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THREE FAMILIES OF DIFFUSE INTERSTELLAR BANDS?

J KRELOWSKI[1, 2] AND G. A. H. WALKER[2]
Geophysics and Astronomy Department, University of British Columbia
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ABSTRACT

The star ζ Persei is at high Galactic latitude ($b = +16°$). The interstellar extinction is probably caused by a single cloud which has unusual relative strengths of the diffuse interstellar bands (DIBs). The intensities of 10 of the yellow/red and the 4430 Å DIBs and the broad 2200 Å interstellar feature are compared with those for three other stars using high signal-to-noise ratio (~ 300) spectra of either 1.1 Å or 0.15 Å resolution. The DIBs in ζ Persei appear to fall into three well-defined groups: (1) 4430 and 6180 Å are absent; (2) 5780, 6196, 6203, 6269, and 6284 Å are about one-third the strength expected for the color excess; and (3) the 2200 Å feature and the 5797, 5850, 6376, 6379, and 6614 Å are of approximately normal strength for the color excess. This suggests that the DIBs may be caused by at least three agents where proportions vary from cloud to cloud. It is noted that other stars with markedly anomalous DIB intensities also tend to lie at high galactic latitude ($b > 15°$).

Subject headings: interstellar: abundances — interstellar: matter

I. INTRODUCTION

The diffuse interstellar bands (DIBs) were first shown to be interstellar by Merrill (1934) and by Merrill *et al.* (1937) and, despite being the object of considerable research ever since, their origin is still unknown. That they are interstellar has been demonstrated by many authors from the obvious correlation of the band intensities with color excess. In some cases it was known that the intensities of the various bands correlate even better with each other than with color excess, which suggested a common origin (Deeming and Walker 1967).

Herbig (1975) has listed 39 DIBs between 4400 and 6700 Å, and he measured their equivalent widths and central intensities in the photographic spectra of 57 early-type stars. Herbig and Soderblom (1982) demonstrated that the sharp DIB at 6196 Å and possibly that at 6614 Å showed several components in certain directions where Galactic rotation introduced differences in radial velocity between the intervening interstellar clouds.

In the course of a recent, extensive study we noticed that certain DIBs in the spectrum of the lightly reddened star ζ Persei [HD 24398, $E(B-V) = 0.29$] show unusual relative intensities, reminiscent of stars such as ζ Ophiuchi ($b = 23°$; Westerlund and Krelowski 1986) θ^1 Orionis ($b = -18°$), and HD 200775 ($b = 14°$; Walker *et al.* 1980), all of which lie at high Galactic latitude. If the cloud were circumstellar, the grains would be subject to the effects of the high UV flux from the star. However in the case of ζ Persei it is likely that the effect is more typical of interstellar clouds at high Galactic latitude. ζ Persei is a member of the Per OB 2 association and lies more than 100 pc above the Galactic plane.

Access to high signal-to-noise ratio Reticon spectra and the apparently anomalous DIB intensity ratios in a single high-latitude interstellar cloud offers the opportunity of recognizing different families of lines. Only the profiles from single clouds can be readily compared with theoretical or laboratory results. Presumably, the DIB intensities in more heavily reddened stars in the Galactic plane correspond to the cumulative absorption from several intervening clouds and would not be expected to show such marked anomalies.

[1] On leave from N. Copernicus University, Toruń, Poland.

[2] Guest Observer, Dominion Astrophysical Observatory, which is operated by the Herzberg Institute of Astrophysics.

II. OBSERVATIONS

The program stars are listed in Table 1 together with relevant photometry, Galactic coordinates, and spectroscopic parallaxes. They are all B1–2.5 supergiants, except HD 40111, which is of luminosity class II. Two have $E(B-V)$ values similar to that of ζ Persei, while HD 40111, with one-half the color excess, has many DIBs of similar strength to the family of intermediate-strength DIBs (as described below) in ζ Persei. HD 91316 was a convenient unreddened standard. The color excesses are derived from the values of $B-V$ given in the *Bright Star Catalogue* (Hoffleit and Jaschek 1982) and the intrinsic colors given by Flower (1977). Of the reddened stars, ζ Persei is the only one not in the Galactic plane and it is only about one-third the distance of the others, which could also account for the sodium D lines being only about one-third the strength expected for the value of color excess.

The red/yellow spectra were all obtained in 1986 January and February with refrigerated 1872F/30 Reticon detectors built at the University of British Columbia (Walker, Johnson, and Yang 1985). The spectra at 4430 Å were obtained earlier with the UBC 0.4 m telescope for another program. The telescopes and reciprocal dispersions used for each spectral region are given in Table 2. The diode spacing is 15 μm, which corresponds to 0.15 Å and 1.1 Å for the 10 Å mm^{-1} and 76 Å mm^{-1} respectively. The average signal-to-noise ratio per point of the recorded spectrum before smoothing is also given.

Only single spectra were obtained, except for the yellow spectral region for ζ Persei, where two spectra were available. The red spectra of the unreddened standard HD 91316 are of lower signal-to-noise ratio than the others because of weather conditions.

