The Magellanic System: Stars, Gas, and Galaxies
Proceedings IAU Symposium No. 256, 2008
Jacco Th. van Loon & Joana M. Oliveira, eds.

doi:10.1017/S1743921308028895

Evidence of Magellanic-like moderate redshift H I-rich galaxies

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Abstract. We present equivalent width measurements and limits of six diffuse interstellar bands (DIBs, $\lambda\,4428$, $\lambda\,5705$, $\lambda\,5780$, $\lambda\,5797$, $\lambda\,6284$, and $\lambda\,6613$) in seven damped Lyα absorbers (DLAs) over the redshift range $0.091 \leqslant z \leqslant 0.524$, sampling $20.3 \leqslant \log N(\mathrm{H\,I}) \leqslant 21.7$. Based upon the Galactic DIB–$N(\mathrm{H\,I})$ relation, the $\lambda\,6284$ DIB equivalent width upper limits in four of the seven DLAs are a factor of 4−10 times below the $\lambda\,6284$ DIB equivalent widths observed in the Galaxy, but are not inconsistent with those present in the Magellanic Clouds. Assuming the Galactic DIB–$E(B-V)$ relation, we determine reddening upper limits for the DLAs in our sample. Based upon the $E(B-V)$ limits, the gas-to-dust ratios, $N(\mathrm{H\,I})/E(B-V)$, of the four aforementioned DLAs are at least ~ 5 times higher than that of the Galactic ISM and are more consistent with the Large Magellanic Cloud. The ratios of two other DLAs are at least a factor of a few times higher. The best constraints on reddening derive from the upper limits for the $\lambda\,5780$ and $\lambda\,6284$ DIBs, which yield $E(B-V) \leqslant 0.08$ mag for four of the seven DLAs and are more consistent with the Magellanic Clouds rather than the Galaxy. Our results suggest that, in DLAs, quantities related to dust, such as reddening and metallicity, appear to have a greater impact on DIB strengths than does H I gas abundance. The molecules responsible for the DIBs in DLA selected sightlines are underabundant relative to sightlines in the Galaxy of similarly high $N(\mathrm{H\,I})$. Using DIBs to study the ISM of DLAs provide evidence that at least some population of DLAs are more Magellanic-like than Galactic-like.

Keywords. astrochemistry, dust, extinction, galaxies: ISM, Magellanic Clouds, quasars: absorption lines

1. Introduction

Since their discovery in 1921 (Heger 1922), the diffuse intersteller bands (DIBs) have remained the longest known interstellar absorption features without a positive identification. There have been several hundred DIBs discovered to date (Jenniskens *et al.* 1994; Tuairisg *et al.* 2000; Weselak *et al.* 2000). The DIBs span the visible spectrum between

4000 and 13000 Å. Despite no positive identifications, several likely organic molecular candidates have emerged as the sources of the DIBs, including polycyclic aromatic hydrocarbons (PAHs), fullerenes, long carbon chains, and polycyclic aromatic nitrogen heterocycles (PANHs) (Herbig 1995; Snow 2001; Cox & Spaans 2006; Hudgins *et al.* 2005). The organic-molecular origin of the DIBs may give them an importance to astrobiology; they are now considered an important early constituent to the inventory of organic compounds on Earth (Bada & Lazcano 2002).

Due to their relatively weak absorption strengths, the DIBs have been difficult to detect in extragalactic sources. Aside from the hundreds of detections within the Galaxy (Jenniskens *et al.* 1994; Tuairisg *et al.* 2000; Weselak *et al.* 2000), DIBs have been detected in the Magellanic Clouds (Welty *et al.* 2006; Cox *et al.* 2006, 2007), seven starburst galaxies (Heckman & Lehnert 2000), the active galaxy Centaurus A via supernova 1986G (Rich 1987), spiral galaxy NGC 1448 via Supernovae 2001el and 2003hn (Sollerman *et al.* 2005), one damped Lyman-α galaxy (DLA) at $z = 0.524$ toward the quasar AO 0235+164 (Junkkarinen *et al.* 2004; York *et al.* 2006), and one galaxy selected by singly ionized calcium (Ca II), J0013−0024, at $z = 0.157$ from the Sloan Digital Sky Survey (Ellison *et al.* 2008).

