

Detailed Structures of the Diffuse Interstellar Bands Near 5800 and 6150 Å

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ABSTRACT. New high-resolution, very high signal-to-noise echelle spectra of the diffuse interstellar bands (DIBs) have been obtained in the wavelength range 5760–5830 and 6100–6200 Å in selected lightly to moderately reddened stars. These spectra have been used to search for the existence of substructures in the so-called 5778 band (first suggested by Herbig 1975) and to identify similar features in another wavelength range. We have detected many weak absorptions in these two spectral regions, and we show that these features are not spectrograph artifacts, telluric (H₂O) lines, or absorption features in the atmospheres of the background stars. Thus they must arise in interstellar medium clouds. The spectra of dark interstellar clouds are much more complex than imagined until very recently. The pattern of weak features changes as the intensity ratio of the major DIBs at 5780 and 5797 Å varies, which suggests that many strong and weak features may belong to the same carrier species.

1. INTRODUCTION

The discovery (Heger 1922) of broad, shallow absorptions centered around 5780 and 5797 Å, mentioned as “possibly stationary” in the spectra of some early-type binary stars, opened the investigation into the nature of diffuse interstellar bands, hereafter called DIBs. To the present day the identification of the carrier(s) of these and other DIBs has eluded spectroscopists.

Many investigators have cataloged the overall absorption characteristics of the DIBs, especially the strongest ones such as the 4430, 5780, 5797, 6284, or 6614 bands.² A comprehensive survey of the properties of these bands from photographic spectra was given by Herbig (1975). In that paper Herbig first drew attention to the possible existence of multiple overlapping features comprising each major band. For example, he found that the prominent DIB at 5780 is inextricably intertwined with a very broad (≈ 20 Å) but extremely shallow DIB usually called the 5778 band. He also suggested the existence of possible further structure within the general profile of the 5778 band, especially noting a feature at about 5774.0 Å.

Chlewicki et al. (1987) described the 5778 band further, specifically indicating detection of two absorption peaks at 5772.5 and 5775.9 Å, and suggesting that other weak features might exist under the broad 5778 profile. They proposed that the absorption strengths of these new features follow the strength variations of the 5797 DIB rather than those of the 5780 one. Their paper also confirmed the existence of the shallow 5795 DIB, which lies in the blue wing of the strong 5797 feature. The 5795 feature had been identified by Herbig (1975), who noticed that a deconvolution of the composite profile of 5797 into two overlapping

Gaussians still left residual absorption about 2 Å blueward of 5797 Å. Both Herbig and Chlewicki et al. assumed the 5795 band to be quite broad and thus its red wing to be completely engulfed by 5797.

Recently, Jenniskens and Désert (1993a,b) have produced a large catalog of DIBs from their spectra of some heavily reddened O-type stars. Their target stars were chosen to have a wide range in rotational velocities, and they searched for features whose profiles were insensitive to variations in stellar $v \sin i$. In particular, they show that the profiles of the C IV features longward of 5800 Å vary from quite sharp to very broad, but the widths of the claimed 5778 substructures remain unchanged. The detailed absorption pattern of the weak DIBs seems not to be identical in all cases, but the resolution and signal-to-noise of their spectra are not high enough to be confident of this point.

The chief drawback of all previous “weak” DIB detection efforts has been the reliance on observations of heavily reddened stars. The lines-of-sight to these stars invariably suffer from the obscuration effects of several clouds. Thus their “physical conditions” are rather ill-defined averages over (usually) an unknown number of clouds, each of which may have very different absorption characteristics (Chlewicki et al. 1986; Krelowski and Walker 1987; Josafatsson and Snow 1987; for a review see Krelowski 1988).

But with the now-routine use of solid-state low-noise detectors in stellar spectroscopy it is possible to detect the extremely shallow DIB absorptions toward lightly reddened stars. The variations in DIB properties may then be correlated with ISM atomic and molecular absorption strengths (e.g., see Herbig 1993), and with peculiarities in dust extinction. For example, Sneden et al. (1991, hereafter referred to as Paper I) discussed the overall absorption characteristics of the 5780 and 5797 bands in lines-of-sight whose ultraviolet extinction properties are similar to those

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²Throughout this paper we shall label the DIB features by the numerical values (in Å) of their approximate central wavelengths.

TABLE 1
Program Star Data

HD	Name	Sp/L	V	B-V	E(B-V)	<i>vsini</i>	Remarks
2905	κ Cas	B1 Ia	4.16	0.14	0.33	62	program
20041	—	A0 Ia	5.79	0.73	0.73	—	program
21389	—	A0 Iae	4.54	0.56	0.56	6	program
23180	σ Per	B1 III	3.82	0.05	0.26	85	program
24398	ζ Per	B1 Ib	2.85	0.12	0.31	59	program
24912	ξ Per	O7 III	4.04	0.01	0.29	216	program
41117	χ^2 Ori	B2 Ia	4.63	0.28	0.44	36	program
43384	—	B3 Ib	6.25	0.45	0.59	51	program
47839	15 Mon	O7 V	4.66	-0.25	0.04	63	comparison
53138	σ CMa	B3 Iab	3.02	-0.08	0.05	44	comparison
87737	η Leo	A0 Ib	3.52	-0.03	-0.02	20	comparison
116658	α Vir	B1 V	0.91	-0.23	0.00	196	echelle div
175191	σ Sgr	B2.5 V	2.02	-0.22	-0.02	201	coude div
205021	β Cep	B1 IV	3.23	-0.22	0.01	28	coude div
218045	α Peg	B9 V	2.49	-0.04	0.00	148	coude div

of σ Scorpii (HD 147165), ζ Ophiuchi (HD 149757), and ν Cygni (HD 202904). They concluded that the equivalent width ratios of the 5780/5797 DIBs could be segregated easily between these groups, but that the breadths (as measured by FWHM of the band profiles) were insensitive to the ultraviolet extinction characteristics. Apparently the varied physical conditions inside dark interstellar clouds change the extinction properties of dust grains together with the abundances of DIB carriers, but the physical structures of the carriers remain unchanged.