The observations were calibrated and reduced as described in detail by Walker, Johnson, and Yang (1985) using a modified RETICENT software package (Pritchet, Mochnacki, and Yang 1982). All the spectra were restored to a constant baseline by subtracting averaged, short, dark exposures. Zero-point drift was corrected by recording input-shorted values with

TABLE 1

THE PROGRAM STARS

Identification	Name	HD	Spectral Type[a]	$B-V$[a]	$E(B-V)$[b]	l	b	d (pc)
A	ρ Leo	91316	B1 Ib	−0.14	0.03	234°54′	+52°48′	770
B	139 Tau	40111	B0.5 II	−0.06	0.16	183 58	+0 49	1100
C	ζ Per	24398	B1 Ib	+0.12	0.29	162 17	−16 42	400
D	κ Cas	2905	B1 Iae	+0.14	0.31	120 50	+0 08	1100
E	3 Gem	42087	B2.5 Ibe	+0.21	0.34	187 45	+1 46	1500
F	χ^2 Ori	41117	B2 Iave	+0.28	0.42	189 42	−0 54	1500

[a] From Hoffleit and Jaschek 1982.
[b] From Flower 1977.

each exposure. Spectra from an incandescent lamp which illuminated the telescope pupil were used to remove diode-to-diode variations in sensitivity. Four-, and sometimes eight-, point normalizations were used to eliminate the differential effects of amplifier gains between the four video lines. All the spectra were transformed to a uniform wavelength scale after correction for Earth's motion. Continua were fitted to short sections of each spectrum, at the same wavelengths and by polynomials of up to order 6. The order of polynomial was usually the same for all the stars in a given section of spectrum. The central depths of the DIBs were measured before applying a Gaussian filter.

The final sections of spectra, filtered with a Gaussian filter with a FWHM of three points (diodes), and normalized to their continua, are shown in Figures 1–7. The sodium D lines are shown in Figure 1 with the various DIBs shown in the other six figures. The letters correspond to the designations in Table 1. The intensity scales are all the same except in the case of Figure 1, where it is half, and the individual DIBs are indicated by approximate wavelengths. Figure 8 shows the profiles of the 6269 and 6284 Å DIBs, formed by dividing the spectrum of HD 2905 by that of the unreddened standard HD 91316. This has the effect of largely compensating for the strong telluric α band of oxygen. It also demonstrates that the two features which flank the 6269 DIB in the spectra in Figure 4 are probably stellar, since they do not appear in Figure 8. Spectra in the region of 4430 Å were only available for ζ Persei and HD 2905.

In Figure 9, ultraviolet extinction curves $E(\lambda - 2740)/E(B-V)$ vs. $1/\lambda$] are plotted for each star. These were derived from the spectrophotometric data in the *TD-1* photometric catalogs of Jamar *et al.* (1976) and Macau-Hercot *et al.* (1978). HD 91316 was used as the unreddened standard [indeed, the only suitable unreddened standard for such small values of $E(B-V)$]. The stars are identified by their letter from Table 1.

TABLE 2

OBSERVATIONS AND SIGNAL-TO-NOISE RATIOS

HD	RANGE (Å) 4200–4600[a]	5700–5900[b]	6140–6400[c]	6500–6700[a]
91316..........	...	420	100	...
40111..........	...	310	300	120
24398..........	290	930, 420	620	520
2905..........	300	470	380	...
42087..........	...	340	310	...
41117..........	...	...	...	250

[a] UBC 0.42 m telescope, dispersion 76 Å mm^{-1}.
[b] DAO 1.22 m telescope (except HD 91316, 1.83 m), dispersion 10 Å mm^{-1}.
[c] DAO 1.83 m telescope, dispersion 10 Å mm^{-1}.

The central depth of the 2200 Å interstellar feature, a_{2200}, is defined as

$$2.5 \log a_{2200} = E(2200 - 2740) .$$

Table 3 lists the characteristics adopted for the lines which were measured in Table 4 and which are identified in the figures. Central intensities as a percentage of the continuum and equivalent widths in mÅ were measured for the DIBs from our spectra and are listed in Table 4 for the reddened stars. While the wavelength limits were well defined for the sharper lines, they were less clear for the broader, weak features.

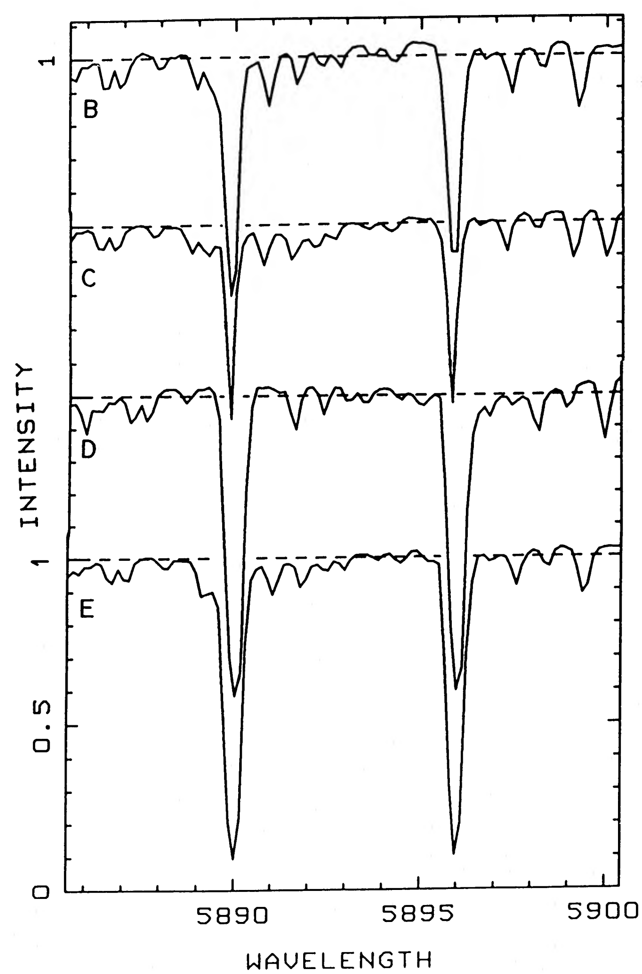

FIG. 1.—Reticon spectra of the sodium D lines for the four reddened stars designated by letter in Table 1. The spectra have been normalized to the continua as shown.

