Dusting off the Diffuse Interstellar Bands

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ABSTRACT

Using over a million and a half extragalactic spectra we study the properties of the mysterious Diffuse Interstellar Bands (DIBs) in the Milky Way. These data provide us with an unprecedented sampling of the skies at high Galactic-latitude and low dust-column-density. In this first paper we present our method, study the correlation of the equivalent width of 12 DIBs with dust extinction and with a few atomic species, and the distribution of four DIBs over nearly 15 000 deg\textsuperscript{2}. As previously found, DIBs strengths correlate with extinction and therefore inevitably with each other. However, we find that DIBs can exist even in dust free areas. Furthermore, we find that the DIBs correlation with dust varies significantly over the sky. DIB under- or over-densities, relative to the expectation from dust, are often spread over hundreds of square degrees. These patches are different for the four DIBs, showing that they are unlikely to originate from the same carrier.

Key words: ISM: general – ISM: lines and bands – ISM: molecules – dust, extinction – surveys – techniques: spectroscopic – astrochemistry

1 INTRODUCTION

The diffuse interstellar bands (DIBs) – unidentified absorption features that have been detected so far in the optical and near infrared wavelength range – are a long standing mystery in astronomical spectroscopy (e.g., Jenniskens & Desert 1994, Herbig 1995, Snow 1995, Snow 2001). The first DIBs were discovered in stellar spectra in 1919 (Heger 1922) and were stationary in the spectra of binary stars, thus associated with the interstellar medium (Merrill 1936; Merrill & Wilson 1938).

So far, hundreds of DIBs have been found, and large molecules and their ions as the most likely candidate carriers (see Herbig 1995 for a review). Many carriers of DIBs have been proposed since their discovery, from polycyclic aromatic hydrogen carbonates (Salama et al. 1999; Zhou et al. 2006; Leidlmair et al. 2011), to fullerenes (Kroto et al. 1985), and various hydrocarbon molecules and ions such as HC\textsubscript{5}N\textsuperscript{+}, HC\textsubscript{4}H\textsuperscript{+}, and linear C\textsubscript{6}H\textsubscript{2} (Motylewski et al. 2000, Krebowski et al. 2010 and Maier et al. 2011 respectively). However the small number of wavelength matches that have been observed and the large number of features in interstellar spectra have so far prevented reliable identifications. Given the large number of known DIBs, a secure identification of a given carrier with a set of lines will require not only state-of-the-art laboratory spectroscopy, but also astronomical evidence that these specific lines are co-located and their strength correlated.

DIBs studies are generally based on stellar spectra, typically at low galactic latitude and relatively high extinction. Moreover, many studies are based on exquisite spectra, albeit only through a handful of sight lines, and thus suffer from a difficulty to draw general overarching conclusions. Recently, studies have raised these numbers to hundreds of stars (e.g., Friedman et al. 2011; hereafter F11) and even larger samples (Kos et al. 2013 who studied the 8620 Å DIB using 500 000 spectra). Zasowski et al. (2014) use 60 000 in-
frared spectra, Yuan & Liu (2012) use 2000 stellar spectra from the Sloan Digital Sky Survey (SDSS), and Maíz Apellániz et al. (2014) are compiling a sample that will consist of thousands of stellar spectra.

The public domain already includes a large number of spectra that could be used to study DIBs in a statistical manner. Poznanski et al. (2012) (hereafter P12) used a million SDSS spectra of galaxies and quasars to study the mean properties of the Milky Way Na I D absorption doublet. They showed that even though every spectrum has low signal-to-noise (S/N), by binning the spectra in large numbers (typically more than 3000) one can detect the doublet and measure its equivalent width (EW). As we show below, updating the data and optimizing the method of P12, we can recover and study many DIBs, through many sight lines, even though the DIBs are much weaker than the sodium doublet.

Since our sample consists of more than 1.5 million spectra that span over 15 000 deg$^2$ we are less prone to the systematics and variance that arise when one compares individual sight lines. Furthermore, we are probing a high Galactic-latitude environment that has been barely studied before. Last, our low-resolution spectra, despite the obvious drawbacks, offer a significant advantage over standard Echelle observations. In high-resolution spectra the DIBs often cross over dispersion orders, rendering the determination of the continuum flux extremely difficult. As a consequence, equivalent widths of relatively broad features suffer from significant biases.

