

DETECTION OF DIFFUSE INTERSTELLAR BANDS IN THE MAGELLANIC CLOUDS¹

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ABSTRACT

With the Ultraviolet Visual Echelle Spectrograph mounted at the Very Large Telescope, we have observed at unprecedented spectral resolution the absorption spectrum toward reddened stars in the Magellanic Clouds over the wavelength range of 3500–10500 Å. This range covers the strong transitions associated with neutral and charged large carbon molecules of varying sizes and structures. We report the first detection of diffuse interstellar bands (DIBs) at 5780 and 5797 Å in the Small Magellanic Cloud and the variation of the 6284 Å DIB toward several targets in the Large Magellanic Cloud. The variation of DIBs in the Magellanic Clouds compared with Galactic targets may be governed by a combination of the different chemical processes prevailing in low-metallicity regions and the local environmental conditions.

Subject headings: galaxies: ISM — ISM: lines and bands — ISM: molecules — Magellanic Clouds

1. INTRODUCTION

The diffuse interstellar bands (DIBs) are a large number of absorption lines between 4000 and 10000 Å that are superposed on the interstellar extinction curve (Herbig 1995). Since the discovery of the first two DIBs in the 1920s, the identification of the DIBs remains an important problem in astronomy (Herbig 1995; Snow 2001; Ehrenfreund et al. 2001). In the last 75 years, DIBs have been observed toward more than a hundred stars. The number of known DIBs present in current observational data is ~300 and continuously increases as a result of the higher sensitivity of detectors (Jenniskens & Désert 1994; Tuairisg et al. 2000). At present, no definitive identification of any of the carriers of the DIBs exists. The development of DIB research in recent years indicates that most DIB carriers are probably large carbon-bearing molecules that reside ubiquitously in the interstellar gas (e.g., Ehrenfreund & Charnley 2000). Polycyclic aromatic hydrocarbons (PAHs), fullerenes, and carbon chains are among the most promising carrier candidates (Salama et al. 1996; Tulej et al. 1998; Ehrenfreund & Foing 1996; Foing & Ehrenfreund 1994, 1997). Theoretical models of large carbonaceous carrier molecules constrain the formation and destruction rates of such species in the diffuse medium (Le Page, Snow, & Bierbaum 2001). The first detection of substructures in the profiles of several DIBs also supports the molecular nature of some DIB carriers (Sarre et al. 1995; Ehrenfreund & Foing 1996; Krelowski

& Schmidt 1997; Le Coupanec et al. 1999; Walker et al. 2001). Recent studies suggest that the environmental behavior of DIBs reflects an interplay of ionization, recombination, dehydrogenation, and destruction of chemically stable, carbonaceous species (Herbig 1995; Cami et al. 1997; Sonnenstrucker et al. 1997; Vuong & Foing 2000). Therefore, investigations of DIBs in regions of different metallicities, UV radiation fields, and local electron and hydrogen densities can constrain the physicochemical properties of the different DIB carriers. A handful of DIBs have been observed in extragalactic targets (e.g., Vladilo et al. 1987; Morgan 1987; Heckman & Lehnert 2000; Snow 2002). In this Letter, we report on recent observations of SMC and LMC targets obtained with the high-resolution Ultraviolet Visual Echelle Spectrograph (UVES) mounted at the Very Large Telescope (VLT) of the European Southern Observatory.

2. OBSERVATIONS AND DATA REDUCTION

On 2001 September 24–27, using the UVES on the VLT, we obtained high-resolution ($R \approx 80,000$ – $110,000$) optical spectra of reddened targets in our Galaxy and in the Magellanic Clouds. Observations were performed under excellent conditions at Paranal, with a relative humidity of less than 10% and seeing between 0".4 and 0".8. Bright reddened targets were selected in different local environments in the SMC and LMC. The relative faintness of the targets (especially those in the SMC) resulted in a signal-to-noise ratio of typically 150 for extragalactic targets and 300 for reference stars in the Galaxy. The spectra were reduced using IRAF and IDL routines. The targets were corrected for telluric absorption lines by dividing the spectrum by that of an unreddened standard star.

3. RESULTS

Although the UVES spectra show many different DIBs, we will focus in this Letter on a few of the best known DIBs. In a series of forthcoming papers, a more detailed analysis will be presented of the entire DIB spectrum toward the Magellanic Clouds.

