STUDIES OF DIFFUSE INTERSTELLAR BANDS V. PAIRWISE CORRELATIONS OF EIGHT STRONG DIBs AND NEUTRAL HYDROGEN, MOLECULAR HYDROGEN, AND COLOR EXCESS

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ABSTRACT

We establish correlations between equivalent widths of eight diffuse interstellar bands (DIBs), and examine their correlations with atomic hydrogen, molecular hydrogen, and $E_{B-V}$. The DIBs are centered at $\lambda\lambda$ 5780.5, 6204.5, 6283.8, 6196.0, 6613.6, 5705.1, 5797.1, and 5487.7, in decreasing order of Pearson’s correlation coefficient with $N$(H) (here defined as the column density of neutral hydrogen), ranging from 0.96 to 0.82. We find the equivalent width (EW) of $\lambda$5780.5 is better correlated with column densities of H than with $E_{B-V}$ or $H_2$, confirming earlier results based on smaller data sets. We show that the same is true for six of the seven other DIBs presented here. Despite this similarity, the eight strong DIBs chosen are not correlated well enough with each other to suggest they come from the same carrier. We further conclude that these eight DIBs are more likely to be associated with H than with $H_2$, and hence are not preferentially located in the densest, most UV shielded parts of interstellar clouds. We suggest that they arise from different molecules found in diffuse H regions with very little $H_2$ (molecular fraction $f < 0.01$). Of the 133 stars with available data in our study, there are three with significantly weaker $\lambda$5780.5 than our mean $H-\lambda$5780.5 relationship, all of which are in regions of high radiation fields, as previously noted by Herbig. The correlations will be useful in deriving interstellar parameters when direct methods are not available. For instance, with care, the value of $N$(H) can be derived from $W_\lambda$(5780.5).

Key words: ISM: lines and bands – ISM: molecules

1. INTRODUCTION

The diffuse interstellar bands (DIBs) represent a long standing, spectroscopic mystery: hundreds of weak absorption features detected in the optical wavelength range remain unidentified (see Herbig 1995; Snow 1995, 2001 for summaries). While they were noted in stellar spectra as early as 1919 (Heger 1922), the DIBs had their suspected interstellar nature demonstrated more than a decade later (Merrill 1936).

Most of the early hypotheses regarding the progenitors (carriers) of DIBs centered on molecules, but by the early 1970s solid-state (i.e., grain) carriers were thought to be more likely (Herbig 1975). Molecules were re-introduced in the mid-1970s (Danks & Lambert 1976; Douglas 1977; Smith et al. 1977), and now most researchers have adopted large molecules or their ions as the most likely candidates (see Herbig 1995 for a review). Efforts to match laboratory spectra with observed DIB profiles have not been successful. Tulej et al. (1998) reported a match between the laboratory spectrum of C$_7$ and five narrow DIBs, but with improved laboratory and astronomical data this was subsequently shown to be incorrect (McCall et al. 2001). Motylewski et al. (2000) found a weak astronomical feature at approximately the same laboratory wavelength and profile as HC$_5$N$. More recently, Krelowski et al. (2010) have suggested that the laboratory spectrum of HC$_4$H$^+$ closely matches a newly identified, weak DIB at 5068.8 Å. However, confirmation of these claims by a match with a second line in laboratory and astrophysical spectra has not yet been made. Thus, the carriers still remain unidentified.

The DIBs have, thus, become recognized as a new window into the chemistry of the interstellar medium—if we could only identify their carriers. Attempts to identify the DIBs have included (1) searches for molecules in the laboratory with the same spectroscopic signatures as the DIBs (Leach 1995; Herbig 1995; Allain et al. 1996; Salama et al. 1996, 1999; McCall et al. 2000), (2) modeling of the structures detected in some DIB profiles in terms of rotational excitation of gas-phase molecules (Cossart-Magos & Leach 1990; Sarre et al. 1995; Galazutdinov et al. 2002a, 2008), and (3) searches for correlations of DIBs with other interstellar parameters (Wampler 1963, 1966; Snow et al. 1977; Sneider et al. 1978; Wu et al. 1981; Herbig 1993; Jenniskens & Desert 1994; Sonnentrucker et al. 1997, 1999; Thorburn et al. 2003; Weselak et al. 2004, 2008).

Finally, searches for correlations between individual pairs of DIBs were also carried out for the purpose of finding whether some of the DIBs were better correlated with each other than other pairs of DIBs. The reasoning was that these studies could reveal sets of DIBs that came from the same or similar carriers. The works of Krelowski & Walker (1987), Josafatsson & Snow (1987), Westerlund & Krelowski (1989), Cami et al. (1997), and Weselak et al. (2001) led to the identification of “families” of DIBs. The DIB pair thought to show the best correlation
is comprised of the $\lambda 6196.0$ and $\lambda 6613.6$ DIBs (Cami et al. 1997; Moutou et al. 1999; Galazutdinov et al. 2002b). Since no observed correlation was perfect, agreement on which DIB belonged to which family, or whether pairs of DIBs arise from the same carrier, was not always reached when comparing these studies.

To address these issues we compiled a large spectral database toward approximately 200 stars, which has generated a series of papers on diverse properties of DIBs. Thorburn et al. (2003, Paper I) describe the relationship between $C_2$ and certain DIBs. Hobbs et al. (2008, 2009, Papers II and III) present spectral atlases of DIBs toward the spectroscopic binary star HD 204827 and toward HD 183143. McCall et al. (2010, Paper IV) revisited the $\lambda \lambda 6196.0, 6613.6$ correlation. The unprecedented data quality and statistics of our survey (see Section 2) show that this pair has the highest correlation of any known pair and the data would be consistent with a perfect correlation if the errors were underestimated by only a modest amount. In the present paper, we extend our investigation to more fully study the eight strong DIBs $\lambda \lambda 5780.5, 6204.5, 6283.8, 6196.0, 6613.6, 5705.1, 5797.1,$ and $5487.7$, in order of decreasing Pearson’s correlation coefficient with $N(H)$. We also examine the DIB–DIB correlations as well as the correlation of the DIBs with the column density of molecular hydrogen and with color excess.

This paper is organized as follows. In Section 2, we briefly describe how the survey data were obtained and reduced, and we present an extensive list of the line-of-sight parameters and DIB EWs toward the 133 stars reported here. In Section 3, we present a large variety of correlation coefficients and plots, and the slopes and intercepts of correlation plots between $\lambda \lambda 5780.5$ with the other DIBs and with $N(H), N(H_2)$, and $E_{B-V}$. In Section 4, we discuss these results, including the importance of systematic errors which arise among measurements of DIB EWs. In Section 5, we summarize the results of this study.