In Section 2 and 3 we present the data and our method, which includes extensive simulations for uncertainty estimation. We use these in Section 4 to study the relation of DIB strength with dust, sodium, and calcium, integrated over the entire SDSS footprint. In Section 5 we study the distribution over the sky of 4 DIBs after we correct for the general dependance on dust column density. We review and discuss our findings in 6.$^1$

## 2 STACKING SPECTRA

The wavelengths and basic parameters of DIBs are gathered from the catalog of Jenniskens & Desert (1994), later updated with new discoveries from Jenniskens et al. (1996) and Krelowski, J. et al. (1995). Jenniskens & Desert (1994) observed the spectra of four reddened early type stars, systematically searching for diffuse interstellar bands in the 3800–8680Å wavelength range. We choose all the DIBs that are in the wavelength range of the SDSS spectra, remaining with 276 DIBs in total.

The SDSS ninth data release (DR9) includes more than

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$^1$ While performing this analysis we became aware of a similar effort by Lan et al. (2014). We decided to finish the two analyses independently and submit the two papers simultaneously. Section 6 briefly compares their work to ours.

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Figure 1. Top to bottom: a random SDSS QSO spectrum with $m_r = 21$ mag, multiplied by 0.1 (black), a stack of 70 000 spectra with a median color excess of $E(B-V) = 0.05$ mag (blue dotted), a stack of the entire SDSS sample (blue dashed), and a simulated DIB spectrum based on the catalog of Jenniskens & Desert (1994, blue).

Figure 2. Example fit for the 5780.6 Å DIB. Black line is the stacked spectrum, coloured lines are the individual Gaussian components. The horizontal grey line represents the limits of the fitting range as defined in section 3, and the red dashed line is our fit: a sum of all the Gaussians.
Dusting off DIBs

200,000 QSOs and about 1.3 million galaxies with low resolution (R = 1800) and low S/N (compared to spectra typically used for DIBs studies). From these we choose spectra with redshift $z < 0.005$ in order to avoid contamination from absorption lines in the rest frame of the QSOs and galaxies. After excluding stellar spectra that were mistakenly identified as QSOs and galaxies (we identified these stars via their Balmer absorption lines), we remain with 1,307,656 galaxies and 213,959 QSOs, more than a million and a half spectra in total, about 50 percent more than P12 who used DR8.

For correlation with the column density of dust we use the maps of Schlegel et al. (1998) (hereafter SFD) who used all-sky measurements of infrared emission as a tracer of dust content.

We expand the method used by P12 to the entire wavelength range of the SDSS spectra: first we linearly interpolate every spectrum to an identical wavelength grid of 0.5 Å resolution, in the 3817 – 9206 Å range. We use the Savitzky-Golay smoothing algorithm (Savitzky & Golay 1964) with a 2nd order polynomial fit and a moving window size of 150 Å to fit and divide out the continuum, thus obtaining normalized fluxes. This removes all intrinsic features except for narrow lines. We then group the spectra by their color excess value, $E(B - V)$ (or coordinates in Section 5), using the maps of SFD, and combine them by calculating the median at every wavelength.

The grouping and stacking of spectra is performed within a database we built for that purpose, using the SciDB open-source scalable array-databaseootnote{www.scidb.org}, that allows large datasets to be accessed rapidly by parallel processes, with native complex analytics. Technical details will be published in Yao et al. (in preparation).

In figure 1 we show the result of stacking 70,000 spectra, as well as stacking the entire SDSS, compared to a single spectrum. The gain in S/N is obvious. When comparing the stacked spectra to a simulated spectrum based on the DIB catalog, one can see that we recover not only the strong 5780.6 Å line, but also the much weaker lines such as the 5719.4, 5752.1 and 5797.1 DIBs. The median extinction value of the 70,000 stacked spectra is higher than for the entire SDSS sample.

3 EW MEASUREMENTS AND UNCERTAINTIES

Since our resolution is too low to resolve any line structure we can simply fit Gaussians to measure the EW of the DIBs. Due to the large number of DIBs in the wavelength range and the low resolution of the SDSS spectra, most of the lines are blended. For each DIB we set the initial fitting range to be 10 times the line’s full width half maximum (FWHM). In case there are no other DIBs in the initial fitting range we define the DIB as isolated and the fit is straightforward. Otherwise, for every additional DIB in the initial fitting range, we increase the range until it includes all the blended lines around the initial DIB. We then fit multiple simultaneous Gaussian functions, one for each DIB in the range. For every included line we allow the central wavelength and width to vary within the cataloged uncertainty.

