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THE FIELD HORIZONTAL-BRANCH STAR HD 109995: NEW RESULTS WITH COADDED ULTRAVIOLET AND OPTICAL REGION SPECTRA

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ABSTRACT. A comprehensive ultraviolet and optical region abundance analysis of the field horizontal branch Population II A-type star HD 109995 is described. Coaddition of IUE high dispersion images and DAO 6.5 Å/mm IIaO spectrograms improved the signal-to-noise ratio of the data. We have identified ultraviolet lines whose analysis will provide more complete and accurate elemental abundances than those obtained from optical region spectra alone. A preliminary elemental abundance analysis of the optical region shows that log $Z/Z_\odot \simeq -2$. A first attempt to synthesize two Fe II ultraviolet resonance lines yields an iron abundance a few tenths of a dex higher than the average obtained from optical region Fe II lines.

1. INTRODUCTION

HD 109995 is one of the prototype field horizontal-branch Population II A-type stars. From a study of low dispersion IUE exposures, Bohm-Vitense (1980) found its mass is about 0.5 $M_\odot$ and its temperature 8100 K, with these values somewhat dependent on the exact metallicity. Abundance analyses (e.g., Wallerstein and Hunziker 1964, Kodaira et al. 1969, Kodaira 1973) show it is metal-poor (log $Z/Z_\odot \simeq -1.5$) with the anomalies generally increasing with atomic number. In the optical only lines of Na I, Mg I, Mg II, Al I, Si I, Si II, Ca I,

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Ca II, Sc II, Ti II, V II, Cr I, Cr II, Mn I, Fe I, Fe II, Sr II, Y II, and Ba II have been studied. But the derived abundances except for those from Ti II, Fe I, and Fe II lines, depend on at most two lines per atomic species.

To improve our knowledge of the abundances of HD 109995, we have undertaken the first high dispersion ultraviolet analysis with IUE satellite data of a Population II field horizontal-branch A star and a new photographic region analysis. Further Adelman with D. S. Hayes and A. G. Davis Philip have observed C I, N I, and O I lines in the infrared with CCD detectors in the coude spectrograph of Kitt Peak National Observatory. The O I triplet λλ7772-7775 is definitely present. From these observations C, N, and O abundances (or upper limits) will be derived consistent with our forthcoming ultraviolet and optical study. An earlier study by Kodaira and Tanaka (1972) found that C and O are at least deficient by a factor of ten.

2. ULTRAVIOLET LINE IDENTIFICATIONS

We have obtained eight SWP and six LWP high dispersion IUE images of HD 109995. Two exposure times were used with each camera to increase the region of good exposure. The images for each camera were added as described by Adelman and Leckrone (1985) to increase the signal-to-noise ratio.

Longward of λ1500, the ultraviolet energy distribution of HD 109995 is fairly flat in F_λ. But shortward of this wavelength it rapidly decreases in brightness. As the sensitivity of the IUE camera-detector combinations increase towards the longward portions of their spectral ranges, the primary regions for our line identification study are λλ1400-2100 and λλ2450-3050. Some, especially strong lines can be distinguished from noise shortward of these regions.

In the ultraviolet, the line density is much greater than the optical region. But it is not as great as nor are the lines as strong as those in θ Leo (A2V), the coolest Population I star for which we have coadded many IUE high dispersion spectra. Figures 1 through 3 show selected regions of the uv spectrum. Figure 1 shows λλ2590-2602 where there are strong Fe II lines, Figure 2 λλ1740-1750 with two strong N I lines, and Figure 3 λλ1655-1660 with C I multiplet 2.

