonald Observatory 2.7 m telescope. We employed the coudé echelle spectrograph (Tull et al. 1995) and a 2048 $\times$ 2048 Tektronix CCD and made no changes to the instrument between the two observations. We achieved a resolving power of 58,000 (as measured on a Th-Ar lamp spectrum) with a signal-to-noise ratio ($S/N$) of $\sim 400$ pixel$^{-1}$ at 6700 Å. Spectra of a hot star were also obtained within 1 hr and at a similar air mass in order to compensate for telluric features in the spectra of 16 Cyg A and B.

Data for 16 Cyg A and B were reduced in as nearly an identical manner as possible, in both cases following the general method described in Gonzalez (1997). Each image was processed with the same bias and flat fields, and corrections for scattered light were made with the same fitting functions in both spectra. In addition, continua of individual orders were normalized with exactly the same functions in both stars. These steps were undertaken to minimize possible systematic differences between line depths that would ultimately impact our differential analysis. Our efforts yielded continuous one-dimensional spectra in the blue up to 5500 Å, with gaps thereafter up to roughly 10,000 Å.

3. ANALYSIS

3.1. Equivalent Widths

To eliminate potential bias in measuring the equivalent widths (EWs) of spectral features, one of us (G. G.) renamed each spectrum, and the other (C. L.) performed the measurements and analysis with no prior knowledge of which spectrum was associated with which star. We employed a list of high-quality atomic lines used in our previous studies of planet-bearing stars and measured the EWs of 60 Fe I and eight Fe II lines spanning broad ranges in $\chi_l$ from 0.09 to 6.22 eV and in EW from 4.7 to 119.8 mÅ. In every case the EW was measured for a line first in one star and then imme-
Table 1

Fe I and Fe II Equivalent Widths: 16 Cyg A and B

This table is available only on-line as a machine-readable table.

Immediately afterward in the second star before moving on to the next line. This procedure was followed to minimize any systematic differences in EW measurements between the two stars. Telluric contamination in some Fe lines was addressed by dividing the science object spectra by that of a hot star, and where performed, this division, as well as considerations of blending by nearby features, was treated identically for each line in each star. Our line list and measured EW values are presented in Table 1.

3.2. Standard Analysis

We employed the measured EWs from § 3.1 and associated gf-values taken from Gonzalez et al. (2001) and Gonzalez & Laws (2000) to derive a set of basic stellar parameters (\(T_{\text{eff}}\), \(\log g\), and \([\text{Fe/H}]\)) and associated uncertainties for 16 Cyg A and B, using the methods described extensively in G98 and Gonzalez & Vanture (1998). Briefly, all four of these parameters were systematically iterated with a recent version of the LTE abundance code MOOG (Sneden 1973) using Kurucz (1993) model atmospheres until the mean Fe I and Fe II abundances were equal and correlations of the individual Fe I line abundances with both \(\chi\) and the logarithm of reduced equivalent width (REW) were zero.

Following the method described in Gonzalez & Vanture (1998), uncertainties in \(\xi\) were determined from the standard deviation in the slope of a least-squares fit to the Fe I versus \(\log (\text{REW})\) data. This resulting uncertainty in \(\xi\) was summed in quadrature with the standard deviation in the slope of a least-squares fit to the Fe I versus \(\log (\text{REW})\) data to estimate the uncertainty in \(T_{\text{eff}}\). We combined these uncertainties in \(\chi\) and \(T_{\text{eff}}\) with the observed scatter in modeled Fe I line abundances to calculate our final uncertainty in \([\text{Fe/H}]\).

Our results using these standard methods are presented in Table 2, and we confirm previous studies: 16 Cyg A and B are very similar to each other, as well as to the Sun. Each member of the pair is slightly metal-enhanced relative to solar, however, with 16 Cyg A presenting a 0.03 dex over-abundance of Fe relative to 16 Cyg B, although this difference is not significant given our formal estimates of uncertainty.

3.3. Differential Analysis

To reduce the uncertainties in our estimates from § 3.2, we reanalyzed our EW data from these two stars employing a technique similar to that described and effectively utilized throughout this paper, all stated uncertainties are at the 1\(\sigma\) level.