One can see the process in figure 2: the initial DIB is...
5780.6 Å. Since the DIB is blended we increase the fitting limits until all the blended lines are included. We then fit simultaneously 17 Gaussian functions and extract the Gaussian that represents the line of interest. We compute the EW by integrating over the best fitting Gaussian function.

To estimate our uncertainty and look for possible biases we measure the flux and the EW of synthetic lines. We first create 50 synthetic absorption lines by randomly assigning their depth, FWHM and central wavelength. The synthetic lines are Gaussian shaped with amplitudes and FWHMs that are similar to the DIBs typical values: amplitudes near $10^{-3}$ and FWHM of the order of a few Å. We inject them into the spectra and for half of the Gaussians introduce an extinction dependent amplitude. We then process the spectra as before, normalizing, removing broad source signal, and stacking. To probe the entire wavelength range we perform 200 iterations of the process which results in 10 000 synthetic absorption lines in total.

Accuracy should compel us to simulate the effect of our entire pipeline on the synthetic lines, which entails their introduction into the spectra before stacking. However, we find that injecting the synthetic lines after stacking produces identical results. This requires much less computational resources (since we operate on tens of spectra, rather than hundreds of thousands), and shows that we do not introduce a significant bias during the stacking process.

Figure 3 shows on the right four representative synthetic lines. The figure shows only the line’s best fit Gaussian though all the absorption lines in the range of the plot are fitted. Clearly the synthetic lines can be detected and we find that their EW can be measured down to 5mÅ, which we subsequently use as our upper limit in case of a non-detection.

The synthetic lines allow us to measure the errors caused by uncertain continuum estimation and line blending that are typically the main causes for uncertainty underestimation (e.g., Herbig 1995 and F11). For example, McCall et al. (2010) stated that the nearly perfect correlation between the DIB pair 6196 Å and 6613 Å deviates from a perfect correlation due to a systematic error caused by the continuum uncertainty.

We try the following baseline definitions: fitting a linear and 2nd polynomial order curve to the fitting range, setting the baseline to be a constant at the 88th-98th percentile of the flux in the fitting range, or forcing the baseline to be unity in every fitting range. For every method we measure the EW of the synthetic lines and compare it to the EW we introduced. One can see in figure 3 the EW of the synthetic lines vs. E(B − V) for the 88th, 90th and 94th baseline. We find that defining the baseline to be constant as the 90th percentile of the flux in the fitting range predicts the initial EW with the smallest scatter. Furthermore, we find that for that same definition there is no systematic offset in the fluxes we measure. We therefore use it, as it minimizes both statistical and systematic errors.

P12 found a systematic shift, where their EW measurements on the SDSS spectra were consistently underestimated by about 10 percent. They assigned this shift to a bias that arises from the uneven distribution of the sample which is skewed towards low extinction spectra. Although we do not find a systematic shift in the flux for the 90th baseline, we find a systematic shift of 3 percent between the...
Dusting off DIBs

4 CORRELATIONS OF DIBs WITH OTHER ISM SPECIES

4.1 DIBs and dust extinction

Since their discovery studies have shown that DIBs EW correlate with reddening, though with a non negligible scatter. As the S/N increased and the measurements were refined, it became apparent that much of the scatter is intrinsic and not due to measurement errors (Herbig 1995).

To measure the EW as a function of dust column density we bin the spectra over similar values of E(B − V) as derived from the SFD maps. We tested various numbers and sizes of bins. For 0.02 < E(B − V) < 0.3, where we have the majority of the spectra, we fix the number of objects per bin. The number of bins for this color-excess range was determined by varying it from 10 to 100, every time comparing the resulting EW to the extinction. We found that the results are always consistent and stable and do not depend on the number of bins. However, we have only 1500 spectra at E(B − V) > 0.3, spanning a large range of color-excesses. Since 1500 spectra are not sufficient for obtaining the necessary S/N for DIBs measurement, we exclude this range from further analysis. All the spectra at E(B − V) < 0.02 (nearly 400,000), where the EW is very small and difficult to measure, are stacked in a single bin. Below, we present results using 24 bins that seem to sample the relation well. We note that our last bin reaches E(B − V) = 0.3, but the median color excess of its spectra is close to E(B − V) = 0.11, so that our effective dynamic range is between no extinction and E(B − V) ≈ 0.15.

