PROPERTIES OF DIFFUSE INTERSTELLAR BANDS AT DIFFERENT PHYSICAL CONDITIONS OF THE INTERSTELLAR MEDIUM

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Received 2013 February 27; accepted 2013 June 23; published 2013 August 19

ABSTRACT

Diffuse interstellar bands (DIBs) can trace different conditions of the interstellar medium (ISM) along the sightline toward the observed stars. A small survey was made in optical wavelengths, producing high-resolution and high signal-to-noise spectra. We present measurements of 19 DIBs’ properties in 50 sightlines toward hot stars, distributed at a variety of galactic coordinates and interstellar reddening. Equivalent widths were obtained by fitting asymmetric Gaussian and variable continua to DIBs. Conditions of the ISM were calculated from eight atomic and molecular interstellar lines. Two distinctly different types of DIBs were identified by carefully comparing correlation coefficients between DIBs and reddening and by different behavior in UV-shielded (ζ) and nonshielded (σ) sightlines. A ratio of DIBs at 5780 Å and 5797 Å proved to be reliable enough to distinguish between two different sightline types. Based on the linear relations between DIB equivalent width and reddening for σ and ζ sightlines, we divide DIBs into type I (where both linear relations are similar) and type II (where they are significantly different). The linear relation for ζ type sightlines always shows a higher slope and larger x-intercept parameter than the relation for σ sightlines. Scatter around the linear relation is reduced after the separation, but it does not vanish completely. This means that UV shielding is the dominant factor of the DIB equivalent width versus reddening relation shape for ζ sightlines, but in σ sightlines other physical parameters play a major role. No similar dependency on gas density, electron density, or turbulence was observed. A catalog of all observed interstellar lines is made public.

Key words: astrochemistry – dust, extinction – ISM: lines and bands – local interstellar matter
Online-only material: color figures

1. INTRODUCTION

Diffuse interstellar bands (DIBs) are absorption lines at visual and near visual wavelengths observed in the spectra of reddened stars (Herbig 1995). Their carriers are not known and so the identification of DIBs remains one of the longest standing problems in astronomical spectroscopy. Several carriers from the family of fullerene molecules and polycyclic aromatic hydrocarbonates were proposed (e.g., Leilimair et al. 2011; Salama et al. 1999; Zhou et al. 2006), but only some approximate wavelength matches were observed. Naphthalene and anthracene matched DIB 5450 (Iglesias-Groth et al. 2008, 2010) in some sightlines, diacetylene matched the profile of DIB 5069 (Krelowski et al. 1992, hereafter JD94) which corresponds to UV-shielded and nonshielded sightlines, probing cloud cores and external regions, respectively. Vos et al. (2011) shows that there are fundamental differences between the two groups in correlations between DIBs, reddening, and gas.

Around 400 DIBs are known (Hobbs et al. 2009), but only a minority of these are strong enough to be useful for a more detailed study. Hobbs et al. (2008) and Jenniskens & Desert (1994, hereafter JD94) give good catalogues of DIBs; the latter one is used in this paper to identify DIBs in our spectra.

In this paper we investigate relations between 19 observed DIBs; atomic lines of Na I, Ca I, Ca II; molecular lines of CH, CH+, and CN; and reddening in a sample of 50 different sightlines toward O and early B-type stars. Section 2 presents the spectroscopic data used in this paper. In Section 3 we propose a previously undescribed method in this field of fitting DIBs with asymmetric Gaussian functions, which gives better results for the equivalent width than a simple flux integration method. In Section 4 we investigate sorting DIBs into different families. Sections 5 and 6 present measured conditions of the ISM and their impact on correlations between DIBs and reddening. The last section contains the discussion and conclusions.

2. OBSERVATIONS AND DATA REDUCTION

2.1. Observations

Spectra used in this study were obtained with the 1.82 m telescope of the Observatory of Padua in Asiago and an echelle spectrograph. Observations were made in six observing sessions from 2011 January 16 to 2012 November 26. A setup used for this study covered the spectral range from 3700 Å to 7300 Å.
with a resolution power around 23,000 in 34 echelle orders. Exposure times were sufficient to achieve a S/N above 300 for most of the spectral range in our interest. Peak S/N is around 5700 Å and exceeds 500 in a majority of the spectra. Exceptions are some of the spectra from the first observing session that have a somewhat lower S/N. The S/N drops to 65% of the peak around 4300 Å and 6700 Å and to below 20% at 3900 Å.

Program stars were selected with a prior knowledge of reddening and spectral type only. Spectral types are limited to B3 and hotter, except for one A2 star and two B5 stars. The A2 star has a high rotational velocity and should not corrupt the ISM spectrum. Fifty sightlines cover different parts of the Galactic plane that were observable. Some of the stars belong to the same OB associations, as marked in Figure 1. We tried to select stars in a way that ensured the reddening range was covered as uniformly as possible.

Only stars with a color excess up to 1.2 mag were observed due to the moderate light collecting power of the telescope (stars brighter than 8.5 mag in the V band can be observed with reasonable exposure times). Histograms in Figure 2 show the distribution of sightlines on galactic latitude and reddening. Table 1 shows the basic parameters of individual observed stars.

### 2.2. Data Reduction

Data reduction was done using NOAO’s Image Reduction and Analysis Facility (IRAF). Flat field frames, dark frames, and bias frames were taken during every observing session. Spectra were normalized, but no atmospheric extinction correction was applied because all of the observed DIBs lie at wavelengths with no or negligible telluric lines. There was only one major DIB at 6281 Å (JD94) that was corrupted by telluric lines. We left this one out of our study. Spectra were shifted into the heliocentric velocity frame.

Figure 3 shows all 19 DIBs that were measured in the spectra. A comparison with a B1 giant spectrum is also shown. Many more DIBs can be detected, especially in highly reddened stars, but we only focused on those visible in all 50 sightlines. Stellar spectrum was not subtracted from the observed spectrum due to simplicity and because most stellar spectra lack any lines at DIBs’ positions.