Are the differences exhibited by strong DIB features along different lines-of-sight repeated in the weaker substructures? More fundamentally, do the weaker substructures even exist? Positive answers to these questions may be very important for the future identification of DIB carriers. The strong diffuse bands (the most frequently observed ones) usually have variable intensity ratios, and so are expected to be formed by different carriers. Convincing identification of any carrier requires matching the laboratory spectrum of the proposed carrier with the spectrum of a system of at least several interstellar spectral features attributable to a single origin. Perhaps weak features form such systems with the strong ones. Thus it is important to detect the 5778 substructures, as well as similar features in other spectral ranges.

To this end we have gathered new high-resolution, very high signal-to-noise echelle and coude spectra of several stars with well-known DIB properties and ultraviolet extinction characteristics. In Sec. 2 the observations and reductions are presented, and in Sec. 3 we discuss the steps involved in making positive detections of very weak DIBs. Section 4 is devoted to an attempt to show correlations between the new very weak DIBs and the major DIBs, and in Sec. 5 we summarize our new weak DIB discoveries.

2. OBSERVATIONS AND REDUCTIONS

2.1 Target Stars Selection

In Table 1 we give the basic data for the observed stars and some information about the observational material. We determined the interstellar stellar reddening values by comparing the cataloged values of the color indices with the intrinsic ones determined by Papaj and Krelowski

(1992). The other data are taken from the latest version of the *Yale Catalog of Bright Stars* (Hoffleit and Warren 1992). The stars of Table 1 are segregated into categories of “program,” “divisor,” and “comparison” stars. The program stars are the reddened objects known to exhibit major DIB structures in their spectra; these are principal targets of our investigation.

For the effective elimination of slow continuum variations, and for telluric (H_2O) line removal, it was necessary to obtain spectra of some divisor stars. The ideal divisor star would have a pure blackbody continuous spectrum. Since no ordinary star has such a spectrum, we chose divisor stars that (a) have very early spectral type, to minimize the number of stellar absorption features, (b) rotate as rapidly as possible, to turn the few stellar lines into quasicontinuum features, and (c) possess the lowest possible reddening, to keep the divisor line-of-sight free of detectable DIBs. See Table 1 for the properties of the chosen divisors. At the telescope we attempted to observe the divisor stars as close in airmass to the program stars as possible. Given the stringent criteria for divisor star selection this requirement could not always be met, so any small mismatches in airmass (leading to different telluric line strengths) were adjusted during the reduction procedures.

To help distinguish interstellar from stellar absorption features, we also observed a set of comparison stars. These objects were chosen to (a) match the various spectral types of the program stars as closely as possible, (b) possess roughly the same $\nu \sin i$ of the program stars, and (c) be essentially unreddened. If a star with these qualities could be identified for each program star, it would be possible simply to divide program star and comparison star spectra, leaving only ISM absorption features in the quotient spectrum. In practice, this is a nearly impossible task. First, very few stars are completely free of ISM absorption features. While DIB structures may not be obvious in spectra of stars with $E(B-V) \simeq 0.00$, almost all of these objects do have detectable ISM Na D lines. Second, spectral type matching (i.e., matching of stellar absorption line strengths) is quite difficult because there are often large uncertainties in the published spectral types of even the bright stars under consideration here. Thus we chose several comparison stars covering a broad range of spectral types and luminosity classes.

2.2 Observations

To assess the influence of instrumental idiosyncrasies on the unambiguous identification of DIB substructures, we observed the well-known, bright star σ Persei (HD 23180) with three high-resolution McDonald Observatory spectrographs: the 2.7-m Tull coude spectrograph, the 2.1-m coude spectrograph, and the 2.1-m Sandiford echelle spectrograph.

We obtained the data for other program stars with the Sandiford echelle spectrograph. This instrument, described by McCarthy et al. (1993), possesses refractive collimator and camera optics, a 23.2 gr mm^{-1} echelle grating with a blaze angle of 65° , a prism cross-disperser, and a Reticon

400×1200 CCD with 27×27 μm pixels. This configuration yields a spectral dispersion of 0.050 $\text{\AA mm}^{-1}$ at 5790 $\text{\AA}$. With an entrance slit of 1.1 arcsec the effective resolution is $R \equiv \lambda/\Delta\lambda \approx 64,000$ (empirically determined FWHM values of Th–Ar hollow cathode lamp features). Full spectral coverage over 1200 $\text{\AA}$ is achieved in one exposure with 26 orders, and each order has ~ 15 $\text{\AA}$ of overlap on either end with the adjacent order.

Some data for *o* Per were obtained with the conventional coude spectrograph of the 2.1-m telescope. This instrument has all-reflecting optics, and the dispersing elements chosen was a 1200 gr mm^{-1} grating blazed at 6000 $\text{\AA}$ in first order; the detector was a Tektronix 512×512 CCD with 27×27 μm pixels. This combination yielded spectra with linear dispersion of 0.123 $\text{\AA/pixel}$, and spectral coverage of approximately 63 $\text{\AA}$. The spectrograph slit of 0.45 arcsec was set to project onto two pixels at the detector. The resulting measured FWHM of the lines of the Fe–Ne hollow cathode spectrum gave a resolution of $R \approx 19,000$.

Finally, we gathered additional spectra of *o* Per with the same 2.7-m coude spectrograph configuration employed for the observations of Paper I. A similar 1200 gr mm^{-1} , 6000 $\text{\AA}$ blaze grating, a TI 800×800 CCD with 15×15 μm pixels, and all-reflective collimator and camera optics produced spectra with reciprocal dispersions of 0.066 $\text{\AA/pixel}$, and spectral coverage of ≈ 53 $\text{\AA}$. Use of a 0.30 arcsec slit, which projects onto two CCD pixels, yields Th–Ar hollow cathode line FWHM resolutions of $R \approx 35,000$.

