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LINE IDENTIFICATION STUDIES USING TRADITIONAL TECHNIQUES AND WAVELENGTH COINCIDENCE STATISTICS

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ABSTRACT

Traditional line identification techniques result in the assignment of individual lines to an atomic or ionic species (e.g. Ca I, Fe II). These methods may be supplemented by wavelength coincidence statistics (WCS). We discuss the strengths and weaknesses of these methods using spectra of a number of normal and peculiar B and A stars that have been studied *independently* by both methods. The present results support the overall findings of some earlier studies. WCS would be most useful in a *first* survey, before traditional methods have been applied. WCS can quickly make a global search for all species and in this way may enable identifications of an unexpected spectrum that could easily be omitted entirely from a traditional study. This is illustrated by O I. WCS is a subject to well-known weaknesses of any statistical technique, for example, a predictable number of spurious results are to be expected. The dangers of small number statistics are illustrated here. WCS is at its best relative to traditional methods in finding a line-rich atomic species that is only weakly present in a complicated stellar spectrum.

1 A Resume of Line Identification Techniques

The traditional method of atomic line identifications in a stellar spectrum is based on the comparison of stellar and atomic line intensities and wavelengths. Special attention is given to multiplets (cf. Moore 1954) as the relative intensities of lines within a multiplet are only weakly dependent on the excitation conditions of most spectroscopic sources. The standard procedure is to see if members of a given multiplet are present with appropriate relative strengths. Then one looks for other lines with similar excitation potentials and similar laboratory strengths.

This powerful and valid procedure is of great importance, but its usefulness may be limited in complex spectra. Serious blending distorts stellar line intensities from predictions based on multiplet membership or on lower excitation potential. Often there is only one strong line in a multiplet. The concept of a multiplet in LS coupling breaks down as a result of perturbations of the LS coupling terms. For example, the low lying transitions in Fe II can be reasonably well represented in terms of LS coupling, but many of the higher lying transitions consist of strongly mixed LS terms. An experienced spectroscopist may recognize this from the laboratory intensities or the presence of intercombination lines, but the former are often badly non-linear, and sometimes unavailable.

A supplementary procedure is to establish the presence of a group of lines via unbiased statistical methods which include that of wavelength coincidence statistics (WCS). Since individual lines are not identified, WCS is, strictly, speaking, not a 'line' identification technique, although we do not introduce a different terminology to reflect this. Cowley and Hensberge (1981, henceforth CH) made a detailed comparison of the results of WCS with the standard techniques applied by Merrill and Greenstein (1956) to the technetium star R Andromedae. In addition, CH investigated the expected number of spurious coincidences from WCS. A rigorous derivation of this number is difficult to establish, but CH showed how useful approximate results could be obtained by modeling the procedure. The probability Ω that WCS will make an individual, spurious identification may also be established by Monte Carlo trials. Clearly Ω depends on a variety of circumstances such as the stellar line density, the coincidence tolerance, the quality of the laboratory lists, etc. Details are given by CH, but results that are valuable for orientation purposes are that Ω is of order 0.025 to 0.030. Table 3 of CH then shows that if Ω is 0.025, one expects 9 spurious identifications at the $\geq 95\%$ confidence level out of 364 species sought. Moreover, the model allows one to predict with confidence that at least four and no more than 15 such spurious results will be found.

We can gain insight into these results. If we test for N species in a nonsense spectrum and take 0.05 as the significance border, the expected number of spurious results is not 0.05 N, but a number often half that size. This is because the number of coincidences required for significance is typically *small*, often less than 10. It is rare that a significant number of coincidences occurs with a probability of *exactly* 0.05. Usually it is less than that, say 0.02 to 0.03. Cases where one or more *fewer* coincidences occur have probabilities greater than 0.05, and are, therefore, discarded. The average *improbable* result occurs with a probability about half of 0.05, and the number of expected spurious events is 0.02 N to 0.03 N. In our case N has been of order 300 to 400, so the expected number of chance coincidences ranges from 6 to 12. The case of HR 4816 discussed below, which was examined at $\Delta\lambda = \pm 0.06$ Å and ± 0.03 Å illustrates these ideas.

