THE ASTROPHYSICAL JOURNAL, **261**:L51–L54, 1982 October 1

DIFFUSE INTERSTELLAR BANDS TOWARD STARS WITH LOW COLOR EXCESS

C. KRISHNA KUMAR
Department of Physics and Astronomy, Howard University
AND
S. R. FEDERMAN AND PAUL A. VANDEN BOUT
Department of Astronomy and McDonald Observatory, University of Texas at Austin
Received 1982 May 3; accepted 1982 June 16

ABSTRACT

The equivalent widths of the 5780 Å and the 5797 Å diffuse interstellar bands have been measured in the spectra of stars with low color excesses [$E(B-V) \leq 0.12$]. The bands are strong where the column densities of interstellar H_2 are high [$N(H_2) \geq 10^{19}$ cm^{-2}] and weak or absent where the H_2 column density is low [$N(H_2) < 10^{17}$ cm^{-2}]. The agent responsible for the bands appears to be molecular, and defects in bulk material are ruled out as the band carrier. Abundance considerations appear to preclude gas phase molecules, suggesting molecular grain mantles as the carrier of the diffuse interstellar bands.

Subject headings: interstellar: matter — interstellar: molecules

I. INTRODUCTION

The nature of the absorbers responsible for the diffuse interstellar bands (DIBs) remains a mystery nearly five decades after their initial discovery. We do not even know whether the absorbers are gas phase molecules or dust particles, let alone their exact chemical composition and structure. Smith, Snow, and York (1977) have exhaustively reviewed the problem. We present here the initial results of an observational program which aims to determine whether the bands are due to molecules or dust.

Copernicus observations (Spitzer and Jenkins 1975) have shown that, for the lines of sight to stars with $E(B-V) \leq 0.1$, the column density of interstellar molecular hydrogen, $N(H_2)$, is either larger than 10^{19} cm^{-2} or less than 10^{17} cm^{-2}. For larger color excesses, $N(H_2)$ is generally larger than 10^{19} cm^{-2}. In the spectra of stars with low color excesses, the DIBs are unlikely to be saturated. This expectation is based on Herbig's (1975) extensive measurements of DIB strengths and their correlation with $E(B-V)$. If the H_2 column density is low, other molecules should also be rare. Observations of interstellar CO (Federman *et al.* 1980) and of CH and CH^+ (Federman 1982) confirm this expectation. Therefore, a comparison of DIB strengths in the spectra of stars with low and high $N(H_2)$, but with the same low $E(B-V)$, can discriminate between molecular and dust origins of the DIBs.

II. OBSERVATIONS

We have measured the strengths of the DIBs at 5780.45 Å and 5797.03 Å in the spectra of eight and five stars with low color excesses respectively. The stars that we observed are listed in Table 1. The $N(H_2)$ values are from Savage *et al.* (1977). The observations were made on 1982 January 12 at the coudé focus of the McDonald 2.7 m telescope. A Cu_2SO_4 filter and an additional interference filter were used to eliminate unwanted orders of the grating spectra. The peak transmission of the interference filter was at 5780 Å and the bandpass of the filter was 80 Å (FWHM). The transmission was nearly constant within the bandpass. The spectra were recorded using the 1024 element silicon photodiode array (Vogt, Tull, and Kelton 1978). The dispersion of the spectra was 4.4 Å mm^{-1}; the spectral resolution was 0.22 Å (2 diodes). According to Herbig (1975), the FWHM of the 5780 Å band is 2.6 Å and that of the 5797 Å band is 1.3 Å. As the results below show, the spectral resolution was sufficient to test for the reality of the observed bands. A Fe-Ne lamp was used as the source for the comparison spectrum.