2. OBSERVATIONS AND DATA ANALYSIS

From 1999 to 2002 we obtained a high signal-to-noise data set on DIBs in the spectra of about 200 stars spanning a large range of reddening, $E_{B-V} \sim 0.01–3.31$ mag (Papers I, II, and III), and their associated diatomic or triatomic molecules (Oka et al. 2003). The reader is referred to those papers for details, and we give only a brief description of the data analysis here. The echelle spectrograph (Wang et al. 2003) was used on the Apache Point Observatory 3.5 m telescope to obtain spectra at a resolving power $\lambda / \Delta \lambda = 38,000$ from 3600 Å to 9000 Å at a nominal signal-to-noise ratio of roughly 1000 at 5780 Å for each sight line (see Paper I). Stellar lines are distinguished from DIBs in reddened stars by comparison with stars of the same spectral type but with low reddening. Telluric lines are removed by use of a complex scheme that measures patterns of behavior in key telluric absorption lines and makes a blanket correction for each observation, depending on air mass and humidity. DIBs that were generally uncontaminated by stellar and telluric blends were measured as described extensively in Papers I and II.

DIB absorption features pose special challenges for any study, such as this one, seeking to quantify EWs. Ultimately, the goal of DIB EW measurements must be to include all blended absorption from the same chemical species without including blended absorption from other chemical species. However, correctly distinguishing contaminating features from those belonging to the same compound itself presupposes knowledge of those chemical species and their spectra. As long as the DIBs carriers remain unidentified, the shape and width of the spectral profiles will remain uncertain. The band structure could be due either to blending with features from other carriers or to blending with features from higher rotational levels of the same species, or could be due to both types of blends.

For this study, and for the previous papers in this series, continuum normalization was accomplished by use of eighth-order Legendre polynomials. For the broadest DIBs, absorption spanned multiple spectral orders. In these cases, continuum profiles were estimated by interpolation across multiple orders. EWs were hand-measured by one of us (J.D.), along with inspection of each DIB in comparison with nearly unreddened standard stars in order to identify stellar lines. Limits of integration were set by where the DIB absorption recovered to the continuum. Where the profile did not fully recover to the continuum, we set the limits at inflection points in the profile, which often indicate an appropriate endpoint (Krelowski & Sneden 1993). We made no assumption that the line shapes have Gaussian profiles. EWs were computed with direct integration.

We do not presume that the present choices of integration endpoints are in any way definitive, nor do we suppose that any prior work has made similar choices with any more assurance of correctness or fewer reasonable arguments in favor of their choices. Integration endpoints chosen in the present study reflect a primary interest in repeatable measurements and minimal sensitivity to continuum location error, both of which are essential to reducing the scatter in correlations from measurement error but do not prevent scatter from other, less easily avoided causes. We do not recommend that the present EWs be combined from those reported in studies by other investigators without carefully considering the specific definitions of what constitutes the measurement criteria for each diffuse band.

The quantity used to investigate correlations differs from study to study, even among the same investigators. For example, Moutou et al. (1999) used central depths, stating that they are less sensitive to contamination than are EWs, although they point out that depths reflect well the correlation in EW. Weselak et al. (2001) find in their study that central depths correlate better than EWs. On the other hand, in a study at very high spectral resolution ($220,000$) of the profiles of $\lambda \lambda 6196, 6614$, Galazutdinov et al. (2002a) found a correlation in the EWs of the DIBs but not in the FWHMs. The FWHM of $\lambda 6196$ varies by 50% over the seven sight lines sampled, whereas for $\lambda 6614$ it is nearly constant within observational errors. The substructure of both profiles varies among the sight lines but in an unrelated way for the two DIBs. Interstellar atomic lines do not reveal Doppler broadening, so the authors believe the absorption arises in a single cloud.

Until the identification of DIBs is secure, by definitive matches with laboratory spectra, no single method can be

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11 Due to uncertainty in the rest wavelength of DIBs, and differing practices by various authors for truncating or rounding wavelengths, the nomenclature of DIBs in the literature is confusing. Indeed, with the increasing number of known DIBs (Hobbs et al. 2008, 2009) quoting wavelengths to only integer significant figures. For the three narrow DIBs, $\lambda \lambda 5780.5, 6613.6, 5797.1$, the central wavelength found by Hobbs et al. (2009) for HD 183143 are 0.1 Å longward of the wavelengths given here. This may be the result of component structure differences in the velocity profiles for these sight lines.

12 We represent the column density of neutral atomic hydrogen by $N(H)$. This is often mistakenly denoted $N(H_1)$. However, $H_1$ actually denotes the spectral line of atomic hydrogen.
deemed superior. We have elected to base our correlation studies on measurements of EWs rather than FWHM or the central depths of profiles. While the latter two measures are less likely to suffer from contamination by nearby, unrelated species, they will fail to account for broad absorption due to $R$- or $P$-branch transitions, for example. The strength of these branches depends on the unknown rotation temperature of the molecules along the line of sight, which can vary from cloud to cloud, and even within a cloud. As shown in Figure 1 of Oka et al. (2003), the absorption can occur over a rather large wavelength interval. Another reason to use EWs rather than central depth is that most of these sight lines intersect multiple clouds, so our results represent averages over the intervening clouds. Doppler splitting could affect measures of central depth, especially for narrow DIBs. As long as there is not saturated component structure, EWs will not suffer from this error. Finally, measures of EWs are independent of the resolution of the instrument used, which is not true of FWHM or central depth.

Standard techniques were used for cosmic ray removal, flat fielding, background and bias subtraction, and extraction to one dimensional spectra. The spectra from adjacent orders were co-added to give a blazeless spectrum. A set of 35 lines that were most free of stellar blending or telluric line contamination were initially measured. The estimates of correlations among DIBs and between DIBs and other interstellar quantities are based on DIB measurements presented by Paper I for an expanded set of stars, on the common $H$ and $H_2$ column densities of Rachford et al. (2002, 2009), and on color excess values collected from the literature by one of us (LMH) based on the color scale of Johnson (1963). Errors on each data point were estimated by measurements in adjacent parts of the continuum, free of other DIBs and of stellar or telluric lines, and then were propagated through the analysis. One sigma errors are used throughout. McCall et al. (Paper IV) give an extensive discussion of additional errors that may affect the data. They suggest that our errors may be underestimated by about a factor of two due to systematic effects, the three most likely of which are continuum placement errors, the possible presence of unidentified weak DIBs close to the DIBs being measured, and the residual errors arising from imperfect removal of telluric water vapor lines. In the present study, however, we use the formally propagated errors described in Paper I.