![Figure 1](image-url)
by Langer et al. (1998) in searching for small metallicity variations among red giants in M92. Essentially, this method mirrors the "standard" method discussed above, but instead of determining chemical abundances for each star by averaging the results determined from individual lines and subsequently comparing these averages between stars by taking the differences in abundances calculated for each line individually. This differential strategy effectively eliminates uncertainties in $g_f$-values and allows one to take advantage of the increased precision in $\Delta[\text{Fe/H}]$ to constrain differential values of the other stellar parameters further.

We used our values for $T_{\text{eff}}$, $\log g$, and $\xi_t$ from § 3.2 to calculate $[\text{Fe/H}]$ for each line in each star and then determined differential Fe I abundances ($\Delta[\text{Fe/H}]$) for each line individually.² If the $T_{\text{eff}}$ and $\xi_t$ values from § 3.2 were both correct, then plots of $\Delta[\text{Fe/H}]$ versus both $\chi_l$ and $\log (\text{REW})$ would be uncorrelated. Our initial such plots using these "$\Delta$" values as inputs, however, showed slopes of 0.003 $\pm$ 0.002 dex eV$^{-1}$ for $\Delta[\text{Fe/H}]$ versus $\chi_l$ and $-0.010 \pm 0.009$ dex/ log (REW) for $\Delta[\text{Fe/H}]$ versus $\log (\text{REW})$ (for comparison, these values in our standard analysis of 16 Cyg A in § 3.2 were 0.001 $\pm$ 0.006 and 0.003 $\pm$ 0.024, respectively). While these results are only slightly larger than their standard uncertainties, we note that they are both more precise and appreciably larger in magnitude than the final "zero-slope" conditions that resulted from our standard analysis. Such correlations indicate that the values of $\Delta T_{\text{eff}}$ and $\Delta \xi_t$ calculated from the results in Table 2 are off by some amount, and so we iterated $\Delta T_{\text{eff}}$ and $\Delta \xi_t$ by changing $T_{\text{eff}}$ (16 Cyg B) and $\xi_t$ (16 Cyg B) until these correlations were forced to zero.³ Figure 1 presents a visualization of the effect of changing $\Delta T_{\text{eff}}$ and $\Delta \xi_t$ on the $\chi_l$ and $\log (\text{REW})$ slopes. For $\log g = 4.21$ and 4.26 for 16 Cyg A and B, respectively, we find our best solution at $\Delta T_{\text{eff}} = 62 \pm 14$ K and $\Delta \xi_t = 0.05 \pm 0.01$ km s$^{-1}$, where the stated uncertainties were calculated in precisely the same manner as described in § 3.2. We note that these values are in very good agreement with our earlier, though less precise, results generated via the "standard" method.

Figures 2a and 2b show our final plots of $\Delta[\text{Fe/H}]$ versus both $\chi_l$ and $\log (\text{REW})$ for our optimal values of $\Delta T_{\text{eff}}$ and $\Delta \xi_t$; immediately apparent is the fact that for the vast majority of lines analyzed, $\Delta[\text{Fe/H}]$ is positive. We find a mean value of $\Delta[\text{Fe/H}]$ and its associated uncertainty of 0.025 $\pm$ 0.009 dex, where the stated uncertainty in $\Delta[\text{Fe/H}]$ was calculated via the method described in § 3.2, utilizing the uncertainties in $\Delta T_{\text{eff}}$, $\Delta \xi_t$, and the observed scatter of $\pm 0.021$ dex in individual line $\Delta[\text{Fe/H}]$ values. Uncertainty in $\Delta \log g$ produced an effect of $\pm 0.001$ dex in $\Delta[\text{Fe/H}]$ and was not considered in the stated error of the mean value of $\Delta[\text{Fe/H}]$. This uncertainty is in fact dominated by uncertainty in $\Delta T_{\text{eff}}$, with a $\pm 14$ K change effecting a $\pm 0.008$ dex change in $\Delta[\text{Fe/H}]$.