Figure 4 shows the 5780.6, 5797.1, 5039.1 and 6613.7 lines and their EW vs. E(B − V) compared to the slopes of the relation F11 and Kos & Zwitter (2013, hereafter K13) have deduced (we forced the relations to pass through the origin for K13). We present in table 1 the best fitting linear parameters and the correlation coefficients we find for 12 DIBs that can be measured given our S/N. We only present DIBs for which the uncertainties in the linear parameters are smaller than the parameters.

Some of the DIBs in table 1 have an EW-dust relation that does not intercept the origin. We define as such relations where the B parameter is more than 1σ away from the origin and mark them in the table. This would indicate that some DIBs can exist in regions devoid of dust. Interestingly, the 2175 Å bump in the extinction curve of galaxies, which has often been discussed as related to DIBs, shows a similarly surprising decoupling from dust extinction (Zafar et al. 2012).

Our spectra are integrated over the entire Galaxy, summing contributions from multiple clouds, and at the low extinctions we probe – mostly inter-cloud gas. The scale height of dust in the Milky Way is of a few hundreds pc (e.g., Drimmel & Spergel 2001), but the coronal gas (or hot ionized medium) can be found up to 10 times farther away at high Galactic latitude. If the scale height of DIBs is larger than that of dust – if DIBs can reside further into the harsh halo, or at least somewhat outside the dusty disk – then we expect their EWs to be larger in our sample than previously measured at lower Galactic latitudes, as we integrate over larger columns of DIB carriers for a given dust column density.

Studies have suggested that DIB ratios might be linked to UV irradiation and extinction and argued that the scatter in the EW-E(B − V) relations of DIBs is due to different radiation fields in interstellar clouds (see Kreowski et al. 1992 and K13). K13 addressed this issue by dividing their spectra into 2 groups, σ (not UV shielded) and ζ (UV shielded) sight lines, based on the EW ratio between 5780.6 Å and 5797.1 Å, claiming that intermediate sight lines must also exist since the transition between the two types should be

| DIB   | Origin-Intercept | A     | B     | Corr |
|-------|-----------------|-------|-------|------|
| 5039.1| n               | 0.3 ± 0.1 | 0.069 ± 0.007 | 0.89 |
| 5704.7| y               | 0.4 ± 0.2 | 0.014 ± 0.008 | 0.89 |
| 5747.8| y               | 0.2 ± 0.1 | 0.002 ± 0.008 | 0.89 |
| 5779.5| n               | 0.23 ± 0.09 | 0.026 ± 0.004 | 0.9  |
| 5780.6| y               | 0.81 ± 0.07 | -0.003 ± 0.003 | 0.89 |
| 5797.1| y               | 0.3 ± 0.2 | 0.001 ± 0.011 | 0.91 |
| 5941.2| n               | 0.2 ± 0.1 | 0.032 ± 0.007 | 0.89 |
| 6010.6| n               | 0.2 ± 0.1 | 0.018 ± 0.008 | 0.89 |
| 6204.3| y               | 0.3 ± 0.2 | 0.003 ± 0.008 | 0.89 |
| 6281.1| n               | 1.1 ± 0.2 | 0.028 ± 0.008 | 0.92 |
| 6516.5| n               | 0.2 ± 0.1 | 0.071 ± 0.005 | 0.87 |
| 6613.7| y               | 0.17 ± 0.15 | 0.003 ± 0.009 | 0.9  |

Parameters for the best linear fit of DIB EW vs. E(B − V); EW[A] = A · E(B − V) + B, and the correlation coefficient. We separate the DIBs into those that have relations that intersects the origin, and those that do not.
smooth. They showed that dividing the spectra into \( \sigma \) and \( \zeta \) sight lines reduces the scatter in EW-reddening relation and that the behavior of the EW and reddening differs for some of the DIBs for the different sight lines. F11 deduced EW-reddening relation with a slope that is within the range of the two types of sight lines. Yuan & Liu (2012) and Phillips et al. (2013), find similar slopes for the 5780.6 Å line.

