Diffuse Interstellar Bands in $z < 0.6$ Ca II Absorbers

Sara L. Ellison$^1$, Brian A. York$^1$, Michael T. Murphy$^{2,3}$, Berkeley J. Zych$^2$, Arfon M. Smith$^4$ and Peter J. Sarre$^4$

$^1$Department of Physics and Astronomy, University of Victoria, Victoria, B.C., V8P 1A1, Canada
$^2$Institute of Astronomy, University of Cambridge, Madingley Rd., Cambridge, CB3 0HA, UK
$^3$Centre for Astrophysics & Supercomputing, Swinburne University of Technology, Hawthorn, Victoria 3122, Australia
$^4$School of Chemistry, The University of Nottingham, University Park, Nottingham, NG7 2RD, UK

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ABSTRACT

The diffuse interstellar bands (DIBs) probably arise from complex organic molecules whose strength in local galaxies correlates with neutral hydrogen column density, $N$(H$^1$), and dust reddening, $E(B−V)$. Since Ca II absorbers in quasar (QSO) spectra are posited to have high $N$(H$^1$) and significant $E(B−V)$, they represent promising sites for the detection of DIBs at cosmological distances. Here we present the results from the first search for DIBs in 9 Ca II-selected absorbers at $0.07 < z_{abs} < 0.55$. We detect the 5780 Å DIB in one line of sight at $z_{abs} = 0.1556$; this is only the second QSO absorber in which a DIB has been detected. Unlike the majority of local DIB sight-lines, both QSO absorbers with detected DIBs show weak 6284 Å absorption compared with the 5780 Å band. This may be indicative of different physical conditions in intermediate redshift QSO absorbers compared with local galaxies. Assuming that local relations between the 5780 Å DIB strength and $N$(H$^1$) and $E(B−V)$ apply in QSO absorbers, DIB detections and limits can be used to derive $N$(H$^1$) and $E(B−V)$. For the one absorber in this study with a detected DIB, we derive $E(B−V) = 0.23$ mag and $log N$(H$^1$) $\approx$ 20.9, consistent with previous conclusions that Ca II systems have high H I column densities and significant reddening. For the remaining 8 Ca II-selected absorbers with 5780 Å DIB non-detections, we derive $E(B−V)$ upper limits of 0.1–0.3 mag.

Key words: quasars: absorption lines – dust, extinction – ISM: abundances – ISM: lines and bands – ISM: molecules – line: identification

1 INTRODUCTION

Damped Lyman alpha (DLA) systems are usually considered to be the class of QSO absorber with the highest neutral hydrogen column densities [$N$(H$^1$) $\geq 2 \times 10^{20}$ cm$^{-2}$]. Nonetheless, the DLAs are characterised by generally low metallicities and gas-phase depletion fractions (e.g. Khare et al. 2004, Akerman et al. 2005, Prochaska et al. 2007) and low reddening due to dust (Murphy & Liske 2004, Ellison, Hall & Lira 2005). The DLAs are also poor in molecules, as demonstrated by both their generally low fractions of H$_2$ (e.g. Ledoux et al. 2003) and the lack of a detection for any other molecular species, such as OH or CO (e.g. Curran et al. 2006). Although the handful of DLAs which do exhibit molecular H$_2$ absorption may be biased, e.g. towards high metallicities (Petitjean et al. 2004), such systems can offer a novel insight into the physical conditions of the galactic interstellar medium (ISM, e.g. Srianand et al. 2005, Noterdaeme et al. 2007). In addition to the study of H$_2$, one avenue that is just starting to be explored is how the diffuse interstellar bands (DIBs; see reviews by Herbig 1993, Sarre 2006) may be used to probe the intermediate redshift ISM. Although lacking definitive identifications, the strength (both absolute and relative) of these broad absorption features in the Milky Way (MW) and other nearby galaxies exhibit dependencies on (and sometimes, tight correlations with) neutral gas content, dust reddening, metallicity and local radiation field (e.g. Herbig 1993, Cox & Spaans 2006, Welty et al. 2006, Cow et al. 2007). Moreover, if DIBs are as strong in DLAs as they are in the MW (i.e. for a given $N$(H$^1$)), then they should be relatively easy to detect at intermediate redshifts.