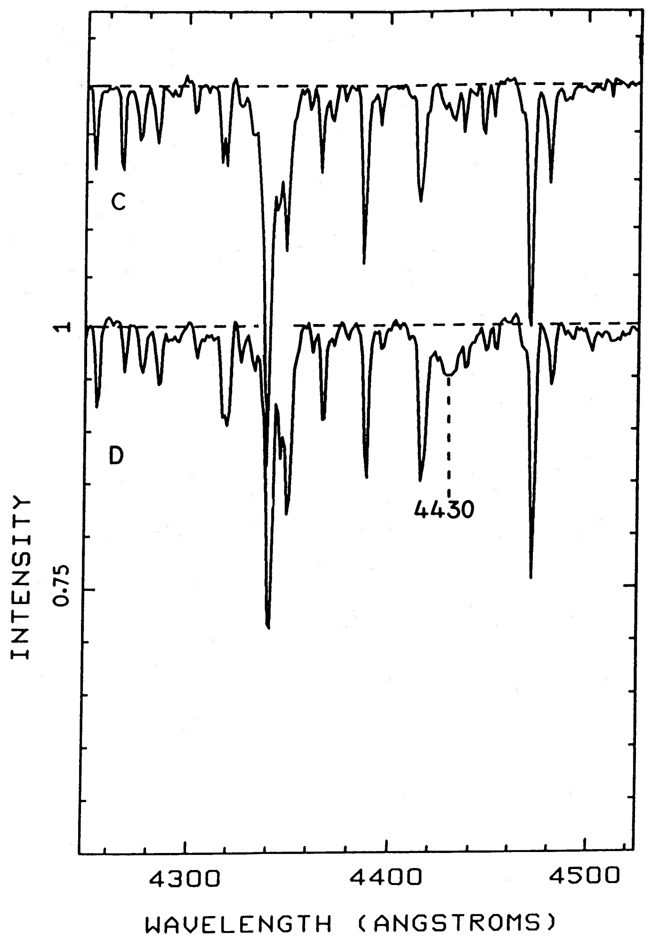

FIG. 2

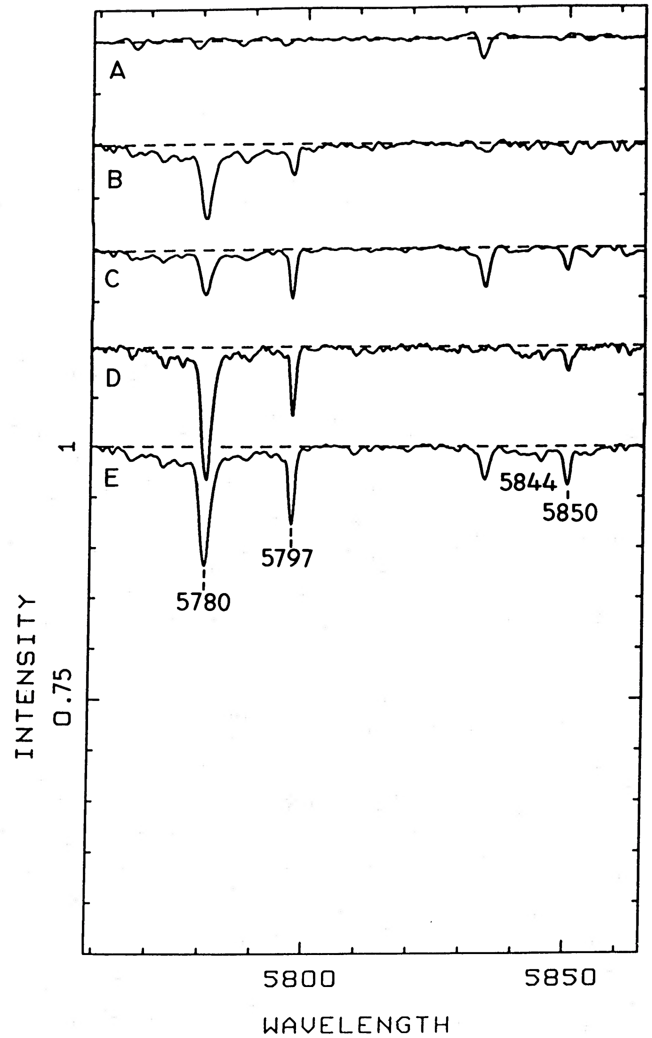

FIG. 3

FIG. 2.—Reticon spectra in the region of the 4430 Å DIB for ζ Persei and HD 2905.

FIG. 3.—Reticon spectra in the region of the 5780, 5797, 5844, and 5850 Å DIBs for each of the program stars. The letter designations are those of Table 1.