There are several environmental factors that are known to enhance or inhibit DIB strengths. Two important environmental factors that are often probed in galaxies are the H I content, $N(\text{H I})$, and the reddening, $E(B-V)$. $N(\text{H I})$ is a measure of the gas phase and $E(B-V)$ is a measure of the dust phase of the ISM in galaxies. $N(\text{H I})$ in DLAs is typically measured as a column density via the Lyman-α line in absorption, as observed using a bright background source such as a quasar. DLAs are, by definition, rich in H I gas, with a $\log N(\text{H I}) > 20.3$ atoms cm^{-2}.

The ISM, and by extension the host galaxies, of DLAs are still relatively poorly understood (Ellison *et al.* 2005). We compare the DIB strengths in DLAs with the strengths of DIBs in the Galaxy and the Magellanic Clouds, along sightlines with known H I abundances and reddening measurements, and find that the ISM of many DLAs are more similar to the ISM of the Magellanic Clouds. DLAs, as a population, may represent unrecognized Magellanic-like galaxies. The results of further similar studies of DIB strengths in galaxies may hold significant implications in our understanding of the H I and dust abundances of galaxies with cosmic time.

For this study, fully explained in Lawton *et al.* (2008), we catalogue the strengths of the λ 4428, λ 5780, λ 5797, λ 6284, and λ 6613 DIBs relative to the $E(B-V)$ and $N(\text{H I})$ content of each of the seven DLAs in our sample. Observations were obtained, with seven facilities, of seven DLAs toward six QSO sightlines. The facilities and instruments used for this project are the *VLT*/FORS2, *VLT*/UVES, *APO*/DISIII, *Keck*/HIRES, *WHT*/ISIS, and *Gemini-S*/GMOS.

2. Analysis and results

There are two detections included in this work, the λ 5705 and λ 5780 DIBs first reported by York *et al.* (2006), in the $z = 0.524$ DLA toward AO 0235+164. For all other DLAs in our sample, we report upper limits on the λ 4428, λ 5780, λ 5797, λ 6284, and λ 6613 DIB equivalent widths. We measured the equivalent width limits using a generalized method of the Schneider *et al.* (1993) technique for finding lines and limits. We compare our measured limits to the expected DIB equivalent widths from the known Galactic DIB–$E(B-V)$ and DIB–$N(\text{H I})$ relations (Welty *et al.* 2006). The $N(\text{H I})$ quantities are known for the DLAs; however, Junkkarinen *et al.* (2004) published the only reddening known for the DLA galaxies in our sample, AO 0235+164, with a measured

https://doi.org/10.1017/S1743921308028895 Published online by Cambridge University Press