Table 1 includes a list of all 133 stars in this study, their spectral types and luminosity class, $N$(H), $N$(H$_2$), $E_{B-V}$, and the EWs of the eight DIBs we focus on here. This analysis excludes the 17 lines noted as being correlated with C$_2$ (Paper I) and C$_3$ (Oka et al., 2003), whose relationships with K i, CO, CH, and other molecular species will be the subject of a future study by our group. Rachford et al. (2009, 2009) did a reanalysis of $N$(H) and $N$(H$_2$) along some of the sight lines included in the current study. The values that they found of these quantities differ from those derived in the original analysis by less than 1σ in all cases, much less than the cosmic dispersion of these quantities. We therefore use the results of our original, homogeneous data analysis, as presented by Rachford et al. (2002).

3. DIB PROFILES AND CORRELATION PROPERTIES

The DIBs chosen for this study were meant to avoid the broadest DIBs, for which our echelle measurements can underestimate the line strengths (Hobbs et al., 2009) due to continuum placement difficulties. They were also meant to focus on the classic strong DIBs, which do not include the C$_2$ DIBs found by Thorburn et al. in Paper I. The strongest DIBs with FWHM less than that of $\lambda$5780.5 are included ($\lambda\lambda$5797.1, 6613.6). The DIB at $\lambda$6283.8 is the second strongest DIB after $\lambda$4428.1, so it was included to test for any evidence of saturation in the range of $E_{B-V}$ for our stars, even though it has FWHM = 4.77 Å (Table 2). Another much weaker DIB, $\lambda$5487.7, was included as a comparison. Two lines were included because of their previously known correlations with other DIBs: $\lambda$5705.1 (used in Paper I to test for saturation in $\lambda$5780.5) and $\lambda$6196.0, previously noted for its close correlation with $\lambda$6613.6. An eighth line ($\lambda$6204.5) was included since it has two narrow components that are blended and it is not clear if they should be measured together or separately. This characteristic is shared by other DIBs, such as $\lambda$5849.8 and $\lambda$6606.7, but we selected $\lambda$6204.5 because it is among the strongest DIBs. The DIBs in Paper I were analyzed with respect to their correlation with each other. The DIBs chosen for this paper are at the high end of correlation coefficients and include all the moderately well correlated DIBs. All other DIBs from Paper I are less well correlated with each other than those in this paper.

Spectral profiles of these eight DIBs toward HD 183143 and HD 204827 are shown in Figure 1. HD 183143 has been observed by many DIB investigators (e.g., Herbig 1975; Jenniskens & Desert 1994; Tuairrisg et al. 2000) and is the basis for the atlas discussed in Paper III. HD 204827, discussed in Paper II, reveals several narrow, weak DIBs which are not evident in HD 183143, and vice versa. Some broad DIBs are not seen in common in the two stars, as well. We note that the central wavelength for each band in Figure 1 is slightly longer for HD 183143 than for HD 204827, a systematic difference anticipated and discussed in some detail in Papers II and III. The unavoidable uncertainty in the precise zero point for DIB wavelengths arises primarily from the combination of the multiple interstellar clouds present along both stellar lines of sight and the unknown identities and laboratory spectra of the molecules presumed to cause the DIBs. The median offset for the eight bands in Figure 1 corresponds to about 7 km s$^{-1}$. Had we arbitrarily chosen to assign the laboratory K i wavelength to the mid-point between the two main components of the interstellar K i line toward HD 183143 (Paper III, Figure 2), for example, this systematic median offset would effectively be removed. This result implies that the DIBs show component structure. Indeed, Doppler splitting in the narrow DIB $\lambda$6196.0, matching the splitting of interstellar K i, about 15 km s$^{-1}$, was observed in high-resolution spectra of HD 183143 by Herbig & Soderblom (1982). However, in our observations the scatter in the mean is such that some DIBs may be dominant in one component and some in others. The offsets for the narrowest DIBs are clear. We will address this issue in a future paper (D. G. York et al., in preparation).

Figure 1 also illustrates our choice of integration limits for the DIBs along these two sight lines, and the ambiguities this involves. For example, $\lambda$5780.5 is either at the bottom of a broad feature or else is flanked by a series of narrow, possibly related, features. Not knowing the origin of each feature, we assumed the former interpretation as did, for example, Galazutdinov et al. (2004). For $\lambda$6204.5 we include the extended red wing. Porceddu et al. (1991) conclude that $\lambda$6205 is a separate DIB on the basis of a varying central depth ratio of the two features. They further conclude that these differences are due to differences in the physical parameters within a single interstellar cloud, based on the lack of observed Doppler splitting in the narrow $\lambda$6196.0 DIB, at their moderate resolving power (30,000) and SNR (200–300). For $\lambda$5797.1 we include the blue wing, in contrast to Galazutdinov et al. (2004), who believe it is blended.
with a much broader feature at \( \lambda 5795 \). As shown in Section 3.2, we find very good correlations associated with \( \lambda 6204.5 \) and lower ones for \( \lambda 5797.1 \). Determining which features correlate best may prove to be a useful tool for guiding the placement of integration limits. However, it is impossible to know the correct approach in advance, so we favor systematic repeatability until the true profile can be established by species identification in the laboratory.

Also shown in Figure 1 are the DIBs identified in atlas Papers II and III (black and red tick marks), the stellar lines also shown in Figure 1 are the DIBs identified in atlas Papers II and III (black and red tick marks), the stellar lines...
Figure 1. Continuum normalized spectral profiles of the eight DIBs toward HD 204827 (black) and HD 183143 (red). Filled circles indicate the limits of integration for calculating equivalent widths. Black arrows indicate the locations of stellar lines identified in the DIB atlas for HD 204827 (Paper II) and red arrows the stellar lines for HD 183143 (Paper III). Green arrows show additional stellar lines identified in the low-reddened comparison stars for these two stars. Note the apparent offset in LSR velocity of the DIBs in the spectra of the two stars. See the text for an explanation. The vertical scale in all panels is the same to clearly show the relative strengths of the DIBs. The spike just to the left of the $\lambda 6613.6$ DIB is an artifact.