The first systematic search for DIBs in DLAs has recently been carried out by Lawton et al. (in preparation) in 7 $z < 1$ absorbers. In only one case were DIBs detected: the 4428, 5705 and 5770 Å bands were all detected in the $z \sim 0.5$ DLA towards AO 0235+164 (Junkkarinen et al. 2004, York et al. 2006a). Lawton et al. showed that for the 6 non-detections in their DLA sam-

1 We cite all DIBs with reference to their normal air wavelengths, although their vacuum values have been used in practice in order to be consistent with our spectral wavelength calibration; see Section 2.
ple, the strength of the 5780 Å DIB [which shows one of the tight-
est correlations with $N$(H$1$) in the MW] is often at least 3 times
weaker in DLAs for a given $N$(H$1$) compared with Galactic sight-
lines. The 6284 Å DIB is even more under-abundant in DLAs for a
given $N$(H$1$): 4–10 times weaker than towards Galactic sight-lines.
A similar result has been found for DIBs in the Large and Small
Magellanic Cloud (LMC and SMC; [Weily et al. 2006]) where the
5780 Å DIB is typically 10–30 times weaker than expected from the
Galactic relation. On the other hand, the 5780 Å DIB strength cor-
relates well with $E(B−V)$ in both Galactic and Magellanic Cloud
sight-lines, and the detection towards AO 0235+164 also lies on the
same relationship [York et al. 2006d]. These results hint that DIB
formation/survival and high dust content are closely linked
and that DIBs are therefore most likely to be detected in galaxies
with high reddening.

Wild, Hewett & Pettini (2006) have recently suggested that absorbers identified via high equivalent widths (EWs) of Ca II may select the highest $N$(H$1$) and highest $E(B−V)$ absorbers. For example, whereas DLAs have been constrained to have $E(B−V) < 0.04$ (Murphy & Liske 2004; Ellison et al. 2005), Wild et al. (2006) find that absorbers with Ca II λ3934 EWs >0.7 Å have $E(B−V)$ values up to ~0.1 mag. Ca II absorbers may therefore be promising sites for the detection of DIBs.

2 TARGET SELECTION, OBSERVATIONS AND DIB SEARCH

Wild & Hewett (2005) presented a sample of $0.8 < z < 1.3$
Ca II absorbers selected from the Sloan Digital Sky Survey (SDSS). However, the typical rest wavelengths of the strong DIB features (approximately 4500–7000 Å) makes the Wild & Hewett (2005) sample unsuitable for an optical search for the diffuse bands. We have recently conducted an independent search for Ca II absorbers in the SDSS at $z < 0.6$ (see Zych et al. 2007) and found over 40 new absorbers. We selected 9 high-EW (Ca II) targets in Table 1 as it can be seen that the 4428 Å DIB is always resolved in our spectra. Figure 1 shows this detection together with the corresponding Ca II (from the SDSS spectrum) and Na I absorption. The redshifts of the 5780 Å DIB and Na I lines are in excellent agreement with the Ca II absorption. Depending on the method of weighting the individual exposures, the velocity offsets between various absorption features in the final spectrum are always < 50 km s$^{-1}$, i.e. less than one half of a resolution element; often the agreement is < 20 km s$^{-1}$. We measure the EW of the 5780 Å feature using both a simple integration of optical depth, as well as by a Gaussian de-blend in order to account for the presence of a second (unidentified) absorption feature offset by ~130 km s$^{-1}$ to the red of the DIB. The unidentified feature does not correspond to any known stellar or interstellar features at $z = 0.1556$ and we conclude that it is likely to be due to gas at a different redshift. We also repeat the EW measurements in the UVES$^{b}$ popper reduction; all EW values are in excellent agreement and lie within the statistical 1 σ error derived from the spectral error array. Our final quoted EW (see Table 2) adopts an average of the EWs determined from various measurement methods and spectral combinations.

