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OBSERVATIONS OF NARROW DIFFUSE INTERSTELLAR BANDS TOWARD STARS WITH LOW REDDENING

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ABSTRACT

Measurements of the narrow diffuse interstellar bands at λλ5780, 5797, and 6613 are presented for 22 stars with $E(B-V) \lesssim 0.1$. For this low amount of reddening the lines of sight have molecular column densities that are largely either greater than 10^{18} cm^{-2} or less than 10^{17} cm^{-2}. The bands are observed to be stronger where $N(H_2)$ is large. The correlation with H_2 content suggests a molecular origin for the bands, but abundance considerations argue against a gas-phase carrier. An interaction between impurity sites and molecular complexes on grain surfaces is suggested as an origin of the diffuse interstellar bands that is consistent with these data and other observational constraints. A limited set of data for the 6284 Å band does not contradict this picture. All of the observed bands occur at the velocity of the strongest atomic component, indicating that the bands do not originate in molecules sputtered from grains by high-velocity gas.

Subject headings: interstellar: abundances — interstellar: grains — interstellar: matter — interstellar: molecules

I. INTRODUCTION

The origin of the diffuse interstellar bands (DIBs) remains an unsolved problem in astronomical spectroscopy. Traditionally, the DIB carrier has been identified with either the interstellar grains or gas-phase molecules. In a summary of the problem, Smith, Snow, and York (1977) presented arguments both for and against the dust-particle origin and the gas-phase molecular origin of the bands. Observations have recently been made to decide between the dust and the gaseous molecule hypotheses. Herbig and Soderblom (1982) have looked for rotational fine structure in the 6195 Å, 6613 Å, 6993 Å, and 7223 Å bands, the presence of which would indicate a molecular origin, and found none. Earlier studies by Danks and Lambert (1976) and Snell and Vanden Bout (1981) searched for fine structure in the 5780 Å band and found no evidence for it.

Another approach to the problem is to measure the strengths of the DIBs in the spectra of stars with nearly the same reddening but vastly different column densities of interstellar molecular hydrogen. Results from the *Copernicus Observatory* (Savage *et al.* 1977) show that for most lines of sight with low reddening [$E(B-V) \lesssim 0.1$ mag] the column density of interstellar H_2 is either greater than 10^{19} cm^{-2} or less than 10^{17} cm^{-2}. Smith *et al.* (1981) measured the equivalent widths of the narrowest known band at 6196 Å in the spectra of 26 stars with low and high $N(H_2)$ but varying amounts of reddening and concluded that the band was probably produced by molecules. We measured the 5780 Å and the 5797 Å bands (Kumar, Federman, and Vanden Bout 1982, hereafter Paper I) in the spectra of nine stars with low and high $N(H_2)$ and $E(B-V) \sim 0.1$ mag and concluded that the 5780 Å band was probably produced in molecules located in grain mantles. Meyer (1983) measured the strengths of the 5780 Å band in the spectra of five stars with low $N(H_2)$ *only* and concluded that interstellar grains produce the band.

Since the publication of Paper I, measurements have been made of the strengths of the 5780 Å and 5797 Å bands in the spectra of 13 more stars with low and high $N(H_2)$. The 6613 Å band was also observed in the spectra of 14 stars with differing $N(H_2)$, and the 6284 Å band was observed toward a few stars. The observations are described in § II; comments are made in § III on individual cases, and the empirical results are discussed. The implications of the observational results for the origin of the DIBs are discussed in § IV. We suggest that a *combination* of molecules and grains is responsible for the DIBs, whereby the bands are produced by an interaction between adsorbed molecules and impurity sites on the surfaces of grains.