Table 2

| DIB (FWHM) | Correlation Coefficient | Reduced $\chi^2$ | Number of Sight Lines | Correlation Coefficient$^c$ | $a^e$ | $b^e$ |
|------------|-------------------------|-----------------|-----------------------|-----------------------------|-------|-------|
| 5780.5 (2.11) | 0.94 | 1.209 | 74 | 0.90 | 19.00 ± 0.08 | 0.94 ± 0.04 |
| 6283.8 (4.77) | 0.89 | 1.250 | 71 | 0.87 | 17.65 ± 0.20 | 1.30 ± 0.07 |
| 6204.5 (4.87) | 0.89 | 1.559 | 69 | 0.84 | 19.02 ± 0.11 | 1.12 ± 0.06 |
| 6196.0 (0.42) | 0.89 | 2.035 | 68 | 0.79 | 19.90 ± 0.06 | 0.95 ± 0.05 |
| 6613.6 (0.93) | 0.87 | 2.794 | 70 | 0.77 | 19.89 ± 0.06 | 0.67 ± 0.03 |
| 5705.1 (2.58) | 0.83 | 1.278 | 52 | 0.73 | 19.38 ± 0.16 | 1.08 ± 0.09 |
| 5797.1 (0.77) | 0.82 | 3.269 | 65 | 0.72 | 19.59 ± 0.09 | 0.85 ± 0.05 |
| 5487.7 (5.20) | 0.78 | 1.516 | 55 | 0.60 | 19.28 ± 0.16 | 1.13 ± 0.09 |

Notes.

$^a$ All entries computed using logarithmic values of DIB equivalent widths.

$^b$ Data in Columns 2, 3, 4, 6, and 7 exclude $\rho$ Oph A, $\theta^1$ Ori C, and HD 37061.

$^c$ FWHM from Paper II. All wavelengths are in units of Å.

$^d$ Includes all sight lines.

$^e$ Coefficients for $\log(N(H)) = a + b \times \log[W_{\lambda}(\text{DIB})]$. 

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(black and red arrows), and a few additional stellar lines (green arrows) observed in the spectra of the lightly reddened comparison stars. Broad DIBs, like \( \lambda 6283.8 \), may include multiple weak DIBs identified in the atlases. The criteria for selecting the DIBs are clearly described in these papers, but no claim is made regarding whether these separate DIBs really arise from the same carrier molecule. Thus, including or excluding them is equally justified. Note that our choice to include them does not significantly affect our results. For example, the three DIBs in the wings of the HD 183143 profile have EWs of 28, 22, and 19 mÅ (Paper III) which, even in total comprise only a few percent of the 1910 mÅ EW of the main DIB. Similarly, for HD 204827 the EWs of the two flanking DIBs are 3 and 14 mÅ (Paper II), compared to 518 mÅ for the main DIB. For HD 6283.8, may include multiple weak DIBs identified in the atlases. The criteria for selecting the DIBs are clearly described in these papers, but no claim is made regarding whether these separate DIBs really arise from the same carrier molecule. Thus, including or excluding them is equally justified. Note that our choice to include them does not significantly affect our results. For example, the three DIBs in the wings of the HD 183143 profile have EWs of 28, 22, and 19 mÅ (Paper III) which, even in total comprise only a few percent of the 1910 mÅ EW of the main DIB. Similarly, for HD 204827 the EWs of the two flanking DIBs are 3 and 14 mÅ (Paper II), compared to 518 mÅ for the main DIB. For HD 6283.8, may include multiple weak DIBs identified in the atlases. The criteria for selecting the DIBs are clearly described in these papers, but no claim is made regarding whether these separate DIBs really arise from the same carrier molecule. Thus, including or excluding them is equally justified. Note that our choice to include them does not significantly affect our results. For example, the three DIBs in the wings of the HD 183143 profile have EWs of 28, 22, and 19 mÅ (Paper III) which, even in total comprise only a few percent of the 1910 mÅ EW of the main DIB. Similarly, for HD 204827 the EWs of the two flanking DIBs are 3 and 14 mÅ (Paper II), compared to 518 mÅ for the main DIB. For HD 6283.8, may include multiple weak DIBs identified in the atlases. The criteria for selecting the DIBs are clearly described in these papers, but no claim is made regarding whether these separate DIBs really arise from the same carrier molecule. Thus, including or excluding them is equally justified. Note that our choice to include them does not significantly affect our results. For example, the three DIBs in the wings of the HD 183143 profile have EWs of 28, 22, and 19 mÅ (Paper III) which, even in total comprise only a few percent of the 1910 mÅ EW of the main DIB. Similarly, for HD 204827 the EWs of the two flanking DIBs are 3 and 14 mÅ (Paper II), compared to 518 mÅ for the main DIB.

These stars are included in the sample. Table 2 also includes the correlation coefficients for the remaining DIBs with log(\( N(H) \)), as well as the coefficients of the best linear fits, excluding the same three outliers.

Figure 3 shows the relation between \( N(H_2) \) and \( W_5(5780.5) \). For the full data set it is clear that there is a very poor relationship between the two quantities, especially compared to Figure 2 for \( N(H) \) and \( W_5(5780.5) \). It is noteworthy that stars with \( N(H_2) \) ranging over a factor of more than 10\(^{5} \) can have identical values of \( W_5(5780.5) \). A special set of sight lines is denoted by open squares in Figure 3: those with fractional abundance of \( H_2 \) \( f = [2N(H_2)]/[N(H)+2N(H_2)] > 0.5 \). This molecular fraction is a line-of-sight average, so the value of \( f \) for some individual clouds almost certainly must be greater than 0.5. In these clouds most hydrogen is in the form of \( H_2 \). Considering a slightly less restricted set of sight lines, those for which log(\( N(H_2) \)) > 18 we find \( r = 0.65 \), considerably lower than the correlation coefficient of \( N(H) \) with \( W_5(5780.5) \). The correlation coefficients for all eight DIBs with \( N(H_2) \) are given in Table 3. The reduced \( \chi^2 \) values are far greater than for the DIB–log(\( N(H) \)) relations shown in Table 2.

Figure 4 shows the correlation of \( E_{B-V} \) with \( W_5(5780.5) \). Reddening errors are difficult to quantify, but we estimate them to be approximately 0.03 mag. This plot covers a large range in \( E_{B-V} \), from 0.01 to 3.31 mag. The three points with the highest values of \( E_{B-V} \) are Cyg OB2 12, Cyg OB2 5, and HD 229059, all of which are in the Cyg OB2 cloud. There is significant scatter in this plot, with \( r = 0.82 \), indicating that \( \lambda 5780.5 \) is not directly associated with the column density of dust grains responsible for the optical differential extinction. The correlation coefficients for all eight DIBs with \( E_{B-V} \), as well as the coefficients for the best-fit lines, are given in Table 4. Again, the reduced \( \chi^2 \) values are far greater than for the DIB–log(\( N(H) \)) relations. Note that the best-fit lines have not been constrained to go through the origin in any of the plots presented in this paper.