4. DISCUSSION

4.1. Reliability

We note that the atmospheric parameters for 16 Cyg A and B calculated using the "standard" method stand in good agreement with previous published studies, a hearten-

² In the following discussion, all "$\Delta$" values are of the form $\Delta X = X_{16\text{CygA}} - X_{16\text{CygB}}$.

³ Additionally, one consistently discrepant Fe I line at 6864.32 Å was discarded.
ing fact in light of discrepancies in EW measurements\textsuperscript{4} as well as variations in methodology among the various authors. We believe that our absolute values are more reliable than those of other recent studies as a result of our use of more Fe\textsc{i} lines spanning a larger range in $\chi_i$ and EW (D00, for example, only employed 20 Fe\textsc{i} lines with the smallest $\chi_i$ and EW values being 2.18 eV and 24 mA, respectively). Furthermore, using our method of differential analysis, we are able to fine-tune the observed values of $\Delta T_{\text{eff}}$ and $\Delta g_{\ast}$ and as a result have shown for the first time a statistically significant difference in [Fe/H] between 16 Cyg A and B. In Figure 3 we compare our resulting $\Delta$[Fe/H] values with those of previous studies (Alexander 1967; Perrin & Spite 1981; Wallerstein 1962).

The magnitude of this difference remains quite small, though, and while we have strived to eliminate possible systematic differences in our observations and analyses of these two stars, we must consider other potential mechanisms that might mimic true differences in chemical abundance before we can conclude that 16 Cyg A is in fact enhanced in Fe relative to 16 Cyg B. Most notably, measured values of [Fe/H] are known to vary with chromospheric activity levels. A recent study of Ca\textsc{ii} fluxes in planet-bearing stars by Henry et al. (2000), however, shows low values of $R_{\text{HK}}$ for 16 Cyg B, indicating little variability and surface activity. Our own spectra confirm the low levels of Ca\textsc{ii} H and K emission and show no signs of significant differences between 16 Cyg A and B in this regard. Furthermore, Hipparcos data set the photometric variability of each of these stars at the 0.007 mag level. We therefore are confident that differences in chromospheric activity do not play a significant role in accounting for the measured values of $\Delta$[Fe/H].

In addition, we examined possible systematic errors that might be introduced as a result of assumptions in our atmospheric modeling, such as the possibility that a difference in the temperature minimum between the two stars might yield differing values of [Fe/H] for the same $T_{\text{eff}}$ (Wallerstein 1972). To test against this, we compared the central absorption in the Mg\textsc{i} triplet near 5170 Å, and we found no evidence supporting differences in temperature minima between 16 Cyg A and B. We further argue that given the common ages of $9 \pm 2$ Gyr (G98) and similar values of $T_{\text{eff}}$, log $g$, and luminosity of these two stars (confirmed independently from photometric analyses; see Friel et al. 1993), it is unlikely that any systematic errors in this strictly differential study might be due to more subtle model assumptions, such as that of LTE. We therefore conclude that our measured value of $\Delta$[Fe/H] is reliable to the level of our stated uncertainty and that the photosphere of 16 Cyg A is significantly more iron-rich than that of 16 Cyg B.

4.2. Possible Explanations

An obvious explanation for the observed value of $\Delta$[Fe/H] is that it represents a primordial difference in the chemical composition of 16 Cyg A and B. Little high-resolution work exists on abundance differences between members of multiple star systems, however, and models of

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{feh.png}
\caption{Comparison of $\Delta$[Fe/H] values for 16 Cyg A and B from various published studies, with 1\,\sigma error bars.}
\end{figure}

\textsuperscript{4} Two typos in G98 were discovered in the course of preparing this paper: EWs for the Fe\textsc{i} feature at 6710.32 Å were mistakenly repeated for 6733.15 Å (the latter was not measured in that study), and EWs for the Ti\textsc{i} feature noted at 6126.22 Å were actually from a Ti\textsc{i} line at 6261.11 Å.
the formation of stellar systems are currently not sophisticated enough to address deviations in chemical abundance at the level of precision that we report here. We intend to pursue actively the former shortcoming by employing our differential method on a wide sample of stellar systems; however, until such primordial fluctuations are at least empirically, if not theoretically, constrained, there is little more that can be said for or against this hypothesis.