In the present study we ran 20 Monte Carlo tests for each program star to broaden our understanding of the expected number of "improbable" chance coincidences in WCS trials. All trials were run with a coincidence tolerances of ± 0.06 Å except for those specifically noted. For each of the "nonsense stellar line lists" indicated in Table 1, we

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give the number of times an event with a probability ≤ 0.05 occurred. The nonsense lists were created by adding and subtracting up to 20 Å from the real wavelength sets. We used 2 Å increments to insure that the results from one list would not be correlated with those from the next.

For each star, the numbers in the columns (excluding the last) total to 20. Thus for τ Her, 1 out of 20 times there was a case with 4 species (spuriously) identified at the ≥ 95% confidence level; there were 3 cases with 5 species so identified, and so on.

The last column, which refers to the WCS analysis of the unshifted stellar list, gives the number of improbable (≤0.05) events that were 'rejected' on the basis of the traditional, non-WCS methods. To avoid subjectivity, we considered a rejection to be any species that was not used in the abundance determination, that is, for which a finite number of lines does not appear in Tables 3, 5, and 6 below. For HR 4816, which is not included in these tables, we considered a species to be 'rejected' if it does not appear under HD 110066 (HR 4816) in Adelman's (1973b) Table 3. If our understanding of the process is correct, this number should typically fall in the middle of the distribution listed for the trials with the nonsense stellar lists.

For most of the stars, the number of spurious identifications is well contained between 6 and 12 as expected. This is in good agreement with the 'rejections' calculated in the simplistic way we have described.

The line statistics are somewhat different for HR 4816 (the first entry). The shift toward larger numbers of spurious identifications may be accounted for in terms of the higher line density in HR 4816. Because of this higher line density, the number of hits required for significance is also higher than for the other stars. This diminishes the effect due to discrete, small numbers, and drives up the "typical" value of p closer to 0.05. If we use 300 to 400 for N, and take a typical p to be 0.04, then we expect 12 to 16 results. This is in good agreement with the entries for HR 4816. To test this, we ran additional trials with a tolerance of ± 0.03 Å, to force the number of significant coincidences towards smaller numbers. The results are shown in the last row of Table 1. The shift towards smaller numbers of spurious results is expected.

One could also use gf-values in line identification work (cf. Tech 1971). Rogerson and Ewell (1985) predicted the intensities of individual lines in the Copernicus spectrum of τ Sco with a rudimentary model (Te, log (Pe)) and assumed abundances. This is an approximation to the full synthesis of a stellar spectrum and possibly should precede it.

Rogerson and Ewell's technique included an examination of multiplet strengths, and should be considered a superset of the traditional techniques. Cowley and Merritt (1987) were able to show that *even after* the careful work of Rogerson and Ewell, valuable additional information about the star could be obtained by WCS.

The ultimate test and confirmation of line identifications ought to be complete spectral synthesis. Thus far, the method has not been applied globally, nor have quantitative methods been developed to supplant the confidence levels of WCS. Selected spectral regions have been synthesized for example by Cowley and Greenberg (1988), who attempted to verify the presence of the third spectra of lanthanides that had been indicated by WCS. Leckrone *et al.* (1990) illustrate the interaction of stellar spectra and atomic physics, showing how the inclusion of newly classified atomic lines improve the fits to observations.

The discussion below will illustrate the similarity of results obtained by the independent application of WCS and traditional methods.

2 Observations and Analytical Methods

The present study is based on the following material:

1) coadditions of 10 or more 2.4 Å/mm IIaO spectrograms taken at the Dominion Astrophysical Observatory (Adelman 1988a, b, 1989, 1990, Adelman et al. 1987) for 6 normal B and A and 9 Mercury-Manganese stars which have signal-to-noise ratios of order 80 in well exposed regions,

2) coadditions of 10 or more 6.8Å/mm IIaO spectrograms taken at the Dominion Astrophysical Observatory of 3 halo A type stars (see, Adelman, Fisher, and Hill 1987),

3) reticon observations at 2.4 Å/mm obtained at the Dominion Astrophysical Observatory of Vega with a S/N of order 500 (Adelman and Gulliver 1990, Gulliver and Cowley 1990), and

4) high dispersion coude spectrograms of the sharp-lined magnetic Ap star HR 4816 taken at Lick, Mt. Wilson, and Palomar Observatories (Adelman and Adelman 1988).