### 3. MEASUREMENTS

#### 3.1. Fitting Asymmetric Gaussians

Most of the DIBs are not corrupted by stellar lines. Exceptions are DIBs at 4428 Å, where the DIB is blended with several stellar lines and the combined spectrum is too complicated for deblending, and DIBs at 4726 Å and 5705 Å, which are blended with one stellar line at 4727.3 Å and 5701.2 Å, respectively. These lines can be deblended in some of the cases. The DIB 5705 seems to suffer much less from blending than the other two lines and is therefore the only one of the above three DIBs included in the further analysis. The other complicated cases are DIBs 5780 and 6202 which are blended with other wider DIBs. In the case of 5780, the blended DIB is 7.5 times wider (JD94) and much shallower and was treated as a part of the local continuum. The DIB 6202 is blended with two other DIBs, one with a FWHM of 1.2 Å at 6203.19 Å, and the other one with a FWHM of 11.7 Å at 6207.8 Å (JD94). The DIBs 6202 and the blended one at 6203.19 Å were considered as a single DIB because we were unable to deblend them. From Figure 3 it can be seen that the two DIBs are not separated and are represented well with a single asymmetric Gaussian, a function form, we use for other DIBs (see below). The DIB 6202 is never contaminated by a Cτ stellar line at 6205.6 Å. We note that the measured profile of 7079 is notably different from the one reported in the literature. At the wavelength of a narrow DIB, we detect a depletion of the continuum three times as wide as the DIB 7079 in JD94. We checked for possible misfitted continuum due to telluric lines of H2O that lie in this region, but could not find any reason for it. We measured the profile of the depletion, excluding few narrow and weak telluric lines that blend with the depletion when fitting the profile. Precise enough removal of the telluric contamination was not possible due to the variable atmospheric conditions on most of the nights. Due to the discrepancy with the literature and possible strong telluric contamination, we excluded this DIB from the further analysis. Other DIBs can be extracted by subtracting a simple local continuum fit. From here on, only 16 DIBs will be studied, excluding 4428, 4726, and 7079 from the original 19 measured DIBs.

Figure 3 shows all DIBs observed and discussed in this paper. At least for the strongest DIBs, it is evident that their profile cannot be represented by a single Gaussian curve. The deviation from the Gaussian curve is not due to multiple components with different radial velocities, but due to unresolved fine structure of the DIB itself. The next order of approximation after a simple Gaussian curve is to allow for the profile to be asymmetric. Asymmetry can be introduced into the Gaussian curve in many ways, two of which are presented in this paper. Both gave satisfactory results when representing the profile of DIBs.

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**Figure 1.** All-sky map of all observed stars. Blue circles (white in the printed journal) are ζ and red circles (black in the printed journal) are σ sightlines, as defined in Section 6. The thick red (gray in the printed journal) line is the celestial equator. The underlying image shows galactic dust (Schlegel et al. 1998).

(A color version of this figure is available in the online journal.)

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**Figure 2.** Left: distribution of sightlines on galactic latitude. Two sightlines at $b = 51^\circ$ and $b = -44^\circ$ are excluded from the histogram. Right: distribution of sightlines on reddening.
An asymmetric Gaussian is a curve composed of two Gaussians with different widths. We choose the following definition:

$$
A(x; \mu, \sigma_1, \sigma_2, C) = C \frac{1}{\sqrt{2\pi} \sigma} \left[ \left(1 - \chi(x; \mu)\right) \exp \left(-\frac{(x - \mu)^2}{2\sigma_1^2}\right) + \chi(x; \mu) \exp \left(-\frac{(x - \mu)^2}{2\sigma_2^2}\right) \right]
$$

where $$\sigma_1$$ and $$\sigma_2$$ are widths of both Gaussian components and $$\mu$$ is the position of the Gaussian along the x-axis and corresponds to the position of the maximum or minimum of the spectral line. $$C$$ is the area under the curve and represents the equivalent width of a spectral line in a normalized spectrum. Such a function preserves most of the properties of the usual Gaussian.

$$
\chi(x) = \begin{cases} 
1 & \text{if } x > 0, \\
0 & \text{otherwise}, 
\end{cases}
$$

$$
\sigma = \frac{\sigma_1 + \sigma_2}{2}
$$
Figure 3. All observed DIBs in the spectrum of star HD 161056 (solid line) and a synthetic spectrum of a B1 giant with solar metallicity and rotational velocity of 50 km s$^{-1}$ (dashed line). The synthetic spectrum is shifted in flux for 0.03. All spectra are normalized. Each box is 10 Å wide and 0.17 units high, except for the boxes for DIBs at 4428 Å and at 6202 Å, which are 20 Å wide and the box for DIB at 5780 Å, which is 40 Å wide. The box is centered at the wavelength indicated on the top. This is also the name used for each DIB throughout the paper. The DIBs of interest are indicated with a vertical dash.

Gaussian function. The area under the curve will always have the value of $C$ and it is continuously differentiable at $(x - \mu) = 0$. The asymmetry of the spectral line can be expressed with an asymmetry index

$$a = \frac{\sigma_1 - \sigma_2}{\sigma_1 + \sigma_2},$$

where a negative value indicates that the line profile is wider toward the red part of the spectrum and a positive value indicates a widening toward the blue part of the spectrum.

An exponentially modified Gaussian is a convolution between a Gaussian and an exponential function. It can be analytically
expressed as

\[
\mathcal{M}(x; \mu, \sigma, \lambda, C) = C \left[ \frac{\lambda}{2} \exp\left( \frac{\lambda}{2}(2\mu + \lambda \sigma^2 - 2x) \right) \right. \\
\left. \times \operatorname{erfc}\left( \frac{\mu + \lambda \sigma^2 - x}{\sqrt{2} \sigma} \right) \right] \\
\text{erfc}(x) = 1 - \text{erf}(x),
\]

(3)

where \(\sigma\) is the width of a Gaussian part, \(\lambda\) is a parameter of an exponential part, \(\mu\) is the mean value of the Gaussian, and \(C\) is the area under the curve. In this case, \(\mu\) does not correspond to the maximum or minimum of the function and the minimum must be calculated numerically. However, the first three moments of the exponentially modified Gaussian are easy to express as:

- mean = \(\mu + \frac{1}{\lambda}\)
- variance = \(\sigma^2 + \frac{1}{\lambda^2}\)
- skewness = \(\frac{2}{\sigma^3 \lambda^3} \left[ 1 + \frac{1}{\sigma^2 \lambda^2} \right]^{-3/2}\).

(4)

After comparing fits of both functions (Figure 4 shows an example of fits for one DIB) to some of the strong DIBs in different spectra, we decided to use the asymmetric Gaussian only. Fits with the asymmetric Gaussian were slightly better and the Levenberg–Marquardt minimization of four parameters proved to be much more computationally stable with the asymmetric Gaussian than the exponentially modified Gaussian. Minimization of the exponentially modified Gaussian was even less stable when introducing linear or quadratic continuum. A simpler evaluation of four basic parameters also prevailed toward the use of the asymmetric Gaussian for further analysis.