The prominent jump in the data points in Figure 3 is at \( W_5(5780.5) \approx 50 \) mÅ, corresponding to \( E_{B-V} \approx 0.1 \), according to Figure 4. This matches well the value of \( E_{B-V} \approx 0.08 \) that marks the beginning of a sharp transition from low to high values of \( N(H_2) \) in interstellar clouds (Savage et al. 1977). This level of reddening indicates the presence of a sufficient density of dust grains to favor the formation of \( H_2 \), and a high enough
The eight DIBs in our sample are $\lambda\lambda 5780.5, 6204.5, 6283.8, 6196.0, 6613.6, 5705.1, 5797.1$, and $5487.7$, in order of decreasing correlation coefficient with $N(H)$. In Table 3, we give the mutual correlation coefficients between all pairs of DIBs in this study. Of the 28 pairs, 27 have correlations greater than 0.9. The exception is $\lambda\lambda 5797.1–5487.7$, with $r = 0.87$. DIBs which arise from the same carriers, or whose carriers may have been formed in the presence of a third, common carrier, would have correlation coefficients very close to unity. None of the pairs considered here have such a high correlation, with the exception of $\lambda\lambda 6196.0–6613.6$, as discussed in Paper IV.

We now consider correlations between the DIBs and $N(H)$ (Table 2). Table 6 also gives the coefficients of the best-fit lines for the DIB–$W_{\lambda}$ plots, excluding the three outliers.

Figures 5 through 11 show the relationship between $\lambda 5780.5$ and the other seven DIBs. Correlation coefficients are given in Table 6, with the modified set, which excludes the three outlier sight lines, in Column 2, and the full set in Column 5. Note that correlations for the full and modified sets are identical to within our errors. This is not true for the full and modified set for the relation between the DIBs and $N(H)$ (Table 2). Table 6 also gives the coefficients of the best-fit lines for the DIB–$W_{\lambda}(5780.5)$ plots, excluding the three outliers.

Figures 5 through 11 show the relationship between $\lambda 5780.5$ and the other DIBs in our sample. We note here some of the characteristics of these plots.

Figure 5 shows the $\lambda 6204.5$ versus $\lambda 5780.5$ relationship (correlation coefficient $r = 0.97$). The greatest outliers in terms of the number of standard deviations off the best-fit line in both the $x$ and $y$ directions combined, are HD 40839, HD 194839, HD 147889, AE Aur, τ CMa, and μ Sgr. However, with a correlation coefficient of 0.97, this is one of the best correlations observed, even better than $\lambda 5780.5$ with $N(H)$ ($r = 0.94$).

Figure 6 shows the correlation of the DIBs $\lambda 6196.0$ and $\lambda 5780.5$ ($r = 0.97$). The outliers here include 6 Cas, HD

| DIB     | Correlation Coefficient | Reduced $\chi^2$ | Number of Sight Lines | Correlation Coefficient$^d$ | $\rho^2$  |
|---------|-------------------------|-----------------|-----------------------|-----------------------------|-----------|
| 5780.5  | 0.82                    | 48.44           | 133                   | 0.82                        | $(8.36 \pm 3.48) \times 10^{-3}$ |
| 6283.8  | 0.82                    | 16.60           | 127                   | 0.82                        | $(7.71 \pm 0.78) \times 10^{-2}$ |
| 6204.5  | 0.83                    | 26.71           | 119                   | 0.83                        | $(7.22 \pm 0.67) \times 10^{-2}$ |
| 6196.0  | 0.85                    | 25.59           | 117                   | 0.85                        | $(5.07 \pm 0.56) \times 10^{-2}$ |
| 6613.6  | 0.84                    | 45.27           | 120                   | 0.83                        | $(1.96 \pm 0.37) \times 10^{-2}$ |
| 5705.1  | 0.80                    | 13.55           | 91                    | 0.80                        | $(1.74 \pm 0.16) \times 10^{-1}$ |
| 5797.1  | 0.84                    | 25.16           | 113                   | 0.84                        | $(2.86 \pm 0.57) \times 10^{-2}$ |
| 5487.7  | 0.80                    | 12.84           | 93                    | 0.79                        | $(6.41 \pm 1.31) \times 10^{-2}$ |

Notes.

$^a$ All entries computed using linear values of DIB equivalent widths.

$^b$ Data in Columns 2, 3, and 4 exclude $\rho$ Oph A, $\theta$ Ori C, and HD 37061.

$^c$ Includes all sight lines.

$^d$ Coefficients for $E_{B-V} = a + b \times W_{\lambda}(5780.5)$. 

| DIB     | Correlation Coefficient | Reduced $\chi^2$ | Number of Sight Lines | Correlation Coefficient$^d$ | $\rho^2$  |
|---------|-------------------------|-----------------|-----------------------|-----------------------------|-----------|
| 5780.5  | 0.65                    | 39.60           | 64                    | 0.65                        | $(1.98 \pm 0.01) \times 10^{-3}$ |
| 6283.8  | 0.46                    | 9.99            | 63                    | 0.46                        | $(9.57 \pm 0.17) \times 10^{-3}$ |
| 6204.5  | 0.60                    | 24.61           | 63                    | 0.60                        | $(5.99 \pm 0.08) \times 10^{-3}$ |
| 6196.0  | 0.74                    | 21.10           | 63                    | 0.74                        | $(2.11 \pm 0.02) \times 10^{-2}$ |
| 6613.6  | 0.80                    | 21.82           | 64                    | 0.80                        | $(4.63 \pm 0.04) \times 10^{-3}$ |
| 5705.1  | 0.56                    | 10.62           | 49                    | 0.56                        | $(1.20 \pm 0.03) \times 10^{-2}$ |
| 5797.1  | 0.79                    | 14.83           | 63                    | 0.79                        | $(5.74 \pm 0.06) \times 10^{-3}$ |
| 5487.7  | 0.47                    | 10.42           | 52                    | 0.47                        | $(9.67 \pm 0.25) \times 10^{-3}$ |

Notes.

$^a$ All entries computed using logarithmic values of DIB equivalent widths and only for sight lines with $\log(N(H_2)) > 18$.

$^b$ Data in Columns 2, 3, and 4 exclude $\rho$ Oph A, $\theta$ Ori C, and HD 37061.