The spectrograms were measured interactively with REDUCE (Hill and Fisher 1986) except those of HR 4816 which were measured with a Grant Machine. Equivalent widths as well as wavelengths were measured using REDUCE and for all stars except for HR 4816, abundances were derived in the work just cited.

Both WCS and traditional methods provide more information than a mere "yes/no" for the presence of an atomic or ionic species. Some information is available on the "strength" of the species in the stellar spectrum, although this strength has a different meaning in the case of the two techniques. The WCS parameters may readily be used to describe the "richness" of a given species, e.g. many lines of Fe II are present. We briefly describe these parameters here. More details are found in the references, especially CH.

From a set of N laboratory lines, usually 200 sets of nonsense wavelengths are constructed by adding small random numbers to the former. We adopt a coincidence window, typically ±0.06 Å, and determine the number of hits H on the laboratory lines. From the nonsense lines, we determine the average number of hits $<H>_R$, and its variance. Let

$$\sigma^2 = \sum_i (<H>_R - H_i)^2.$$

We then define a significance parameter $S = (H - <H>_R)/\sigma$. The fraction of the 200 trials that an equal or greater number of coincidences is obtained on the nonsense wavelengths as on the laboratory ones, is called 'p'. The parameter p is a Monte Carlo probability that the H hits on the laboratory lines occurred by chance. The quantity 100*(1-p) gives the percent confidence level at which the null hypothesis (that nonsense wavelengths give as many hits) may be rejected.

We put the WCS results into six categories, for simplicity, designating each category by a special symbol as illustrated in Table 2. The three and four-star categories typically indicate a rich, well-identifiable species, such as Ti II or Fe II. Occasionally these categories can occur when all or nearly all of a relatively small number of lines sought are found (eg. H = N, or H = N-1) in a stellar spectrum with a low line density. In this case $<H>_R$ can be much less than one, and the S parameter can be large enough that hits will rate 3 or 4 stars.

We also require an illustrative figure to characterize the traditional methods. The present work uses the number of lines employed in the abundance studies cited. If this number is something other than zero, we may assume an identification. Moreover, the number of lines used will give an indication of the 'strength' of the presence of the species. Various caveats must be applied. Only some of the metal lines seen in a stellar spectrum are usable in a fine analysis as some lack good gf-values, some are badly blended, and some are too close to cores of very strong lines. For Ca II, only the K line was available for abundance work, and the number "1" can hardly reflect the strength of

Ca II. A similar comment can be made for Si II which is usually identified by five lines of multiplets 1 and 3. The WCS parameters as well, contain little information in such cases. Various corrections might be applied to the parameters we have chosen to characterize results from both WCS and traditional methods, but the additional effort is not justified.

3 Results

Several improvements to the WCS laboratory line lists were made as a result of the present survey. In several stars, we found an improbable number of coincidences with the Mn III and Co II lines from the laboratory lists of Zaidel *et al.* (1970) and Velasco and Adames (1966), respectively. In both cases, the published lists had not been purged of impurities. Si III lines were present in the Mn III list, while Ca II (including H and K) lines were in the Co II lists. These impurities have been purged from more recent compilations (e.g. Reader and Corliss 1980). Users of WCS must always be aware of possible contaminations, especially for older laboratory lists.

The case of Fe III is most interesting. The initial runs failed to identify this species in a number of our stars for which abundances had been determined from Fe III lines. The source of the difficulty was traced to the intensities from the study by Glad (1956). The original list included lines from his list with intensities greater than 13. The list thus *excluded* the line at 4419.60 Å, the strongest Fe III line in the domain surveyed!! Glad's intensities are based on non-thermal sources, and are, therefore, unsuitable for the present purposes. Many of the results reported below rate three WCS stars. They are based on a new list of Fe III lines generated with the help of relative intensities calculated from Kurucz (1988)'s oscillator strengths. We assumed an excitation temperature of 10080 K ($\theta = 0.50$). The six strongest lines between 4000 Å and 5000 Å are 4352.58 Å, 4371.34 Å, 4382.51 Å, 4395.76 Å, 4419.60 Å, and 4431.02 Å. *None* of these have intensities greater than 13 in Glad's list! The first three wavelengths are not even listed by Reader and Corliss (1980).