A fit of two Gaussians was considered as well, but with six parameters in addition to two or three parameters of the continuum, the fit was highly constrained.

Initial parameters were estimated interactively by marking the limits, center of each DIB, and area where the continuum is fitted. The initial equivalent width was calculated by integrating the spectrum between both limits. Other initial parameters, including linear local continuum, were estimated from manually marked points on the spectrum. The DIB, together with the continuum, was then fitted by the Levenberg–Marquardt method. Errors of the final parameters were calculated from a covariance matrix. All of the lines were fitted in one sitting. All fits were visually inspected to assure that the Levenberg–Marquardt method converged toward expected values.

To be sure that a modified Gaussian correctly summarized all of the information in the observed DIB profile, we took an image of the DIB 6613 from Galazutdinov et al. (2002), traced the DIB profile, and smoothed to the resolution of our spectra. DIB 6613 shows the most prominent substructure and should be a good test of the performance of the asymmetric Gaussian fit. Figure 5 shows the result. Differences between the asymmetric Gaussian fit and smoothed spectrum were well below the noise level of our spectra.

### 3.2. Comparison of Fitted Equivalent Width with Integrated Equivalent Width

Equivalent width is defined by integration of a spectrum over a region of interest:

\[
W = \int_{\lambda_1}^{\lambda_2} \left( \frac{F_c - F_o}{F_c} \right) d\lambda,
\]

(5)

where \(\lambda_1\) and \(\lambda_2\) are integration limits on each side of the line and \(F_c\) and \(F_o\) are fluxes of continuum and observed spectrum. With \(\lambda_2\), approximated with a suitable smooth function, one can reduce the number of free parameters and the error of the derived equivalent width.

Another possibility is averaging some spectra with strong DIBs and good S/N in order to get an average shape of DIBs. This profile is then fitted to other spectra with only two parameters: position and strength (Chen et al. 2013; Raimond 2002).
et al. 2012). This method is sensitive to systematic errors and noise manifestation in an averaged DIB profile for weak bands.

We have to keep in mind that a large portion of error comes from insufficient knowledge about the continuum. Fitting a profile to a spectral line will not reduce this part of the error. We will show that the error of the continuum determination is smaller than the error of the integrated equivalent width, but equal to or larger than the error of the fitted profile. Therefore, the representation of the observed line profile with a smooth function significantly reduces the combined errors in S/N = 300 to S/N = 400 spectra.

All DIBs were fitted with an asymmetric Gaussian, even if their profile appeared symmetric upon visual inspection. Other atomic and molecular lines were fitted with an ordinary symmetric Gaussian profile, except the sodium lines where the equivalent widths were integrated instead of fitted.

By fitting the local continuum by polynomials of different orders, we get different continuum estimates. If the spectrum around DIB is filled with other spectral lines or uneven continuum, different polynomials will give different continuum fits. If the continuum strongly depends on the type of polynomial used for the area of the DIB, a larger error is assigned to this DIB’s equivalent width.

Figure 6 shows how the error in continuum determination influences equivalent width measurement. We used a linear fit in most of the cases in the final equivalent width measurements. A constant continuum has never been forced. In some cases (around 30%) where the continuum appeared nonlinear, a quadratic fit was used. Errors in continuum determination are hard to calculate precisely. Our estimated errors on continuum determination alone vary from around 2 to 12 mÅ for narrow and wide DIBs, respectively.

This error is larger than the error of equivalent width calculated from the fitted profiles, but about two times smaller than the error of equivalent widths obtained by a simple sum of pixel fluxes over the DIB’s profiles as shown in Figure 7. By fitting DIBs with asymmetric Gaussians, the error is driven by insufficient knowledge about the continuum, not by the noise in the DIB profile. This justifies the use of asymmetric Gaussians as DIB profile templates.

Fitting asymmetric Gaussians or any other simple asymmetric functions cannot be extrapolated to high S/N or high-resolution spectra. Some DIBs have a very well known substructure (Galazutdinov et al. 2002; Sarre et al. 1995) that is significantly different from asymmetric shapes that are assumed in this work. The resolution and S/N of our spectra are too low to detect this substructure. Even the strongest DIBs in our spectra with known substructure only show asymmetry and no substructure.
most of the sightlines. Several different sources were used and the paper gives no uncertainties for reddening data. For the first observing session, we used reddening from Maeder (1975) where several B type stars with well known reddening are listed. Reddening for two very well studied stars was taken from Slyk et al. (2006). Some of the data were taken from Valencic et al. (2004). This catalog, made from UV and IR photometry, includes reddening and total extinction in the V band as well as uncertainties, that are around 0.04 mag for $E(B-V)$ for most of the stars. The last reddening source was Neckel et al. (1980). Extinction was calculated from $UBV$ and H$eta$ photometry. Only total extinction in the V band is given, but it was calculated from measured reddening with a total-to-selective extinction coefficient of 3.1 for all sightlines, so the reddening can be recalculated without loss of information. Typical errors in $E(B-V)$ are of the order of 0.05 mag. Reddening in some sightlines has more than one reference in the literature. In these cases, the average value was used.

4. CORRELATIONS AND GROUPS OF DIBs

4.1. Correlations

Calculation of the correlation coefficient:

$$
\rho_{x,y} = \frac{\text{cov}(x, y)}{\sigma_x \sigma_y}
$$

(7)

is the most basic measure of dependence of the two quantities $x$ and $y$. Equivalent widths of DIBs are expected to correlate with each other and with reddening and abundances of some other atoms, ions, and molecules. We measured parameters of interstellar lines of Na i (5891.6 Å and 5897.6 Å), Ca i (4227.9 Å), Ca ii (3934.8 Å and 3969.6 Å), CH (4300.3 Å), CH+ (4232.3 Å), and CN (3874.6 Å). All of the correlation coefficients of measured equivalent widths and reddening are in Table 3.

Correlations with sodium and calcium lines must be treated separately, because they are saturated even in sightlines with low reddening. The relation from Munari & Zwitter (1997) for the Na D line was used to modify measured equivalent widths into a linear scale. Correlations were then calculated with calculated column densities. For Ca i and Ca ii lines, relations from Welty et al. (2003) were used. Molecular lines are weak enough to assume a linear relation between column density and equivalent width.

Several pairs of DIBs show a very high correlation value of 0.9 or more. This suggests that these DIBs might have the same carrier, but correlation does not necessarily imply causation.