The correlation measured by Herbig (1975) between $E(B-V)$ and the equivalent width of the 5780 Å band predicts that, for $E(B-V) = 0.1$, the expected central depth of the band is about 2%. Our aim, therefore, was to measure a band depth of 1% at the 3 σ level to establish its reality. To meet this criterion, a signal-to-noise ratio of 300 had to be attained. The integration time on each star was such that the ratio of signal to random noise (photon count fluctuations and readout noise) exceeded 600. However, systematic errors in the readout process and possibly weak stellar lines generally degraded the signal-to-noise ratio to 300. Figure 1 shows the spectra in the 5780 Å and 5797 Å wavelength regions. The data points are 0.22 Å apart, and the

TABLE 1

EQUIVALENT WIDTHS OF DIBs

STAR	$E(B-V)$	LOG $N(H_2)$ (cm^{-2})	W_λ (5780) (mÅ) Measured	Expected	W_λ (5797) (mÅ) Measured	Expected
ε Per	0.09	19.53	49 ± 3	...	15 ± 3	...
λ Ori	0.12	19.11	45 ± 3	...	18 ± 3	...
γ Cas	0.08	17.51	18 ± 3	36	...	...
δ Ori	0.07	14.68	8 ± 4	31	1 ± 3	11
ε Ori	0.08	16.51	25 ± 3	36	1 ± 3	12
15 Mon ...	0.07	15.55	19 ± 3	31	...	...
α Leo......	0	15	3 ± 3	0	0 ± 3	0
ρ Leo......	0.08	15.61	3 ± 3	36	...	...

intensities are the average signal recorded by two adjacent diodes. The 1 σ rms error in the continuum is roughly equivalent to the diameter of the data points. The telluric feature seen to the left of the 5780 Å line is actually a blend of two atmospheric lines at 5779.965 Å and at 5780.157 Å. In our spectra, the equivalent width, W_λ, of the feature is about 5 mÅ. In the solar spectrum, the combined W_λ of the two lines is 5.5 mÅ.

The measured equivalent widths of the bands are given in Table 1. The uncertainties in W_λ were computed from the measured noise in the smoothed spectra. In most cases, the rms value of the fluctuations in the continuum level was about 3×10^{-3}. For the stars in common with the study of Wu (1972), the two determinations of W_λ agree to within the somewhat larger errors stated there.

III. RESULTS

It is quite obvious from Figure 1 that, in the spectra of the two stars with high H_2, namely λ Ori and ε Per, the band is much stronger than in the spectra of the other stars. If the band were due to dust, then W_λ would be expected to be proportional to $E(B-V)$. Assuming a relation of the form $W_\lambda = aE(B-V) + b$, Herbig (1975) finds $b > 0$, whereas Snell and Vanden Bout (1981) find $b < 0$ from measurements of heavily reddened stars. The latter predict $W_\lambda = 0$ for $E(B-V) \leq 0.14$, whereas Herbig predicts $W_\lambda = 160$ mÅ for $E(B-V) = 0$. Our results differ appreciably from either of these relationships; we adopted $b = 0$ to investigate the possibility that W_λ is strictly due to dust. In Table 1 we list the W_λ^* expected for each direction with little H_2, where

$$W_\lambda^* = \frac{[W_\lambda(\lambda\text{ Ori}) + W_\lambda(\varepsilon\text{ Per})] \cdot E_{B-V}(\text{Star})}{[E_{B-V}(\lambda\text{ Ori}) + E_{B-V}(\varepsilon\text{ Per})]}.$$

It is seen that in all cases the measured W_λ is significantly less than the expected W_λ^*. We observed α Leo as a check for spurious lines that might be produced by instrumental or other effects. The spectrum of α Leo shows no such spurious lines. Observations of heavily reddened stars (e.g., Herbig 1975) have shown that the measured strength of the band can differ by up to a factor of 2 from the mean and, hence, the fact that the measured equivalent widths of the bands are different from the expected values is not surprising. However, it is significant that (1) the band is weaker than expected in all low H_2 stars, and (2) the band is very weak or absent in the spectrum of ρ Leo and δ Ori.

Figure 1 and Table 1 show that the 5797 Å band is present only in the spectra of λ Ori and ε Per. The measured upper limit to W_λ in δ Ori and ε Ori is at least a factor of 5 less than the expected value. Furthermore, this band is much weaker than the band at 5780 Å for ε Ori. For the remaining stars with little H_2 along the line of sight, the data lack sufficient signal-to-noise ratios to be of use in the analysis.