Our primary atomic line identification sources were The Ultraviolet Multiplet Table (Moore 1950, 1952, 1962), the finding list for Moore's newer multiplet tables (Adelman et al. 1985), A Multiplet Tables of Astrophysical Interest (Moore 1945) for longward of λ3000, NSRDS-NBS 68, part I (Reader and Corliss 1980), and studies of particular atomic species: Ti II (Huldt et al. 1982), Cr II (Johansson, private communication), and Fe II (Johansson 1978). There are still many lines without good identifications. The majority of identified lines are those of Fe II. The following atomic species have lines which

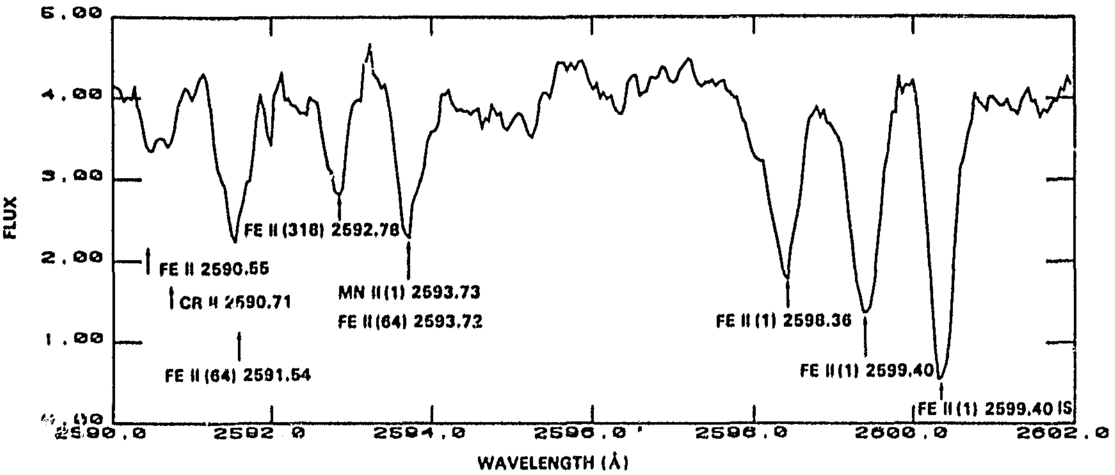

Fig. 1. The λλ2590-2602 region of HD 109995. The strongest identified lines are those of Fe II. The interstellar (IS) component of Fe II (1) 2599.40 is shifted longward by 1.14 Å as the stellar radial velocity is -132 km s^{-1}. This spectrum is the coaddition of three LWP images.

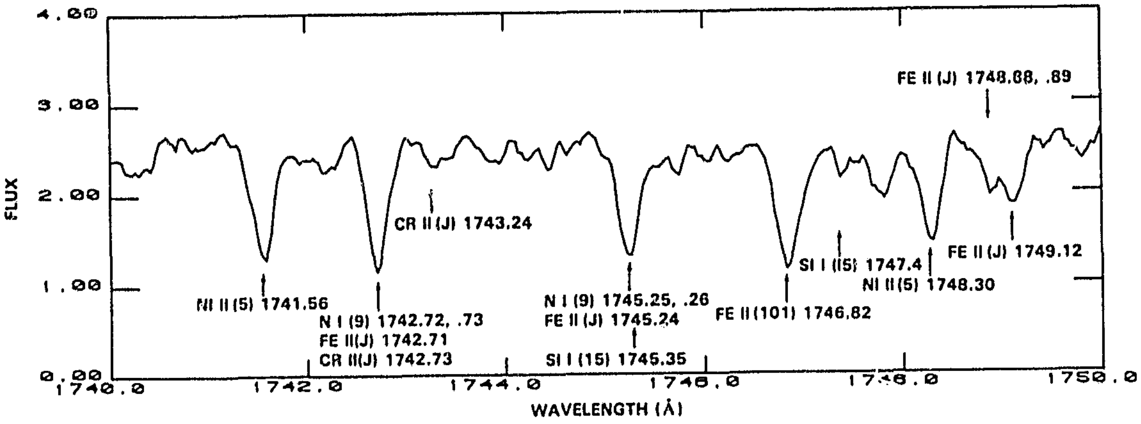

Fig. 2. The λλ1740-1750 region of HD 109995. The two lines of N I multiplet 9 are blended with weaker lines of other elements. To deduce the nitrogen abundance, the abundances of these other elements must also be determined. Also seen are two lines of Ni II multiplet 5. The Fe II lines with a J for their multiplet numbers are from Johansson (1978). This spectra is the coaddition of five SWP images.