II. OBSERVATIONS

The observations were made during 1982 June, November, and December with the coudé spectrograph of the 2.7 m telescope at McDonald Observatory. A silicon photodiode array (Vogt, Tull, and Kelton 1978) was used as a detector. A grating blazed at 6000 Å was used in first order with dispersions of 4.36, 4.31, and 4.28 Å mm^{-1} at λλ5780, 6284, and 6613, respectively. The resolving power was approximately 30,000. The telluric oxygen band at λ6276 makes it difficult to obtain high-quality data for the diffuse band at λ6284, and only five measurements of this band were made. The wavelength scales were determined from spectra of an Fe/Ne lamp. Second-order spectra of wavelengths shortward of 5150 Å were blocked with an OG 515 Schott filter. The array was exposed to a tungsten lamp after each observation, and the stellar data were divided by the lamp data to produce flat continua in the final spectra.

The spectra were first reduced with the software package for the silicon photodiode array detector (Vogt, Tull, and Kelton 1978). Then a program that produces flat continua and removes systematic instrumental effects was applied to the data. For the 6284 Å data only, the stellar spectra were also divided by the spectrum of ρ Leo in an attempt to remove the telluric band. The ρ Leo spectrum was used because even strong DIBs are weak toward ρ Leo, making it reasonable to assume that λ6284 is not present. Examples of the reduced spectra of the bands at λλ5780, 5797, and 6613 are shown in

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Figure 1; an average over two diodes is represented by each point. The thin lines labeled IS indicate the velocities where strong interstellar absorption from atomic species occurs (see, e.g., Hobbs 1974). Lines labeled T indicate the presence of telluric features. The rest velocities of the DIBs (Herbig 1975) are indicated by lines labeled L. The spectrum for θ^1 Ori C is included as an example of λ5780 toward a more heavily reddened star.

Table 1 lists the measured band strengths, as well as $E(B-V)$ and $N(H_2)$ from Savage *et al.* (1977), for each direction. When a band was clearly present in the spectrum of a star, the equivalent width W_λ was measured with a planimeter. When necessary, W_λ for telluric features was subtracted from the measured W_λ for the bands. The errors quoted in Table 1 for the values of W_λ were determined in the following manner: (1) the root-mean-square error ϵ_{rms} was taken to be one-fourth the peak-to-peak noise in the continuum; and (2) the error in equivalent width was calculated by multiplying ϵ_{rms} by the square root of the number of diodes in the wavelength interval and by the reciprocal dispersion ($\sim$0.11 Å per diode). A typical value for ϵ_{rms} was 3×10^{-3}. If no band was apparent, the residual area over a wavelength interval corresponding to the extent of the band observed in other directions was measured.

Our observations of ρ Leo require comment. We have reported (Paper I) equivalent widths for $\lambda\lambda$5780 and 5797 consistent with zero (3 ± 3 mÅ) for this line of sight, while Meyer (1983) has reported significantly larger equivalent widths of 24 ± 4 mÅ and 9 ± 3 mÅ, respectively. Because of the discrepancies, we reobserved ρ Leo and detected absorption features near the interstellar velocity for the star (see Fig. 1). The new measurements give $W_\lambda(5797) = 15 \pm 2$ mÅ and $W_\lambda(5797) = 14 \pm 2$ mÅ, within 2 σ of Meyer's measurements. However, our spectrum of ρ Leo near λ6613 is contaminated by a stellar feature, and Blades and Somerville (1977) have concluded that the same is true for λ4430. We note that our measurements of λ5780 for 20 Tau and θ^1 Ori C are very likely contaminated by a stellar line as well.

The stars α Leo and σ Sgr were observed to test for spurious instrumental effects. Because these stars have zero reddening and very low $N(H_2)$ ($< 10^{15}$ cm^{-2}), no DIBs are expected in their spectra. The observational results reported here testify to the absence of instrumental effects.