The finite charge capacity of all CCD systems used here limited the signal-to-noise from any single integration to $S/N \leq 200$. To obtain very high S/N for the final spectra, we obtained multiple exposures of many program stars. Since the targets are relatively bright ($V < 7$), the addition of several spectra assured the capture of a large number of photons ($\geq 10^5$ per resolution element) in the final reduced spectra. As stressed in Paper I, this procedure insured that photon shot noise was not a major limiting factor in the S/N of the reduced spectra. We therefore concentrated on attempts to control the uncertainties due to fluctuations in the background (dark) levels and pixel-to-pixel sensitivity variations.

The background level was quite low (the CCD chips were cooled to $< -115^\circ\text{C}$), especially in comparison to the photon level of our spectra. A much more serious concern was to obtain an effective flatfield for our program star spectra. We gathered many exposures of a tungsten lamp, which effectively canceled the pixel-to-pixel sensitivity variations over short pixel scales (≤ 10 pixels). The use of divisor stars cancelled most of the residual departures from flatness over long pixel scales (~ 50 pixels).

2.3 Reduction Procedures

We employed several sets of reduction routines to produce the final spectra. First, all raw CCD frames were subjected to bias subtraction and overscan region trimming with standard routines of the IRAF software package. Then, for the single-order 2.1- and 2.7-m coude observa-

tions we reduced the images to one-dimensional spectra by application of IRAF flat fielding and aperture summation algorithms.

Extraction of the spectra from the 2.1-m Sandiford echelle images proved to be a more complex task, chiefly because the spacing between echelle orders is quite small in the yellow and red spectral regions. In particular, the scattered light level is fairly high, and care must be taken to estimate the relative contributions of “local” scattered light (caused by the far wings of adjacent orders) and of “global” scattered light (caused by anomalous reflections/refractions of light from distant orders). Also, the close packing of the orders forces extra attention to the algorithms that must locate and “trace” (i.e., characterize the x and y pixel locations) of the echelle orders. For these tasks we employed special two-dimensional spectrum reduction software written by McCarthy and Tomaney, who kindly allowed us access to their routines. We used the version of this software that now is running in the IRAF environment.

The basic wavelength scales implanted on the stellar spectra came from cubic Chebyshev polynomial fits to Th–Ar lamp exposures. Additionally, we routinely checked the zero points of the scales by identifying telluric features in the program stars. The implied mean wavelength differences were always ≤ 0.03 $\text{\AA}$.

The final spectrum manipulations were done with special single-order spectrum reduction software (Fitzpatrick and Sneden 1987). The most critical step in this reduction phase involved the division of the program star spectra by the appropriate divisor star spectra. As mentioned previously, this division performed the tasks both of final flat-fielding and telluric line removal. Since it was impossible to observe program and standard stars at the exactly same airmasses, some adjustment of the strengths of the H_2O features in the standard star was performed before division.

The tilts of echelle and cross-disperser elements chosen for echelle spectrograph observations are usually compromises that put some features in the middle of the CCD image frames and some near the edges. Our choice yielded a clean profile of the 5797 band near the center of one of the orders, but the 5780 band then fell near the blue edge of the same order. Fortunately the ~ 15 $\text{\AA}$ of overlap between orders in this spectral region gives us the opportunity to merge orders for a continuous spectrum. Thus after the standard-star division we next rebinned the two orders containing the 5780 band to create spectra sampled at constant wavelength intervals, and computed weighted means of these orders in the overlap regions. The weights were simple normalized increasing linear functions of the wavelength distance from each of the order edges. In this scheme, the points at the particular order edges (which should be the most uncertain) received very low weight, while those in the middle of the order overlap would be equally weighted between the two orders. In Fig. 1 we show an example of this procedure, which illustrates both the muting of the order “edge uncertainties” with this procedure and the reasonable agreement between the general profiles of the 5780 band in both orders. Note that the

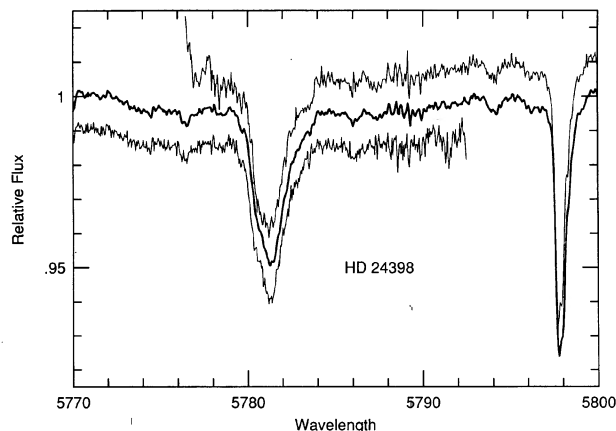


FIG. 1—An example of the merging of ends of echelle orders for Sandiford spectrograph data. The spectrum of HD 24398 was chosen for display by random pick from among the target stars that have the highest S/N spectra and weakest DIB substructures of our sample; the spectrum quality is representative of our other data. The individual echelle orders are shown as thin lines in the figure, bracketing the thick line of the merged-order spectrum. The merged spectrum also has undergone three-pixel running mean smoothing for display. The vertical scale of the merged spectrum is correct, and the other spectra have been shifted vertically for display.

telluric line removal has been accomplished before the merging procedure. In the remaining figures the DIB spectra from the Sandiford echelle will always be from merged spectra.