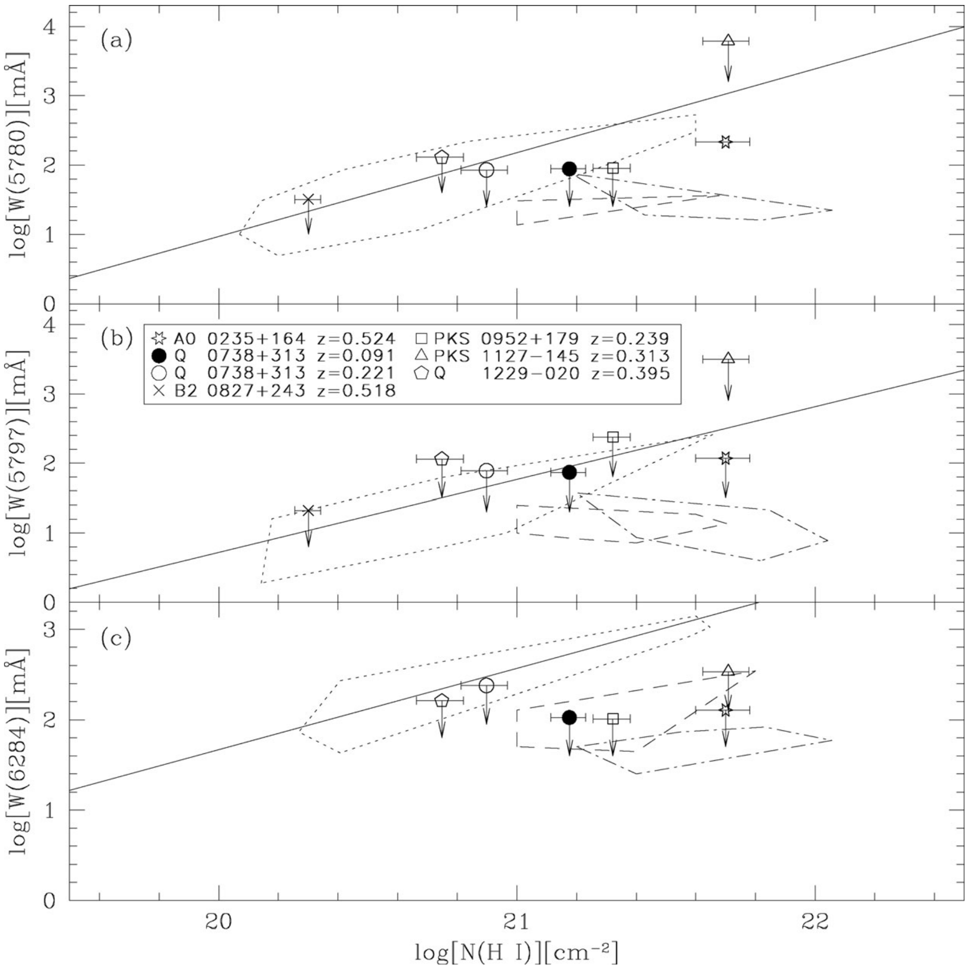

Figure 1. The DIB equivalent width–N(H I) relations (Welty *et al.* 2006) with our DLAs added. —(*a*) λ 5780 DIB. —(*b*) λ 5797 DIB. —(*c*) λ 6284 DIB. The solid lines are the best-fit weighted Galactic lines. The region enclosed by the dotted lines contain the Galactic data. The regions enclosed by the dashed lines contain the LMC data. The regions enclosed by the dot-dash lines contain the SMC data. Error bars are 1σ, and upper limits are marked with arrows. The vertical error bars for AO 0235+164 in panel (*a*) are smaller than the point size and all values for this DLA are from York *et al.* (2006).

$E(B-V) = 0.23$ mag. We estimate the upper limit to the reddening using our equivalent width limits and the Galactic DIB–$E(B-V)$ correlation. Our equivalent width limits are robust enough to constrain the upper reddening limits near the $E(B-V) < 0.04$ mag limit found by Ellison *et al.* (2005) for the highest redshift DLA galaxies.

The results from the N(H I) model suggests that the organics that give rise to the DIBs in DLAs are underabundant relative to Galactic sightlines of the same hydrogen column density. Fig. 1 shows this by plotting the measured equivalent widths and upper equivalent width limits for the DLAs in our sample. The line is the best-fit to the Galactic data from Welty *et al.* (2006). The Galactic points are observed to lie within the dotted region while the Large Magellanic Cloud (LMC) sightlines are observed to lie within the dashed region. The Small Magellanic Cloud (SMC) sightlines are all within the dot-dashed region. The λ 6284 DIB gives the best constraints and shows that this DIB is