we are certain are present in our IUE spectra: C I, C II, N I, O I, Mg I, Mg II, Al II, Al III, Si I, Si II, P II, S I, Cl I, Ti II, V II, Cr II, Mn II, Fe I, Fe II, Co II, Ni II, Zn II, and Ge II. We expect both to improve the accuracy of abundances based on only a few optical lines and to derive abundances of additional elements. For a few atomic species, comparison of resonance lines and those arising from higher lying lower levels, might yield information on possible non-LTE effects.

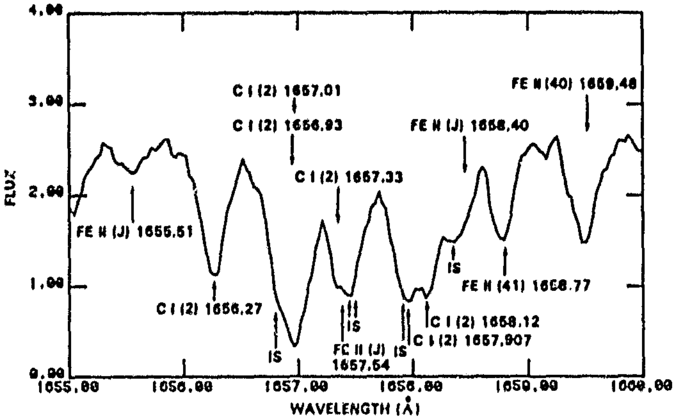

Fig. 3. The λλ1655-1660 region of HD 109995. The lines of C I multiplet 2 and Fe II lines are identified. The positions of the interstellar (IS) components of the C I lines are indicated.

3. OPTICAL REGION SPECTRA

There are considerable uncertainties in the published equivalent widths of the metal lines of HD 109995 in the literature (e.g., Wallerstein and Hunziker 1964 vs. Kodaira et al. 1969). To resolve these differences and to produce an improved set of equivalent widths, 15 6.5 Å/mm IIaO spectrograms of HD 109995 were obtained at the Dominion Astrophysical Observatory in March 1985. Using the procedures discussed in Hill and Adelman (1985), they were added together to increase the signal-to-noise ratio. The S/N of the coadded spectrum is estimated conservatively to be 30. The equivalent widths were measured by fitting Gaussian profiles through the metal lines. The radial velocity of −132 km s^{-1} is the same as that of Kodaira et al. (1969). However, we find v sin i = 17 ± 1 km s^{-1} compared with 27 km s^{-1} found by Peterson et al. (1983). The IUE data are consistent with the former, but not the latter value.

The optical lines were identified primarily by use of A Multiplet Table of Astrophysical Interest (Moore 1945). Certain weak lines included in previous studies were not positively identified, in particular the V II and Ba II lines identified by Wallerstein and Hunziker (1964) and the Mn I, Y II, and Ba II lines identified by Kodaira et al. (1969). The equivalent widths of the former authors (WH) tend to be smaller than those of this study while those of the latter authors (KGO) tend to be larger. This study's values are close to the average of these two previous studies. The least squares relations for W_λ in mÅ are as follows:

$$W_\lambda(\mathrm{DAO}) = 1.25\, W_\lambda(\mathrm{WH}) + 2.73$$

and

$$W_\lambda(\mathrm{DAO}) = 0.81\, W_\lambda(\mathrm{KGO}) - 6.08.$$

The Hγ profile published by Kodaira et al. (1969) is in good agreement with that derived from the coadded DAO spectrograms. The line shoulders are well-matched with the coadded Hγ profile being slightly shallower in the core and deeper in the wings. The latter is an effect of a better signal-to-noise ratio.