TABLE 3

DIFFUSE INTERSTELLAR BAND CHARACTERISTICS

DIB	Wavelength Range (Å)	Comments
5705?	5703.2–5707	Shallow, quite symmetric
5778?	5766–5792	Very shallow, quite symmetric
5780	5778–5784	Strong, steeper blue wing, measured from 5778 Å profile
5797	5794.5–5800	Possible broad blue wing from 5792 Å: Herbig's 5795 Å DIB, only sharp component measured
5850	5847–5852.5	Symmetric, sharp, strong
6177	6155–6198	Symmetric, very broad, shallow
6196	6194.5–6198	Steeper red wing, extremely sharp, strong
6203	6200–6210	Broad red wing, sharp strong core
6269	6268–6272	Sharp, symmetric, strong
6284	6278–6291	Steeper blue wing, strong
6376	6375.5–6377.5	Steeper blue wing, weak

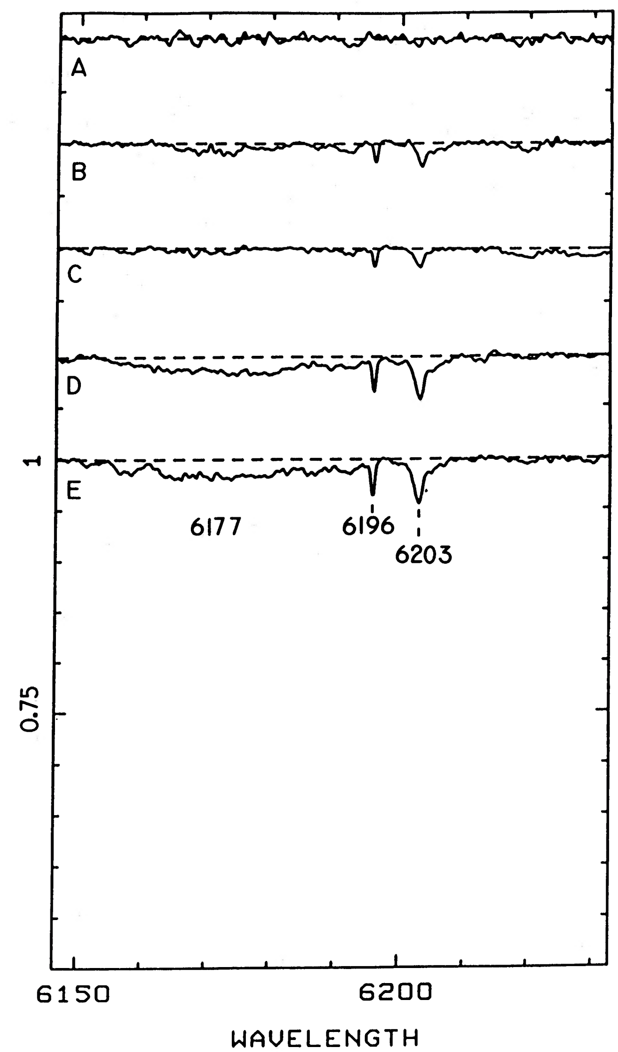

FIG. 4.—Same as Fig. 3 for the 6177, 6196, and 6203 Å DIBs

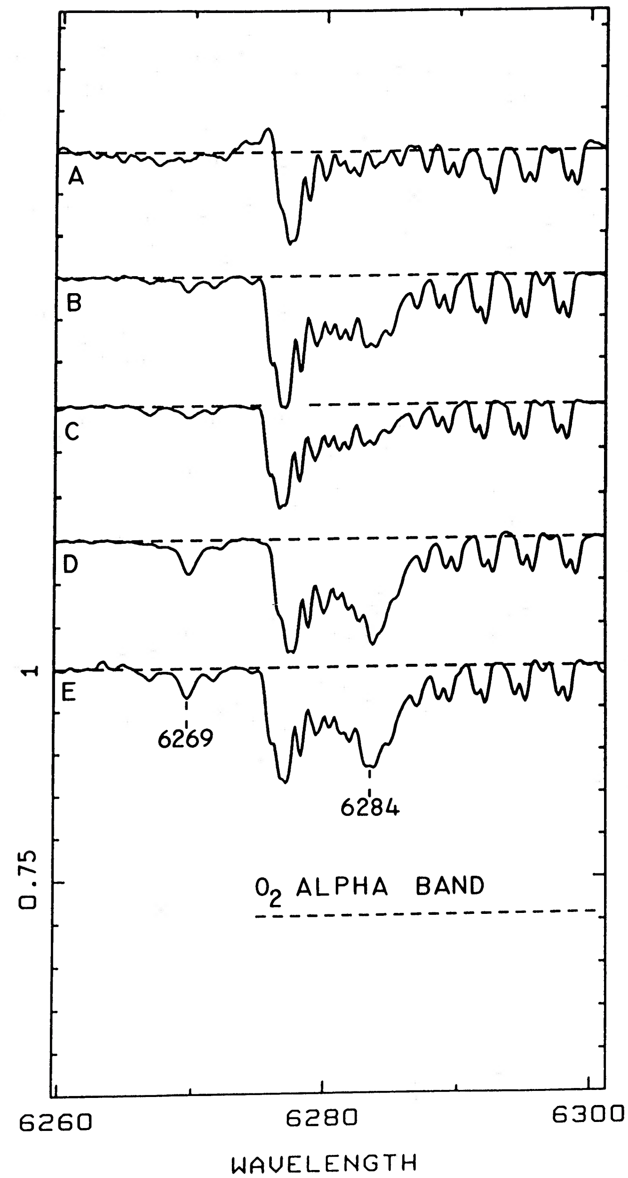

FIG. 5.—Same as Fig. 3 for the 6269 and 6284 Å DIBs

TABLE 4

DIB EQUIVALENT WIDTHS (mÅ) AND CENTRAL INTENSITIES