We constructed a similar list for Mn III, but obtained no positive WCS results. No Mn III identifications are reported here. The searches were based on only three lines, whose expected intensities (based on solar abundances) were a factor of 10 or more lower than the *weakest* of the Fe III lines listed above.

Table 3 contains the comparison for the normal and superficially normal stars. It is complete for species with lines used to derive elemental abundances and for species with ratings **** and ***. The lower categories (?, *, and **) are shown only when an abundance was determined.

The Vega study covered the region λλ4314-4807 with a signal-to-noise ratio of 500 while the other studies the region approximately λλ3712-4645 with a S/N of about 80 except for that of α Dra which had a S/N of about 60. The number of lines examined at the bottom of Table 3 gives an idea of the line density.

The agreement is mostly as expected; the cases in Table 3 where 10 or more lines were used for abundances have three or four stars (asterisks) from the WCS trials. These are well-identified species. At the other extreme, consider cases were *no* lines were used for abundances. This implies a species was not identified by traditional methods or that all possible lines were obliterated by blends. In either case, the species should be considered weak at best, or absent altogether. For such cases we expect no stars from WCS beyond a predictable, yet small, number of instances that may be attributed to improbable chance coincidences. Let us consider a few specific examples from Table 3 where stars appear even though n=0. We discuss O I and Al II.

In the case of O I, abundance determinations were not made simply because the presence of the species was not anticipated. The WCS results for O I are based on coincidences with only 3 or 4 of 5 lines from Moore (1976). We are, therefore, dealing with small number statistics and caution is indicated. In 21 Aql, a reconsideration of the basic data confirms that O I is present. Two of the coincidences occur with previously unidentified features. Another of the stellar wavelengths, at 4368.23 Å, had been identified with an unclassified Fe II line. This Fe II line may simply have been an unremoved contamination, possibly O I, in the laboratory study, Ironically, modern work on Fe II (Johansson 1990) reveals a *predicted* high-excitation line at 4363.28 Å. However, this is almost certainly *not* the transition that is listed in *A Multiplet Table of Astrophysical Interest* (Moore 1945) which is too weak in these stars. Thus O I remains a good possibility.

We have used our own measured unpublished equivalent widths and the stellar parameters cited in the papers above to deduce the log O/H values for many of these stars. These values are given in Table 4. Weise et al. (1966) give gf values for the two O I multiplets. As multiplet 3 consisted of three weak lines, two of which are blended together, we give the results for the whole multiplet . The lines, however, may be subject to non-LTE effects as they have high lying lower excitation potentials.

The solar value of log O/H = -3.09 (Grevesse 1984) is somewhat greater than the values for the three normal stars. This may reflect errors in the equivalent widths, or in the gf-values, or that these stars do not have solar oxygen abundances. We see no difference between the distribution for the normal stars and for the HgMn stars. Roby and Lambert (1990) found a similar oxygen abundance for 21 Aql, log O/H = -3.22.

The case of Al II also involves small number statistics - one or two coincidences. For Vega, an abundance by Adelman and Gulliver (1990) was based on the 4 mÅ line 4663.056 Å. Their result, log Al/H = -6.3 is nearly an order of magnitude below the solar value, -5.5. This agrees with the low aluminum abundance found for Vega by Sadakane and Nishimura (1981) and Sadakane, Takada, and Jugaku (1983). Consequently, we do not think it is unreasonable that Al II be weakly present in some of these stars. It is doubtful that the WCS results are indicative, however, since the chance coincidence of one of the Al II wavelengths with Cr II 4588.22 Å is sufficient to bias the small number statistics.

HD 64488, HD 109995, and HD 161817 are metal poor halo A type stars. Adelman, Fisher, and Hill (1987) show reproductions of these spectra which cover approximately λλ3685-4840. Line identifications are compared in Table 5. The Se I result in HD 109995 is based on 1 coincidence out of three lines sought at a tolerance of 60 mÅ. If the tolerance is increased to 120 mÅ, an additional coincidence is found, and the probability that this is due to chance is less than 1 in 200 (based on 200 random trials). Both coincidences are with *unidentified* weak features.