3.1. The $\lambda\lambda 5780$ and 5797 DIBs

We first focus on the two well-known DIBs readily observed at 5780 and 5797 Å in Galactic targets. Figure 1 shows the 5765–5810 Å wavelength range containing these DIBs for three

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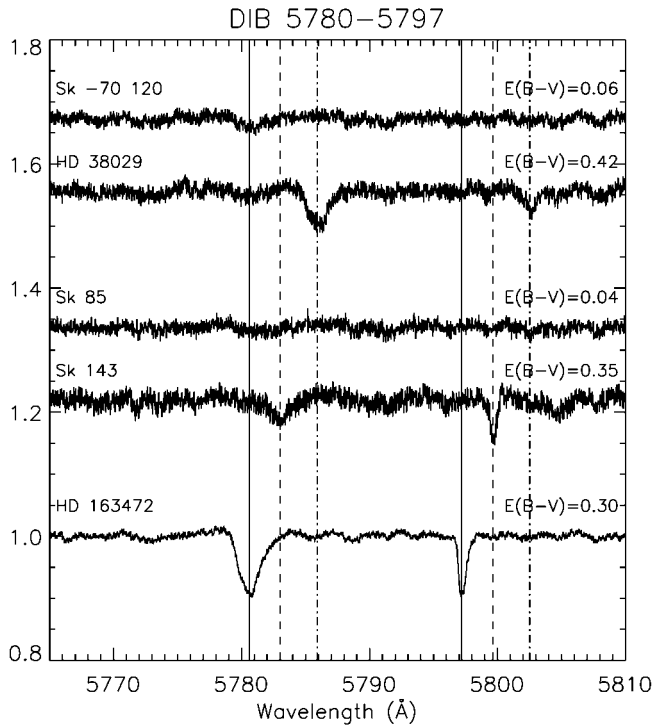


FIG. 1.—Spectra of the two best known DIBs, $\lambda\lambda 5780$ and 5797 . All spectra are normalized to the continuum and shifted for display. The spectrum at the bottom shows a Galactic translucent cloud source (HD 163472). The two middle spectra show an SMC target, Sk 143 (AzV 456), and an unreddened SMC standard, Sk 85 (AzV 242); the two top spectra show an LMC target, HD 38029, and an unreddened LMC standard, Sk $-70^{\circ}120$. The solid vertical lines indicate the Galactic rest wavelengths for those DIBs, the dashed lines indicate the wavelengths expected for these DIBs at SMC velocities, as determined from the NaD lines, and the dash-dotted lines indicate the wavelengths expected for these DIBs at LMC velocities. Both DIBs are clearly detected in both the SMC and LMC reddened targets.

target stars with similar E_{B-V} values: a Galactic reference star (HD 163472), an SMC target (Sk 143), and an LMC target (HD 38029). For comparison, we also show the corresponding SMC and LMC unreddened standard stars Sk 85 and Sk $-70^{\circ}120$, respectively. The high radial velocities of the SMC and LMC targets cause these bands to appear at longer wavelengths, allowing a clear distinction between Galactic foreground material and genuine SMC or LMC absorption, owing to the high resolution of these observations. The radial velocities corresponding to the SMC and LMC targets can be derived from the interstellar NaD lines; the expected redshift for the $\lambda\lambda 5780$ and 5797 DIBs corresponding to the radial velocity derived from these NaD lines is indicated by the vertical lines in Figure 1 (and for the $\lambda 6284$ DIB in Fig. 2). The SMC and