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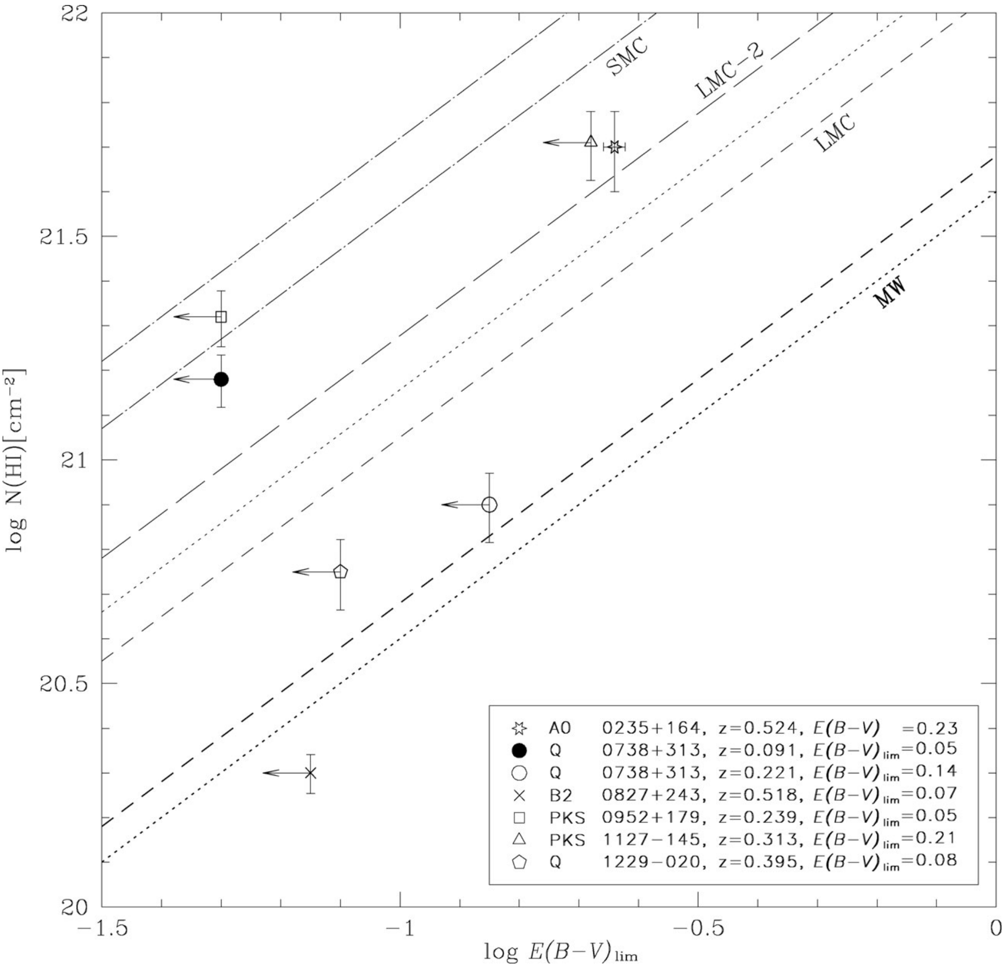

Figure 2. The gas-to-dust ratios of the DLAs in our sample relative to measured values in the Galaxy (MW), the LMC, and the SMC. The figure is modified from Cox *et al.* (2006). The plot measures the log column density [cm^{-2}] versus the upper limit to the log reddening for each DLA. The A0 0235+164 reddening measurement of 0.23 ± 0.01 is from Junkkarinen *et al.* (2004). The top two lines represent measured SMC gas-to-dust ratios while the middle three lines represent the LMC, and the bottom two lines represent the MW. The dot-dashed SMC lines are the upper and lower gas-to-dust ratios of Bouchet *et al.* (1985), with 52×10^{21} cm^{-2} mag^{-1} and 37×10^{21} cm^{-2} mag^{-1}, respectively. The long-dashed LMC line gives the gas-to-dust ratio of 19.2×10^{21} cm^{-2} mag^{-1} from the LMC-2 data of Gordon *et al.* (2003). The dotted LMC line is a linear fit to the LMC data in Cox *et al.* (2006) and gives a gas-to-dust ratio of 14.3×10^{21} cm^{-2} mag^{-1}. The short-dashed line is the average LMC regions from Gordon *et al.* (2003) and has a gas-to-dust ratio of 11.1×10^{21} cm^{-2} mag^{-1}. The dashed MW line gives a gas-to-dust ratio of 4.8×10^{21} cm^{-2} mag^{-1} (Bohlin *et al.* 1978), and the dotted MW line is the fit to the Galactic data from Cox *et al.* (2006) which yields a ratio of 4.03×10^{21} cm^{-2} mag^{-1}. Four of the DLAs in our sample have gas-to-dust ratios more consistent with the LMC than the MW.

at least 4–10 times weaker in four of our DLAs compared to what is expected in the Galaxy. As is the case for the Magellanic Clouds, the Galactic DIB–$N(\mathrm{H\,I})$ relation does not apply to DIBs in DLAs.

