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LETTER TO THE EDITOR

Diffuse interstellar bands in M 33

M. A. Cordiner[1], K. T. Smith[2], N. L. J. Cox[3], C. J. Evans[4], I. Hunter[1], N. Przybilla[5], F. Bresolin[6], and P. J. Sarre[2]

[1] Astrophysics Research Centre, School of Mathematics and Physics, Queen's University, Belfast, BT7 1NN, UK
e-mail: m.cordiner@qub.ac.uk
[2] School of Chemistry, The University of Nottingham, University Park, Nottingham, NG7 2RD, UK
[3] Herschel Science Centre, European Space Astronomy Centre, ESA, PO Box 78, 28691 Villanueva de la Cañada, Madrid, Spain
[4] UK ATC, Royal Observatory Edinburgh, Blackford Hill, Edinburgh, EH9 3HJ, UK
[5] Dr. Remeis-Sternwarte Bamberg, Sternwartstr. 7, 96049 Bamberg, Germany
[6] Institute for Astronomy of the University of Hawaii, 2680 Woodlawn Drive, 96822 Honolulu, HI, USA

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ABSTRACT

Aims. We investigate the diffuse interstellar band (DIB) spectrum in the interstellar medium of the Local Group spiral galaxy M 33.
Methods. Optical spectra of the M 33 supergiant star J013346.96+303642.8 were taken at a resolving power of ~3000 using the DEIMOS spectrograph of the W. M. Keck Observatory.
Results. We report the first detection and measurement of DIBs in M 33. The $\lambda\lambda$5705, 5780, 5797, 6203, 6269, 6283, and 6613 DIBs are detected at velocities matching the M 33 Na I absorption lines. The λ4428 DIB is tentatively detected. The stellar spectrum is classified as A3 Ia and the line-of-sight interstellar reddening is derived. Diffuse interstellar band (DIB) equivalent widths and radial velocities are presented.
Conclusions. The overall spectrum of DIBs observed in M 33 is found to be similar to that observed in the Milky Way. However, along this line-of-sight, the M 33 DIB equivalent widths per unit reddening are large compared with those typically observed in the Galaxy.

Key words. astrochemistry – galaxies: Local Group – galaxies: ISM – ISM: lines and bands – ISM: atoms – ISM: dust, extinction

1. Introduction

More than 300 diffuse interstellar bands (DIBs) are now known but the carriers have remained unidentified since their discovery almost 90 years ago. It is debated whether the DIB carriers arise from dust, gas, or the large-molecule component of the interstellar medium (see the review by Sarre 2006). The substructure present in many of the DIB profiles indicates that they are caused by large gas-phase molecules (Sarre et al. 1995; Ehrenfreund & Foing 1996).

Extragalactic DIB research is useful because it broadens the range of physical and chemical conditions with respect to which the properties of the carriers may be analysed. Previous studies of DIBs outside the Milky Way (MW) were reviewed by Snow (2002). Recent research on the relationships between atoms, molecules, dust and DIBs in external galaxies has focused on the Large and Small Magellanic Clouds (e.g. Ehrenfreund et al. 2002; Cox et al. 2006, 2007; Welty et al. 2006). Beyond the Magellanic Clouds, studies are few, and have generally been confined to sightlines probed by bright supernovae (e.g. Sollerman et al. 2005; Cox & Patat 2008), or background quasars (e.g. York et al. 2006). Based on data recorded in the same observing run as the present study, Cordiner et al. (2008) made the first measurements of diffuse interstellar bands in M 31 and measured DIB equivalent widths along two sightlines that were considerably stronger per unit E_{B-V} than the MW average.

M 33 presents the opportunity to study the effects on the DIB carriers of the chemical and physical conditions found in this Local Group spiral galaxy. This Letter presents the spectrum of the supergiant star J013346.96+303642.8 in M 33 and we report the first detection of DIBs in the M 33 galaxy. The observed DIB properties are discussed in relation to those in other galaxies and the physical and chemical conditions in the M 33 ISM.

2. Observations

Forty-three bright stars were observed throughout the disc of M 33 in November 2003 using the Keck DEIMOS spectrograph. Two angles of the 1200 G grating were used to cover the wavelength regions of approximately 3500–6300 and 6000–9000 Å with a spectral resolution $\Delta\lambda \approx 1.8$ Å (corresponding to a resolving power between 2200 and 4500). The total exposure time was 2.25 h in the blue region and 1.5 h in the red, during which the seeing was 0.5–0.8″. The data were reduced using the deep2 pipeline then Doppler-corrected to the LSR frame. Table 1 shows the co-ordinates and photometry of J013346.96+303642.8 (from Massey et al. 2006). This target was selected for analysis in this Letter because its spectrum shows the most prominent DIBs of the forty-three stars observed. The star is spatially well-resolved and distinct from any neighbouring objects that might have contaminated its spectrum or photometry. The rest of the data will be presented elsewhere.