DIB (Å)	HD 40111		HD 24398		HD 24398		HD 2905		HD 42087	
	E.W.	*I*	E.W.	*I*	E.W.	*I*	E.W.	*I*	E.W.	*I*
4430	...	...	0	0%	...	...	1037	5.2%	...	...
5778	167	1.2%	82	0.5	...	...	176	1.1	256	1.5%
5780	153	6.7	96	4.5	110	4.9%	282	12.1	248	11.8
5897	55	3.5	71	6.5	78	6.5	89	7.0	120	10.0
5850	19	1.4	38	2.3	37	3.0	49	2.6	68	4.8
6177	140	0.64	0	0	...	...	394	1.3	362	1.5
6196	17	2.0	14	1.9	...	...	37	3.8	33	3.5
6203	65	2.4	33	1.8	...	...	115	4.5	112	4.4
6269	31	1.8	21	1.3	...	...	64	4.2	59	4.2
6284	286	5.4	130	2.9	...	...	365	9.0	424	9.0
6376	...	...	14	1.5	...	...	19	1.8	15	2.0
$(D_1 + D_2)/2$	305	64.0	175	55.5	169	51.5	510	90.2	490	90.0
a_{2200}	...	1.6	...	2.4	...	...	...	3.0	...	5.7

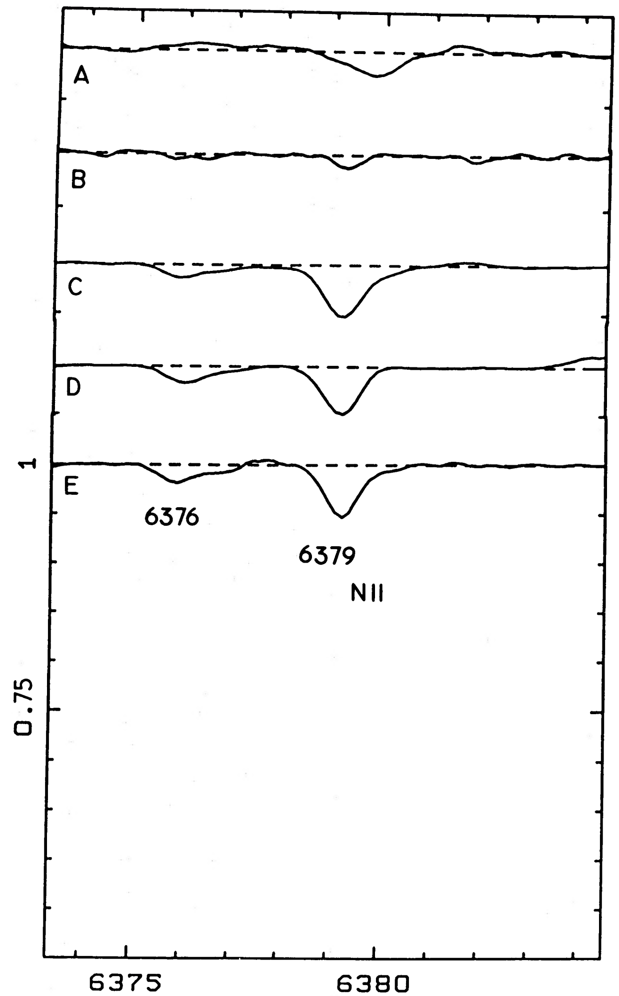

FIG. 6

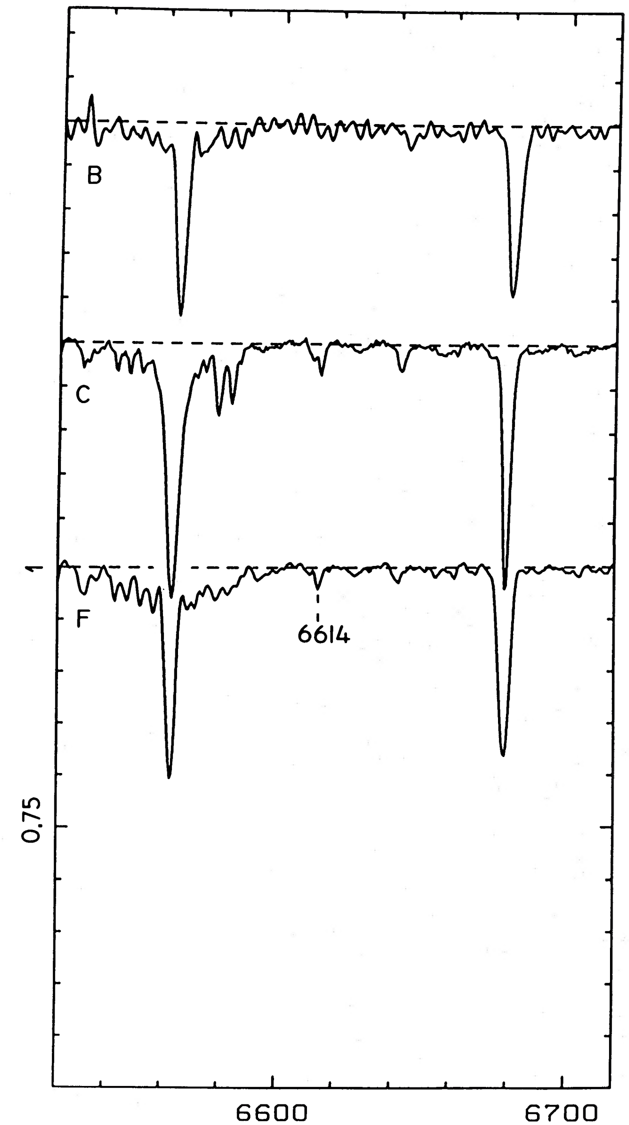

FIG. 7

FIG. 6.—Same as Fig. 3 for the 6376 and 6379 Å DIBs
FIG. 7.—Reticon spectra in the region of the 6614 Å DIB for three of the reddened stars. The letter designations are those of Table 1.