IV. DISCUSSION

Our results show that, for $E(B-V) \leq 0.1$, there is no simple relation between W_λ and color excess but that W_λ does depend on molecular column density. Our data thus substantiate the findings of Smith *et al.* (1981) and Herbig and Soderblom (1982) regarding a molecular origin for the λ6196 and λ6613 bands respectively. Our measurements strengthen the conclusion of Smith *et al.* (1981) by definitely proving that, for directions with low $E(B-V)$, the directions with substantial H_2 content have significantly stronger bands than directions with little H_2. These results suggest that the band is not produced by the core of the dust particle, via a mechanism, for example, like that suggested by Purcell and Shapiro (1977). However, the band may not be due to a molecule in the gas phase either. Let N be the column density of the absorber calculated from the measured W_λ. We find that the ratio $N/N(H_2)$ has the values $10^{-8}/f$ for λ Ori, $4 \times 10^{-9}/f$ for ε Per, and $2 \times 10^{-6}/f$ for ε Ori, where f is the usual oscillator strength. If the absorber is a small molecule, the ratios are rather

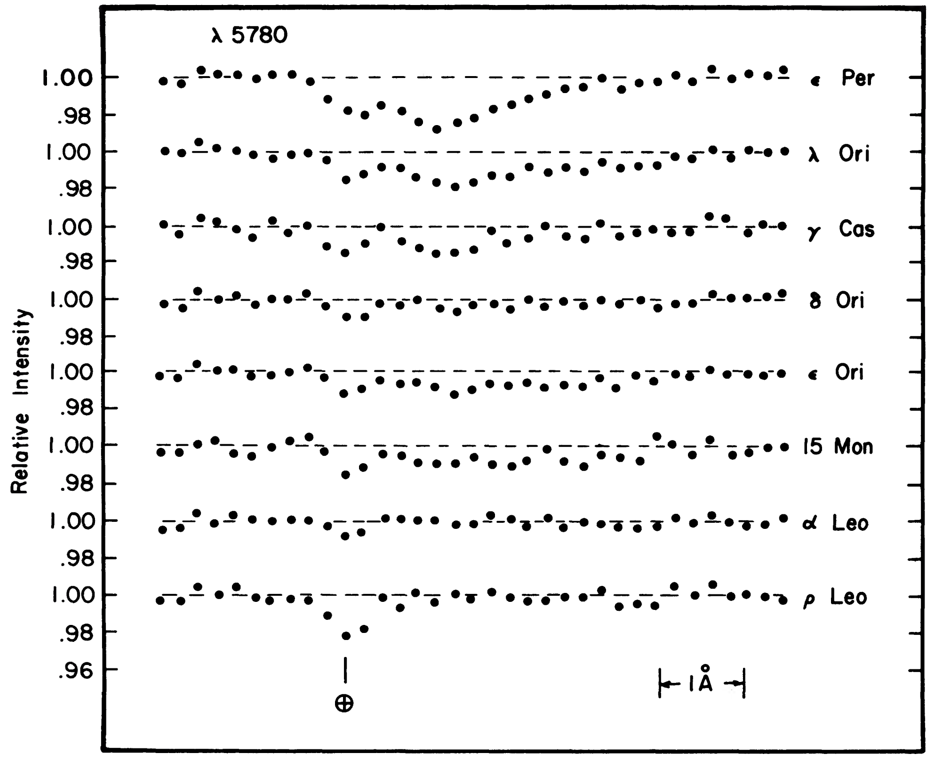

FIG. 1*a*

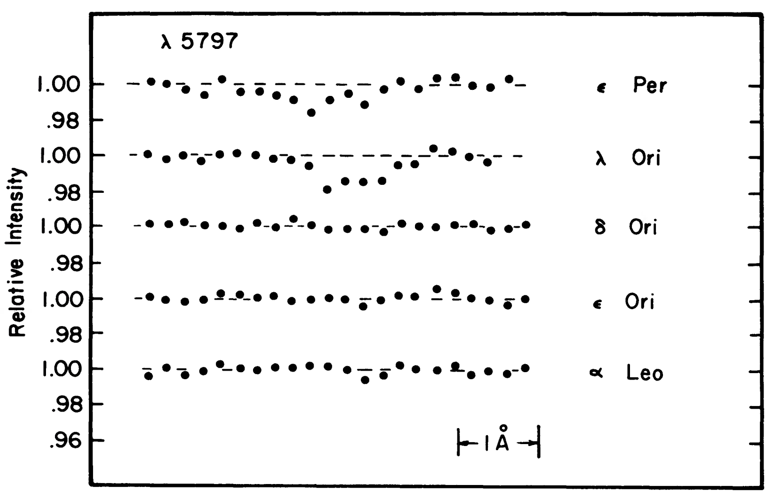

FIG. 1*b*

FIG. 1.—(*a*) Spectra recorded near λ5780 for eight stars of $E(B-V) \lesssim 0.1$ with widely varying column densities of interstellar H_2. The spectra are aligned in wavelength by the telluric feature at 5780.06 Å. (*b*) Same as (*a*) for the λ5797 region. Here, the leftmost data point corresponds to 5795.16 Å.