4. CHOICE OF MODEL AND PRELIMINARY RESULTS

The criteria to be used in the selection of a final model atmosphere for HD 109995 are the match of the model's predictions with the ultraviolet and optical region fluxes, especially the Balmer jump region, and Hγ profile; equal abundances from Fe I and Fe II lines; and the model having the same metallicty as the star. Bohm-Vitense (1980) showed that the ultraviolet fluxes would be reasonably fit by an 8000 K, log g = 3.0 model with log $Z/Z_\odot$ = -1.5.

For an intial estimate of the iron abundance and microtubulent velocity, we selected 8000 K and 8500 K, log g = 3.0 and 3.5 models with log $Z/Z_\odot$ = -1 and -2 from Kurucz (1979). The Fe I and Fe II gf-values are from the critical compilation by Martin, Fuhr, and Wiese (1986). The Fe II damping constants were calculated from the sums given by Kurucz (1981) and those for Fe I are semi-classical approximations. Microturbulent velocities are found by requiring that there be no dependence of the deduced Fe abundance on equivalent width. Both optical and ultraviolet lines indicated that [Fe/H] ≈ -2 in accord with the results of Kodaira (1973).

Comparison of the predictions of log $Z/Z_\odot$ = -1.5 and -2.0 model atmospheres calculated with the ATLAS6 code (Kurucz 1979) with optical spectrophotometry over λλ3400-6790 of Philip and Hayes (1983) indicates 8250 K, log g = 3.40. However, the predicted fluxes do not agree well with those derived from IUE low dispersion exposures. The uv fluxes and Hγ profile suggest a cooler effective temperature of order 300 K. The log $Z/Z_\odot$ = -1.5 model fluxes agree slightly better with the uv fluxes than those of the log $Z/Z_\odot$ = -2.0 model. This indicates that the model atmospheres are underblanketed compared to the star.

As the log $Z/Z_\odot$ = -1.5 and - 2.0 model atmospheres which fit the optical fluxes are very similar, we decided to use our log $Z/Z_\odot$ = -2.0 model for the abundance analysis. A microturbulence of 1.4 ± 0.1 km s^{-1} was found from analysis of the Fe I and Fe II lines. In Table I we give the values of log N/H and [N/H] = log N/H - $(\log N/H)_\odot$ for HD 109995, the values of log N/H for the Sun, and the average log N/H for ten Population I B and A stars analyzed with the same gf values (Adelman 1985). The differences between the Ca I and Ca II and the Cr I and Cr II results are also seen in the Population I stars. The latter difference may well be due to the poor quality of the Cr II gf-values. The abundance anomalies for the most part agree quite well with those of Kodaira (1973) who found HD 109995 more metal-poor than most other researchers. The major differences are that both calcium and chromium are more deficient in the present analysis despite the differences between the neutral and singly-ionized line results.

Table I: Comparison of Abundances

Atomic Species	HD 109995		Sun	Pop I Stars
	log N/H	[N/H]	log N/H	log N/H
Mg I	-5.90	-1.52	-4.38	-4.23
Mg II	-5.44	-0.96	-4.38	-4.29
Al I	-8.00	-2.49	-5.51	-5.81
Si II	-5.84	-1.47	-4.37	-4.40
Ca I	-7.48	-1.82	-5.66	-5.71
Ca II	-7.74	-2.18	-5.66	-5.96
Sc II	-10.87	-1.91	-8.96	-9.16
Ti II	-8.32	-1.30	-7.02	-6.97
Cr I	-8.44	-2.56	-5.88	-6.05
Cr II	-7.57	-1.69	-5.88	-5.78
Fe I	-6.51	-2.14	-4.37	-4.30
Fe II	-6.24	-1.87	-4.37	-4.37
Sr II	-11.66	-2.46	-9.10	-8.88