If, on the other hand, the observed difference in $[\text{Fe}/\text{H}]$ is not entirely primordial, then it must be set by variations in the evolutionary history of these two stars. A potential clue to the responsible mechanisms may lie in the aforementioned fact that the Li abundances of 16 Cyg A and B differ by a factor of at least 5 (D00). While Ryan (2000) has noted that planet-bearing stars do not as a whole appear to differ from the field population in their values of $[\text{Li}/\text{H}]$, a finding supported by the larger sample discussed in Gonzalez et al. (2001), it remains a challenge for standard theories of stellar atmospheres and evolution to explain the large difference in $[\text{Li}/\text{H}]$ between 16 Cyg A and B given the considerable similarity of their physical characteristics and presumably shared environmental history.

In response, various authors have discussed the possibility that the chemical composition of stellar photospheres can be affected by the presence of planetary companions. Cochran et al. (1997) and King et al. (1997) proposed that dynamical interactions between a rotating star and its protoplanetary disk might significantly alter the angular momentum evolution of the star and hence the rate at which the star depletes Li. This model is well supported by the recent investigations of Li and Be abundances reported by D00, wherein these authors conclude that models of slow rotational mixing can explain the relative abundances of Li and Be in 16 Cyg A and other anomalously Li-rich F and G stars. Such a mechanism cannot explain the more subtle variation in Fe that we report here, however.

Alternately, G98 proposed that the increased lithium content of 16 Cyg A’s photosphere may be the result of that star having consumed planetary material in its outer convection zone. Such self-pollution by materials of either chondritic or gas-giant composition would indeed produce an increase in the Li abundance, while only slightly affecting the Fe and Be abundances (G98; D00). If our result indicating that 16 Cyg A is slightly enhanced in Fe relative to 16 Cyg B is not a primordial effect, then it lends tentative support to this scenario. From the estimates presented by G98, we calculate that the observed difference in $[\text{Fe}/\text{H}]$ between 16 Cyg A and B can be explained by the accretion of 2.5 $M_{\odot}$ of chondritic or 0.3 $M_{\odot}$ of gas-giant material. The amount of Li enhancement due to accretion of these bodies is difficult to determine, given the marked nonlinear time, $T_{\text{eff}}$, and dynamical dependence of Li depletion, along with the unknown timing of the putative accretion event(s). Nevertheless, it remains plausible that the observed difference in Li between 16 Cyg A and B is explainable by accretion at some intermediate age.

The authors are grateful to George Wallerstein for helpful discussions and support through the Kenilworth Fund of the New York Community Trust, as well as to the anonymous referee, whose helpful comments greatly increased the clarity of our manuscript. This work has utilized the Simbad database at CDS, Strasbourg, France, in addition to the abstract services of ADS.

REFERENCES

Alexander, J. B. 1967, MNRAS, 137, 41
Cochran, W. D., Hatzes, A. P., Butler, R. P., & Marcy, G. W. 1997, AJ, 483, 457
Deliyannis, C. P., Cunha, K., King, J. R., & Boesgaard, A. M. 2000, AJ, 119, 2437 (D00)
Friel, E., Cayrel de Strobel, G., Chmielewski, Y., Spite, M., Lebre, A., & Bentolila, C. 1993, A&A, 274, 825
Gonzalez, G. 1997, MNRAS, 285, 403
Gonzalez, G. 1998, A&A, 334, 221 (G98)
Gonzalez, G., & Laws, C. 2000, AJ, 119, 390
Gonzalez, G., Laws, C., Tyagi, S., & Reddy, B. E. 2001, AJ, 121, 432
Gonzalez, G., & Vanture, A. D. 1998, A&A, 339, L29
Henry, G. W., Baliunas, S. L., Donahue, R. A., Fekel, F. C., & Soon, W. 2000, AJ, 531, 415

Note added in proof.—We have performed similar differential analyses on 16 Cyg A and B and calculated $\Delta[X/H]$ for 13 elements other than Fe. These $\Delta[X/H]$ values show a significant positive correlation with grain condensation temperature of $(1.4 \pm 0.5) \times 10^{-4}$ dex K$^{-1}$, which also lends support to the “self-pollution” model.