For Se I in HD 109995, we ran a special test with 2000 trials, using the tolerance of 120 mÅ. The two coincidences now have a probability estimate of 0.004, that is 4 in 2000 or 1 in 500 of being due to chance. Since our laboratory list contains some 400 species, a result whose chance occurrence is only 1 in 400 is to be *expected* with each WCS survey. Thus, we feel justified in rejecting these coincidences as an identification. We do this largely because Se I is not well identified in stars with much richer metallic line spectra, and sharper spectral lines. A new laboratory study of Se I would, however, be welcome.

Table 6 is the comparison for nine HgMn stars. The O I hits for κ Cnc, HR 8349, and 53 Tau again stand out because the O I lines were not anticipated in these stars and, therefore, not used for abundances. We have extended the analyses as for the normal stars (see Table 4). Here we find some differences with respect to Roby and Lambert (1990), part of which is due to their using too large microturbulences. They find log O/H

= -3.32 for κ Cnc and -3.61 for ϕ Her, which are almost the reverse of our values.

WCS gives no support for the O II line identifications in HR 8349. After a review of the original data and an examination of the new Multiplet Table for O II (Moore 1990), the identification appears less probable than originally thought. Slightly higher signal-to-noise data and/or spectral synthesis techniques may be able to confirm this marginally possible identification.

WCS did not confirm the presence of Fe III in ϕ Her or 53 Tau. In both stars, the abundance was based on weak absorptions (3.7 and 2.6 mÅ, respectively) near the strongest expected Fe III line 4419.60 Å. The measured stellar wavelengths, respectively, 4419.63 Å and 4419.66 Å, may indicate the presence of perturbers. The most likely candidate is Fe II 4419.69 Å, a 'second generation' line (cf. Johansson and Cowley 1981) that may be found in Kurucz's (1981) tabulation. Adelman (1989) gives an abundance of iron for 53 Tau based on a single Fe III line that is nearly a factor of 6 greater than the mean of the abundances from the Fe I and Fe II lines. In this case, it seems reasonable to attribute the measured feature, mostly, to the perturber. But for ϕ Her for which the iron abundance from the Fe III line is in better accord with those from Fe I and Fe II lines, this explanation is not probable.

The possibility of Ga I lines being present in stars with Ga II lines was considered when the traditional method was used. In κ Cnc and HR 7664, 2 out of 2 'improbable' Ga I coincidences occurred. In both cases, more reasonable, alternative identifications were possible with Fe II and Mn II. As with Se I above, we repeated the WCS tests, using 2000 random trials, and found that for both stars the 2 out of 2 coincidences at a 60 mÅ tolerance occurred 5 times, (p = 0.025). Again we note that one event at this level is *expected* among the WCS tests for each star. Note that since the coincidences were with lines from well identified ions, the two improbable events in κ Cnc and HR 7664 are not unrelated.

The suggestions of Ag I lines in 28 Her and ν Cnc and of Au II lines in 28 Her were investigated. The Ag I WCS results are from 2 out of 3 coincidences. However, they are with rather weak Ag I lines. As in both cases the features are well explained by Mn I and Fe I lines, we attribute the coincidences to chance. As with the cases discussed above, we made improved estimates of these coincidences based on 2000 random trials. For 28 Her the probability was 0.018, while for ν Cnc, it was 0.019. Neutral silver has two (5s-5p) resonance lines at λ3280 and λ3282 which should be used for the identification of the relatively simple Ag I spectrum.

One of the strongest Au II lines, λ4052.59, was identified in 28 Her in our "traditional" work with a 9 mÅ feature. The 7 mÅ stellar feature at λ4016.08 is only 0.02 Å short of another Au II wavelength. The "three-star" result in Table 6 was based on these 2 (out of 3) coincidences using lines suggested by Dworetsky (1971). We exchanged Dworetsky's wavelengths for the newer Ehrhardt and Davis (1971) measurements, and still found a marginally significant result with 98.5 % confidence, based on 2000 trials. We have also used a longer list of 6 lines from the Ehrhardt and Davis list. No additional coincidences were found, and the significance level drops to 91.5% confidence, below our "significance" threshold. The clear presence of lines from both Pt (Z=78) and Hg (Z=80) makes the presence of lines from Au (Z=79) entirely reasonable. Higher signal-to-noise spectra of the relevant regions should be obtained to confirm this identification.