The slopes of the EW and reddening relation we find for the DIBs above are even higher than K13 steepest \( \zeta \) sight lines by 30 percent. Since the relation we obtained is based on binning different spectra and averaging them we would expect our relations to be intermediate and more similar to other published results. Furthermore, we probe an environment that is not UV shielded at all, with very low column densities.

However, a simple comparison between our sample and all the studies discussed above is misleading, since most of their sight lines are at high extinction which dominates the fit. F11 do have many stars we can compare to, and it seems clear that we tend to measure EWs which are larger than they measure for most DIBs. This is consistent with our discussion for the positive intercept, an indication that the scale height of DIBs is greater than that of dust.

We examine whether we can find a dependence of the dust-DIB relations on Galactic latitude. We split our data into three bins of latitude, above 45 deg (56 percent of the spectra), below \(-45\) deg (13 percent), and in between (31 percent). Within each bin we measure the EW of the 5780.6 Å as a function of color excess. Only below \(-45\) deg we find a different slope than the \(0.8 \pm 0.07\) we find over the entire sky. Instead we find a slope for the best fitting line that is even higher, \(1.4 \pm 0.2\). This results should be taken as indicative only, since it is based on a small number of spectra, but it hints that the correlation between the dust and DIB-carrier column densities may be quite different in different regimes, even at supposedly similar extinctions. As
we show in section 5, the DIB-dust relation can change dramatically between sight lines, in a non-trivial way that is not necessarily correlated with latitude.

### 4.2 DIBs vs. NaID, CaII

Unlike previous works, where interstellar lines may blend with a stellar contribution (e.g., K13), by construction our spectra include only contributions from the ISM without a stellar component. This allows us to derive more robust relations between DIBs and atomic species. We measure the EWs of interstellar Na ID doublet and Ca II H&K lines and plot them against the EWs of the strongest DIBs: 5780.6 Å and 5797.1Å. We present the plots in figure 5 and the parameters of the best linear fit in table 2. These relations should only be applied in the linear regime of the curve of growth which we probe here, at $E(B - V) < 0.15$.

Clearly there is a significant correlation between all these constituents, as found before (e.g., Herbig 1993; Kos & Zwitter 2013). This is to be expected if the DIBs and known atomic species are co-located.

### 5 MAPPING DIBs

#### 5.1 Tiling the sky

Figure 6 shows the distribution of our sample in Galactic coordinates, compared to the samples of F11 and K13. Clearly, we sample much higher Galactic latitudes and span a much larger, and continuous, area on the sky. The average density of spectra in SDSS is about 100 spectra per deg$^2$. In order to obtain a sufficiently high S/N for detecting DIBs we must stack hundreds or thousands spectra, even when restricting ourselves to the few strongest lines. However, in order to study the distribution of the DIBs as a function of sky coordinates with the highest possible resolution we wish to group as few sight lines as possible.

We optimize as follows. We start by dividing the sky into 12 288 Healpix pixels, each pixel with an area of 3.35 deg$^2$. Healpix provides an algorithm for subdividing the surface of a sphere into equal-area pixels which are arranged into lines of equal latitude. We group the pixels using a modified closest-neighbor algorithm using extinction from SFD as a proxy for similarity. Every pixel starts as a one sized group and the group’s extinction is defined as the average extinction over all the spectra in it. For every group that contains less than 5000 spectra, we select the closest extinction group out of the nearest neighbors, merging the groups to a single group and updating the mean extinction. We continue merging groups until every group contains a sufficient number of spectra.

The bottom part of figure 6 shows the final 250 groups we obtain. Most of the groups cover an area of 20–40 deg$^2$ and a small number groups (roughly 30 groups) cover an area of 50–100 deg$^2$. In figure 7 we present the average color excess and its standard deviation per group. One can see that the majority of the groups have a relatively small scatter, typically smaller than 20 percent.

#### 5.2 The distribution of DIBs on the sky

From here on we study the following DIBs: 5780.6, 5797.1, 6204.3 and 6613.7 Å, which are all well-studied, strong, and isolated enough to be detected with a relatively small number of spectra being stacked. The stacking and EW measurement procedure are identical to the one described in Section 2. Since we use bins with a somewhat smaller number of spectra we define a DIB as detectable when its EW is higher than 7 m Å, rather than the 5 m Å found before.