Let us take the Na lines and Ca ii line at 3969 Å for example. Two Na lines correlate very well with each other (correlation coefficient is 0.97) but they also correlate well with the Ca ii line (correlation coefficients are 0.89 and 0.81). All of the correlations with reddening are worse than that. A conclusion that Na and Ca ii lines have the same carrier is obviously false. Therefore, a better way to determine common carriers is needed.

4.2. Common Carriers Identification

If we have the correlation coefficients for the correlation between one DIB and reddening and another DIB and reddening, statistical limits for the correlation coefficient between both DIBs can be calculated (Olkin 1981).
We take a correlation matrix for two DIBs (A and B) and reddening R:

\[
C = \begin{bmatrix}
1 & \rho & \sigma \\
\rho & 1 & \tau \\
\sigma & \tau & 1
\end{bmatrix}, \quad \rho = \text{corr}(A, B), \quad \sigma = \text{corr}(A, R), \quad \tau = \text{corr}(B, R),
\]

where Greek letters are correlation coefficients between every pair of quantities. A correlation matrix has the property that its determinant must always be larger than or equal to zero. This property can be transformed into the inequality

\[
\sigma \tau - \sqrt{(1-\sigma^2)(1-\tau^2)} \leq \rho \leq \sigma \tau + \sqrt{(1-\sigma^2)(1-\tau^2)},
\]

which are essentially lower and upper limits for \( \rho \). This equation is symmetric for any of the three correlation coefficients.

If two DIBs correlate well with each other, but each of them correlates well with reddening, it cannot be concluded that they have the same carrier. They could just as well have two different carriers that correlate with reddening in the same manner.

When we calculate both limits, it is possible to estimate which pairs of DIBs are more likely to have the same carrier. These will be the ones that correlate much better with each other than with reddening. We assume an expected correlation (\( \rho_e \)) to be in the middle of the lower (\( \rho_l \)) and upper (\( \rho_u \)) limit for \( \rho \). We introduce a factor \( \mathcal{P} \), which should increase with the probability that two DIBs have the same carrier. \( \mathcal{P} \) will be called the probability factor and is equal to:

\[
\mathcal{P} = (\rho - \rho_e) / \rho_e,
\]

where \( \rho_e \) is the calculated correlation factor. The difference between the calculated and expected correlation factors is multiplied by the calculated correlation factor, because we are only interested in pairs with high correlation. High correlation and large positive differences imply a higher probability that the two DIBs share the same carrier.

Let us return to the example of the Na and Ca II lines. The probability factor that two Na lines have the same carrier is 0.36 and for two Ca II lines it is 0.38. Probability factors indicating that Na and Ca II lines have the same carrier are between 0.09 and 0.15.

This method will not identify ions and will not distinguish between two different elements with very similar influence on reddening. However, this method performs well on observed interstellar elements and is worthy to be tried on DIBs. Because the carriers of the DIBs are not known, we will compare the results with correlation plots in Section 6.

5. DIBS AND REDDENING

Table 3 shows that most of the DIBs correlate well with reddening. However, the correlations are not perfect. An obvious scatter is present, with reduced \( \chi^2 \) distinctively lower than 1. Reduced \( \chi^2 \) is computed as described in Press et al. (2002) with the method `chisq` and the linear fits (where used) were calculated as described in method `fitexy`.

We put a lot of care into the error estimation. The scatter of measurements in the correlation plots is due not to errors but shows varying conditions of the ISM.

6. \( \sigma \) AND \( \zeta \) SIGHTLINES

Krelowski et al. (1992) showed that the parts of the ISM that are shielded from the UV radiation field produce different ratios between equivalent widths of DIB 5780 and 6797. UV shielded sightlines are named type \( \zeta \) after a sightline toward star \( \zeta \) Oph and non-shielded sightlines are named type \( \sigma \) after \( \sigma \) Sco. Intermediate sightlines must also exist so that the transition between two types is smooth. The original definition is based on the central depth of the two DIBs, where the boundary ratio of the central depths \( A_{5797} / A_{6780} \) equals 0.4. This corresponds to approximately 0.3 for the ratio of equivalent widths. Due to a smooth transition, the exact boundary ratio is not very important. We show in Figure 9 that the points denoted as \( \sigma \) and \( \zeta \) sightlines form a mixed group without a sharp boundary, even when the adopted value for the boundary ratio is varied by 10% in either direction. There are always some points representing \( \zeta \) sightlines in the area dominated by \( \sigma \) sightline points and vice versa.
Table 3: Correlation Coefficients for Each Pair of Measured DIBs, Observed Atomic and Molecular Lines, and Reddening