Adelman (1973a, b) determined abundances of the cool, magnetic Ap star HR 4816 (=HD 110066). It was among the early objects studied by WCS (Cowley, Hartoog, and Cowley 1974). Bidelman (cf. Bidelman, Cowley, and Roemmelt 1989) recently published a slightly updated version of his unpublished identification list for HR 4816 which was based on a single 2 Å/mm Lick spectrogram. Additional references are given in the papers cited.

For the present study, the traditional identifications are from Adelman and Adelman (1988) who used numerous spectrograms. There were 3714 lines in λλ3661-4918. We extract the wavelengths from the highest dispersion spectrogram for each region. The following species rated **** (see also Table 2): Ti II, Cr II, Mn II, Fe I, and Fe II. They were all identified by traditional methods as were the *** species Ca I, Cr I, Ce II, and Gd II. The ** species include Mg I, Mg II, Si II, Sc II, Mn I, Y II, La II, Sm II, Eu II, Dy II, and Tm II. Of these all were found by traditional methods. Only Tm II is a possible identification. Of the sixteen * species, eight (Ca II, Ti I, V II, Co II, Sr II, Mo II, Nd II, and Gd III) were identified by traditional methods as well as 4 of 16 ? species (Al I, Ni I, Sr I, and Ba II). The WCS rankings for the most part are in good accord with assessments from traditional methods. WCS did not support Si I, but this is not surprising as this identification is based solely on Si I λ3905.523. S II, Co I, Cd I, Ce III, Pr II, Er II, and U II were identified by traditional methods but not WCS. A review of our earlier material suggests that Zr II is most likely very weak.

4 Final Comments

Thus WCS provided a useful supplement to traditional techniques especially in identifying O I lines which were overlooked. It has cast some additional doubts on questionable identifications. One must take advantage of its strengths and be aware of its shortcoming, especially those associated with the use of small numbers.

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TABLE 1

Monte Carlo Trials with Nonsense Stellar Lists

	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	Number of Rejections
τ Her			1	3	2	3	1	3	1	4	1			1													6
21 Aql			2	1	4	5	1	3				1	1	1	1												11
134 Tau			3	1	4		1	4	2		3	1	1														6
α Dra	1	1	2	1	1	2	4	2	2	3			1														6
o Peg						3	4	2	3	1	3	1	1		2												7
Vega	1	2	3	4	2	4	1		2						1												6
θ Leo	1			2	2	3	1	1	2	3	1		1	1	2												4
HD 64488		1	2	3	4	2	4		1	1					1		1										8
HD 109995			2		4	3	3	1	3	2	1						1										7
HD 161817				1	2	5	1	3	3	1	2	2															8
κ Cnc				2		2	2	3	2		2	3				1	1	1	1								9
HR 8349			1	1	3	3	3	3	2			2		1		1											8
HR 7664		1		1	2	1	1	3	2	2	3	2				1	1										5
μ Lep			1	1	2	4	1	2	4	1	1			2		1											3
53 Tau				3	2	2	2	2	2	4		1		2													11
ϕ Her				4	2	4		1	1	1	3	4															5
ι CrB				3	3	1	2	4	1	4			1		1												9
28 Her		1	1	3	1	1	6	2			1	2	1					1									4
ν Cnc				2	1	2	2	2	4	3		1	1	1	1												6
HR 4816								1			4	1	1	5		1	1	1	2	2					1		14
HR 4816 ±0.03			4	1		1		4	3	2	3	1	1														

TABLE 2

Meaning of WCS Categories

symbol	meaning
	H<N; p>0.05
?	All lines in search list found (H = N) but p >0.005
*	0.005<p<0.05
**	p<0.005; S<4
***	p<0.005: 8>S≥4
****	p<0.005; S≥8

TABLE 3

Normal Star Comparisons Between the Number of Lines (n) Used in Elemental Abundance Analyses vs. Wavelength Coincidence Statistics Ratings