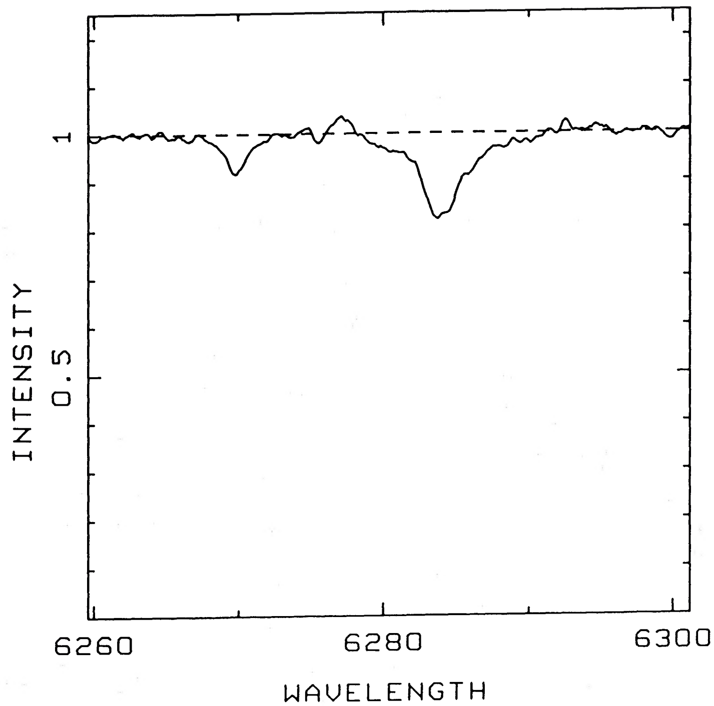

FIG. 8.—Profiles of the 6269 and 6284 Å DIBs in the spectrum of HD 2905 formed by taking the ratio between the spectra of the unreddened star HD 91316 and HD 2905. This largely compensates for the telluric O_2 α-band absorption.

