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AN ELEMENTAL ABUNDANCE ANALYSIS OF THE SUPERFICIALLY NORMAL A STAR VEGA

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ABSTRACT

An elemental abundance analysis of Vega has been performed using high-signal-to-noise 2.4 Å mm^{-1} Reticon observations of the region λλ4313–4809. Vega is found to be a metal-poor star with a mean underabundance of 0.60 dex. The He/H ratio of 0.03 as derived from He I λ4472 suggests that the superficial helium convection zone has disappeared and that radiative diffusion is producing the photospheric abundance anomalies.

Subject headings: stars: abundances — stars: early-type — stars: individual (α Lyr)

I. INTRODUCTION

Vega (α Lyr = HR 7001 = HD 172167), the fifth brightest star in the visual, has been studied extensively as it serves as the primary standard for photoelectric photometry. This mildly metal weak star was born roughly one galactic rotation ago. It is chemically peculiar, but we have not known why. The theoretical basis for understanding these anomalies has developed slowly over the past few decades, partly because of the poor quality of the observational material upon which it rests. To read the cosmochemical history of matter as written in abundance patterns requires accurate values for many atomic species.

Chemical separation may affect the photospheric abundances in up to 50% of stars with effective temperatures greater than 6500 K. Vega's chemical anomalies are sufficiently mild that only recently has it been possible to demonstrate them convincingly (Sadakane, Nishimura, and Hirata 1986; see also Dreiling and Bell 1980, Bell and Dreiling 1982). With reliable abundance data from many elements, the surficial abundances provide clues to the hydrodynamical state and history of the stellar matter. Such information is urgently needed in the areas of stellar structure and evolution. Truly sensitive observational methods of fixing such critical parameters as the mixing length to the pressure scale height l/H or the microturbulence ξ have been missing. But recently Michaud's (1986) explanation for the lithium depletion of the Hyades dwarfs closely constrains the l/H ratio to a value between 1.6 and 1.2

II. THE OBSERVATIONAL DATA

The observations were obtained by C. R. Cowley with 1.2 m telescope of the Dominion Astrophysical Observatory (DAO) using the coudé spectrograph and a 1 × 1872 bare Reticon with 15 μm pixels. The instrumental profile of the spectrograph plus Reticon has a FWHM of 0.09 Å (Rice and Wehlau 1982; Fletcher, Harmer, and Harmer 1980). The 2.4 Å mm^{-1} spectra cover the region λλ4313–4809 in nine intervals each 65 Å wide with an average overlap of 10 Å. At each interval from two to five spectra were obtained, each bracketed by observations of the comparison lamp. The Reticon data were processed using the program RET72 (Hill and Fisher 1986) which allowed division by the lamps, normalization of amplifier gains, and FITS file output.

The program REDUCE (Hill and Adelman 1986; Hill and Fisher 1986) was used to measure the comparison spectra and to linearize and rectify the stellar spectra. The usual line lists for the Fe-Ar and Th-Ne comparisons were augmented to include some 20 lines in each spectral interval. The thorium spectrum of the last interval was identified using Breckinridge, Pierce, and Stroll (1975). The linearized spectra sampled in wavelength steps of 0.02 Å were co-added to further increase the signal-to-noise ratio and then rectified. The program TSTACK (Hill and Fisher 1986) combined all nine intervals co-adding the overlapping sections. The combined spectrum was again rectified with the average signal-to-noise for the continuum regions being 1000 to 1.

III. THE LINE SPECTRUM

The final spectrum was measured using the program VLINE (Hill and Adelman 1986, Hill and Fisher 1986) by the two authors as well as by Louis G. Foley, a student of S. J. A. This enabled a comparison of the results as determined by two experienced users and also by a novice user. The values of A. F. G. were measured by fixing a flat continuum at 1.0 and for very weak lines, fitting pure rotational profiles with a fixed $v \sin i$ of 22.4 km s^{-1}. Those of S. J. A. were measured by setting the continuum locally and without any fixed profile parameters. Lines whose FWHM were not close to the average value were remeasured. Both experienced users tried to resolve blends into their separate components.