5. ULTRAVIOLET LINE SYNTHESIS

We have undertaken fully self-consistent abundance analyses of nine stars, including HD 109995, six normal late B and early A-type dwarfs, and two Bp HgMn stars, which are based on the combination of high signal-to-noise optical region and IUE spectra. The rationale and methodology are briefly described in Leckrone and Adelman (1985). The techniques and problems associated with the detailed synthesis of the complex line blends found in IUE sectra are discussed in Leckrone (1984). Our initial efforts have focused on the synthesis of two resonance features of Fe II, λ2607.09 and λ2625.7. The log gf values of these lines are particularly well known (to about 10%). Moreover, since the optical region spectrum of iron is rich and well understood, we can immediately establish whether the IUE data yield quantitative abundances consistent with ground-based observations. Preliminary results for the normal stars indicate agreement between λ2607 and the average optical iron abundance to within about ± 0.1 dex, while λ2626 typically yields values higher than the optical average by about 0.25 dex. Since abundances derived from optical region spectra alone are usually uncertain by at best 0.2 dex, the agreement between IUE and optical region data can be viewed as reasonably good, giving confidence that the rich ultraviolet spectra will yield reliable and unique abundance information.

Figure 4 illustrates the preliminary synthesis of Fe II λ2607 in HD 109995. The calculations utilized the model atmosphere, micro-

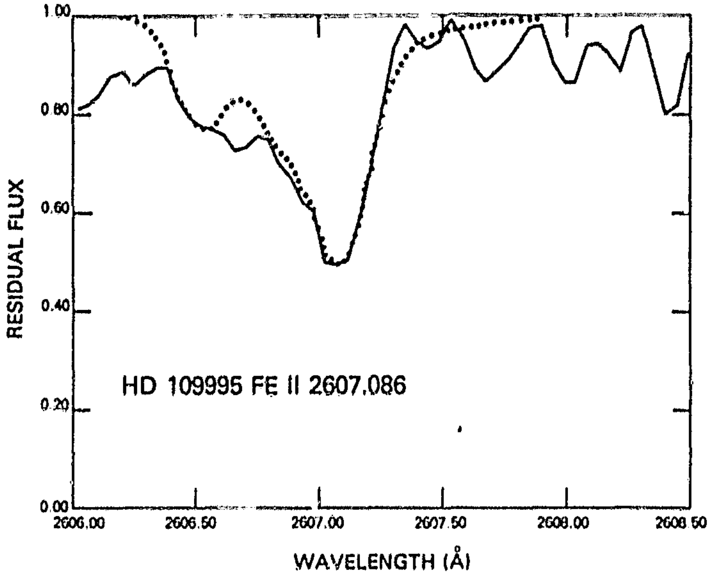

Fig. 4. The profile of the ultraviolet resonance line of Fe II at λ2607.09 in HD 109995. The solid curve portrays the observations, while the dotted curve represents the computed profile with log Fe/H = − 6.0. The computations include approximately 55 relatively weak contaminant blending lines, but is dominated by λ2607.

turbulent velocity and rotation described in Sections 3 and 4. Abundances of contaminant blending species (principally Ti, V, Cr, Mn, and Co) were either adopted from Kodaira (1973) or were taken as 2 dex below solar. The observational data is based on a coadditon of only 3 of our 6 LWP high dispersion images. When we incorporate our recently obtained data, the signal-to-noise ratio of the observations will be somewhat improved. The best fit to λ2607 was obtained with log Fe/H = −6.0, while log Fe/H = −5.6 was obtained for λ2626. These are somewhat higher than the average value, − 6.2, obtained from optical Fe II lines. No great signficance should yet be attached to these differences, however, pending further refinement of the model atmosphere, development of the final coadded IUE spectra, and analysis of many more ultraviolet lines.

It is important to note that the problems of signal-to-noise and the resolution of blends which make analyses of the IUE spectra very difficult will be greatly ameliorated by the Hubble Space Telescope High Resolution Spectrograph. It is only with the latter instrument that moderately weak ultaviolet lines will be observed with sufficient accuracy to allow their reliable analysis.

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