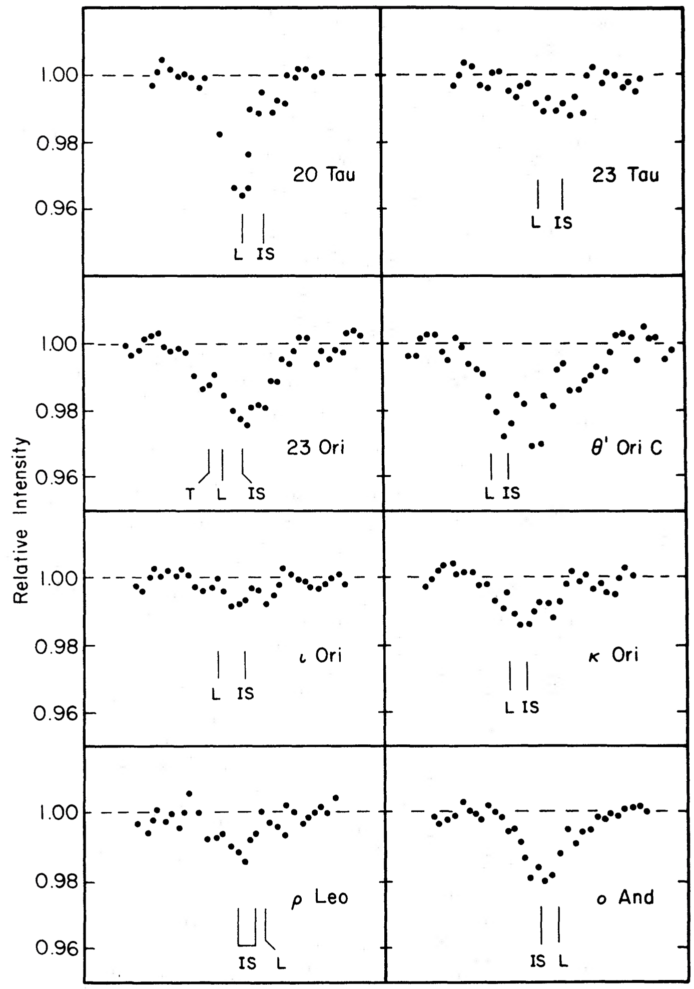

FIG. 1*a*

FIG. 1.—Examples of spectra for the narrow diffuse interstellar bands, where each point is the sum of two adjacent diodes (0.2 Å separates the points along the horizontal axis): (*a*) λ5780; (*b*) λ5797; and (*c*) λ6613. The rest velocities (L), velocities of strong interstellar components (IS), and, when appropriate, telluric features (T) are shown.

III. RESULTS

a) *5780 Å Band*

The equivalent widths of the 5780 Å band, given in Table 1, show that this band is stronger where $N(H_2)$ is large than where it is small. For the 12 lines of sight with $N(H_2) \geq 10^{18}$ cm^{-2}, the $W_\lambda(5780)$ values range from 18 to 120 mÅ, with a mean of 43 mÅ. The range of the values of W_λ in the spectra of the eight stars with $N(H_2) \leq 10^{17}$ cm^{-2} is from 8 to 25 mÅ, with an average of 13 mÅ. The α Leo and σ Sgr data, which were used to check for instrumental effects, were not included in the average. While it is evident that on the average the band is stronger where the column density of H_2 is larger than where $N(H_2)$ is low, it should be noted that a difference of about three orders of magnitude in the $N(H_2)$ value alters $W_\lambda(5780)$ by less than an order of magnitude. This tendency of $W_\lambda(5780)$ to vary approximately as log $N(H_2)$ may be meaningful for purposes of understanding the origin of the DIB only if it is not due to differences in the reddening of the two groups of stars.