Although the order merging procedure has proven very robust for the search for weak DIB features whose breadths are $< 1 \text{ \AA}$ (FWHM), a caution must be given here. The overall continuum placement at the ends of our echelle orders is somewhat arbitrary at the $\pm 1\%$ level. This uncertainty does not affect the detection of the “narrow” features that we seek, but it compromises our ability to gauge the depth of the extremely broad ($\sim 20 \text{ \AA}$) and shallow 5778 and 6177 DIBs which stretch over more than one echelle order. The blaze functions for typical echelle gratings vary so rapidly that they ultimately are ill-suited for the description of these and other very broad DIBs. To study these DIBs one would be better served by using a low-order ordinary grating with slowly varying blaze function. In order not to give the reader any false impression from our data about the profiles of the 5778 and 6177 DIBs (they have depths $< 2\%$ in all our stars), we have chosen to eliminate them by treating these very broad features as local continuum points in our final flatfield adjustments. Remember, we look here only for DIB substructures from very high-resolution data; coarser resolutions with ordinary grating instruments should be employed for the shapes of the 5778 and 6177 DIBs. This arbitrarily chosen continuum level makes, however, measurements of weak feature intensities impossible.³

³Probably a well-formed attack on the central intensities of overlapping DIB features has at least two prerequisites: well calibrated absolute or relative flux spectra, and some knowledge of the intrinsic profile of at least one of the overlapping features.

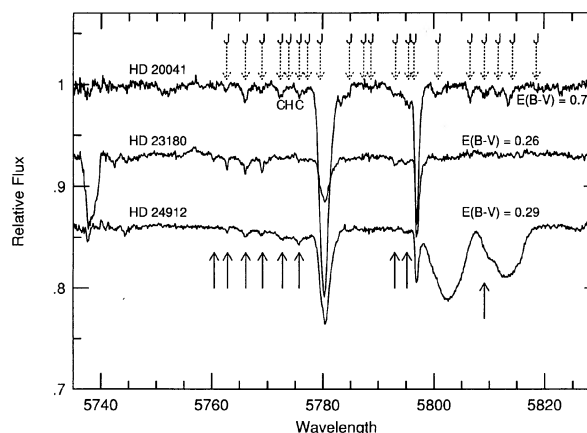


FIG. 2—The spectra of three program stars near $5800 \text{ \AA}$; our claimed detections of very weak DIBs are shown with solid arrows at the bottom of the figure. The earlier literature claims are given by dashed arrows at the top of the figure. An “H” at the top of feature indicates that it was suggested by Herbig (1975), a “C” is a feature from Chlewicki et al. (1987); and a “J” is one from Jenniskens and Désert (1993a). Note that not all features are detectable in all target lines-of-sight.

Finally, we smoothed the data. A uniform smoothing was desired for all spectra, so we computed running means of every three pixels ($0.15 \text{ \AA}$). Since the DIB features are broad compared with our spectrograph resolution, the smoothed profiles were not very sensitive to the choice of the number of pixels in the averaging process. As in Paper I one can see that the S/N of the resultant spectra are quite high (> 500 in most cases).

3. DETECTION OF WEAK DIB SUBSTRUCTURES IN THE $5800 \text{ \AA}$ REGION

In Fig. 2 we present the reduced spectra near $5790 \text{ \AA}$ for several of our program stars. At the top of the figure we have marked the wavelengths of the DIB substructures that have been proposed by Herbig (1975), by Chlewicki et al. (1987), and by Jenniskens and Désert (1993a). Several of these wavelengths coincide with weak absorption troughs in the spectrum. At the bottom of the figure we have marked wavelengths of weak substructures that we believe are real ISM DIB features. Our principal tasks in this section lie in the demonstration of the reality of these features, in the assignment of them to the interstellar medium, and in the identification of other weak ISM features in this spectral region. Not all very weak ISM absorptions in the visible spectral region are substructures superimposed on stronger DIBs. Therefore the proposed new ISM absorptions will collectively be referred to as “weak features” in this section.

3.1 Tests of the Reality of the Weak DIB Features

3.1.1 The Instrumental Effect Test

In Fig. 3 we display the spectra of HD 23180 obtained with the three different spectrographs. Inspection of the various spectra displayed here suggests the existence of a

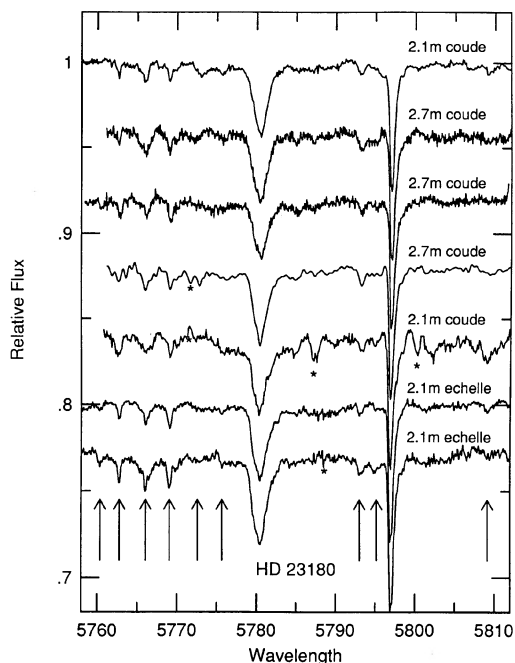


FIG. 3—A comparison of the spectra of HD 23180 obtained with different telescope-detector combinations. Solid arrows mark the wavelengths of our claimed weak DIB detections and asterisks indicate a few nonrepeating instrumental artifacts.

few “flat-fielding effects,” i.e., features that appear in only one of the spectra and that undoubtedly are instrumental in origin. We have marked a few such features in Fig. 3. Probable causes of these features include spectrograph stray light and misalignments between stellar and flat lamp light paths. However, the vast majority of weak features repeat throughout the spectrograph configurations. It is clear that they cannot be instrumental artifacts. We emphasize that no prominent features of instrumental origin have been observed in spectra of this wavelength region taken with the Sandiford echelle spectrograph.