A least squares comparison of the unblended equivalent widths in mÅ for the lines in Table 2 (which contains S. J. A.'s values) yields

$$W_\lambda(\mathrm{S.\,J.\,A}) = 0.985(\pm 0.004)W_\lambda(\mathrm{A.\,F.\,G.}) - 0.29(\pm 0.14)$$

and

$$W_\lambda(\mathrm{L.\,G.\,F}) = 1.003(\pm 0.004)W_\lambda(\mathrm{S.\,J.\,A}) + 0.00(\pm 0.00)\,.$$

Hence experienced measurers using slightly different tech-

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niques with the same program obtained essentially identical results, and a novice measurer using the same techniques as an experienced measurer can obtain very similar results.

The primary source of line identifications was Moore (1945) supplemented by Moore (1970) for C I, Huldt *et al.* (1982) for Ti II, Iglesias and Velasco (1964) for Mn II, and Johansson (1978) for Fe II. Line of H I, He I, C I, Mg I, Mg II, Al II, Ca I, Sc II, Ti II, Cr II, Mn I, Mn II, Fe I, Fe II, Ni I, Ni II, and Ba II were found. Lines of most of these species have been previously been identified by other investigators. A comparison of the stellar and laboratory wavelengths of 20 clean Fe I and Fe II lines was used to derive the radial velocity -13.26 ± 0.22 km s^{-1}. This value is similar to most of those listed by Abt and Biggs (1972).

The mean $v \sin i$ of 22.4 km s^{-1} was found by fitting 14 unblended, moderately strong lines in the region λλ4500–4630. This compares with Uesugi and Fukada's (1970) weighted mean value of 17 km s^{-1} and Millard, Pitois, and Praderie's (1977) value of 18 ± 2 km s^{-1}.

Dreiling and Bell (1980) published high-quality equivalent widths of a few Ti II, Fe I, and Fe II lines. Twenty-four, which are unblended, also appear in our spectrum. A least-squares comparison for equivalent widths in mÅ yields

$$W_\lambda(\mathrm{DAO}) = 0.944(\pm 0.044) W_\lambda(\mathrm{DB}) - 3.66(\pm 2.42)\ .$$

The agreement is only fair considering the quality of the data. That the continuum as shown in two figures in Dreiling and Bell (1980) is drawn in higher than where we would accounts for the nonzero constant term. The linear term may reflect the higher resolution of the DAO data. The scatter about the least-squares line is surprisingly large.

Gigas (1986) published Fe I and Fe II equivalent widths measured by Mitton using high-dispersion photographic spectrograms recorded by R. and R. Griffin at Mount Wilson Observatory. A least-squares comparison for 20 equivalent widths in mÅ yields

$$W_\lambda(\mathrm{DAO}) = 0.906(\pm 0.028) W_\lambda(\mathrm{M}) - 1.28(\pm 1.30)\ .$$

Again the agreement is not as good as one might hope considering the data quality. The scatter about the least-squares line is less than for the Dreiling and Bell data. Again there is a small offset in the continuum level. That the linear term is not unity might reflect how the line profiles were drawn or errors in the plate calibration.

IV. STELLAR PARAMETERS

Kurucz (1979) using the energy distribution of Vega determined by Hayes and Latham (1975) and profiles of Hα, Hβ, and Hγ measured by Peterson (1969) found $T_{\mathrm{eff}} = 9400 \pm 200$ K and $\log g = 3.95 \pm 0.05$ for a solar metallicity, He/H = 0.10 by number model. This model's opacity distribution function was constructed using a microturbulence of 2 km s^{-1}. Code *et al.* (1976) found by comparison $T_{\mathrm{eff}} = 9660$ K; Dreiling and Bell (1980), $T_{\mathrm{eff}} = 9650 \pm 200$ K and $\log g = 3.9 \pm 0.2$; Lane and Lester (1982), $T_{\mathrm{eff}} = 9500$ K, $\log g = 3.9$; and Glusheva (1983), $T_{\mathrm{eff}} = 9400$ K, $\log g = 4.0$. As we were using ATLAS model atmospheres (Kurucz 1979) we adopted the compatible model atmosphere. This model is somewhat under–line-blanketed for its assumed metalicity. But Vega is slightly metal poor. Further, the derived microturbulence (see below) is somewhat less than that used in constructing the model. Kurucz (1990) is now constructing models which address these, presumably, minor effects.