From our equivalent width limits we can estimate the upper limit to the reddening assuming the Galactic DIB–$E(B-V)$ relation holds for DLAs. There are little data on DIBs in DLAs; however, Ellison *et al.* (2008) create a fit to all known extragalactic points for the $\lambda\,5780$ DIB. The Galactic $\lambda\,5780$ DIB–$E(B-V)$ relation appears to remain valid when the extragalactic DIB equivalent width measurements are included. Our upper limits for $E(B-V)$ yield lower limits to the gas-to-dust ratios for our DLAs; these results are shown in Fig. 2. $E(B-V)_{\rm lim}$ are the upper limits for the reddening determined by our best equivalent width limits. The best-fit lines for the Galaxy (MW), the LMC, and the SMC are given from the literature. Our limits are robust enough to constrain the gas-to-dust ratio for the DLAs as being at least ~ 5 times higher than the Galaxy for four of the DLAs. Those four DLAs have gas-to-dust ratios that are more consistent with the LMC or the SMC. The reddening limits allow us to extend the results of Ellison *et al.* (2005) to lower redshift DLAs. The $E(B-V) < 0.04$ mag from Ellison *et al.* (2005) appears to also be a relatively robust result for moderate redshift DLAs. Four of the seven DLAs have reddenings of $E(B-V) \leqslant 0.08$ mag.

3. Discussion

The LMC and SMC are sufficiently gas-rich that they would both be classified as DLAs if background QSOs probed through many of their intervening H I clouds. It is possible that DLAs may represent a population of gas-rich galaxies that are similar to the Magellanic Clouds. However, care should be taken when estimating global properties of a galaxy from a single line-of-sight. In the Galaxy, DIB strengths and ratios vary significantly based on the local environmental conditions. An example of this can be found within the SMC. The SMC Wing is the only location within the dwarf galaxy where DIBs are observed and is noticeably enshrouded in dust such that the molecules responsible for the DIBs are likely to be adequately protected from UV radiation (Ehrenfreund *et al.* 2002). The sightline Sk 143 toward the SMC Wing, along with containing DIB absorption, exhibits the 2175-Å dust bump (Ehrenfreund *et al.* 2002). This feature is unusual for the SMC but commonly found in the Galaxy. The only DLA with known DIB absorption, toward QSO AO 0235+164, is also the only DLA in our sample with the 2175-Å feature (Junkkarinen *et al.* 2004). Furthermore, the $\lambda\,6284$ DIB observed along the SMC Wing sightline Sk 143 is uncommonly weak relative to the other observed DIBs, which is the same trait observed in the DLA toward QSO AO 0235+164 (York *et al.* 2006).

DLA metallicities are known to be low, on the order of ~ 0.1 solar metallicity, with the exception of AO 0235+164, which is metal abundant (Junkkarinen *et al.* 2004). Little is published about the radiation in moderate redshift DLA galaxies. Both the LMC and SMC have sub-solar metallicities with $Z \approx 0.4\ {\rm Z}_{\odot}$ and $Z \approx 0.2\ {\rm Z}_{\odot}$, respectively (Welty *et al.* 2006), relatively low reddening, and a large H I abundance. These are all similarities they share with the general DLA population. Further observations of DLAs will need to be done in order to understand the levels and sources of ionizing radiation, the dust grain populations, and the sizes and morphologies of their parent galaxies at all redshifts in order to put them into context with the Magellanic Clouds. Ongoing numerical simulations are also providing evidence that some population of DLAs may be gas-rich satellite or dwarf galaxies. Work done by Kacprzak *et al.* (2008), with ΛCDM cosmological simulations from Ceverino & Klypin (2007), show that lines-of-sight through an edge-on simulated galaxy, of approximately Galactic mass and at a redshift $z = 0.923$, probe many satellites of approximately LMC mass that would be classified as DLAs.

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At the conference dinner inside Wrenbury Hall.

https://doi.org/10.1017/S1743921308028895 Published online by Cambridge University Press