3.1.2 The Telluric Line Test

In Fig. 4 we display the spectra of a program and a divisor star before division, and show the resultant quotient spectrum. In the top panel the Na D line region is shown; it was chosen because here there are many obvious telluric H_2O lines contaminating the stellar spectra. In the bottom panel the 5800 Å spectral region is shown. The star HD 24398 has deliberately been chosen here because it has the weakest substructure features, ones that should be most sensitive to uncertainties in telluric line cancellation. The telluric H_2O lines in the 5800 Å region are extremely weak, and can be noticed only on nights of very high humidity. These H_2O lines are so weak on “dry” nights that we ignore any small line depth mismatches between program and divisor stars. We suspect that residual telluric absorptions *after* division set the ultimate limit on the S/N achievable with our data. In both wavelength regions excellent cancellation of the telluric lines is achieved; residual

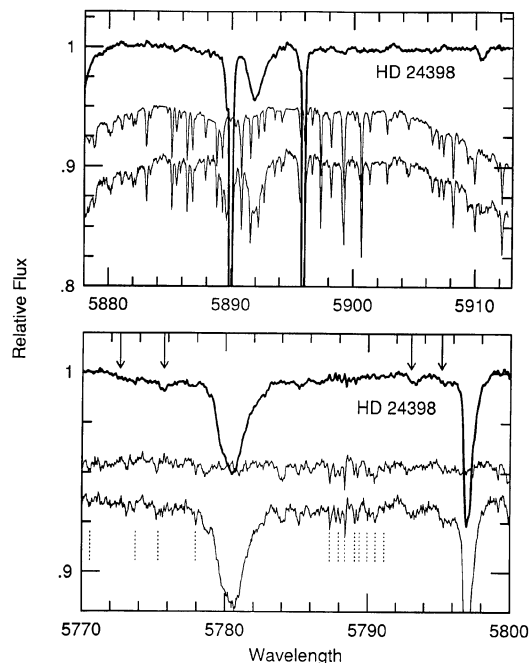


FIG. 4—An example showing the presence of telluric H_2O contaminating lines and their cancellation via division of program spectrum by divisor spectrum. HD 24398 is the program star displayed here, and the divisor star is Spica. In each panel the vertical scale of the top spectrum is correct and the other spectra have been shifted vertically for display. The lowest spectrum (thin line) of each panel is the dividend HD 24398 spectrum, containing telluric, interstellar, and stellar features; the middle spectrum (thin line) is that of divisor Spica, essentially featureless except for the telluric lines; the top spectrum (thick line) is the quotient HD 24398 spectrum (three-pixel smoothing has been applied). In the Na D spectral region of the top panel, the H_2O lines are obvious and need not be identified. In the 5800 DIB region the telluric contaminants are much weaker, so we have marked vertical dashed lines to indicate features both identified in the Moore et al. (1966) solar atlas and detectable on our spectra. We also have used vertical arrows to indicate the wavelengths of very weak DIB features.

telluric features are always $<0.3\%$ of the continuum flux. The weak features are left intact, surviving cancellation of telluric contaminants.

3.1.3 The Stationary Velocity Test

For each target star, we defined the rest interstellar wavelength scale with the Na D lines on our spectra. But, as the spectra in Fig. 5 demonstrate, the D lines usually exhibit multiple ISM components in our program stars. In these cases we adopted the wavelength of the D-line flux minimum as a compromise ISM rest wavelength zero point. For all program stars, translation of the 5800 spectra onto the ISM wavelength scale in this manner yielded excellent wavelength alignment (± 0.1 Å) for the major 5780 and 5797 DIBs. More importantly here, the weak features also achieved excellent star-to-star wavelength registration. At the same time, no such agreement could be seen in the wavelengths of readily identifiable stellar absorption features; each is in a different rest wavelength frame. This suggests that the weak features are not of stellar atmosphere origin.

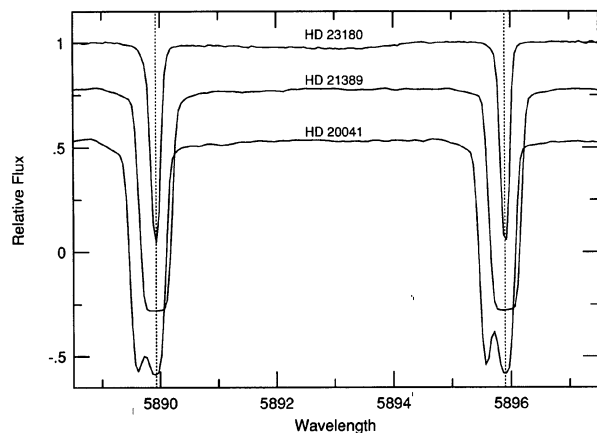


FIG. 5—A comparison of the observed sodium line profiles in spectra of three of our program stars. The dotted vertical lines denote the adopted rest Na D wavelengths of the most opaque ISM in each line-of-sight. The figure illustrates the difficulty of applying correct Doppler shifts to the interstellar features where sodium lines reveal that the sightline intersects more than one cloud. For the purpose of determining the weak DIB rest wavelengths, listed in Table 2, we used only targets with narrow sodium lines, like HD 23180.

As a direct test, the spectra of the program star HD 23180 taken on successive nights demonstrate the detachment of the weak feature wavelength scale from the stellar one. HD 23180 (HR 1131, α Per) is a double-lined spectroscopic binary (the secondary is 2.8 mag fainter than the primary) with an orbital period of 4.42 days. In Fig. 6 we show two spectra of this star taken about 22 hr apart. The ISM Na D lines remain stationary (top panel) as the stellar 5876 He I line oscillates in response to the orbital period. The shift in the position of the stellar lines is 3.2 Å between the two nights. And the weak features (bottom panel) remain fixed in the ISM Na D velocity space as the Si III line at $\lambda_0 = 5739.73$ and the Fe III line at $\lambda_0 = 5833.94$ also shift from night to night.