For all other Ca II absorbers with non-detections, the $3 \sigma$ de-
tection limits are given in Table 2 For the DIBs that we would expect to be resolved in our spectra (the 4428 Å band in all cases and, e.g., the 6284 Å band towards J0013+0249) we assumed that the absorption would have an observed FWHM of $1+z$ times the typical Galactic value (see above). This allowed us to calculate the

The 9 targets in Table 1 were observed in long slit mode with the FORS2 spectrograph on the Very Large Telescope (VLT) in

2 In Table 1 we give the full SDSS identification for each QSO but elsewhere we use abbreviated names.

3 The FWHM resolution was calculated as an average across the wavelength range based on Gaussian fits to unresolved sky lines and 2D arc frames.

4 These values are in good agreement with the slightly newer compilation of Triwirdi et al. (2009), with the exception of the 4428 Å DIB which is reported to have an average (over 3 reddened Galactic lines of sight) of FWHM of 17.5 Å.

Chile during ESO’s Period 77 (1 April 2006 – 30 September 2006). Observations were obtained through a 1 arcsec slit with the CCD binned 2×2. Grism selection depended on absorber redshift; the exposure time, choice of grism and the resulting FWHM resolution and signal-to-noise (S/N) ratios per pixel are listed in Table 1. The data reduction procedure followed standard steps for long slit spectra using IRAF: a median bias frame was subtracted from each science frame, followed by division by an average lamp flat field. The spectra were optimally extracted, wavelength calibrated by use of a CuAr lamp and converted to a vacuum-heliocentric scale. We experimented with different methods of combining individual exposures, including the usual SCOMBINE task in IRAF with weightings according to S/N, and also using UVES$^{b}$ popler, as described in Zych et al. (2007). Both gave very similar results.

We searched the final spectra for absorption associated with the 4428, 5705, 5780, 5797, 6284 and 6613 Å diffuse bands. The first of these bands is intrinsically broad with an average (rest-frame) FWHM measured from 4 Galactic stellar sight-lines of FWHM ~12.3 Å [Jenniskens & Desert 1994]. The other 5 DIBs are narrower, with FWHM values of ~2.2, 2.1, 1.0, 2.6 and 1.1 Å respectively in Galactic sight-lines [Jenniskens & Desert 1994]. Comparing these values with the resolution of our spectra in Table 1 it can be seen that the 4428 Å DIB is always resolved in our spectra. We usually do not resolve the narrower DIBs; taking into account the 1+z broadening, the expected FWHM values of the DIBs is 2–3 Å, compared with our typical spectral resolution of 3–5 Å.

Our search yielded one DIB detection: the 5780 Å band at $z = 0.1556$ towards J0013+0024, the absorber with the highest apparent Ca II EW in our sample. Figure 1 shows this detection together with the corresponding Ca II (from the SDSS spectrum) and Na I absorption. The redshifts of the 5780 Å DIB and Na I lines are in excellent agreement with the Ca II absorption. Depending on the method of weighting the individual exposures, the velocity offsets between various absorption features in the final spectrum are always < 50 km s$^{-1}$, i.e. less than one half of a resolution element; often the agreement is < 20 km s$^{-1}$. We measure the EW of the 5780 Å feature using both a simple integration of optical depth, as well as by a Gaussian de-blend in order to account for the presence of a second (unidentified) absorption feature offset by ~130 km s$^{-1}$ to the red of the DIB. The unidentified feature does not correspond to any known stellar or interstellar features at $z = 0.1556$ and we conclude that it is likely to be due to gas at a different redshift. We also repeat the EW measurements in the UVES$^{b}$ popper reduction; all EW values are in excellent agreement and lie within the statistical 1 σ error derived from the spectral error array. Our final quoted EW (see Table 2) adopts an average of the EWs determined from various measurement methods and spectral combinations.
number of pixels over which the absorption would be expected to extend. For the unresolved lines, we assumed that the number of pixels was equal to the FWHM spectral resolution (in Å, see Table 1) divided by the dispersion (in Å/pixel).