The mean $E(B-V)$ of the eight stars in the low $N(H_2)$ set is 0.070 mag, and the mean for the 12 stars in the high $N(H_2)$ set is 0.073 mag. However, four stars in the high $N(H_2)$ set are in reflection nebulae and may have reddening that is measured systematically low. If these stars (δ Per, 20 Tau, η Tau, and 23 Tau) are omitted, the mean $E(B-V)$ for the eight remaining stars is 0.100 mag, slightly larger than the mean for the low H_2 group. The mean values of $E(B-V)$ for the two groups are in the ratio of 1.4 to 1, whereas the corresponding mean $W_\lambda(5780)$ values are in the ratio of 3.5 to 1. If this DIB has a grain origin independent of the presence of molecules, the two ratios should be the same. Is it possible that the observed different values for these ratios are caused by errors in the measured reddening of the stars? Errors in $E(B-V)$ could, of course, lead to an error in the ratio of the mean $E(B-V)$ values of the two groups. If this were the sole cause of the difference, then, either the true mean $E(B-V)$ of the low $N(H_2)$ group is 0.028 mag, instead of the observed

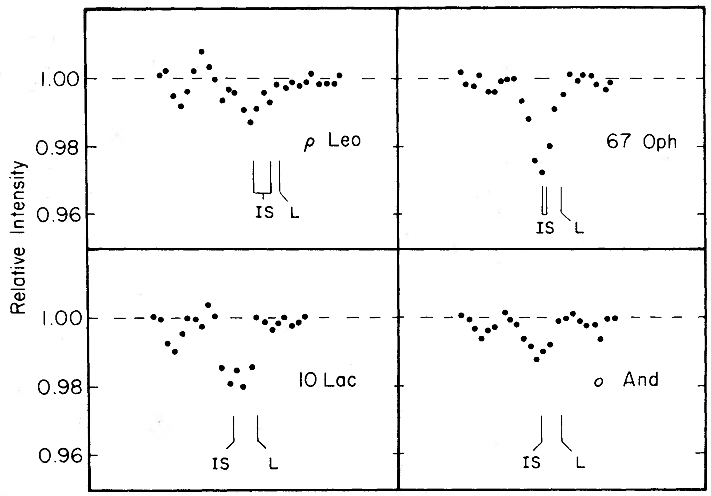

FIG. 1b

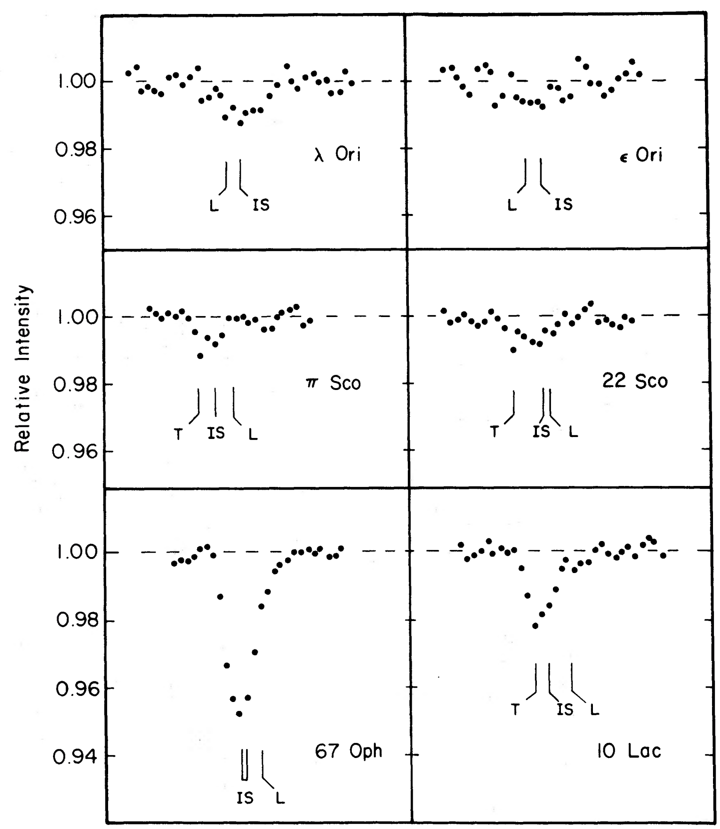

FIG 1c

0.07 mag, or the true mean $E(B-V)$ of the high $N(H_2)$ group is 0.25 mag, instead of the observed 0.10 mag. The latter possibility can be ruled out without further discussion. The uncertainty in $E(B-V)$ of a star due to errors in the photometric measurements is typically 0.02 mag, and, hence, the uncertainty in the mean of a group of eight stars will be about 0.008 mag. It is clear that the mean of the low $N(H_2)$ group has a very small probability of being as low as 0.028 mag due to random errors only. In considering the group means, the only source of systematic error known to effect the sampled stars, namely, contamination from reflection nebulae, has been eliminated by discarding the affected stars.