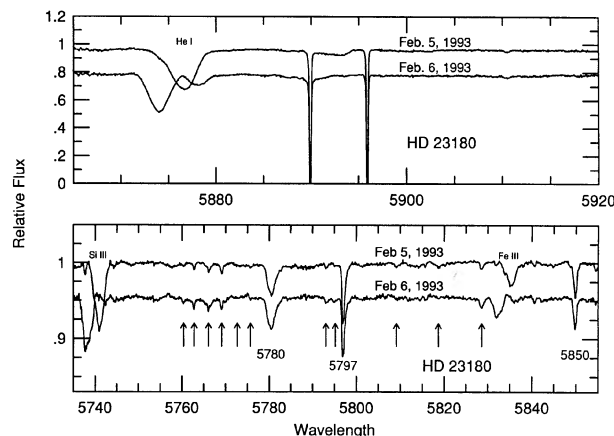


FIG. 6—Two spectra of the close binary HD 23180 recorded during the two subsequent nights. Note the substantial Doppler shifts of the stellar lines and the stationarity of the shown interstellar features: sodium lines, well-known strong DIBs, and our claimed detections marked with solid arrows.

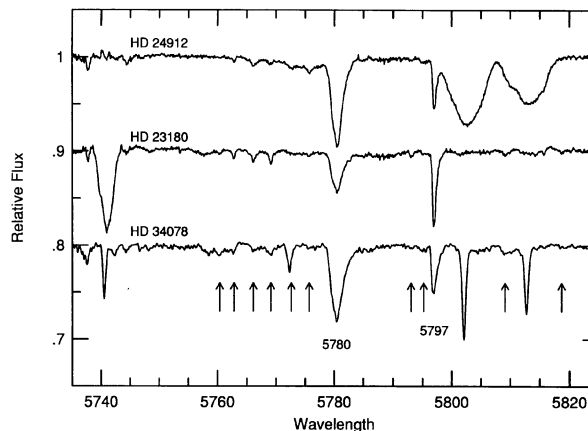


FIG. 7—Three spectra of stars with the $v \sin i$ (from top to bottom) 216, 85, and 6 km s^{-1} . The profiles of Si III and C IV lines apparently vary whereas those of diffuse bands remain unchanged.

3.1.4 The Stellar Rotational Velocity Test

Here we follow Jenniskens and Désert (1993a,b) in comparing stars of different $v \sin i$ values. In Fig. 7 we present three spectra of stars with different rotational velocities. The profiles of the weak features are insensitive to such stellar variations.

3.1.5 The Stellar Spectrum Synthesis Test

It is difficult to disentangle stellar and ISM features when both are weak and shallow. Strong, broad stellar features such as Si III 5739.74 Å or C IV 5801.79 and 5812.39 Å lines are easily distinguished in the spectra of early B and O stars. However, in late B or A stars the spectra are much more line-rich. We have produced synthetic stellar spectra to show where the stellar and ISM lines might overlap in such stars. Model stellar atmospheres were generated by Venn with the ATLAS9 code (the latest version of a code described by Kurucz 1970), line lists were taken from an expanded version of the Kurucz and Peytremann (1975) atomic line compilation, and we used the spectrum synthesis code of Sneden (1973). A synthetic spectrum representative of an early A supergiant ($T_{\text{eff}} = 9900$ K, $\log g = 2.2$) was computed with an assumption of solar metallicity.

In Fig. 8 the computed spectrum is compared to comparison and program stars of the same spectral type. The synthetic spectrum has been smoothed to match approximately the observed line breadths in the stellar spectra. The synthetic and observed spectra of late B and early-type supergiants are dominated by features of Fe II in the 5800 Å spectral region. Generally however, the predicted stellar features do not coincide with the wavelengths of weak features. We do note that a couple of Fe II lines contaminate the profiles of the major 5780 and 5797 DIBs. Moreover, any description of the weak alleged 5795 DIB must take into account some possible stellar absorption at 5796 Å. We conclude that many weak IS features may be severely contaminated with weak stellar lines and thus any weak

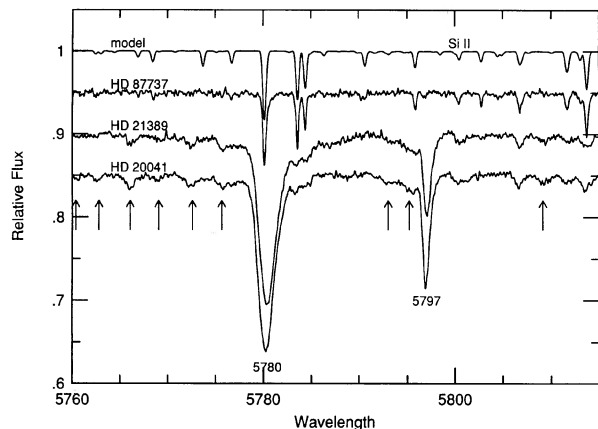


FIG. 8—The stellar spectrum synthesis test performed for A0 supergiants. The model spectrum is at the top of the figure. HD 87737 is the unreddened, slowly rotating star. Note that the model spectrum is very similar to this one. The lines shown belong to Fe II, except that of Si II, which is marked. Both model and unreddened star spectra facilitate the detection of possible stellar contaminations in the interstellar spectra. Note that EW (5780) may be enhanced in A0 I spectra due to Fe II lines. The same phenomenon can change much more severely the absorptions of weak IS features.

interstellar band should be established only after being observed in several reddened stars of different spectral types and luminosity classes.

3.2 Confirmed Weak Features near 5800 and 6150 Å

We have also considered the spectral range 6090–6203 Å which, according to Herbig (1975) contains two sharp features centered near 6113 and 6196 Å and a very broad DIB, 6177. We remind the reader that we have artificially eliminated the 6177 DIB from the reduced spectra, and will have no further comment on it.