Gray and Evans (1973) also observed Hβ and Hγ profiles and found that they agreed well with those of Peterson (1969) who included a correction for the instrumental profile. We independently extracted the Hγ profile from a high signal-to-noise observation of Vega made with the short camera of the 1.2 m coudé spectrograph of the DAO. The agreement with Peterson (1969)'s values is generally better than 1% and often better than 0.5%. We extracted the Hδ profile. Its values agreed with the profile calculated from the adopted model using the program BALMER6 (D. M. Peterson and R. L. Kurucz, private communication) to within 1%.

V. THE HELIUM-TO-HYDROGEN RATIO

Only one He I line λ4472 was definitely identified in the high-dispersion region under study. We calculated line profiles for a variety of He/H ratios with the adopted solar helium model atmosphere using the program OMEGA (H. L. Shipman, private communication; Shipman and Strom 1970). For comparison with the observations the theoretical line profiles were convolved with a pure rotation profile whose $v \sin i$ value corresponded to 23 km s^{-1}. The resulting fit showed that $\mathrm{He/H} = 0.030 \pm 0.005$ for Vega. The error was derived by attempting this fit using different $v \sin i$ values for the rotational profile and different values of He/H for the theoretical profiles.

As the observed He/H ratio was not that assumed in the calculation of the model atmosphere, a correction must be made to the derived surface gravity (see, e.g., Auer *et al.* 1966). Thus $\log g = 4.03$ rather than 3.95. Although this difference is not very large, it might be important as Vega's photometry is often used to determine the correspondence of theoretical grids of models with observed values (see, e.g., VandenBerg and Bell 1985). Comparison of the predicted fluxes of the adopted model and a model with He/H = 0.03, $T_{\mathrm{eff}} = 9400$ K, and log $g = 4.03$ shows a systematic difference of ∼0.01 mag throughout the optical region with individual flux values showing deviations up to 0.01 mag from this mean.

VI. ANALYSIS OF THE METAL LINES

The program WIDTH6 (R. L. Kurucz, private communication) was used to deduce the abundances of metal lines from the measured equivalent widths and adopted model atmosphere. The line damping constants were derived for neutral and singly ionized Ca-Ni lines from Kurucz (1990), the Stark broadening of Mg II λ4481 from Sahal-Brechot (1969), and the remaining line damping constants from semiclassical

TABLE 1

ξ AND log Fe/H DETERMINATIONS

Species	Number of Lines	ξ (km s^{-1})	log Fe/H	*gf*-values	Minimum Scatter ξ (km s^{-1})
Fe I......	19	0.4	-5.02 ± 0.14	MF and KX	0.5
	16	0.6	-5.06 ± 0.13	MF	0.6
Fe II.....	33	0.8	-5.13 ± 0.16	MF and KX	0.8
	23	0.8	-5.14 ± 0.13	MF	0.9
	adopted	0.6	...	...	...

NOTE.—We omitted Fe II λ4583.83 from our analysis. This strong line yields a somewhat large value of the abundance and increases the derived values of ξ by ∼0.5 km s^{-1}. We believe the *gf*-value in Fuhr *et al.* 1988 is not an optimal choice.