Meyer (1983) was of the opinion that the differences in the $W_\lambda(5780)$ values between the low and high $N(H_2)$ samples, noted earlier in Paper I, could be ascribed to uncertainties in the $E(B-V)$ of the stars. The larger body of data presented here shows: (1) the $W_\lambda(5780)$ value varies approximately as log $N(H_2)$; (2) uncertainties in $E(B-V)$ are sufficiently small to rule out a $W_\lambda(5780)$ variation due to dust alone; and (3) as mentioned by Meyer (1983), the band is definitely detected

TABLE 1

DIFFUSE INTERSTELLAR BAND MEASUREMENTS

HD	Star	$E(B-V)$	$W_\lambda(5780)$ (mÅ)	$W_\lambda(5797)$ (mÅ)	$W_\lambda(6284)$ (mÅ)	$W_\lambda(6613)$ (mÅ)	$\log N(H_2)$ (cm^{-2})
5394	γ Cas	0.08	18 ± 3	...	...	3 ± 1	15.00[a]
22928	δ Per	0.01	19 ± 2	-1 ± 2	...	3 ± 2	19.30
23408	20 Tau	0.00	48 ± 2[b]	3 ± 2	...	...	19.75
23480	23 Tau	0.08	19 ± 2	-2 ± 2	...	...	20.12
23630	η Tau	0.00	12 ± 2	5 ± 1	...	...	19.54
24760	ϵ Per	0.09	49 ± 3	15 ± 3	...	20 ± 1	19.53
34149	23 Ori	0.11	55 ± 3	3 ± 2	...	...	18.00[c]
36486	δ Ori	0.07	8 ± 4	1 ± 3	...	3 ± 1	14.68
36861	λ Ori	0.12	45 ± 3	18 ± 3	...	19 ± 2	19.11
37043	ι Ori	0.07	13 ± 2	-1 ± 2	...	...	14.69
37128	ϵ Ori	0.08	25 ± 3	1 ± 3	...	7 ± 2	16.57
38771	κ Ori	0.07	23 ± 1	3 ± 1	...	...	15.68
47839	15 Mon	0.07	19 ± 3	...	...	...	15.55
87901	α Leo	0.00	3 ± 3	0 ± 3	...	-4 ± 2	<14.98
91316	ρ Leo	0.08	15 ± 2	14 ± 2	...	[d]	15.61
143018	π Sco	0.08	23 ± 2	4 ± 2	31 ± 1	8 ± 1	19.32
148605	22 Sco	0.10	38 ± 2	4 ± 2	34 ± 3	5 ± 2	18.74
149438	τ Sco	0.06	6 ± 1	3 ± 1	0 ± 2	0 ± 1	14.50
164353	67 Oph	0.12	119 ± 2	24 ± 1	...	53 ± 1	20.26
175191	σ Sgr	0.00	-3 ± 1	-2 ± 1	...	0 ± 1	<14.00
214680	10 Lac	0.11	57 ± 3	17 ± 2	...	18 ± 1	19.22
217675	o And	0.05	43 ± 2	43 ± 2	11 ± 1	18 ± 2	19.67

[a] $N(H_2)$ from Ferlet *et al.* 1980.
[b] See text.
[c] $N(H_2)$ from Frisch and Jura 1980.
[d] Contaminated with stellar feature.