Figure 9 contains two panels. The upper one shows spectra of three unreddened comparison stars with spectral types ranging from O7 to A0 I. The lower shows spectra of five reddened program stars covering the same range of spectral types and luminosity classes (see Table 1). The features appearing in all reddened, but no in unreddened stars are marked with arrows.

The two strong DIBs at 6113 and 6196 Å were originally catalogued by Herbig (1975). One weak feature at 6194.5 Å has been added in this spectral region by Smith et al. (1981), with the comment that many similar very weak lines may await discovery. Our work confirms their suspicions. Two additional features (6108.21 and 6116.65) have been proposed by Jenniskens and Désert (1993b)—they coincide with our findings. We observe five additional features (see Table 2). Note that the 6113 DIB may be severely contaminated by a stellar feature if observed in A0 supergiants.

Table 2 contains the list of weak features which successfully passed the tests described above. Some other weak features may exist, but their identification is ambiguous because of stellar line contamination or simply due to their weakness (in our lightly reddened stars). Generally we

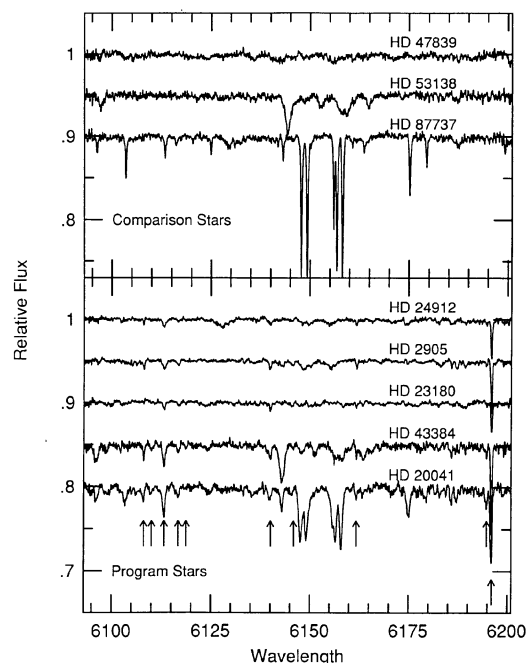


FIG. 9—The red spectral range with the two strong DIBs already detected by Herbig (1975). Upper frame: unreddened comparison stars. Lower frame: reddened stars in the same range of spectral types and luminosity classes (Table 1). Solid arrows at the bottom of the lower frame mark all the interstellar features which may be identified in our spectra (Table 2).

avoid identifying as interstellar any feature which is located in the place of a stellar line unless it is observed in other spectra that are free of such contamination. Weak IS features are, of course, much more sensitive to stellar contamination than the strong ones—many weak stellar lines which appear in our high-resolution, high signal-to-noise spectra remain unidentified. This is why several tests must be carefully applied.

We have also attempted to indicate the relative strengths of the very weak DIBs by giving in Table 2 an equivalent width for each DIB feature. These numbers are the averages (rounded to the nearest mÅ) of the equivalent widths measured on our two spectra of HD 23180 and our single spectrum of HD 24398. These stars were selected for this exercise because they have similar reddening [$E(B-V) \approx 0.3$], similar UV extinction curves, and similar equivalent widths of the major DIBs at 5780 (EW ≈ 93 mÅ), 5797 (EW ≈ 66 mÅ), and 6196 (EW ≈ 18 mÅ). Although HD 2905 and HD 24912 have essentially the same $E(B-V)$ values, their major DIB strengths are strikingly different (for instance, both have much stronger 5780 features than do HD 23180 and HD 24398). In Sec. 4 we will comment on some tentative correlations between the weak and strong DIBs. Here we simply give rough averages of the DIB equivalent widths in HD 23180 and HD 24398, leaving a detailed study of the strengths of the weak features in different lines-of-sight to a future paper.

The equivalent widths listed in Table 2 were derived by measuring the amount of absorption in a feature, using a simple numeric integration scheme. We must caution

TABLE 2
Diffuse Band Identification

λ Å	$\sigma(\lambda)$ Å	Certainty	Comment	EW mÅ
5760.37	0.16	u	--	2
5762.80	0.04	c	J	4
5766.08	0.08	c	J	11
5769.07	0.12	c	J	8
5772.63	0.26	u	C, J	<3
5775.70	0.09	c	C, J	2
5780.44	0.07	c	H	93
5793.04	0.17	c	J	4
5795.20	0.14	c	J	4
5796.94	0.03	c	H	66
5809.13	0.17	u	J	5
5818.69	0.07	u	J	4
5828.62	0.15	c	J	6
6108.09	0.06	c	J	2
6110.07	0.16	u	--	3
6113.26	0.07	c	H	7
6116.92	0.11	c	J	6
6118.70	0.04	u	--	3
6140.05	0.15	c	--	9
6145.65	0.11	c	--	4
6161.94	0.09	c	--	3
6194.86	0.10	c	SSJC	3
6196.09	0.04	c	H	18

References: J = Jenniskens & Désert (1993a,b)
H = Herbig (1975)
C = Chlewicki et al. (1987)
SSJC = Smith et al. (1981)

against overinterpretation of these numbers. Remember from above that only two stars with similar major DIB properties have been studied. Recall also that some extremely broad ISM features, such as the 5778 DIB, have been artificially cancelled in our spectra. Thus the equivalent widths of the very weak features represent only the absorptions relative to local (within a few Å) continua. Finally, the central depths of some of the very weak features are so small that the continuum placement and feature wavelength extent decisions can greatly influence the derived equivalent widths. Fairly substantial error bars (often 50% uncertainty is appropriate) should be attached to the numbers given in Table 2. Many more lines-of-sight need to be analyzed before quoting equivalent widths of these very weak features with confidence.