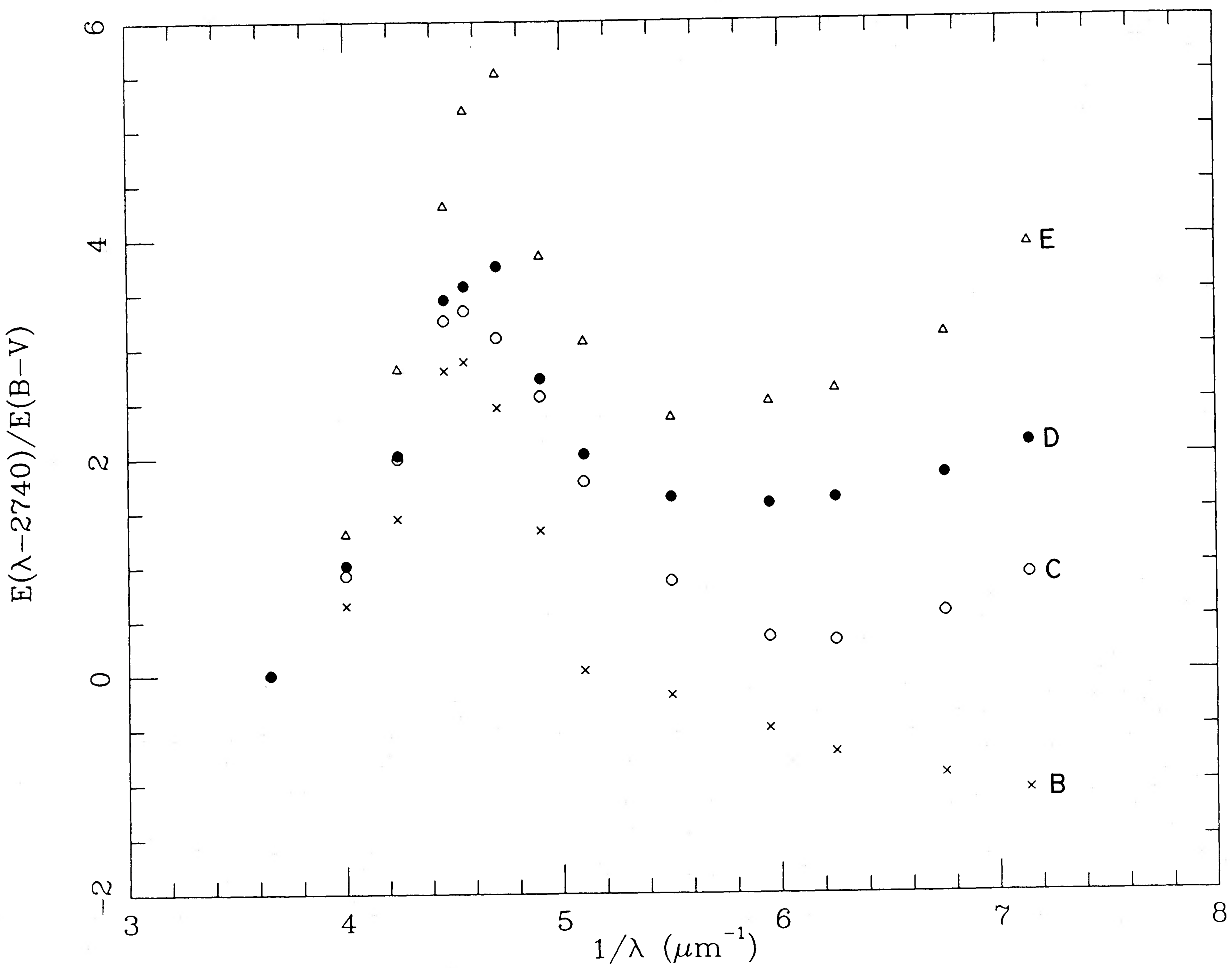

FIG. 9.—Ultraviolet extinction curves for each of the reddened stars in Table 1

Indeed, the reality of two of the latter remains in question, as noted by question marks in Table 3.

Tentative rms error estimates for the central depth and equivalent width measurements based on a comparison of the pairs of DIBs measured in the yellow for ζ Persei are 0.3% of the continuum and 5 mÅ respectively. These estimates do not include systematic errors introduced by the choice of continuum level. However, as the continuum points were chosen to be the same in all the spectra and the same order of polynomial was used in making the best fit, the rms estimates should be those appropriate to the comparison of the various line strengths in § III.

We propose to present a comparison of our DIB measurements with those of other authors in a later paper based on the more extensive data mentioned above.

III. DISCUSSION

It is clear from Figures 1–7 that the relative strengths of the DIBs in ζ Persei differ significantly from those in the other three stars in some cases. The effects are particularly marked for some of the stronger features.

In Figures 10 and 11 the equivalent widths and central depths of the DIBs in HD 2905 are compared with those of the other three stars. The horizontal axis gives the ratio of the quantity in question for the indicated star to the value for HD 2905 (designated "kappa"). The numbers in the boxes correspond to the wavelengths of the DIBs. Also plotted are the ratios for a_{2200}. Values for the weak 5705 and 5778 Å DIBs have been omitted as they are particularly uncertain. An error of 0.1 has been adopted for each ratio based on the two sets of spectra for ζ Persei, and that is indicated by the width of the boxes.

Figures 10 and 11 simply quantify the anomalous line intensities noted by eye in Figures 1–7 for ζ Persei. The pattern in both Figures 10 and 11 is similar. The intensities of the DIBs in HD 40111 are only about half those in HD 2905, but the relative values are remarkably similar. The majority of the DIBs in HD 42087 are of the same strength as those in HD 2905 with at least three, 5797, 5850, and 2200 Å, significantly stronger. For ζ Persei there are three well-defined groups:

i) the broad DIBs at 4430 and 6180 Å are absent;

ii) the 5780, 6196, 6203, 6269, and 6284 Å DIBs are one-third of their expected intensity;

iii) the 5797, 5850, and 6376 Å DIBs and a_{2200} are of approximately normal strength.

The 6379 Å DIB appears to belong to group (iii) but, as can be seen from the spectra in Figure 6, which were taken at 0.15 Å per diode, it is blended with a stellar absorption line of N II. From inspection of Figure 7 it seems likely that the 6614 Å DIB also belongs to group (iii), but being one of the narrowest of the DIBs it was not adequately resolved at 0.5 Å per diode and hence was not measured. The 5705, 5778, and 5844 Å DIBs appear to belong to group (ii), but these features are very broad and weak and, consequently, their measured intensities are not considered to be reliable.

The reality of the families receives additional support from the fact that three of the features in class (iii) for ζ Persei are also unusually strong for HD 42087.

The continuous, interstellar, ultraviolet extinction curve for ζ Persei in Figure 8 does not seem to show any peculiarities which might be associated with the anomalous DIB intensities. The curve for ζ Ophiuchi (Bless and Savage 1972) has a strongly enhanced far-UV absorption, which suggest an enhanced population of fine grains. There is nothing similar for ζ Persei. However, such differences for lightly reddened stars must be