	τ Her		21 Aql		134 Tau		α Dra		o Peg		Vega		θ Leo	
Ion	n	WCS	n	WCS	n	WCS	n	WCS	n	WCS	n	WCS	n	WCS
He I	4	****	4	****	3	***	2	***	2		1	*	2	*
C I	0		0		0		0		0		5	***	0	
C II	3	****	4	***	3		3	*	1		0		0	
N II	3	***	4	****	0		0		0		0		0	
O I	0		0	***	0	*	0	***	0	**	0	*	0	
O II	1:		0		0		0		0		0		0	
Mg I	0		3	***	3	***	2	***	1	***	1	*	1	***
Mg II	7	****	7	****	7	****	6	****	7	***	5	***	7	***
Al I	0		1		2	***	2	***	2	*	0		2	***
Al II	0		0	*	0	*	0	**	0		1	***	0	
Al III	2	*	1		0		0		0		0		0	
Si I	0		0		0		1		1		0		0	
Si II	5	****	5	****	5	***	5	***	5	***	0		5	***
Si III	3	***	2	*	0		0		0		0		0	
S II	11	****	18	****	2		1		5	***	0		2	
Ca I	0		0		1		1		8	***	4	***	9	****
Ca II	1	***	1	***	1	****	1	***	1	***	0		1	***
Sc II	0		0		1		1	*	8	***	6	***	5	***
Ti II	2	*	12	***	31	****	38	****	64	****	32	****	51	****
V II	0		0		2	**	5	**	26	****	0		14	****
Cr I	0		0		1		2		3	***	0		3	***
Cr II	0		13	****	19	****	20	****	36	****	7	****	25	****
Mn I	0		0		0		1	**	6	***	1	***	3	***
Mn II	0		0		0	*	0		13	****	2	*	4	***
Fe I	0		6	**	39	****	44	****	247	****	19	***	163	****
Fe II	29	****	63	****	58	****	48	****	108	****	33	****	64	****
Fe III	2	***	3	***	0		0		1	*	0		0	
Co I	0		0		0		1		5	***	0		2	
Co II	0		0		0		0		1		0		0	****
Ni I	0		0		0		0		12	***	3	***	5	***
Ni II	2	*	5	***	2	*	4	**	5	***	1		5	***
Sr II	0		0		2	***	2	****	3	*	0		3	***
Number of Lines	134		219		251		255		1078		193		592	

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TABLE 3 (continued)

Ion	o Peg		Vega		θ Leo	
	n	WCS	n	WCS	n	WCS
Y II	11	****	0		8	***
Zr II	27	****	0		16	****
Ba II	1	*	1	*	1	*
La II	10	***	0		1	
Nd II	2	*	0	*	0	
Eu II	1	*	0		0	*
Dy II	2	*	0		0	
Er II	2		0		0	
Hf II	2	**	0		0	

TABLE 4

O I Line Analyses

Star	λ3947.29		λ4346.80		Mean
	Wλ	log O/H	Wλ	log O/H	log O/H
α Dra	16	-3.46	8	-3.75	-3.60
21 Aql	9	-3.29	11	-3.19	-3.24
o Peg	21	-3.38	20	-3.35	-3.36
53 Tau	11	-3.38	8	-3.51	-3.44
κ Cnc	5	-3.54	4	-3.63	-3.58
ϕ Her	14	-3.33	18	-3.17	-3.25

Note: The gf-values are from Wiese *et al.* (1966).

TABLE 5

Halo A Star Comparisons Between the Number of Lines (n) Used in Elemental Abundance Analyses vs. Wavelength Coincidence Statistics Ratings

	HD 64488		HD 109995		HD 161817	
Ion	n	WCS	n	WCS	n	WCS
Mg I	1		6	****	5	****
Mg II	1	***	1	***	3	*
Al I	1		2	*	2	*
Al II	0		0		0	***
Si II	2		5	***	5	***
Ca I	2	*	2		12	****
Ca II	1	****	1	****	1	***
Sc II	1	*	1	***	7	***
Ti I	0		0		1	
Ti II	13	***	30	****	51	****
V II	0		2	*	8	***
Cr I	0		2	*	3	***
Cr II	4		6	****	14	****
Mn I	0		0		3	***
Fe I	9	***	41	****	136	****
Fe II	10	*	20	****	30	****
Co I	0		0		3	***
Ni I	0		0		4	***
Se I	0		0	***	0	
Sr II	2	*	2	****	2	***
Y II	0		1		4	***
Zr II	0		0		6	***
Ba II	0		0		1	*
Eu II	0		0		1	
Pt I	0		0	***	0	***
Number of Lines	116		228		464	