$^c$ Includes all sight lines.

$^d$ Coefficients for $\log[N(H_2)] = a + b \times \lambda\lambda 5780.5$. 

**Figure 4.** $E_{B-V}$ vs. $W_{\lambda}(5780.5)$. The inset in this and the following correlation plots shows a close-up view of the region near the origin. The best-fit line has not been constrained to go through the origin in any of the plots in this paper.
Table 5

| DIB   | 5780.5 | 6204.5 | 6196.0 | 6283.8 | 6613.6 | 5705.1 | 5797.1 | 5487.7 |
|-------|--------|--------|--------|--------|--------|--------|--------|--------|
| 5780.5 | 1      | 0.97   | 0.97   | 0.96   | 0.96   | 0.98   | 0.93   | 0.95   |
| 6204.5 | 0.97   | 1      | 0.96   | 0.98   | 0.94   | 0.96   | 0.91   | 0.95   |
| 6196.0 | 0.97   | 0.96   | 1      | 0.93   | 0.99   | 0.93   | 0.96   | 0.94   |
| 6283.8 | 0.96   | 0.98   | 0.93   | 1      | 0.91   | 0.96   | 0.86   | 0.92   |
| 6613.6 | 0.96   | 0.94   | 0.99   | 0.91   | 1      | 0.93   | 0.95   | 0.91   |
| 5705.1 | 0.98   | 0.96   | 0.93   | 0.94   | 0.93   | 0.94   | 0.92   | 0.97   |
| 5797.1 | 0.93   | 0.91   | 0.96   | 0.86   | 0.95   | 0.90   | 1      | 0.87   |
| 5487.7 | 0.95   | 0.95   | 0.94   | 0.92   | 0.91   | 0.93   | 0.97   | 1      |

Notes.

a All entries computed using linear values of DIB equivalent widths.
b Excluding ρ Oph A, θ1 Ori C, and HD 37061.

Table 6

| DIB | Correlation Coefficient | Reduced $\chi^2$ | Number of Sight Lines | Correlation Coefficient $^c$ | $a^d$ | $b^d$ |
|-----|-------------------------|-----------------|-----------------------|-------------------------------|-------|-------|
| 5705.1 | 0.98                  | 2.20            | 91                    | 0.98                          | −0.25 ± 1.07 | 0.228 ± 0.004 |
| 6204.5 | 0.97                  | 6.92            | 119                   | 0.97                          | −0.24 ± 0.88 | 0.412 ± 0.004 |
| 6196.0 | 0.97                  | 11.66           | 116                   | 0.97                          | −0.63 ± 0.17 | 0.111 ± 0.001 |
| 6613.6 | 0.96                  | 28.05           | 119                   | 0.96                          | −13.39 ± 0.52 | 0.467 ± 0.003 |
| 6283.8 | 0.96                  | 3.82            | 125                   | 0.96                          | 28.24 ± 5.8 | 2.32 ± 0.03 |
| 5487.7 | 0.95                  | 4.86            | 93                    | 0.95                          | −2.29 ± 1.13 | 0.233 ± 0.005 |
| 5797.1 | 0.93                  | 26.35           | 113                   | 0.93                          | −1.65 ± 0.72 | 0.384 ± 0.003 |

Notes.

a All values computed using linear values of DIB equivalent widths.
b Data in Columns 2, 3, 4, 6, and 7 exclude ρ Oph A, θ1 Ori C, and HD 37061.
c Includes all sight lines.
d Coefficients for $W_{\lambda}(DIB) = a + b \times W_{\lambda}(5780.5)$.

Figure 5. $W_{\lambda}(6204.5)$ vs. $W_{\lambda}(5780.5)$.

Figure 6. $W_{\lambda}(6196.0)$ vs. $W_{\lambda}(5780.5)$.

Figure 7 plots $\lambda 5705.1$ versus $\lambda 5780.5$ ($r = 0.98$). This relation has the highest correlation coefficient and the lowest scatter ($\chi^2 = 2.2$) of any of our DIB pairs. No point deviates from the best-fit line in the $W_{\lambda}(5705.1)$ direction by more than 4σ. The largest outliers are 6 Cas, HD 30614, HD 206773, HD 157857, X Per, and HD 194839. The correlation coefficient is comparable to that of the $\lambda 6196.0 - 6613.6$ pair discussed in Paper IV, and will be subject to additional, detailed study by our group.

The $\lambda 5797.1$ versus $\lambda 5780.5$ plot ($r = 0.92$), Figure 10, also exhibits high scatter, with reduced $\chi^2$ exceeding 26. We notice a group of points falling below the line near $W_{\lambda}(5780.5) = 175$ mÅ. This includes HD 53975 at $(x, y) = (177, 26)$, HD
Figure 7. $W_{\lambda}(6283.8)$ vs. $W_{\lambda}(5780.5)$.

Figure 8. $W_{\lambda}(6613.6)$ vs. $W_{\lambda}(5780.5)$. This shows most clearly the threshold effect—some minimum amount of $\lambda5780.5$ must be present before $\lambda6613.8$ begins to appear.

Figure 9. $W_{\lambda}(5705.1)$ vs. $W_{\lambda}(5780.5)$. This has the smallest reduced $\chi^2$ and the highest correlation coefficient of the DIBs with respect to $\lambda5780.5$.

Figure 10. $W_{\lambda}(5797.1)$ vs. $W_{\lambda}(5780.5)$.

Figure 11. $W_{\lambda}(5487.7)$ vs. $W_{\lambda}(5780.5)$. This has the smallest reduced $\chi^2$ and the highest correlation coefficient of the DIBs with respect to $\lambda5780.5$.

The $\lambda5790.3$ at (183,33), $\beta^2$ Sco at (191,36), $\omega^1$ Sco at (192,40), $\upsilon$ Sco AB at (187,49), and $\beta^1$ Sco AB at (171,34). Other outliers include HD 204827, HD 172028, Herschel 36, and 6 Cas.