### Table 1. Targets and observational setup. S/N values are given per pixel for the regions in which the DIBs were located.

| QSO             | \(z_{\text{abs}}\) | \(\lambda_{4428}\) | \(\lambda_{5750}\) | \(\lambda_{5780}\) | \(\lambda_{5797}\) | \(\lambda_{6284}\) | \(\lambda_{6613}\) | \(\text{Grism}\) | \(\text{Resolution}\) [Å] | \(\text{Coverage}\) [Å] | \(\text{Exp. time}\) [s] | \(\text{S/N}\) |
|-----------------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|
| SDSS J001342.44−002412.6 | 1.644 | 0.1556 | 18.6 | 1200R | 2.3 | 5960–7370 | 5280 | 60−80 |
| SDSS J000943.55+052953.8 | 0.942 | 0.3862 | 16.9 | 600RI | 5.2 | 5495–8620 | 3960 | 160−180 |
| SDSS J104029.94+070528.3 | 1.532 | 0.2063 | 18.6 | 600I | 4.0 | 6925–9470 | 2640 | 40−55 |
| SDSS J113702.03+013622.1 | 1.641 | 0.4492 | 18.6 | 600RI | 5.2 | 5495–8620 | 5280 | 55−75 |
| SDSS J121911.23−004345.5 | 2.293 | 0.4485 | 18.0 | 600RI | 5.2 | 5495–8620 | 2640 | 90−115 |
| SDSS J122608.02−000602.2 | 1.125 | 0.5179 | 18.4 | 600RI | 5.2 | 5495–8620 | 5280 | 100−120 |
| SDSS J143701.20−014180.0 | 0.286 | 0.0725 | 19.1 | 1200R | 2.4 | 5960–7370 | 10560 | 70−85 |
| SDSS J213502.45+103823.5 | 1.511 | 0.0984 | 18.8 | 600B | 4.8 | 3490–6360 | 13200 | 70−85 |
| SDSS J225913.74−084419.6 | 1.290 | 0.5293 | 18.4 | 600RI | 5.2 | 5495–8620 | 5280 | 75−100 |

### Table 2. DIB and metal line rest-frame EWs and 3σ limits. No limit is quoted when the line is not covered by the spectrum or is in a region of bad sky contamination. Ca II values are measured from the FORS spectra when possible, otherwise SDSS values are quoted (F and S flags respectively). The reddening, \(E(B−V)\), is inferred, not measured (see text).

| QSO     | \(z_{\text{abs}}\) | \(\lambda_{4428}\) | \(\lambda_{5750}\) | \(\lambda_{5780}\) | \(\lambda_{5797}\) | \(\lambda_{6284}\) | \(\lambda_{6613}\) | \(\text{Ca II H and K}\) | \(\lambda_{3934}, \lambda_{3969}\) | \(\text{Na I D}_1\) and \(\text{D}_2\) | \(\lambda_{5891}, \lambda_{5897}\) | \(E(B−V)\) [mag] |
|---------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|
| J0013−0024 | 0.1556 | <62 | 94±16 | <45 | <78 | ... | 1.09±0.18, 1.34±0.17 (S) | 1.12±0.02, 0.94±0.02 | 0.23 |
| J1009+0529 | 0.3862 | <124 | <41 | <42 | <58 | ... | 0.51±0.05, 0.19±0.05 (S) | ... | <0.12 |
| J1040+0705 | 0.2063 | ... | <127 | <127 | <155 | <146 | 0.61±0.12, 0.25±0.15 (S) | <0.10, <0.10 | <0.30 |
| J1137+0136 | 0.4492 | <176 | <81 | <82 | <82 | ... | 0.35±0.04, 0.14±0.04 (F) | <0.09, <0.09 | <0.21 |
| J1219−0043 | 0.4485 | <120 | <58 | <60 | <60 | ... | 0.40±0.02, 0.32±0.02 (F) | 0.09±0.02, <0.06 | <0.16 |
| J1226−0006 | 0.5179 | <114 | ... | ... | ... | 0.67±0.02, 0.42±0.02 (F) | ... | ... |
| J1437−0104 | 0.0725 | <53 | <61 | <51 | 1.07±0.20, 0.98±0.30 (S) | 1.31±0.02, 0.85±0.02 | <0.15 |
| J2135+1038 | 0.0984 | <184 | <99 | <102 | ... | 0.90±0.19, 0.43±0.28 (S) | ... | <0.25 |
| J2259−0844 | 0.5293 | <136 | ... | ... | ... | 0.38±0.02, 0.19±0.03 (F) | ... | ... |