TABLE 2

THE ANALYSIS OF THE METAL LINES

mult.	λ(Å)	log gf	Ref.	W_λ(mÅ)	log N/H
C I (log C/H = -3.81±0.09)					
6	4771.72	-1.70	WM	19	-3.81
	4766.62	-2.40	WS	3	-3.96
	4775.87	-2.20	WM	7	-3.78
	4770.00	-2.28	WS	6	-3.77
14	4371.37	-2.08	WM	8	-3.72
Mg I (log Mg/H = -5.07)					
11	4702.99	-0.38	WM	30	-5.07
Mg II (log Mg/H = -5.11±0.05)					
4	4481.23	+0.97	WM	291	-5.05
9	4433.99	-0.90	WS	10	-5.17
	4428.00	-1.20	WS	6	-5.11
10	4390.58	-0.53	WM	24	-5.07
	4384.64	-0.78	WM	14	-5.13
Al II (log Al/H = -6.33)					
2	4663.10	-0.28	WM	4	-6.33
Ca I (log Ca/H = -6.21±0.10)					
4	4454.78	+0.25	WS	16	-6.08
	4434.96	-0.03	WS	6	-6.29
	4425.44	-0.35	WM	4	-6.17
5	4318.65	-0.21	WS	4	-6.29
Sc II (log Sc/H = -9.62±0.04)					
14	4374.46	-0.44	MF	13	-9.54
	4400.36	-0.51	WF	10	-9.61
	4415.56	-0.64	WF	7	-9.66
15	4314.08	-0.10	MF	20	-9.64
	4320.74	-0.26	MF	15	-9.65
	4325.01	-0.44	MF	11	-9.63
Ti II (log Ti/H = -7.47±0.22)					
17	4798.53	-2.43	MF	2	-7.85
18	4518.33	-2.55	KX	2	-7.72
19	4395.03	-0.66	MF	69	-7.22
	4443.80	-0.70	MF	61	-7.43
	4450.49	-1.45	MF	21	-7.67
20	4344.30	-2.09	MF	5	-7.76
30	4545.14	-2.78	KX	3	-7.28
31	4468.49	-0.60	MF	63	-7.44
	4501.27	-0.75	MF	56	-7.49
40	4470.86	-2.28	MF	6	-7.43
40	4417.72	-1.43	MF	28	-7.45
	4464.46	-2.08	MF	10	-7.39
41	4330.71	-2.04	MF	4	-7.85
	4320.96	-1.87	MF	8	-7.70
50	4563.76	-0.96	MF	52	-7.32
51	4399.77	-1.27	MF	31	-7.49
	4394.06	-1.59	MF	10	-7.84
	4418.34	-2.40	MF	7	-7.19
60	4544.02	-2.40	MF	2	-7.77
61	4395.83	-2.17	MF	7	-7.42
	4409.24	-2.29	KX	3	-7.69
82	4571.97	-0.53	MF	69	-7.06
	4529.46	-2.03	MF	9	-7.24
92	4805.10	-1.10	MF	21	-7.42
	4779.98	-1.37	MF	11	-7.51
93	4421.95	-1.77	MF	5	-7.47
94	4316.81	-1.65	MF	5	-7.59
104	4367.65	-1.27	MF	12	-7.22
	4386.86	-1.26	MF	8	-7.43
115	4488.32	-0.82	MF	13	-7.31
	4411.08	-1.06	MF	9	-7.27
	4456.63	-1.66	KX	3	-7.17
Cr II (log Cr/H = -6.76±0.19)					
44	4558.66	-0.66	MF	56	-6.48
	4588.22	-0.63	MF	43	-6.84
	4618.82	-1.11	MF	33	-6.60
	4634.10	-1.24	MF	26	-6.65
	4555.02	-1.38	MF	16	-6.81
	4592.09	-1.22	MF	17	-6.94
	4616.64	-1.29	MF	14	-6.98
Mn I (log Mn/H = -7.16)					
16	4783.42	+0.04	MF	2	-7.16
Mn II (log Mn/H = -7.20)					
-	4755.73	-1.24	KX	2	-7.25
	4764.73	-1.35	KX	2	-7.14
Fe I (log Fe/H = -5.05±0.14)					
2	4375.93	-3.03	MF	2	-5.07
	4427.31	-2.91	KX	3	-4.97
39	4531.15	-2.16	MF	2	-5.02
41	4383.54	+0.20	MF	64	-4.99
	4404.75	-0.14	MF	51	-5.09
	4415.12	-0.62	MF	28	-5.12
42	4325.76	-0.01	MF	47	-5.22
68	4528.62	-0.82	MF	13	-5.04
	4494.57	-1.14	MF	6	-5.11
	4459.12	-1.28	MF	9	-4.77
	4447.72	-1.34	MF	4	-5.07
350	4466.55	-0.59	MF	9	-5.06
	4476.02	-0.73	KX	8	-4.98
409	4647.44	-1.31	MF	2	-4.97
518	4369.77	-0.73	MF	3	-5.31
554	4736.78	-0.74	MF	3	-5.20
821	4678.85	-0.66	MF	5	-4.81
826	4525.14	-0.95	KX	3	-4.75
830	4388.41	-0.59	MF	3	-5.11
Fe II (log Fe/H = -5.12±0.14)					
25	4670.17	-4.10	MF	6	-4.88
26	4580.06	-3.65	KX	5	-5.42
	4461.43	-4.20	KX	3	-5.10
27	4351.76	-2.10	MF	59	-5.14
	4416.82	-2.60	MF	41	-5.08
	4385.38	-2.57	MF	39	-5.16
28	4369.40	-3.67	MF	7	-5.12
32	4384.33	-3.50	MF	8	-5.30
	4314.29	-3.60	KX	9	-5.13
	4413.60	-3.87	MF	3	-5.38
37	4629.34	-2.37	MF	51	-5.04
	4555.89	-2.29	MF	53	-5.03
	4515.34	-2.48	MF	44	-5.08
	4491.40	-2.70	MF	32	-5.16
	4520.22	-2.60	MF	41	-5.06
	4489.18	-2.97	MF	25	-5.08
	4472.92	-3.43	MF	9	-5.20
	4666.75	-3.33	MF	13	-5.12
	4582.84	-3.10	MF	12	-5.38
38	4522.63	-2.03	MF	61	-5.06
	4508.28	-2.21	MF	51	-5.17
	4620.51	-3.28	MF	12	-5.21
	4576.33	-3.04	MF	21	-5.12
	4541.52	-3.05	MF	23	-5.05
43	4731.44	-3.36	MF	18	-4.87
44	4663.70	-4.28	KX	4	-4.70
186	4635.33	-1.65	MF	14	-4.91
222	4493.58	-1.44	KX	2	-5.01
-	4357.57	-2.10	KX	2	-5.36
	4361.25	-2.08	KX	2	-5.35
	4451.54	-1.82	KX	7	-5.02
	4579.52	-2.36	KX	3	-4.82
	4596.02	-1.82	KX	5	-5.12
Ni I (log Ni/H = -6.38±0.24)					
98	4714.42	+0.23	MF	2	-6.66
	4648.66	-0.16	MF	2	-6.25
	4786.53	-0.17	MF	2	-6.24
Ni II (log Ni/H = -6.29)					
9	4362.10	-0.24	KX	3	-6.29
Ba II (log Ba/H = -10.58)					
1	4554.03	+0.16	WM	9	-10.58