4. CORRELATIONS OF WEAK AND STRONG DIB FEATURES

Much previous work (e.g., Paper I) has shown that the the most striking cloud-to-cloud difference in DIB spectra is the varying strength ratio of the major 5780 and 5797 DIBs. Is the pattern of weak IS features dependent on the ratio of these two prominent DIBs?

Inspection of Fig. 2 suggests that the weak features at 5772.63 and 5775.70 Å practically disappear when 5780 is relatively weak. Although our sample size is small at

present, we find that the central depths of both of these weak features (measured relative to the local continuum; remember that the general shape of the 5778 DIB has been eliminated in our spectra) correlate quite well with both the central depth and equivalent width of the 5780 DIB (using measurements of the 5780 DIB either from our own data or from Table 3 of Herbig 1975). We suspect that when enough lines-of-sight are sampled the 5772 and 5775 weak DIBs will probably track the ξ vs. σ DIB "family" split discussed in Paper I. Moreover, the depths of the 5772.63 and 5775.70 weak features also correlate well with the strength of 5778 reported in Herbig's (1975) Table 3. However, the strengths of these features show no obvious correlation with the 5797 DIB. This should not be surprising, recalling again the results of Paper I that 5780 and 5797 show a quite variable ratio *as long as lightly reddened lines-of-sight are considered*.

The ratio of the 5793.05 and 5795.35 features is apparently variable, with the latter one becoming weak together with 5780 Å. We do not include 5795.35 with the two weak features discussed above because we fear that this feature may be contaminated with a Fe II line, especially in A-type stars. Other weak features which lie to the blue of the strong 5780 cannot be easily divided between these following the behavior of 5780, and those following 5797. Our spectra do not seem to support the suggestion of Jenniskens and Xavier (1993) that the 5766.08 feature is associated with the 5797 DIB. We prefer to defer a definitive statement on this question until our sample size is increased by a large amount.

In the red spectral range the ratio of 6108.2 and 6113.2 weak features in HD 23180 is clearly different than in, e.g., HD 2905, imitating that of 5780 and 5797 strong DIBs. The strength ratios of the other weak features do not appear to vary from sightline to sightline. These comments are all we can make with confidence here; we will address the correlations of features with expanded sample sets and expanded wavelength coverage in a future paper. In that work we will be able to begin gathering observed DIBs into "families" containing both strong and weak features, which may be believed to be spectra of single species. This may lead finally to better clues about the DIB carriers.

These new DIB features are far too weak to comment on the shapes of their profiles. The only possibility with our present data set is to notice their presence or absence and to determine their central wavelengths. This is due to their weakness and also the fact they are frequently blended with both weak stellar lines (especially in spectra of supergiants) and telluric features. Some residua of the telluric water vapor lines may thus change the observed profiles of weak DIBs. It is worth mentioning that many weak features, listed above, can be traced in the spectra published by Herbig (1975, 1993).

5. DISCUSSION

Jenniskens and Désert's (1993b) very long list of suggested new DIBs suggests that the absorption spectra of dark interstellar clouds contain hundreds of weak features

of unknown origin. Any consideration of physical processes in H I clouds cannot neglect the presence of this rich, absorption-line spectrum. Yet one must be cautious attributing any weak spectral feature to the family of interstellar absorptions. We suspect that their list (and the lists of others) of ISM features may be incomplete or contain features of stellar or telluric origin. This is because of the small size of analyzed samples and because of the lack of high S/N ratio spectra of lightly reddened stars—most likely to be obscured by single clouds, which may be considered as quite homogeneous environments.

The present paper shows our method of detecting weak interstellar features. As shown in Sec. 3.2, our spectra do confirm many of the features suggested by Jenniskens and Désert. However, some of their detections are either not seen in our spectra, or are most probably blended with weak stellar features, and thus must be considered as very doubtful. For example, the features at 5806.6 and 5811.7 Å, claimed to be ISM lines by Jenniskens and Désert (see Fig. 2), possibly are stellar features (Fe II; see Fig. 8). Probably some of the differences in our results and theirs ultimately can be traced to our use of much higher resolution and somewhat larger signal-to-noise ratio data in our analysis.

On the other hand we add several new findings—weak features appearing in our reddened program stars which have passed successfully our very rigorous tests of interstellar origin. Most of the added features are in the 6150 Å spectral region. We thus expect that additional weak features still await discovery.

The very high S/N ratio available in our spectra allowed us to measure the central wavelengths of the weak interstellar features in spectra of lightly reddened stars in which very narrow and symmetrical sodium lines have been observed. This facilitates the application of proper Doppler shift to the identified features. Heavily reddened and distant supergiants, in which the interstellar features are usually strong, are inviting targets for DIB discovery efforts because the DIB absorptions can become quite deep. However, we must reemphasize their relative inapplicability for this purpose; the typical multiple cloud components in these lines-of-sight create smeared DIB profiles, in which neither the central wavelengths nor the intrinsic profiles can be ascertained with certainty (as first shown by Herbig and Soderblom 1982).

The identification of the DIB carriers may depend on having a full list of DIBs together with their basic properties such as central wavelengths, relative intensities, profile details, and behavior in different types of dark clouds characterized by varied extinction properties. Since well-known strong DIBs probably do not originate with a common carrier, there is no reason to suspect that all weak DIBs will have one simple origin either. The obvious next tasks

are to complete the weak feature search throughout the visible spectral range and to perform a much more extensive correlation analysis among the DIB features. With the techniques outlined in the present paper, we estimate that weak features with depths $\geq 0.3\%$ of the continuum may be detected. This work should continue with an expanded survey of nearby stars, hopefully obscured by single, isolated clouds. In such clouds weak features may behave in different fashions, just as the well-known, strong ones do. Our Figs. 2 and 7 (see also the discussion in Sec. 4) provide preliminary indications of the style of such variations, but the complete description of the strength variations remains to be done.

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