Since the four lines are strongly correlated with extinction, as shown in Section 4.1, the distribution of their EW on the sky is of little interest as it generally follows the SFD map like the top panel of Figure 7. Instead, We measure deviations from this expectation. For every stacked spectrum, we calculate the expected equivalent width $W_e$ based on the color-excess dependence measured over the entire sky in Section 4.1, and show in Figures 8 to 9 the normalized residual, $(EW - W_e)/W_e$ for every DIB. In the absence of scatter or measurement uncertainties a residual map should be zero throughout. We see however that all the maps show significant deviations from that, with typically a large number of small negative residuals and a small number of high positive residuals. This imbalance is at least partially due to the fact that EWs cannot be smaller than our 7 m Å floor, but have no upper limit, so that negative divergence is capped but positive divergence is not.

A few intriguing results are apparent when observing the residual maps. First, they are different from each other. The different DIBs are over (or under) abundant in different areas. This is an indication that that the four lines have four different carriers. Secondly, the DIB density fluctuations often cover areas of hundreds of square degrees, encompassing a few adjacent groups, as neighboring groups tend to have similar residuals. Thirdly, groups that diverge most strongly from the general trend and have extreme residual values (with EWs 3–5 times larger than expected) are small and...
isolated. In figure 10 we show an example for such a group – the EW of 5780.6 Å is normal, but 5797.1 Å is much stronger than expected, and in fact stronger than 5780.6 Å, which is rather unusual. These maps are effectively a measurement of the distribution of the various DIB carriers on the sky, and future comparisons to other ISM species may point to the carrier of each line.

6 CONCLUSIONS

With an unprecedented coverage of almost half the sky, we study the correlations of DIBs strength with dust extinction, a handful of atomic species, and the distribution of DIBs on the sky. Our results can be summarized as such:

- As often determined before, we find for 12 DIBs that their EWs correlate strongly with dust extinction, though about half of them are consistent with existing even when the dust content is negligible.
- The slopes for the DIB-dust relations we measure are usually steeper than previously found, but in a range of very low extinction never probed before. This might also indicate that our random high-Galactic latitude sight lines have distinct properties (e.g., density, UV radiation field, dust composition) from sight lines towards the usual DIB targets.
- The fact that we detect DIBs in sight lines with little to no extinction, more so at very high galactic latitudes, indicates that the scale height of the DIBs carriers is significant, and their distribution may be more extended than the distribution of dust.
- We measure the relations of the 5780.6 and 5797.1 Å lines with the Na I D doublet, and the Ca H&K lines. Since the EW of 5780.6 Å is normal, but 5797.1 Å is much stronger isolated. In figure 10 we show an example for such a group – the EW of 5780.6 Å is normal, but 5797.1 Å is much stronger than expected, and in fact stronger than 5780.6 Å, which is rather unusual. These maps are effectively a measurement of the distribution of the various DIB carriers on the sky, and future comparisons to other ISM species may point to the carrier of each line.

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Figure 6. Top: number of spectra per 3.35 deg$^2$ pixel. The red and green circles represent the coordinates of the stars used by K13 and F11 respectively. Bottom: sky map after grouping in order to reach sufficient S/N. Groups have a typical area of 20–40 deg$^2$. In these and subsequent sky maps areas with no data are filled in dark blue.
Figure 7. Average color excess of every group (top), and relative scatter in each group (bottom; $\sigma/\text{mean}$). The majority of groups are rather uniform, with a color excess that varies by less than 20 percent.
Figure 8. EW residual map for the DIBs 5780.6 Å (top) and 5797.1 Å (bottom). For a given color excess we calculate the divergence of the EW from the expected EW$_e$ – which is based on the whole-sky determination in section 4.1 – the normalized residual is thus $(EW - EW_e)/EW_e$. 

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Figure 9. Same as figure 8 for the DIBs 6204.3 Å (top), and 6613.7 Å (bottom).
Figure 10. Example spectrum (in black) of a sight line where the 5780.6 Å DIB is normal, but the 5797.2 Å is much deeper than expected when compared to sight lines with similar dust column densities (dashed blue). The best fit for the group is shown in dashed red.