| Line  | 4227 | 4726 | 4964 | 5512 | 5545 | 5705 | 5780 | 5797 | 5850 | 6090 | 6196 | 6202 |
|-------|------|------|------|------|------|------|------|------|------|------|------|------|
| Redd  | 1    | 0.41 | 0.51 | 0.74 | 0.73 | 0.57 | 0.57 | 0.64 | 0.78 | 0.89 | 0.84 | 0.78 | 0.54 |
| 4428  | 0.41 | 1    | 0.12 | 0.21 | 0.22 | 0.14 | 0.24 | 0.35 | 0.59 | 0.49 | 0.41 | 0.35 | 0.59 |
| 4726  | 0.51 | 0.12 | 1    | 0.57 | 0.62 | 0.60 | 0.76 | 0.55 | 0.47 | 0.56 | 0.56 | 0.28 | 0.44 |
| 4762  | 0.74 | 0.21 | 0.57 | 1    | 0.74 | 0.59 | 0.47 | 0.67 | 0.72 | 0.69 | 0.70 | 0.49 | 0.74 |
| 4964  | 0.73 | 0.22 | 0.62 | 1    | 0.74 | 0.57 | 0.47 | 0.67 | 0.72 | 0.69 | 0.70 | 0.49 | 0.74 |
| 5512  | 0.57 | 0.14 | 0.60 | 0.59 | 0.66 | 1    | 0.65 | 0.77 | 0.45 | 0.73 | 0.78 | 0.60 | 0.43 |
| 5545  | 0.64 | 0.24 | 0.76 | 0.47 | 0.66 | 0.65 | 1    | 0.47 | 0.54 | 0.72 | 0.65 | 0.53 | 0.55 |
| 5705  | 0.78 | 0.35 | 0.55 | 0.67 | 0.59 | 0.77 | 0.47 | 1    | 0.92 | 0.74 | 0.72 | 0.47 | 0.86 |
| 5780  | 0.89 | 0.59 | 0.47 | 0.72 | 0.67 | 0.45 | 0.54 | 0.92 | 1    | 0.90 | 0.80 | 0.63 | 0.97 |
| 5797  | 0.84 | 0.49 | 0.56 | 0.69 | 0.88 | 0.73 | 0.72 | 0.74 | 0.90 | 1    | 0.94 | 0.74 | 0.91 |
| 5850  | 0.78 | 0.41 | 0.56 | 0.70 | 0.90 | 0.78 | 0.65 | 0.72 | 0.80 | 0.94 | 1    | 0.75 | 0.82 |
| 6090  | 0.54 | 0.35 | 0.28 | 0.49 | 0.61 | 0.60 | 0.53 | 0.47 | 0.63 | 0.74 | 0.75 | 1    | 0.59 |
| 6196  | 0.90 | 0.59 | 0.44 | 0.74 | 0.65 | 0.43 | 0.55 | 0.86 | 0.97 | 0.91 | 0.82 | 0.59 | 1    |
| 6202  | 0.85 | 0.53 | 0.50 | 0.73 | 0.73 | 0.73 | 0.55 | 0.58 | 0.87 | 0.95 | 0.89 | 0.83 | 0.57 |
| 6270  | 0.87 | 0.57 | 0.33 | 0.63 | 0.63 | 0.49 | 0.53 | 0.78 | 0.92 | 0.90 | 0.80 | 0.66 | 0.92 |
| 6379  | 0.69 | 0.31 | 0.52 | 0.61 | 0.79 | 0.59 | 0.63 | 0.63 | 0.72 | 0.88 | 0.83 | 0.85 | 0.76 |
| 6445  | 0.75 | 0.51 | 0.50 | 0.55 | 0.64 | 0.59 | 0.67 | 0.54 | 0.80 | 0.84 | 0.72 | 0.65 | 0.82 |
| 6613  | 0.84 | 0.58 | 0.42 | 0.60 | 0.67 | 0.57 | 0.60 | 0.77 | 0.94 | 0.93 | 0.82 | 0.71 | 0.89 |
| 6660  | 0.57 | 0.32 | 0.34 | 0.51 | 0.72 | 0.57 | 0.43 | 0.55 | 0.61 | 0.78 | 0.73 | 0.56 | 0.67 |
| 6979  | 0.34 | 0.11 | 0.31 | 0.35 | 0.21 | 0.39 | 0.24 | 0.41 | 0.37 | 0.32 | 0.34 | 0.11 | 0.32 |
| 5891 $Na$ | 0.84 | 0.38 | 0.38 | 0.60 | 0.47 | 0.27 | 0.48 | 0.79 | 0.80 | 0.64 | 0.57 | 0.28 | 0.86 |
| 5897 $Na$ | 0.78 | 0.48 | 0.53 | 0.63 | 0.48 | 0.49 | 0.53 | 0.84 | 0.91 | 0.72 | 0.63 | 0.37 | 0.92 |
| 4227 $Ca$ | 0.35 | 0.39 | 0.19 | 0.27 | 0.07 | 0.26 | 0.25 | 0.39 | 0.42 | 0.35 | 0.36 | 0.25 | 0.45 |
| 3934 $Ca_{ii}$ | 0.62 | 0.24 | 0.18 | 0.49 | 0.30 | 0.06 | 0.38 | 0.66 | 0.63 | 0.42 | 0.34 | 0.23 | 0.62 |
| 3969 $Ca_{ii}$ | 0.75 | 0.37 | 0.33 | 0.61 | 0.58 | 0.22 | 0.47 | 0.64 | 0.77 | 0.67 | 0.65 | 0.34 | 0.79 |
| 4300 $CH$ | 0.76 | 0.13 | 0.39 | 0.58 | 0.72 | 0.32 | 0.59 | 0.44 | 0.63 | 0.87 | 0.8 | 0.59 | 0.69 |
| 4322 $CH^*$ | 0.70 | 0.34 | 0.38 | 0.60 | 0.53 | 0.53 | 0.49 | 0.76 | 0.72 | 0.70 | 0.70 | 0.42 | 0.72 |
| 3874 $CN$ | 0.47 | 0.27 | 0.52 | 0.31 | 0.27 | 0.59 | 0.48 | 0.36 | 0.33 | 0.52 | 0.50 | 0.26 | 0.36 |

Notes. Reddening is $E(B - V)$ given in magnitudes. Numbers represent the correlation coefficient between equivalent widths of two spectral lines or one equivalent width and reddening. For Na and Ca lines a column density was used instead of the equivalent width. The table is split into two parts.
The existence of sightlines with different DIB ratios is also reflected in the equivalent width–reddening relation as shown in Vos et al. (2011) for DIB 5780. The relation from Vos et al. (2011) is based on the observations of a small area in Scorpius and gives a different relation than this study, which has the distribution of sightlines along a much larger part of the galactic plane. Figure 10 shows correlations between reddening and equivalent width of 16 DIBs separately for \(\sigma\) and \(\zeta\) sightlines.

From Figure 10 it is evident that the linear relation for \(\zeta\) sightlines is significantly steeper in some cases than the relation for \(\sigma\) sightlines. Higher UV shielding in the centers of the interstellar clouds can explain this if the rate of the dissociation of the DIB carrier molecules due to UV radiation is lower in the centers than in the outer unshielded parts. This results in a higher density of DIB carriers per unit of reddening.

The linear fit for the \(\zeta\) sightlines does not reach zero equivalent width at zero reddening, but at \(E(B-V) \simeq 0.09\) mag. This is due to the fact, that UV shielded regions can only exist where dust density is high enough. This value seems to be characteristic of all observed DIBs.

Based on the slopes of the linear fits, DIBs from Figure 10 can be divided into two types. The DIBs 5705, 5780, 6196, 6202, and 6270 do not show much difference between \(\zeta\) and \(\sigma\) sightlines. We will call this group of DIBs type I. Slopes of the two linear relations are close to each other and the correlation in \(\sigma\) sightlines is slightly lower than the correlation in \(\zeta\) sightlines. The DIBs 4964, 5797, 5850, 6090, 6379, and 6660 have distinctly different relations for \(\zeta\) and \(\sigma\) sightlines. We will call this group of DIBs type II DIBs. The correlation between reddening and equivalent widths for this type of DIBs is significantly better in \(\zeta\) sightlines than in \(\sigma\) sightlines.