TABLE 6

Mercury-Manganese Star Comparisons Between the Number of Lines (n) Used in Elemental Abundance Analyses vs. Wavelength Coincidence Statistics Ratings

	κ Cnc		HR 8349		HR 7664		μ Lep		53 Tau		ϕ Her		ι CrB		28 Her		υ Cnc	
Ion	n	WCS	n	WCS	n	WCS	n	WCS	n	WCS	n	WCS	n	WCS	n	WCS	n	WCS
He I	4	***	3	***	2	*	4		3	*	2		3	*	2		2	*
C II	4	***	3		6	***	3		4	***	3	*	4	*	7	***	2	*
O I	0	***	0	***	0		0	*	0	***	0	**	0	*	0	*	0	
O II	0		3		0		0		0		0		0		0		0	
Mg I	1		2	**	0		1	***	0	***	3	***	2s	***	1	***	2	***
Mg II	6	****	6	***	5	***	5	***	6	****	6	***	4	****	5	****	7	***
Al I	0		1		0		0		0		0		0	*	0		2	***
Si I	0		0		0		0		0		0		0		0		1	
Si II	5	****	5	****	5	****	5	****	5	****	5	****	5	***	5	***	5	***
Si III	3	*	3	**	3	*	2		1		0		0		0		0	
P II	13	****	10	****	11	****	7	***	0		0		4	***	2	***	0	
P III	2		3		0		0		0		0		0		0		0	
S II	4	*	9	***	6	*	2	****	3	**	10	***	9	***	6	***	3	**
Ca I	0		0		0		0		1	**	1	*	0	*	1		1	***
Ca II	1	***	1	***	1	***	1	***	1	***	1	***	1	*	1	****	1	***
Sc II	4	***	6	***	1		3	*	1		13	****	0	**	0		10	****
Ti II	28	****	26	****	48	****	31	****	81	****	60	****	46	****	52	****	65	****
V II	2		0		0		1	*	0		0		13	***	0		2	*
Cr I	0		0		0		0		2	*	2	***	4s	***	2	*	3	***
Cr II	22	****	22	****	13	***	20	****	43	****	50	****	43	****	34	****	40	****
Mn I	6	****	10	****	0		6	****	39	****	14	****	14	***	9	****	3	***
Mn II	86	****	89	****	45	****	67	****	86	****	69	****	68	****	41	****	11	****
Fe I	16	***	11	***	42	****	10	***	13	***	52	****	109s	****	84	****	84	****
Fe II	101	****	88	****	119	****	58	****	44	****	86	****	117	****	100	****	74	****
Fe III	5	***	4	*	9	***	1	*	1		1		1	*	1	*	0	
Co I	0		0		0	*	0		0		0		1		0	*	1	
Ni I	0		0		0		0		0		0		0	*	0		2	?
Ni II	3	***	4	***	5	***	1	***	3	***	4	***	1	****	0		6	***
Ga I	0	***	0		0	***	0		0		0		0		0		0	
Ga II	3	***	0		2	***	2	***	2		2		0		0		0	
Sr II	1	***	2	*	1		3	***	2	***	2	*	3	***	4	***	3	***
Y II	3		17	****	3	**	12	****	12	****	21	****	19	****	23	****	15	****
Zr II	0		17	****	0		1		23	****	24	****	24	****	10	***	24	****
Ag I	0		0		0		0		0		0		0		0	***	0	***
Xe II	3	*	0	*	0		0		0		0		0		0		0	
Ba II	0		0		0		0		1	?	1	?	1	*	1	?	1	?
La II	0		0		0		0		0		0		1		0		0	
Gd II	0		4	***	0		0		0		0		4	*	0		2	
Pt II	0		1		0		0		0		0		6	**	8	****	0	
Au II	0		0		0		0		0		0		0		0	***	0	
Hg I	0		1		0		1		0		1		1		0		0	
Hg II	1	?	1	?	1	*	1	*	0		1	*	1	?	1		1	?
Number of Lines	715		650		632		432		670		759		1113		574		573	

Note: An s after the number of lines for ι CrB indicates those analyzed in the secondary star, otherwise the lines are for the primary.

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