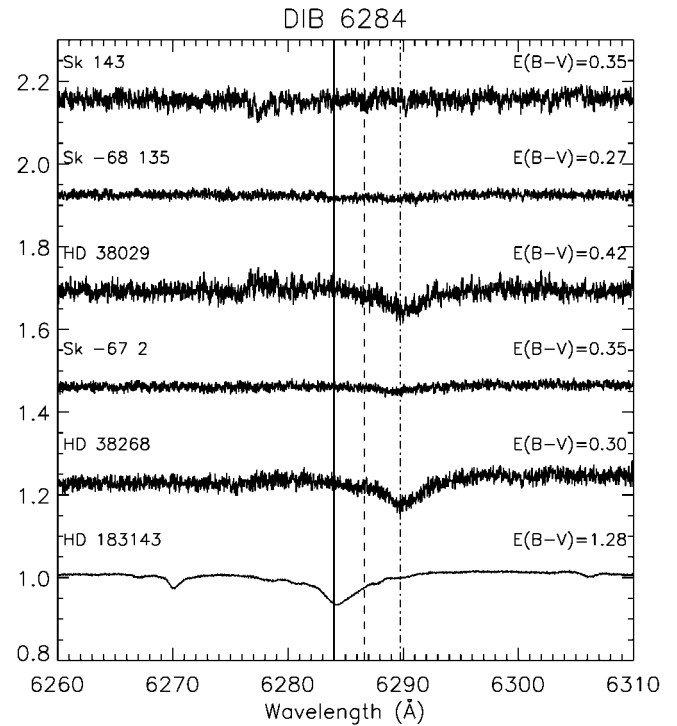


FIG. 2.—Wavelength range around the DIBs at 6270 and 6284 Å shown for Sk 143 in the SMC, four reddened targets in the LMC, and a Galactic reference target (HD 183143). All spectra are normalized and shifted for display. Telluric O_2 lines are removed by dividing the target spectra by the spectrum of a standard star. Shifted DIB positions are indicated by vertical lines as in Fig. 1. The spectrum of HD 183143 is scaled to $E_{B-V} = 0.3$ to facilitate comparison. The LMC sources show a very similar reddening but variations in the 6284 Å DIB strength. The LMC target Sk $-68^{\circ}135$ does not show the $\lambda 6284$ DIB. The origin of the feature around 6277 Å is unclear.

LMC targets presented in Figure 1 show absorption features at the expected wavelengths, while the unreddened standard stars do not. This proves beyond any doubt that the observed absorption bands are indeed DIBs due to interstellar SMC and LMC material. Moreover, the foreground extinction is very low and hardly produces DIBs at the Galactic rest wavelengths.

Table 1 lists the measured equivalent widths for these DIBs in two Galactic targets (HD 183143 and HD 163472) as well as for Sk 143 in the SMC and HD 38029 in the LMC. In order to compare the DIB strengths for different lines of sight, the equivalent widths should be normalized to the E_{B-V} values to account for the amount of interstellar material in the line of sight (it would be better to use the total hydrogen column density for this normalization; however, these data are not available for all stars in our sample). A first useful characteristic is then the variation of the DIBs compared with the values of

TABLE 1
MEASURED EWs (IN UNITS OF mÅ) OF THE DIBs DISPLAYED IN FIGS. 1 AND 2

OBJECT	E_{B-V}	DIB $\lambda 5780$		DIB $\lambda 5797$		DIB $\lambda 6284$	
		EW	R	EW	R	EW	R
HD 183143 (Galactic)	1.28	770 ± 8	1.0 ± 0.0	325 ± 28	1.0 ± 0.0	1730 ± 70	1.0 ± 0.0
HD 163472 (Galactic)	0.30	202 ± 17	1.1 ± 0.1	72 ± 7	0.9 ± 0.1	430 ± 75	1.1 ± 0.2
Sk 143/AzV 456 (SMC)	0.35	98 ± 32	0.5 ± 0.15	42 ± 16	0.5 ± 0.2	≤ 50	≤ 0.10
HD 38029 (LMC)	0.42	106 ± 30	0.4 ± 0.1	37 ± 14	0.35 ± 0.15	420 ± 125	0.7 ± 0.2
HD 38268 (LMC)	0.30	Not obs.	Not obs.	Not obs.	Not obs.	437 ± 72	1.1 ± 0.2
Sk $-67^{\circ}2$ (LMC)	0.35	Not obs.	Not obs.	Not obs.	Not obs.	93 ± 70	0.2 ± 0.15
Sk $-68^{\circ}135$ (LMC)	0.27	Not obs.	Not obs.	Not obs.	Not obs.	≤ 65	≤ 0.2

NOTE.—The ratios (R) of the normalized DIB strengths (scaled to $E_{(B-V)}$) compared with HD 183143 are given.