In general, the correlation between reddening and equivalent width is better in \(\zeta\) sightlines with few statistically insignificant exceptions. The correlation coefficients are listed in Table 5. The \(\chi^2\) test further confirms this with reduced \(\chi^2 \sim 30\%\) smaller for \(\zeta\) sightlines than for \(\sigma\) ones. However, the reduced \(\chi^2\) still does not reach values close to 1.

This distinction between two types of DIBs is also predicted by a method from Section 4.2. Two types of DIBs can be recognized in Table 4. The DIBs that belong to the same type all share higher probability factors than DIBs of the other type or the uncategorized DIBs. For example, the probability factors between every pair of DIBs 4964, 5797, 5850, 6379, and 6660 are all between 0.21 and 0.30. This is considered to be a high probability factor and implies a common carrier. All of these are type II DIBs. Probability factors between these five DIBs and type I DIBs, like 5705, 5780, and 6202 are in the range of 0.03 to 0.12, which is significantly lower.

We also checked for similar behavior due to electron density, gas density, and turbulence or shock wave presence.

Turbulence or slow shockwaves can be detected through the CH\(^+\) and CH ratio (Gredel et al. 2002). One of the most important mechanisms of CH\(^+\) creation involves shockwaves with a minimal velocity of 8 km s\(^{-1}\). High \(N(CH^+)/N(CH)\) thus implies the presence of shockwaves. There are three sightlines that show shocks and three that appear to be quiescent. Others lie in between, where neither shock nor quiescent state can be confirmed (Figure 11). A mild correlation between the ratios of \(W(5797)/W(5780)\) and \(N(CH^+)/N(CH)\) is observed in our sample of ISM spectra, implying that shockwaves are more likely to be present in the ISM exposed to the UV light.

Electron density can be calculated through the ratio of Ca\(^{2+}\) or Ca\(^{3+}\) and Ca\(^{2+}\) lines. Whenever we detect Ca\(^{2+}\) lines, it can be assumed that Ca\(^{3+}\) lines are absent. This is important because Ca\(^{3+}\) has no strong lines in the observed spectral range. Electron density is calculated as (Draine 2011):

\[
n_e = \frac{\sigma(Ca^{2+})}{\sigma(Ca^{3+})} \left( \frac{\Gamma}{\alpha} \right)_{Ca^{2+}},
\]

where \(\sigma\) is a column density. The term \((\Gamma/\alpha)\) is a ratio of a photoionization rate and a radiative recombination coefficient and is on the order of 60 cm\(^{-3}\) (Pequignot & Aldrovandi 1986) for ISM expected in the observed sightlines and does not vary significantly when changing temperature or density. Electron density measured from \(N(Ca^{2+})/N(Ca^{3+})\) is therefore reliable if no deposition of Ca\(^{3+}\) on the grains is present (Welty et al. 2003). The presence of deposition can be evaluated through
Figure 10. Correlations between equivalent width of DIBs and reddening. Lines were fitted to relations for $\sigma$ (red dashed line and square points) and $\zeta$ (solid blue line and circular points) sightlines. Parameters of linear fits are given in Table 5.

(A color version of this figure is available in the online journal.)

$N(\text{Na} \, i)/N(\text{Ca} \, ii)$ (Ritchey et al. 2006). Figure 12 shows $N(\text{Ca} \, i)/N(\text{Ca} \, ii)$ and $N(\text{Na} \, i)/N(\text{Ca} \, ii)$ ratios.

Gas density (Figure 13) is proportional to $N(\text{CN})/N(\text{CH})$ (Pan et al. 2005). Because the chemistry of molecules is much more diverse, a precise relation cannot be established (Crawford 1990). However, a correlation exists and the approximate relation to transform ratios into density is (Pan et al. 2005):

$$n = \frac{N(\text{CN})}{N(\text{CH})} \times 960 \, \text{cm}^{-3}.$$  \hspace{1cm} (12)

No behavior similar to UV shielding was observed when separating sightlines based on turbulence (Figure 11), electron density (Figure 12), or gas density (Figure 13).
7. CONCLUSIONS AND DISCUSSION

The above results show that modeled asymmetric Gaussians fit very well to DIB profiles in spectra with a resolution power of 23,000 and a high S/N. However, asymmetric Gaussians are purely artificially constructed functions and do not resemble any physical properties of DIBs. It is well known that DIB profiles have fine substructure, but at lower resolutions the profiles can be fit with simple functions. In addition, asymmetric Gaussians seem to adequately fit all observed DIBs. Estimated errors are lower than errors given by a simple integration of observed pixel fluxes. Fitting also yields line widths and asymmetries that are otherwise hard to measure at a comparable precision.

The correlation of measured equivalent widths was observed for all pairs of spectral lines and reddening. As it is dangerous to make conclusions about common carriers from DIBs alone,
we always compared correlations of three quantities, accounting for a statistical probability of how two correlation coefficients influence the third one. This is important, because correlation is imperfect not only due to errors of the measured equivalent width but also due to different behavior of DIBs in different sightlines. The DIBs identified to be similar with this method, also appear to have a similar relation when separating sightlines into $\sigma$ and $\zeta$ types in the reddening versus DIB strength plots.
Figure 11. Stars plotted in a diagram showing different states of the ISM. The vertical line divides sightlines into \( \sigma \) and \( \zeta \) types. Horizontal lines divide them into shocked, turbulent, and quiescent parts. There is a wide transitional area where most of the sightlines lie.

![Diagram showing ISM states](image)

Table 5
Linear Relations between Reddening and Equivalent Width of Each DIB for \( \sigma \) and \( \zeta \) Sightlines