even in lines of sight with low $N(H_2)$ as long as $E(B-V)$ is not zero. Meyer could not have detected the slow increase in $W_\lambda(5780)$ with $\log N(H_2)$ because he did not observe lines of sight with high $N(H_2)$. Therefore, it is concluded that the 5780 Å band is present even where $N(H_2)$ is low but is stronger where $N(H_2)$ is high. Is this dependence on $N(H_2)$ present even if a linear dependence on $E(B-V)$ is assumed? In Figure 2 the equivalent widths of the 5780 Å band, normalized to unit $E(B-V)$, are plotted against the corresponding $\log N(H_2)$ values. The increase with $\log N(H_2)$ is evident.

b) 5797 Å *Band*

The 5797 Å band is weaker than the 5780 Å band. The data in Table 1 on its strength in the spectra of 20 stars yield only one clear result: The band is present only if $N(H_2) \geq 10^{19}$ cm^{-2}. It is also absent in the spectra of π Sco and 22 Sco even though the $N(H_2)$ values toward these stars are high. The line of sight toward π Sco is well known, however, for showing weak interstellar lines of all species atomic and molecular relative to the amount of molecular hydrogen (Hobbs 1974; Federman 1982). The mean $W_\lambda(5797)$ of the seven stars observed with large $N(H_2)$, excluding the stars in reflection nebulae, is 13 mÅ. The mean $W_\lambda(5797)$ is 8.3 mÅ with the inclusion of the four stars in reflection nebulae. The observed mean for the low $N(H_2)$ group is indistinguishable from 0 mÅ. If $W_\lambda(5797)$ was strictly proportional to $E(B-V)$, then the mean equivalent width for the low $N(H_2)$ group would be 9 mÅ. The present observations are capable of detecting this equivalent width in a sample of 10 stars with confidence; the strength of the $W_\lambda(5797)$ is not proportional to $E(B-V)$ only. If the strength of the band in the low $N(H_2)$ groups was 3.5 times less than in the high $N(H_2)$ group, as was the case with the 5780 Å band, the expected mean of $W_\lambda(5797)$ would be 4 mÅ, which is not detectable with confidence. Therefore, the observational results indicate that the strength of the 5797 Å band varies at least as $\log N(H_2)$, but a faster variation cannot be excluded. Variation with $E(B-V)$ only is unlikely.

c) 6613 Å *Band*

The observational results of 14 stars for the 6613 Å band are practically the same as those for the 5797 Å band (see Table 1). This band appears to be about as strong as the 5797 Å band in most cases except in the spectrum of 67 Oph, where it is twice as strong. As in the case of the 5797 Å band, the variation of the strength of the 6613 Å band cannot be totally attributed to changes in $E(B-V)$, but the strength

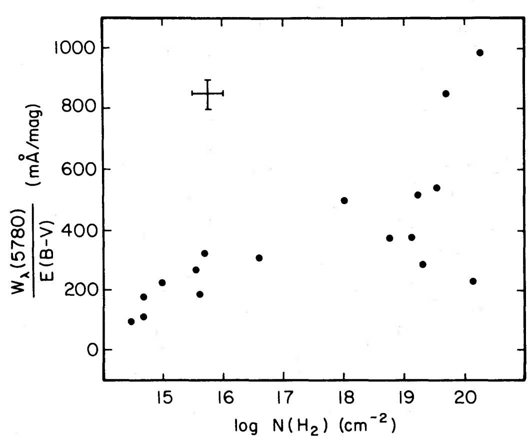

FIG. 2.—Normalized equivalent widths, $W_\lambda/E(B-V)$, vs. $\log N(H_2)$ for the λ5780 band. Data only for directions with $E(B-V) \sim 0.1$ are displayed.

does depend on $N(H_2)$ and does vary with log $N(H_2)$ at least as rapidly as does the strength of the 5780 Å band, possibly faster.