REFERENCES: KX = Kurucz 1989, MF = Martin, Fuhr, and Wiese 1988 and Fuhr, Martin, and Wiese 1988. WF = Wiese and Fuhr 1975, WM = Wiese and Martin 1980, WS = Wiese, Smith and Glennon 1966 and Wiese, Smith, and Miles 1969.

approximations in WIDTH6. Abundances were calculated from Fe I and Fe II lines for a range of possible values to determine the microturbulent velocity. Table 1 lists values for Fe I and for Fe II for which there is no dependence of the abundances on the equivalent widths using *gf*-values only from Fuhr, Martin, and Wiese (1988) and from this source as supplemented by *gf*-values from Kurucz (1990). Thus we can compare results using only the best critically compiled *gf*-values with those derived using these values supplemented by apparently compatible values (see Adelman and Fuhr 1985). The adopted value for the microturbulence of 0.6 km s^{-1} is the mean of all the Fe I and Fe II values. Also given are the values determined by minimizing the rms scatter of the abundances (see, e.g., Blackwell, Shallis, and Simmons 1982). The Fe I lines systematically give smaller values of microturbulence for both methods. Both methods yield quite similar answers for the same atomic species.

Ti II is the only other atomic species with more than 10 analyzable lines in the region studied. For there to be no dependence of the derived abundance on the size of the equivalent widths requires a microturbulence of 1.4 km s^{-1}. Minimizing the rms scatter of the abundances yields 1.3 km s^{-1}. It is desirable to obtain additional high-quality measurements of Fe I and Fe II lines as well as to obtain a sufficient number of other atomic species to both confirm and reconcile these values. For most of the lines analyzed changing the microturbulence by 0.3 km s^{-1} or so will not make a significant difference in the derived abundances.