The $\lambda5487.7$ versus $\lambda5780.5$ plot ($r = 0.95$), shown in Figure 11, exhibits a group of points sitting above the line at both the lowest and the highest column densities. The first group includes HD 201345 at (100,46), HD 186994 at (101,40), $\xi$ Per at (98,22), o Per at (101,31), 40 Per at (115,33), $\phi^1$ Ori at (68,29), and $\theta^1$ Ori B at (61,20). The second group includes HD 194839, HD 166734, HD 183143, Cyg OB2 5, Cyg OB2 12, BD+63 1964, and HD 50064. The two largest outliers below the line are 6 Cas and $\mu$ Sgr. This is the only DIB–DIB plot for which there is a possible systematic deviation from a linear relationship at high column densities. In this case, $\lambda5780.5$ may be saturating at $W_{\lambda}$ $\gtrsim$ 600 mÅ. However, no saturation is indicated at similar line strengths in the correlations with other DIBs, so it is unlikely that this is the cause of this distribution of points. If this is correct, it implies that $\lambda5487.7$ is getting stronger per H atom for high levels of $\lambda5780.5$.

4. DISCUSSION

Most interstellar quantities will show a positive correlation with each other simply due to the increase of interstellar material with distance. This is most clearly reflected in the correlation of DIBs with extinction. For the eight DIBs considered here the correlation coefficients with $E_{B-V}$ range from 0.80 to 0.85 (Table 4), with an average of 0.82. Thus, we may regard $r = 0.86-0.88$ as the minimum required to indicate that two quantities are physically correlated at a significant level.

By this measure $\lambda5780.5$ is the only DIB in our study that is unambiguously well-correlated with $N(H)$, and even in this case the outlier points (Figure 2) are prominent exceptions. These three stars have in common the presence of strong local radiation fields. Noticing that the outliers have particularly low abundances of $\lambda5780.5$ relative to their H column densities.
compared to the general correlation, a possible explanation is that the radiation fields in these regions are hard enough to destroy the carrier of $\lambda 5780.5$, and that local radiation generally regulates DIB abundances, which are likely characterized by distinct critical wavelengths of ionizing radiation. Because all of the DIBs are well correlated with $\lambda 5780.5$, with correlation coefficients 0.92–0.97 (Table 5), but only $\lambda 5780.5$ is very well correlated with $N(\text{H})$ (Table 2), we infer that the critical energy for regulating $\lambda 5780.5$ is similar to the energy that regulates the H abundance, and greater than that of the other DIBs. We note that the destruction mechanism may be simple ionization, but it could also be dissociation. However, the apparent destruction effect in the presence of significant photon fluxes indicates that the $\lambda 5780.5$ carrier might be an ion.

These conclusions are supported by Sonnentrucker et al. (1997), who examined the ionization properties of the DIBs $\lambda \lambda 5780.5, 5971.9, 6379.3,$ and $6613.6$. They conclude that the carriers of these DIBs are separate gas-phase molecules. By comparing $W_\lambda / E_{\lambda - V}$ as a function of $E_{\lambda - V}$ for each DIB, they find that $\lambda 5780.5$ reaches its maximum at the lowest value of $E_{\lambda - V}$, indicating that the carrier of this DIB is the most resistant of the four DIB carriers to strong UV fields.

While the main interstellar clouds in the three outlier sight lines are subject to higher than average radiation fields, they are not the only stars in our sample with this property. The Na I and K I lines in the two Trapezium sight lines, $\theta^1$ Ori C and HD 37061, are exceptionally weak, relative to $N(\text{H})$, $\rho$ Oph A, however, is a bit puzzling. Various Sco-Oph sight lines (and some others in other regions) exhibit relatively weak Na I and K I (Welty & Hobbs 2001). For these targets only $\rho$ Oph A is among the most discrepant in $\lambda 5780.5$ versus $N(\text{H})$, but most other Sco-Oph sight lines tend to be deficient in $\lambda 5780.5$, as well. Unfortunately, we do not have a good quantitative measure of radiation field strength in many cases. One can use the higher H2 rotational level populations ($J = 4, 5$) to estimate this, but the column densities of those levels are often very hard to determine accurately because the lines are generally on the flat part of curve of growth for most sight lines of interest here. We have no measure of H2 toward HD 37061 and the higher J lines have not been reported toward $\rho$ Oph A. The error on $N(\text{H}_2)$ toward $\theta^1$ Ori C is among the largest in our sample. Obtaining more extensive data on the strength of the radiation fields along a large number of sight lines would be a very interesting study.

If two DIBs are formed from transitions between a single ground state and two different vibronic levels, their measured strengths should be perfectly correlated, with a correlation coefficient of unity. This is not quite true even for the best observed DIB–DIB correlation, $\lambda 6196.0$ versus $\lambda 6613.6$. McCall et al. (Paper IV) explore this particular pair and discuss the possibility that the true errors are underestimated. The most likely causes of such a situation are: (1) there are errors in continuum placement, (2) there are blends of DIBs that are not physically related, and (3) there is uncorrected contamination from telluric water vapor lines. The first of these could be especially true for $\lambda 5780.5$, which is superimposed on a much wider feature centered at 5778 Å (Herbig 1975; see also the combined spectral plots shown in Figure 11 of Papers II and III). Without knowing the origin of the features that make up this blend (Krelowski et al. 1997), it is hard to evaluate this effect. For the much narrower $\lambda 5779.1$ DIB the second effect may be operative. The feature is multiple and the line shapes differ from star to star in our data (see Figure 1). We suspect the short wavelength contribution to this DIB is a C II DIB (Paper I), while the long wavelength component is more closely related to $\lambda 5780.5$. This explanation is consistent with the well-known $\sigma - \zeta$ effect of $5780.5$ and $5797.1$: in the prototype “$\sigma$” sight line, $\sigma$ Sco, $\lambda 5780.5$ is much deeper than $\lambda 5779.1$, while in the prototype “$\zeta$” sight line, $\zeta$ Oph, the depths of the two lines are comparable (Krelowski & Sneden 1995). The stars with high $N(\text{H}_2)$ and low $W_\lambda (5780)$ are all $\zeta$-type stars, including strong C II DIBs, and produce a deep blueward component of the proposed C II DIB at 5797.1 Å.

The $\sigma - \zeta$ effect might be more of a geometrical effect than an ionization effect. It is well-known that $\lambda 5780.5$ is poorly correlated with trace neutral species, such as K I and Na I (Welty et al. 2006). This is also true of other $\sigma$-type DIBs that are best correlated with $N(\text{H})$, such as $\lambda \lambda 6283.8, 6204.5$. On the other hand, the $\zeta$-type DIB $\lambda 5797.1$ is better correlated with the trace neutrals (Galazutdinov et al. 2004). These neutrals predominantly exist in the cores of clouds, which provide adequate shielding of the UV field, and where high molecular fractions of H2 exist due to self-shielding. These results are consistent with the $\sigma$-type DIBs existing in the outer regions of clouds and the $\zeta$-type DIBs existing deep in the interior of the clouds. The variable strength ratio of $\lambda \lambda 5780.5, 5797.1$ has been discussed by several authors, such as Krelowski et al. (1997). $\lambda 5797.1$ has the lowest correlation coefficient ($r = 0.93$) with $\lambda 5780.5$ of any of the DIBs in our study (Table 6), even though it still exceeds the value expected from the general growth of interstellar material, as noted above.