In summary, the empirical results are: (1) the equivalent widths of the bands at $\lambda\lambda$5780, 5797, and 6613 depend on the column density of interstellar H_2; (2) dependence of the band strengths on $E(B-V)$ alone is excluded, (3) $W_\lambda(5780)$ varies approximately as log $N(H_2)$; and (4) the strengths of the other two bands vary at least as rapidly as log $N(H_2)$. The observations of the 6196 Å band by Smith *et al.* (1981) show that this band's behavior is similar to that of the 5797 Å and 6613 Å bands discussed here.

d) 6284 Å *Band*

Measurements of the band at 6284 Å were attempted, but the telluric oxygen band in the part of the spectrum makes quantitative analysis difficult. The spectrum of ρ Leo was divided into the spectrum of the other stars to alleviate the problem. As discussed above, the direction toward ρ Leo shows little or no absorption due to DIBs. The direction toward τ Sco does not show appreciable absorption for the other bands, so little absorption is expected for λ6284. A small amount of absorption, ≤ 5 mÅ, may be masked by the telluric features. When the λ6284 result for τ Sco [$N(H_2) < 10^{18}$ cm^{-2}] is compared with directions with a large H_2 content, namely, π Sco, 22 Sco, and o And, the band toward τ Sco is significantly weaker, even including a systematic uncertainty of 5 mÅ. Thus, although only qualitative, the results for the 6284 Å band are consistent with the other observed bands.

IV. DISCUSSION

It is evident from the results of the previous section, that the origin of the DIBs at $\lambda\lambda$5780, 5797, and 6613 is related to the column density of molecular hydrogen. A similar conclusion was reached by Smith *et al.* (1981) with respect to the 6196 Å band. If these DIBs were due to an absorbing molecule in the gas phase, its concentration and, hence, its column density are expected to vary linearly or to some higher exponent of $N(H_2)$. The theoretical chemistry and the observations of carbon monoxide (Federman *et al.* 1980) in diffuse clouds, for instance, bear out this expectation. There is no known case of any molecule whose concentration is expected to vary as slowly as log $N(H_2)$. The approximately logarithmic dependence of $W_\lambda(5780)$ on $N(H_2)$ suggests that the absorbing molecule is not in the gas phase. A possible site for the 5780 Å absorber is in the mantles of the dust grains, originally suggested by van de Hulst (1949); Duley and McCullough (1977) have presented a more recent discussion.

Abundance considerations argue against a gas-phase molecular origin for the DIBs. It is possible to estimate the abundance of the molecular species responsible for the bands by assuming the lines are optically thin. The column density $N(X)$ of the DIB carrier X is given by

$$N(X) = 1.13 \times 10^{17} W_\lambda/\lambda^2 f \text{ cm}^{-2} ,$$

where W_λ is in mÅ, λ is the wavelength of the absorption band in angstroms, and f is the oscillator strength for the transition. For the 5780 Å band alone, $N(X) \gtrsim 7\text{–}33 \times 10^{10}$ cm^{-2} if $f \lesssim 1$. Using the H_2 data in Table 1, we see that the abundance relative to H_2 is quite substantial: $N(X)/N(H_2) \gtrsim 10^{-9}$ to 10^{-6}, where the largest abundances are found for directions with detectable $W_\lambda(5780)$ but little H_2. This abundance can be compared with that for CO in similar clouds (Federman *et al.* 1980): $N(CO)/N(H_2) \sim 10^{-7}$ to 10^{-5}. The abundance of the molecular species responsible for the band at λ5780 is *at least* 1%–10% of the abundance of CO, the most abundant molecule after H_2 in most diffuse clouds.

The high-resolution studies of the 5780 Å band (Danks and Lambert 1976; Snell and Vanden Bout 1981) and of the 6613 Å band (Herbig and Soderblom 1982) show no fine structure within these bands. The lack of structure leads to the conclusion that if the band originates from a gas-phase molecular species, the molecular species has at least three heavy atoms. Gas-phase molecules containing three or more heavy atoms are not expected to be very abundant in diffuse clouds (e.g., Black and Dalgarno 1977), certainly not 1%–10% as abundant as CO.