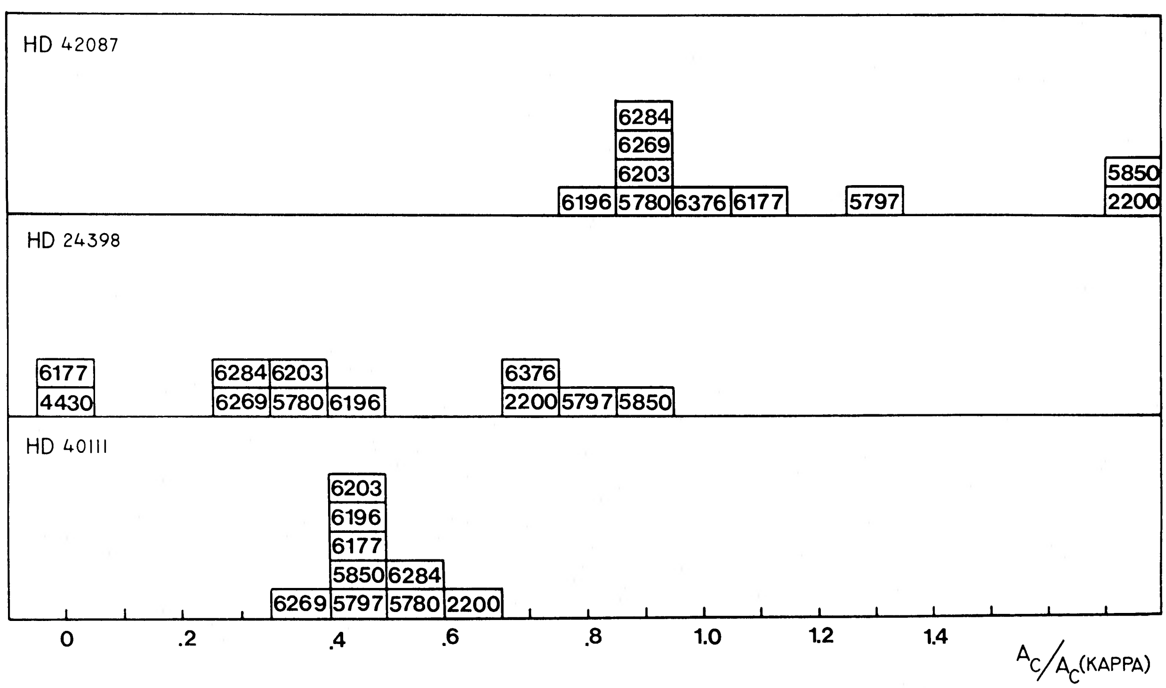

FIG. 10.—Comparison of the central depths of the various DIBs in Table 4 with the values for HD 2905, where A_c(kappa) corresponds to the central depth in HD 2905. The width of the boxes, 0.1, corresponds, approximately, to the average error estimated in each ratio. The numbers correspond to the DIB designations given in the tables.

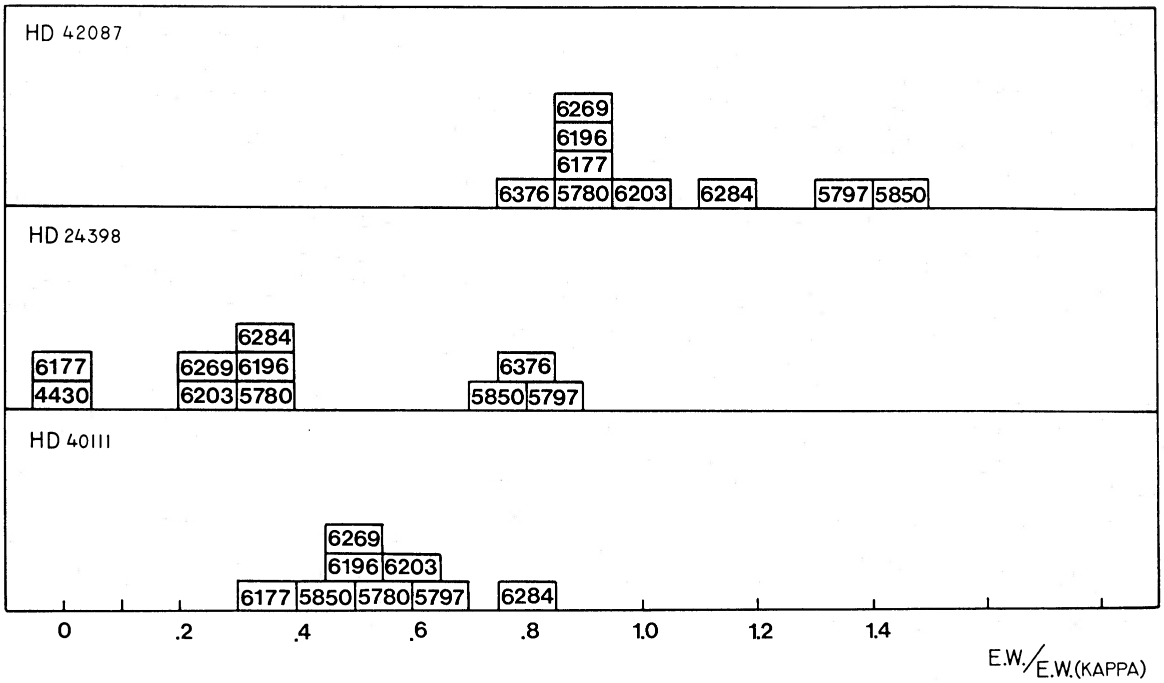

FIG. 11.—Comparison of the equivalent widths of the various DIBs in the reddened stars with the values for HD 2905[E.W.(kappa)] from Table 4. The width of the boxes, 0.1, corresponds to the estimated average error in the ratios. The numbers correspond to the DIB designations given in the tables.

treated with caution, as the shape of the far-UV extinction is critically dependent on a good match between reddened and unreddened standard in terms of spectral type, luminosity, and rotational velocity.

The structure in the sodium D lines and some of the sharper DIBs for HD 2905 and 42087 is more complex than for the other stars, due presumably to the number and velocity differences between the intervening interstellar clouds, but it is not clear that this effects the relative DIB values.

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J. KREŁOWSKI: Institute of Astronomy, Nicholas Copernicus University, Chopina 12/18, Pl-87-100 Toruń, Poland

G. A. H. WALKER: Geophysics and Astronomy Department, University of British Columbia, Vancouver, B.C. V6T 1W5, Canada