| DIB   | Sightline | \( a \)   | \( b \)   | \( a \) Error | \( b \) Error | Corr | Reduced \( \chi^2 \) |
|-------|-----------|----------|----------|--------------|--------------|------|-----------------|
| 4762  | \( \zeta \) | 0.1247   | 0.0158   | 0.0207       | 0.0131       | 0.79  | 3.23            |
| \( \sigma \) | 0.0755   | 0.0029   | 0.0103   | 0.0069       | 0.83         | 6.55  |
| 4964  | \( \zeta \) | 0.0419   | 0.0045   | 0.0068       | 0.0043       | 0.84  | 7.97            |
| \( \sigma \) | 0.0169   | 0.0023   | 0.003    | 0.002        | 0.76         | 6.50  |
| 5512  | \( \zeta \) | 0.0242   | 0.0034   | 0.0054       | 0.0033       | 0.76  | 9.92            |
| \( \sigma \) | 0.0082   | 0.003    | 0.0036   | 0.0028       | 0.52         | 12.9  |
| 5545  | \( \zeta \) | 0.0495   | 0.0024   | 0.0112       | 0.0068       | 0.63  | 9.22            |
| \( \sigma \) | 0.0328   | 0.0033   | 0.0063   | 0.0041       | 0.62         | 10.09 |
| 5705  | \( \zeta \) | 0.12     | 0.0104   | 0.0312       | 0.0191       | 0.77  | 17.19           |
| \( \sigma \) | 0.1098   | 0.0061   | 0.0174   | 0.0114       | 0.74         | 9.6   |
| 5780  | \( \zeta \) | 0.6029   | 0.0834   | 0.0568       | 0.0344       | 0.92  | 4.99            |
| \( \sigma \) | 0.5058   | 0.0142   | 0.0503   | 0.0315       | 0.87         | 13.61 |
| 5797  | \( \zeta \) | 0.1992   | 0.0182   | 0.0202       | 0.0124       | 0.91  | 5.64            |
| \( \sigma \) | 0.1239   | 0.0029   | 0.0139   | 0.0089       | 0.85         | 16.81 |
| 5850  | \( \zeta \) | 0.0898   | 0.0061   | 0.015        | 0.0091       | 0.81  | 10.69           |
| \( \sigma \) | 0.0502   | 0.0014   | 0.0054   | 0.0035       | 0.87         | 5.3   |
| 6090  | \( \zeta \) | 0.0266   | 0.0015   | 0.0042       | 0.0026       | 0.78  | 7.43            |
| \( \sigma \) | 0.0129   | 0.0041   | 0.0039   | 0.0028       | 0.51         | 14.22 |
| 6196  | \( \zeta \) | 0.0603   | 0.0062   | 0.0068       | 0.0042       | 0.9   | 6.83            |
| \( \sigma \) | 0.0479   | 0.0009   | 0.004    | 0.0026       | 0.91         | 6.76  |
| 6202  | \( \zeta \) | 0.0955   | 0.0054   | 0.0142       | 0.0082       | 0.85  | 6.47            |
| \( \sigma \) | 0.0907   | 0.0032   | 0.0104   | 0.0066       | 0.86         | 7.65  |
| 6270  | \( \zeta \) | 0.1158   | 0.0141   | 0.0131       | 0.0082       | 0.9   | 6.24            |
| \( \sigma \) | 0.0844   | 0.0006   | 0.0124   | 0.0082       | 0.81         | 13.28 |
| 6379  | \( \zeta \) | 0.1255   | 0.0093   | 0.0207       | 0.0126       | 0.78  | 13.61           |
| \( \sigma \) | 0.0572   | 0.0043   | 0.0118   | 0.0078       | 0.66         | 40.18 |
| 6445  | \( \zeta \) | 0.0356   | 0.0029   | 0.0067       | 0.0041       | 0.75  | 4.72            |
| \( \sigma \) | 0.023    | 0.0014   | 0.0038   | 0.0025       | 0.64         | 13.28 |
| 6613  | \( \zeta \) | 0.2576   | 0.0171   | 0.0243       | 0.0148       | 0.92  | 5.26            |
| \( \sigma \) | 0.1917   | 0.0031   | 0.0256   | 0.0165       | 0.79         | 28.45 |
| 6660  | \( \zeta \) | 0.0485   | 0.0036   | 0.0056       | 0.0034       | 0.9   | 5.32            |
| \( \sigma \) | 0.0135   | 0.0087   | 0.0042   | 0.0028       | 0.52         | 34.79 |

Notes. Equation is \( W_{445} = a \cdot E(B − V) + b \) if reddening is in magnitudes and \( W \) is in \( \AA \). 1σ errors are given for \( a \) and \( b \), joined by the values of the correlation coefficient and reduced \( \chi^2 \).

![Diagram showing reddening and equivalent width](image)

Figure 12. \( N(\text{Ca I})/N(\text{Ca II}) \) is proportional to electron density if there is no \( \text{Ca II} \) deposition onto dust grains. This can be tested through the \( \text{Na I} \) to \( \text{Ca II} \) ratio, which is very sensitive to \( \text{Ca II} \) deposition. Values between 2 and 10 are common. Values close to 100 would indicate \( \text{Ca II} \) deposition on grains, and values below 1 would indicate a presence of strong shockwaves that break dust grains and release \( \text{Ca II} \). There was no deposition or release of \( \text{Ca II} \) observed. Electron densities are therefore in the range from \( \sim 0.2 \) to \( \sim 15 \ e^{-} \ cm^{-3} \).

![Diagram showing electron density](image)

Figure 13. \( N(\text{CN})/N(\text{CH}) \) traces the gas density. Observed ratios approximately correspond to densities between 95 and 750 \( \text{cm}^{-3} \).

![Diagram showing gas density](image)

Separating \( \sigma \) and \( \zeta \) sightlines based on the ratio of equivalent widths of DIB 5797 to DIB 5780 proved to be successful. Sightlines of both types are coherently distributed in the sky where the sightlines toward the same OB association belong to the same type. Similarly, the nearby sightlines most often
belong to the same type as the light penetrates the same complex of interstellar clouds. Observed sightlines are divided almost in half, which is consistent with the original condition based on line depths. The results are insensitive to the adopted borderline value dividing the two groups. Results are consistent when varying the boundary condition for ±10% around the chosen value of 0.3.

Separating σ and ζ sightlines shows at least two different types of DIBs. We introduce type I DIBs where the behavior of DIB equivalent width and reddening is similar for σ and ζ sightlines, and type II DIBs where it differs significantly. This separation clearly improves correlation coefficients (compared to the correlation before the separation into σ and ζ sightlines) and χ² for ζ sightlines in a type II DIBs, where DIB equivalent width versus reddening relation is significantly different for both types of sightlines. There is either no or only small improvement of the correlation coefficient and χ² for ζ sightlines in type II DIBs. The correlation for σ sightlines in type I and type II DIBs is not or only insignificantly improved. This means that UV shielding is one of the dominant factors of the DIB equivalent width versus reddening relation shape for ζ sightlines, but in σ sightlines other physical parameters play a major role. A complementary explanation could be a skin effect that affects type II DIBs and weakens the DIBs in σ sightlines. See also a discussion in Adámkovics et al. (2005).