Douglas (1977) and Smith, Snow, and York (1977) have argued that a significant abundance of large gas-phase molecules is in principle possible because internal conversion can stabilize such molecules against photodissociation. On the other hand, no molecule with three or more atoms of any kind has been observed optically in diffuse clouds, although Snow and Smith (1981) have searched for H_2O absorption in the ultraviolet and have reported the presence of a (1.8 σ) feature at the correct wavelength. Clegg and Lambert (1982) have reported an upper limit to the abundance of C_3 in diffuse clouds: $N(C_3)/N(H+H_2) < 10^{-9}$.

Molecules with several heavy atoms have been detected in absorption at radio wavelengths against the continuum source Cas A, namely, HC_5N and HC_7N (Bell, Feldman, and Matthews 1981) and C_4H (Bell, Feldman, and Matthews 1983). These authors argue that these molecules are located in diffuse clouds along the Cas A line of sight. Other molecules, characteristic of *dense* interstellar clouds, have been detected toward Cas A (Encrenaz *et al.* 1980; Linke, Stark, and Frerking 1981). Further observations have been made in an attempt to determine the density of the clouds (Batrla, Wilson, and Martin-Pintado 1983; Cernicharo, Guélin, and Bujarrabal 1984), but these studies have produced conflicting results. Although these results present intriguing possibilities for the origin of the DIBs, we conclude that the detection of large molecules in *diffuse* clouds has yet to be demonstrated.

Finally, Smith, Snow, and York (1977) suggested that sputtering of grains in high-velocity gas may release significant amounts of "large molecules." Our measurements seem to rule out the possibility that these large molecules produce the DIBs because the observed DIBs occur at the velocity of the strongest atomic components (see Fig. 1).

The correlation between the strength of certain DIBs and $N(H_2)$ is naturally explained if the DIB carrier lies in grain mantles because H_2 is produced on grain mantles. The surfaces of grains are expected to have impurity sites that can interact with molecules formed or adsorbed on the grain surface. The interaction between surface and molecule naturally leads to broadened lines. If only one heavy atom per molecular complex is required, there is no abundance problem because the carrier column density derived from summing all DIBs is less than 1% of the gas-phase column densities of carbon, oxygen, and nitrogen nuclei (Smith, Snow, and York 1977). However, it must be pointed out that the precise wavelengths for the DIBs (e.g., Herbig and Soderblom 1982) and the similar line shapes from one line of sight to another (e.g., Herbig 1975) do pose a severe problem for this model, requiring a limited number of kinds of impurity sites (e.g., tetrahedral, octahedral, etc.), each with a specific binding energy.

The observations of Snow and Cohen (1974) that the strength of $\lambda\lambda$4430, 5780, and 5797 per magnitude of reddening decreases with extinction in the ρ Oph cloud do not rule out this mechanism. The larger grain size observed in the ρ Oph cloud arise in part from accretion of gas-phase species onto grain surfaces. The presence of additional monolayers of adsorbed gas weakens the strength of DIBs, produced by the mechanism suggested here, by reducing the binding to the surface site (Watson 1975).

We note that the results of Martin and Angel (1974), setting limits to the variation of the polarization across the $\lambda\lambda$4430 and 5780 bands in a few lines of sight, imply that the origin of DIBs is not associated with the grains that produce visible wavelength extinction. This means that the DIB-producing mantles must be found on the surfaces of another population of grains.

V. CONCLUSIONS

An extensive set of measurements of the narrow diffuse interstellar bands at $\lambda\lambda$5780, 5797, and 6613 was obtained for directions with $E(B-V) \sim 0.1$. The strength of each band is larger by factors of 2–3 for directions with $N(H_2) \gtrsim 10^{18}$ cm^{-2} when compared with directions with $N(H_2) < 10^{18}$ cm^{-2}. Thus, molecular species appear to be responsible for the bands. Abundance considerations and the slow dependence of DIB strength on $N(H_2)$ argue against a gas-phase molecular carrier. Interactions occurring in a grain mantle are a possible cause for the bands consistent with our results.

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