large for diffuse clouds since $f \leq 1$. Observations of CO in diffuse clouds (Federman *et al.* 1980) give $N(\text{CO})/N(\text{H}_2)$ values of 3×10^{-7} for ε Per and 4×10^{-5} for ε Ori. These data, although limited, seem to indicate that the ratio $N/N(\text{CO}) \geq 0.01$. This is a rather large ratio, particularly when it is realized that a molecular carrier *in the gas phase* must have more than three atoms because of the lack of structure in the bands when observed at high resolution (Danks and Lambert 1976; Snell and Vanden Bout 1981). It is extremely unlikely that such abundances of heavy molecules could be achieved in these tenuous low-extinction clouds.

Douglas (1977) and Smith, Snow, and York (1977), however, argued that internal conversion can stabilize large molecules against photodestruction. Production paths for the large molecules are very uncertain at the present time. A search for cyanopolyynes (HC_nN; n odd) in diffuse clouds would address this point.

The observed correlation between DIB strength and H_2 column density indicates that the DIBs must have something to do with the presence of molecules. It is possible, therefore, that the band arises in a molecular mantle on the grain by accretion of atoms and lighter, more abundant molecules. Snow and Cohen (1974) argued against grain mantles as the source of DIBs based on observations of DIBs toward much more highly reddened stars. In the ρ Oph cloud the band strengths decreased with increasing total extinction, selective absorption, and grain size. The possibility exists, however, that the bands originate from the interaction of the molecular complex with impurity sites on grain surfaces. As the grain mantle increases in size, the strength of this interaction may be suppressed, accounting for the data of Snow and Cohen for denser clouds. Moreover, the precise wavelengths for the DIBs (e.g., Herbig and Soderblom 1982) and the similar line shapes for different lines of sight (e.g., Herbig 1975) may result from a distribution of impurity sites which depends on the binding energy of the site.

We thank W. H. Smith for his constructive comments. This research is supported in part by NSF grant AST 81-15248 (C. K. K.) and a grant from the Robert A. Welch Foundation (P. V. B).

REFERENCES

Danks, A. C., and Lambert, D. L. 1976, *M.N.R.A.S.*, **174**, 571.
Douglas, A. E. 1977, *Nature*, **269**, 130.
Federman, S. R. 1982, *Ap. J.*, **257**, 125.
Federman, S. R., Glassgold, A. E., Jenkins, E. B., and Shaya, E. J. 1980, *Ap. J.*, **242**, 545.
Herbig, G. 1975, *Ap. J.*, **196**, 127.
Herbig, G. H., and Soderblom, D. R. 1982, *Ap. J.*, **252**, 610.
Purcell, E. M., and Shapiro, P. R. 1977, *Ap. J.*, **214**, 92.
Savage, B. D., Bohlin, R. C., Drake, J. F., and Budick, W. 1977, *Ap. J.*, **216**, 291.
Smith, W. H., Snow, T. P., Jura, M., and Cochran, W. D. 1981, *Ap. J.*, **248**, 128.
Smith, W. H., Snow, T. P., and York, D. G. 1977, *Ap. J.*, **244**, 844.
Snell, R. L., and Vanden Bout, P. A. 1981, *Ap. J.*, **244**, 844.
Snow, T. P., and Cohen, J. G. 1974, *Ap. J.*, **194**, 313.
Spitzer, L, and Jenkins, E. B., 1975, *Ann. Rev. Astr. Ap.*, **13**, 133.
Vogt, S. S., Tull, R. C., and Kelton, P. 1978, *Appl. Optics*, **17**, 574.
Wu, C-C. 1972, *Ap. J.*, **178**, 681.

S. R. FEDERMAN and PAUL A. VANDEN BOUT: Department of Astronomy, University of Texas, Austin, TX 78712

C. KRISHNA KUMAR: Department of Physics and Astronomy, Howard University, Washington, D.C. 20059