### Figure 1. Normalised spectra towards J0013−0024 covering three of the DIBs of interest in our survey, as well as metal lines from Ca II and Na I. All lines are from our FORS spectra, with the exception of the Ca II doublet, where the SDSS spectrum is shown. The spectra have been shifted to a rest wavelength scale for \(z = 0.1556\).

### 3 DISCUSSION

In local (e.g. Galactic, LMC, SMC) sight-lines, the 6284 Å DIB is typically 2–3 times stronger than the 5780 Å DIB (e.g., York et al. 2006a and references therein). The one exception is the unusual SMC wing sight-line towards Sk 143 where the 6284 Å DIB has an EW less than half that of the 5780 Å DIB (Welty et al. 2006). York et al. (2006a) also found that in the one DLA sight-line with \(z<0.6\) Ca II Absorbers (Welty et al. 2006) also found that in the one DLA sight-line of the DIB ratio relations, is shown in Fig. 2. We also show data for the Magellanic Clouds (Welty et al. 2006) and DLAs (York et al. 2006a; Lawton et al. in preparation), where it can be seen that the...
DIBs are weak for their $N$(H I) compared with the Galactic correlation. As shown in Fig. 2 the DIBs in extra-galactic sight-lines are also weak for their Na I column densities. These departures from the Galactic relations are probably due to a combination of effects including ambient radiation field, metallicity and dust-to-gas ratios (Cox & Spaans 2006). Assuming that the Galactic $5780 \text{ Å}$ DIB–$N$(H I) relation provides a lower limit for the H I column density, DIB detections may be useful for constraining $N$(H I) in the absence of Lyα observations. For example, Wild & Hewett (2003) and Wild et al. (2006) have argued that Ca II absorbers represent the high column density end of the DLA distribution. Our detection of the $5780 \text{ Å}$ DIB in the $z_{abs} = 0.1556$ absorber towards J0013$-$0024 supports this hypothesis, and we derive $\log N$(H I) $\geq 20.9$ for this absorber.

Unlike correlations with $N$(H I) and $N$(Na I), Welty et al. (2006) have shown that the $5780 \text{ Å}$ DIB strength follows a single relationship with $E(B-V)$ in both Galactic and Magellanic Cloud sight-lines. York et al. (2006a) found that the single DLA $5780 \text{ Å}$ DIB detection towards AO 0235$+$164 fell on the same relationship. It is not yet clear whether the apparent universality of this correlation is driven by a tight physical connection between dust properties and DIB formation (Cox et al. 2007) or whether it is coincidence of different physical drivers working in different directions (Cox & Spaans 2006). However, if the $5780 - E(B-V)$ is applicable to QSO absorbers, we can use our DIB detection limits to constrain their reddening. Welty et al. (2006) derive a best fit correlation between the $5780 \text{ Å}$ DIB (in mÅ) and the $E(B-V)$ for Galactic sight-lines: $\log E(B-V) = -2.70 + 1.01 \log EW(5780)$. We derive the best fit relation to the $5780 - E(B-V)$ data points of the Galactic plus Magellanic Cloud plus AO 0235$+$164 DLA sight-lines and find $\log E(B-V) = -2.19 + 0.79 \log EW(5780)$ (see Figure 2). The range in $\log E(B-V)$ values around the best fit relation is $\sim 0.4$ dex. This correlation gives a reddening for the Ca II absorber towards J0013$-$0024 of $E(B-V) \sim 0.25$ mag and upper limits for the other 8 Ca II absorbers in our sample of 0.1–0.3 mag. These values provide independent estimates of reddening associated with Ca II-selected absorbers that do not depend directly on the choice of extinction law and can be applied for individual absorbers and not just in a statistical fashion (e.g. Murphy & Liske 2004; Wild & Hewett 2005; Wild et al. 2006).