Our value of the microtubulence is less than the 2.5 km s^{-1} value of Dreiling and Bell (1980) and the 2.0 km s^{-1} value of Sadakane and Nishimura (1981). A similar reduction in the derived microturbulence has been found by comparing recent studies of normal and peculiar B and A stars, which use 2.4 Å mm^{-1} DAO spectra and similar analysis procedures, with older studies in the literature. It is due both to the removal of systematic errors in the *gf*-values and in the equivalent widths. Further Gigas (1986) found values typically twice ours in the visible. Fe I lines yielded smaller values of the microturbulence than did Fe II and Ti II lines. The adopted value of ξ is less than that of the early A type stars *o* Peg and θ Leo (Adelman 1988*a*), but greater than that of α Dra (Adelman *et al.* 1987) which have similar temperatures. The spectra used in these analyses have much smaller signal-to-noise ratios than that for Vega.

Table 2 contains the LTE analyses of the metal lines. For each line, we list the multiplet number (Moore 1945), the laboratory wavelength in Å; the logarithm of the *gf*-value and its source; the equivalent width in mÅ, and the deduced abundance. The scatter of the individual abundances about the mean are given for each atomic species, when appropriate.

As there are still some small uncertainties concerning the effective temperature and surface gravity of Vega, Table 3 presents results of analyses using a model 100 K hotter than and a model with a surface gravity 0.1 dex larger than the adopted model. The agreement between abundances derived from different species of the same element tends to be improved either if the surface gravity or the temperature is slightly increased.

VII. COMPARISON OF PREVIOUS STUDIES

Dreiling and Bell (1980) found log Ti/H = −7.3 and log Fe/H = −4.9 from Ti II and Fe II, respectively, results, which are both 0.15 dex larger than the values derived in this paper. Table 4 compares the results of this study with that of Sadakane and Nishimura (1981) and the Sun (Anders and Grevesse 1989). Our study makes Vega slightly more metal poor than did Sadakane and Nishimura. The differences are due mostly to the better quality data we obtained.

TABLE 3

ABUNDANCES OF VEGA WITH DIFFERENT MODEL ATMOSPHERES

Atomic Species	log N/H Model A	Model B	Model C
He I	-1.52	-1.52	-1.52
C I	-3.81	-3.77	-3.84
Mg I	-5.07	-5.00	-5.10
Mg II	-5.11	-5.10	-5.11
Al II	-6.33	-6.36	-6.31
Ca I	-6.21	-6.12	-6.26
Sc II	-9.62	-9.57	-9.62
Ti II	-7.47	-7.43	-7.46
Cr II	-6.76	-6.74	-6.75
Mn I	-7.16	-7.09	-7.19
Mn II	-7.20	-7.17	-7.19
Fe I	-5.05	-4.97	-5.07
Fe II	-5.12	-5.09	-5.09
Ni I	-6.38	-6.32	-6.42
Ni II	-6.29	-6.27	-6.27
Ba II	-10.58	-10.49	-10.59

Model A: adopted model.
Model B: model with $T_{\rm eff}$ increased by 100 K.
Model C: model with log g increased by 0.1 dex.

Lambert, Roby, and Bell (1982) derived the carbon abundance of Vega (log C/H = −3.43) from C I lines. They used the model of Dreiling and Bell and a microturbulence of 2.0 km s^{-1}. For four lines of multiplet 6, they derived −3.57 compared to our value of −3.83. For this multiplet, the equivalent widths and oscillator strengths are similar for both studies.

Gigas (1986) performed a non–LTE study of Fe I and Fe II lines in Vega. Relative to the Sun he found [Fe/H] = −0.55 dex compared to our value of −0.74 dex. Part of the difference is due to his corrections for non–LTE effects especially for Fe I and to the use of slightly different *gf*-values. Somewhat disturbing is that his corrections of the LTE abundances for