Galactic reference targets. This variation is defined by the ratio R of the equivalent width of a DIB for a target star divided by the equivalent width of the corresponding DIB for a Galactic reference target—in this case, HD 183143—in which both equivalent widths are normalized to the E_{B-V} .

3.2. The $\lambda 6284$ DIB

Figure 2 shows the wavelength range around the 6284 Å DIB in the line of sight toward the Galactic reference target HD 183143 (scaled to an E_{B-V} value of 0.3), four LMC targets, and the SMC target Sk 143. Although the E_{B-V} values are very similar for the targets presented in Figure 2, the strength of the $\lambda 6284$ DIB varies; this is also apparent by looking at the equivalent widths (EWs) and ratios (R) listed in Table 1. Sk 143, the first SMC target that exhibits the $\lambda\lambda 5780$ and 5797 DIBs, shows no hint of the $\lambda 6284$ DIB. The upper limit for the equivalent width indicates that the strength per unit reddening for this DIB is at least 10 times lower than typically measured in the Galactic targets; the LMC sources, on the other hand, show a large range of strengths for this DIB depending on the line of sight.

4. DISCUSSION

Observations of DIBs in the carbon-depleted SMC (metallicity $Z = 0.002$) and LMC ($Z = 0.008$) compared with our Galaxy ($Z = 0.02$) help us to test the hypothesis that many DIBs originate from carbonaceous carrier molecules. Moreover, comparison of DIB observations with extinction properties may also shed light on the nature of the DIB carriers.

4.1. The SMC

The UV extinction curve for the SMC is in general characterized by a roughly linear rise (vs. λ^{-1}) increasing toward shorter wavelengths and the absence of the 2200 Å bump (Prevot et al. 1984; Gordon & Clayton 1998), in contrast to the Galactic curve (Savage & Mathis 1979). The bump feature is likely due to carbonaceous material (Mennella et al. 1998); therefore, the absence of the bump feature may be related to the large underabundance of carbon in the SMC. The non-detection or weakening of DIBs in SMC targets could therefore be interpreted in terms of this carbon underabundance if the DIB carriers are indeed large carbonaceous molecules. However, the 4430 Å DIB has been reported in the mean of three low-resolution spectra of SMC targets (AzV 398, AzV 18, and Sk 191) that do not show the 2200 Å bump.

The clear detection of some DIBs in the UVES spectrum of Sk 143 shows that there are environments in the SMC suitable for at least some of the DIB carriers to form, survive, and attain the proper excitation conditions (the charge and hydrogenation state) required to produce the DIBs. Sk 143 is located in a region called the SMC wing (Caplan et al. 1996), associated with weaker star formation, while the other SMC targets are located in the SMC bar. The low $H\alpha$ flux in the SMC wing indicates that this part of the SMC is much more protected against harsh UV radiation than objects located in the SMC bar. The ratio of the equivalent widths of the $\lambda\lambda 5780$ and 5797 DIBs is often used to characterize the UV and density conditions toward Galactic targets (Cami et al. 1997). Its value of $\sim 2.4 \pm 0.2$ toward Sk 143 is comparable to the ratio for Galactic line of sight conditions toward HD 183143.

Also, the extinction curve for Sk 143 is significantly different from the average SMC extinction and looks more like a typical

Galactic extinction curve (Lequeux et al. 1982). It is the only known SMC source that shows the presence of a 2200 Å bump and a weaker far-UV extinction, suggesting that this line of sight does contain a significant amount of carbonaceous molecular material. The redshift of the DIBs, consistent with radial velocities of the interstellar NaD lines, indicates that this material belongs to the SMC, consistent with the findings by Gordon & Clayton (1998) who report that most of the interstellar medium along the line of sight toward Sk 143 lies in the SMC.

In those SMC environments that are shielded from the harsh UV radiation field, the carbonaceous molecular material responsible for most of the extinction features should be more abundant than in the SMC regions that are fully exposed to the UV radiation field. For Sk 143 (SMC) and HD 38029 (LMC), the relative strength of the $\lambda\lambda 5780$ and 5797 DIBs is only a factor of 2 lower than toward HD 183143. Since the carrier of the $\lambda 6284$ DIB apparently requires a higher UV flux than that of the $\lambda 5780$ DIB to become fully ionized, the weakness of the $\lambda 6284$ DIB might be due to unfavorable conditions for ionization balance (imposed by Φ_{UV}^{7eV}/n_{e^-}), double ionization (Φ_{UV}^{13eV}/n_{e^-}), or dehydrogenation balance (imposed by Φ_{UV}^{7eV}/n_H). Alternatively, the absence of the $\lambda 6284$ DIB may also indicate that not enough carbon is available to form or replenish the $\lambda 6284$ DIB carrier efficiently.