The Ca II EWs of our sample are typically $< 0.7 \text{ Å}$ (see Table 2), for this range of EWs, Wild et al. (2006) determine average reddenings of $E(B-V) = 0.02, 0.03$ and 0.03 mag for MW, LMC and SMC extinction curves respectively.

4 SUMMARY AND FUTURE PROSPECTS

We have reported the results from the first search for DIBs towards 9 Ca II-selected absorbers in the redshift range $0.07 \leq z_{abs} \leq 0.55$. In one case, the $z_{abs} = 0.1556$ absorber towards J0013$-$0024, we detect the $5780 \text{ Å}$ DIB. This absorber has the highest Ca II $\lambda$ 3934 EW in our sample, although there is some contribution from galactic photospheric absorption in the SDSS EW measurement. J1437$-$0104 has only a marginally lower Ca II EW, but a $5780 \text{ Å}$ DIB upper limit that is half that of J0013$-$0024. J0013$-$0024 is only the second QSO absorber in which DIBs have been detected. Assuming that the Galactic relation between $N$(H I) and $\lambda 5780$ EW can be used to derive a lower limit for H I column density, we find $\log N$(H I) $\geq 20.9$. Similarly, the correlation between $\lambda 5780$ EW and $E(B-V)$ in all sight-lines (Galactic and extra-galactic) to date implies a high reddening in this absorber of $E(B-V) = 0.23$ mag. These results provide independent support for the suggestion by Wild et al. (2006) that the Ca II absorbers are amongst the highest $N$(H I) and most highly reddened of the QSO absorbers. Indeed, the $E(B-V)$ derived for J0013$-$0024 is even higher than the typical statistical values derived by Wild et al. (2006) for QSO absorbers. In our sample we derive upper limits to the reddening of $\sim 0.1$–0.3 mag. We also find the interesting result that, in contrast to essentially every local sight-line (with the exception of one SMC wing cloud), both QSO absorbers with detected DIBs have stronger $5780$ Å features than 6284 Å features, possibly due to less intense radiation fields.

What are the prospects for further detections of DIBs in Ca II and other QSO absorption line systems? If the relationship of the $5780 \text{ Å}$ DIB strength with $E(B-V)$ is widely applicable, then tar-
getting the most reddened systems is likely the most profitable path. Nonetheless, this is a challenging prospect; even for an absorber with \( E(B-V) = 0.1 \) mag, the rest frame \( \lambda 5780 \) EW will be \( \sim 30 \) m\( \AA \), which would require an improvement in our current detection limits by typically a factor of 2–3. The best candidates for future observations are likely to be the highest EW Ca\( II \) and Mg\( II \) absorbers, since these appear to be the most highly reddened of the QSO menagerie (Wild et al. 2006; York et al. 2006a; Menard et al. 2007). However, with more detections in hand, it would be possible not only to infer the gas and dust properties of the absorbers, as described above, but also to obtain new insight into the nature of the DIBs themselves. For example, York et al. (2006a) showed that, in the \( z_{abs} \sim 0.5 \) DLA towards AO 0235+164, the ratio of the 5705/5780 \( \AA \) DIBs was consistent with those in Galactic sightlines (e.g. Thorburn et al. 2003). The identification of such DIB ‘families’ may indicate which bands are associated with the same molecular carrier and hence provide guidelines for their chemical identification. If the Galactic 5705/5780 relation holds for the Ca\( II \) absorber towards J0013–0024, we would expect to detect it with an increase of a factor of three in S/N, possible with approximately one more night of integration.

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