Typical type I DIBs are 5705, 5780, 6196, 6202, and 6270. Typical type II DIBs are 4964, 5797, 5850, 6090, 6379, 6613, and 6660. The remaining four DIBs are hard to associate with either of these two types.

Different behaviors of σ and ζ sightlines in type II DIBs is reflected by a different steepness of slopes of the relation between the DIB’s equivalent width and reddening. The change of slope is most obvious when comparing DIBs 6613 and 6660. For DIB 6613 the two slopes have a ratio of 1.24 ± 0.22 and for DIB 6660 it is 3.59 ± 1.19, which is almost 2σ apart. This could indicate that there are more than two types of DIBs. Additional observations will further test this hypothesis.

All results are listed in Tables 1–6. Table 1 lists basic properties of observed sightlines and the quality of the recorded data. Table 2 gives the comparison of some measured equivalent widths with the ones published in the existing literature. Table 3 gives the correlation coefficients for all pairs of the observed interstellar lines and reddening. In a similar format, the probability factors (defined in Equation (10)) are given in Table 4. Table 5 provides linear relations, correlation coefficients, and reduced χ² for reddening versus DIB equivalent width. Table 6 gives the parameters for each of 50 sightlines.

Na i and Ca ii were detected in all sightlines, Ca i and CH in 46, CH* in 45 and CN in 31 sightlines, including lower density σ sightlines. Ca i and molecular lines are weak and all lie in blue part of the spectral range, where the S/N drops to around 200 or less. Therefore, the conditions of the ISM cannot be measured precisely, especially where one of the lines is expected to be very weak. There is also not much variation in the conditions of the ISM. No difference in DIB–reddening relation, when separating sightlines with respect to ISM conditions, is thus expected. More sightlines would be needed to sample more diverse ISM clouds in order

Table 6
Data and Format of Parameters

| DIB  | Position (Å) | Position Error (Å) | W_eq (mÅ) | W_eq Error (mÅ) | Width (Å) | Width Error (Å) | Asymmetry | Asymmetry Error |
|------|--------------|-------------------|-----------|-----------------|-----------|-----------------|-----------|-----------------|
| 4428 | 4427.16      | 0.08              | 202.4     | 24.3            | 5.671     | 0.127           | 0.26      | 0.25            |
| 4726 | 4725.97      | 0.03              | 56.0      | 7.6             | 2.069     | 0.027           | −0.59     | 0.05            |
| 4762 | 4762.61      | 0.07              | 64.9      | 19.1            | 3.657     | 0.308           | 0.48      | 0.62            |
| 4964 | 4963.61      | 0.02              | 6.0       | 1.5             | 0.414     | 0.016           | −0.26     | 0.03            |
| 5522 | 5512.4       | 0.07              | 1.6       | 1.9             | 0.534     | 0.088           | 0.0       | 0.18            |
| 5545 | 5544.75      | 0.02              | 12.8      | 2.7             | 0.752     | 0.02            | −0.31     | 0.04            |
| 5705 | 5704.55      | 0.04              | 51.5      | 8.8             | 2.327     | 0.049           | −0.34     | 0.1             |
| 5780 | 5779.99      | 0.01              | 264.5     | 7.1             | 1.909     | 0.009           | −0.19     | 0.02            |
| 5797 | 5796.71      | 0.01              | 78.3      | 3.5             | 0.896     | 0.007           | −0.26     | 0.01            |
| 5850 | 5849.56      | 0.02              | 25.4      | 3.2             | 0.911     | 0.016           | 0.07      | 0.03            |
| 6090 | 6089.54      | 0.02              | 12.2      | 2.1             | 0.566     | 0.02            | 0.03      | 0.04            |
| 6196 | 6195.65      | 0.01              | 37.6      | 1.8             | 0.613     | 0.031           | −0.32     | 0.04            |
| 6202 | 6202.85      | 0.01              | 53.9      | 3.4             | 1.129     | 0.04            | 0.18      | 0.09            |
| 6270 | 6269.55      | 0.03              | 71.0      | 6.7             | 1.644     | 0.037           | 0.22      | 0.07            |
| 6379 | 6378.99      | 0.01              | 48.4      | 2.1             | 0.563     | 0.005           | −0.02     | 0.01            |
| 6445 | 6445.01      | 0.02              | 17.3      | 2.5             | 0.653     | 0.022           | 0.21      | 0.04            |
| 6613 | 6613.1       | 0.01              | 163.2     | 3.0             | 1.008     | 0.053           | −0.25     | 0.11            |
| 6660 | 6660.47      | 0.01              | 27.1      | 2.8             | 0.757     | 0.015           | 0.37      | 0.03            |
| 7079 | 7077.94      | 0.03              | 116.2     | 9.6             | 1.986     | 0.026           | −0.74     | 0.05            |
| 5891 Na i | 5889.64 | 0.01 | 688.6 | 8.5 | 0.626 | 0.003 | 0.1 | 0.0 |
| 5897 Na i | 5895.61 | 0.01 | 622.1 | 22.2 | 0.606 | 0.008 | 0.0 | 0.0 |
| 4227 Ca i | 4226.63 | 0.01 | 9.7 | 1.5 | 0.298 | 0.006 | 0.0 | 0.0 |
| 3934 Ca ii | 3933.52 | 0.02 | 232.5 | 3.7 | 0.393 | 0.002 | 0.0 | 0.0 |
| 3969 Ca ii | 3968.33 | 0.01 | 114.3 | 1.3 | 0.45 | 0.08 | 0.0 | 0.0 |
| 4300 CH | 4300.14 | 0.02 | 180.0 | 11.1 | 0.254 | 0.002 | 0.0 | 0.0 |
| 4232 CH | 4232.39 | 0.02 | 11.0 | 1.2 | 0.305 | 0.004 | 0.0 | 0.0 |
| 3874 CN | 3874.38 | 0.01 | 9.1 | 1.8 | 0.292 | 0.014 | 0.0 | 0.0 |

Note. Quantities are defined in Section 3.
to be able to separate DIB–reddening relations based on other conditions, in addition to UV shielding. With our sample of observed sightlines, we were unable to separate sightlines based on turbulence, electron density, or gas density.

We thank the anonymous referee and the editor for valuable comments and suggestions that improved the quality of the paper and its presentation. We thank Ulisse Munari and the time allocation committee of the Asiago Observatory for allocating an extensive amount of observing time and the observatory staff for valuable assistance during observations. T.Z. acknowledges support of the Slovenian Research Agency and Centers of Excellence Programs.

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