TABLE 4

COMPARISON WITH VALUES FROM SADAKANE AND NISHIMURA (1981) AND THE SUN

Atomic Species	Vega log N/H AG	Vega log N/H SN	Vega [N/H] AG	Sun log N/H
He I	-1.52	...	-0.51	-1.01
C I	-3.81	...	-0.37	-3.44
Mg I	-5.07	-4.61	-0.75	-4.32
Mg II	-5.11	-4.96	-0.79	-4.32
Al I	...	-6.50	...	-5.53
Al II	-6.33	...	-0.80	-5.53
Ca I	-6.21	-6.11	-0.57	-5.64
Sc II	-9.62	-9.42	-0.72	-8.90
Ti II	-7.47	-7.31	-0.46	-7.01
Cr II	-6.76	-6.90	-0.44	-6.32
Mn I	-7.16	-6.87	-0.55	-6.61
Mn II	-7.20	-6.81	-0.59	-6.61
Fe I	-5.05	-5.09	-0.72	-4.33
Fe II	-5.12	-5.09	-0.79	-4.33
Ni I	-6.38	-5.94	-0.63	-5.75
Ni II	-6.29	-6.31	-0.54	-5.75
Ba II	-10.58	-10.25	-0.71	-9.87

TABLE 5

COMPARISON OF DERIVED AND SOLAR ABUNDANCES

Species	α Dra log N/H	o Peg log N/H	Vega log N/H	θ Leo log N/H	Sun log N/H
He I	-1.40	-1.26	-1.52	-1.22	-1.01
C II/I	-3.78	-4.40	-3.81	...	-3.34
Mg I	-4.75	-4.49	-5.07	-4.53	-4.42
Mg II	-4.82	-4.54	-5.11	-4.66	-4.42
Al I/II	-6.11	-5.58	-6.63	-6.03	-5.53
Ca I	-6.16	-5.61	-6.21	-5.76	-5.64
Sc II	-9.81	-9.30	-9.62	-9.27	-8.90
Ti II	-7.28	-6.86	-7.47	-6.95	-7.01
Cr II	-6.65	-6.17	-6.76	-6.32	-6.33
Mn I	-6.73	-6.42	-7.16	-6.70	-6.61
Mn II	...	-6.22	-7.20	-6.31	-6.61
Fe I	-4.91	-4.32	-5.05	-4.52	-4.33
Fe II	-4.93	-4.35	-5.12	-4.43	-4.33
Ni I	...	-5.31	-6.38	-5.35	-5.75
Ni II	-5.92	-5.00	-6.29	-5.34	-5.75
Ba II	>-10.05	>-8.49	-10.58	>-8.98	-9.87
Teff	10075	9600	9400	9250	
log g	3.30	3.60	4.03	3.55	
ξ (km/s)	0.4	1.8	0.6	1.7	

non–LTE effects increase rather than decrease the agreement of the results found separately from Fe I and Fe II lines. His LTE values are quite close to ours: −5.08 versus −5.05 for Fe I and −4.99 versus −5.12 for Fe II.

VIII. DISCUSSION

Comparison of the solar abundances with those of Vega show that Vega is a metal-poor star with a mean underabundance for 12 elements of 0.60 ± 0.14 dex, which is a factor of 4 less than solar. This result is consistent with the previous studies by Sadakane and Nishimura (1981) and Sadakane, Nishimura, and Hirata (1986) who derived abundances from atomic species of other elements which do not have observable lines in the region under study.

Vega is not the only early A star known to show underabundances of metals. The A0 III star α Dra, the A1 IV star *o* Peg, and the A2 V star *θ* Leo, which were analyzed using photographic spectrum in a manner similar to this analysis, also show some of the same tendencies. Table 5 shows those abundance values for species in common to these analyses (Adelman 1988*b* plus a revision of values from Adelman *et al.* 1987 made consistent with these analyses). Note due to the adoption of some Sc II and Cr II *gf*-values from Martin, Fuhr, and Wiese (1988) not used in previous analyses there are of order 0.05 dex differences in the resultant abundances. Vega is the most metal poor of these stars, with anomalies on average slightly more extreme than those of α Dra.

The calculations of Carbonneau and Michaud (1988) indicate that the superficial helium convection zone disappears when the helium abundance is reduced to 40% of its initial, presumably solar, value. After this time radiative diffusion will rapidly produce substantial abundance anomalies. This appears to have happened in the photosphere of Vega and to a slightly lesser extent in that of α Dra. As Vega is a fundamental standard whose parameters are far better known than most other stars, its study should provide a critical and crucial confrontation between observed values and the predictions of the radiative diffusion mechanism.

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