4.2. The LMC

Of the four LMC targets for which we present observations of the $\lambda 6284$ DIB, two targets (HD 38029 and HD 38268) show a strong $\lambda 6284$ DIB equivalent to Galactic targets, while the other two (Sk $-68^\circ 135$ and Sk $-67^\circ 2$; see Fig. 2 and Table 1) show significant lower strengths for this DIB. It is not clear how to interpret these variable strengths. HD 38029 and HD 38268, both located within 15' of the 30 Dor region in the LMC, show a strong 6284 Å DIB; Sk $-68^\circ 135$, on the other hand, also located in 30 Dor, does not show the 6284 Å DIB. Sk $-67^\circ 2$, the other star that has a very weak $\lambda 6284$ DIB, lies 5° outside the 30 Dor region.

Additional information about the line-of-sight conditions is available only for Sk $-68^\circ 135$, which has been measured by the *Far Ultraviolet Spectroscopic Explorer* (FUSE) satellite (Tumlinson et al. 2002). These measurements allow an estimation of the strength of the local UV radiation field that is reported to be 10–100 times the Galactic mean value. The weakness of the $\lambda 6284$ DIB toward this target remains unexplained.

The relative extinction $\Delta_{\lambda-V}/\Delta_{B-V}$ at 10 eV in the SMC bar (about 12 mag) is twice as much as in the Milky Way (6 mag); this may be effective in shielding it from vacuum UV even if the external ambient field at 7 eV may be 10–100 times the Galactic value. There is not yet a quantitative model for the EUV field (13 eV) that is relevant for double ionization.

Among the possible DIB carriers, PAH IR emission bands have recently been measured in the LMC and SMC. Vermeij et al. (2002) have discussed the variations in the relative strength of PAH features in the LMC and SMC, in view of the different physical environments, e.g., the relation with the PAH/dust ratio and the extinction curve. They find that in the SMC and 30 Doradus region in the LMC, compact PAH species dominate, while PAHs with an open, uneven structure are dominant in Galactic regions and in the non-30 Dor LMC sources.

5. CONCLUSION

We have observed selected targets in the LMC and SMC and Galactic reference targets at high resolution with the VLT/UVES.

For the first time, we have detected the 5780 and 5797 Å DIBs in the sight line toward a target in the SMC. The absence of the 6284 Å DIB toward Sk 143 in the SMC indicates that this line of sight does not contain the proper conditions to form the corresponding DIB carrier.

In the LMC, we observe a large range of strengths in the 6284 Å DIB. The physical properties of dust grains and carbonaceous molecules may be dependent on a multitude of environmental parameters. Two of these are the metallicity and the star formation activity that affect the overall composition and size distribution of the interstellar material. Observations in different regions of the Magellanic Clouds are needed to disentangle the local effect of metallicity, electron and H densities, UV irradiation, and star formation conditions that potentially affect the carriers of the DIBs.

An important source of information for these purposes can be expected from recent measurements with *FUSE*. The mean

molecular fraction detected in the diffuse gas by a *FUSE* survey of H₂ along 70 lines of sight in the Magellanic Clouds implies a total diffuse H₂ mass of $M(\text{H}_2) = 8 \times 10^6 M_\odot$ for the LMC and $M(\text{H}_2) = 2 \times 10^6 M_\odot$ for the SMC. These masses are less than 2% of the H I masses of the clouds, implying a low overall molecular content, high star formation efficiency, and/or substantial molecular mass in cold, dense clouds unprobed by the *FUSE* survey. These global effects in the chemistry and recycling of cosmic dust in the Magellanic Clouds are relevant for the chemical pathways forming large organic molecules and will account for the absence or low abundance of certain DIB carriers and the changing pattern of the DIB spectrum.

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