Most of our sight lines penetrate multiple clouds and therefore average out these effects. Cami et al. (1997) studied 13 stars with only single clouds along the lines of sight. They confirm the classification of DIBs into four different families, including $\sigma$ and $\zeta$. However, the most convincing evidence of this hypothesis will come from mapping several clouds spatially by observing multiple stars at various locations behind the clouds. Correlations among DIBs and with neutral atoms and with molecules, such as H2, C2, CN, and CH will indicate whether the geometrical interpretation is correct. This is the subject of a future study by our group.

Examination of DIBs that fall in the clean parts of the spectra of a number of stars indicate the presence of a number of interstellar absorption components. Galazutdinov et al. (2002a, 2005) argue that most strong DIBs have structure. While these authors conclude the structures are evidence of the R, P, Q rotational structure of molecules of modest size, our study suggests that blends of unrelated DIBs may be the origin of structure in some cases.

The question of what features in the neighborhood of the main DIB to include in the measurements of EW is difficult. We do not have the fine spectral resolution of Galazutdinov et al. (2002a) and cannot separate the blended features in two of our DIBs, $\lambda 5797.1$ and $\lambda 6204.5$, but we have a larger data set at very high S/N. It is difficult even at high resolution to conclude whether lines have structure due to multiple components along a line of sight, blends of unrelated species, or structure from energy levels in a common carrier. Even if we know in advance that DIBs from different carriers are involved, we still do not know what profiles to use in the deconvolution fitting process. We therefore measure the full EW of the blends. Figure 1 shows that the two features in the profile of $\lambda 6204.5$ approximately scale with each other, and this DIB has among the highest correlation coefficients with the other DIBs (Table 5) and with $N(\text{H})$ (Table 2), and the correlation with $\lambda 5780.5$ has low $\chi^2$ (Table 6). In contrast, the features of $\lambda 5797.1$ do not scale with each other, this DIB has low correlation coefficients with the
other DIBs and N(H), and the correlation with $\lambda$5780.5 has very high $\chi^2$. It would appear that the two features blended in the $\lambda$6204.5 feature measure as one feature are either from the same carrier or from two separate carriers that are almost perfectly correlated. As previously noted, such considerations may help guide the correct placement of limits in future studies.

Examination of Table 6 shows that the intercepts of the best-fit lines pass through the origin for the correlation of $\lambda$5780.5 with DIBs $\lambda\lambda$5705.1, 6204.5, 5487.7, and possibly $\lambda\lambda$5797.1 and 6196.0. However, our data show that this is not true for $\lambda$6283.8, and especially $\lambda$6613.6. This may be evidence of a threshold effect, such that a substantial amount of 5780.5 must be produced before 6613.6 can begin to form. Since N(H) is very well correlated with $\lambda$5780.5, this implies that some minimum column density of H is required before the appearance of some DIBs becomes evident.

Figure 7 shows a possible threshold in the opposite sense. This is the only case in which the linear fit has a statistically significant positive intercept, indicating that 6283.8 appears before 5780.5. In addition, below $W_5$(5780.5) $\approx$ 150 mÅ there are significantly more points above the best-fit line than below. Below $W_5$(5780.5) $\approx$ 50 mÅ the distribution flattens, with $W_5$(6283.8) remaining approximately constant as $W_5$(5780.5) decreases. This may be caused by two effects. (1) $\lambda$6283.8 is among the broadest DIBs in this study (FWHM = 4.77 Å, Table 2), making continuum fitting somewhat less reliable than for narrower DIBs. (2) There is considerable telluric contamination in such a wide DIB and our nightly blanket correction for narrower DIBs. (3) Seven of the eight DIBs, excepting $\lambda$5487.7, are better correlated with N(H) than with $E_{B-V}$.

The tight correlation between $W_5$(5780.5) the column density of H2 can vary by a factor of $10^3$. This occurs just at the level of reddening corresponding to the formation of enough H2 to permit self-shielding.

5. SUMMARY

We have used a large database of high signal to noise ratio spectra of 133 stars to perform one of the most extensive comparisons to date between strengths of DIB pairs and between DIBs and N(H), N(H2), and $E_{B-V}$. We have presented linear fit parameters and correlation coefficients for these relationships. We reach the following conclusions.

1. Only one DIB in our study, $\lambda$5780.5, is unambiguously well-correlated with N(H), in the sense that the correlation coefficient exceeds what one would expect from the growth of interstellar material with distance.

2. None of the DIB–DIB correlation coefficients considered here are high enough to conclude that any pair arises from the same carrier. However, as described in Paper IV, the $\lambda\lambda$6196.0–6613.6 pair may be perfectly correlated if the errors were underestimated by a small amount. The correlation of the $\lambda\lambda$5780.5–5705.1 DIBs is also very high and further study is warranted.

3. Seven of the eight DIBs, excepting $\lambda$5487.7, are better correlated with N(H) than with $E_{B-V}$.

4. All eight DIBs are very poorly correlated with N(H2). Even when we restrict the sight lines to those with log[N(H2)] > 18, the correlations are poor. At a single value of $W_5$(5780.5) the column density of H2 can vary by a factor of $10^3$. This occurs just at the level of reddening corresponding to the formation of enough H2 to permit self-shielding.

5. The excellent correlation of $\lambda$5780.5 versus N(H) may be understood if the critical energy of radiation needed to ionize the two species is similar. The greater the flux of H ionizing radiation, the higher the degree of ionization of the $\lambda$5780.5 DIB carrier.

6. Most of the linear fits to the DIB–DIB correlations pass through the origin. This is not true for $\lambda\lambda$6283.8 and 6613.6. This may be due to continuum placement errors, the presence of interfering DIBs, improperly corrected telluric contamination, or a threshold effect, in which one DIB cannot form until a significant amount of another DIB is present.

7. One of the most practical uses of the results presented here is the ability to estimate N(H) in Galactic sight lines based on a measurement of the EW of $\lambda$5780.5. One must be careful to exclude sight lines in high radiation environments since these may be responsible for the outliers in this otherwise tight relationship. In addition, the correlations presented here may be compared to correlations found in other galaxies, and this may help identify the carriers of DIBs.

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