3. Analysis and results

3.1. Stellar spectral type

The spectrum of J013346.96+303642.8 was classified with reference to the Galactic standards of Evans & Howarth (2003), with luminosity class assigned on the basis of the Hγ equivalent width (Evans et al. 2004). The stellar radial velocity of

Table 1. Sightline parameters for J013346.96+303642.8.

RA J2000	Dec J2000	V (mag)	$B-V$ (mag)	Sp. Type	E_{B-V}^{Tot} (mag)	$E_{B-V}^{\mathrm{M\,33}}$ (mag)	v_* (km s^{-1})	S/N @5800 Å
01:33:46.96	+30:36:42.8	17.965 ± 0.004	0.332 ± 0.004	A3 Ia	0.26 ± 0.02	0.22 ± 0.04	-134 ± 1	80

Derived stellar spectral type and LSR radial velocity (v_*) are given. E_{B-V}^{Tot} is the total line-of-sight reddening. $E_{B-V}^{\mathrm{M\,33}}$ is the reddening associated with interstellar matter in M 33 (corrected for the Galactic foreground – see Sect. 3.4).

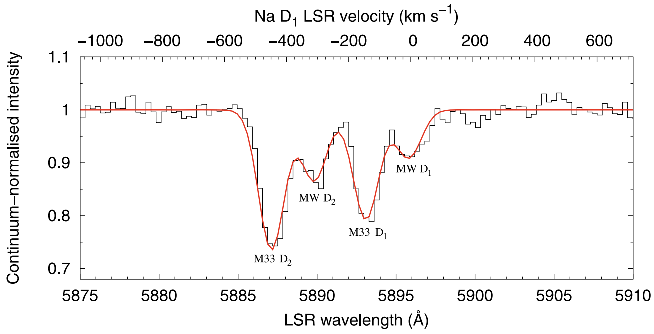

Fig. 1. Observed continuum-normalised Na D spectrum of J013346.96+303642.8 (histogram) with best-fitting model overlaid (red curve). The velocity scale at the top is relative to the Na D_1 rest wavelength. The M 33 and Galactic (MW) absorption components are labelled.

-134 km s^{-1} is the mean of the H I Paschen lines, with a standard error of 1 km s^{-1}.

We analysed Galactic stellar spectra of the same spectral type as the target for the presence of lines overlapping the detected DIBs. No significant contamination of the $\lambda\lambda$5705, 6196, 6203, 6269, 6283 or 6613 DIBs is expected. The λ5780 and λ5797 DIBs may suffer contamination of up to about 5 and 2 mÅ, respectively, as a result of overlapping lines of Fe I. Due to its large width, λ4428 is overlapped by numerous strong stellar lines.

3.2. Interstellar sodium D lines

The observed Na D lines (see Fig. 1) show absorption components due to interstellar gas at velocities consistent with the Galactic and M 33 ISM (around radial velocities of 0 and -150 km s^{-1} respectively). The Na D spectra were modelled using VAPID (Howarth et al. 2002), and the resulting fits are plotted. The mean Na I component radial velocities and the equivalent width (*EW*) of the M 33 D_1 absorption component are given in Table 2. The interstellar Na D lines are contaminated by stellar photospheric Na I. From stellar spectral modelling using SYNSPEC and Kurucz (1993) model atmospheres with solar metallicity, we estimate the stellar contribution to the Na D_1 line *EW* to be at least 160 mÅ (which corresponds to $\gtrsim$40% of the total Na I).

3.3. Diffuse interstellar bands

We examined the spectrum of J013346.96+303642.8 for all strong DIBs in the survey of Jenniskens & Desert (1994) (including all with central depths greater than 0.05 in their Fig. 6). Scaled to the target's reddening, this central depth limit corresponds to $\sim 1\sigma$ of the spectral Poisson noise. The $\lambda\lambda$5705, 5780, 5797, 6203, 6269, 6283 and 6613 DIBs were detected close to the M 33 Na I velocity. Both λ6196 and λ4428 were tentatively detected. The $\lambda\lambda$4726, 4501, 5849, 6376, 6379, 6445, 6532, 6660, 6993 and 8026 DIBs were too weak to be detected. Telluric absorption line contamination prevented analysis of the $\lambda\lambda$6886, 6919, 7224 and 7334 DIBs.

Table 2. Measured and literature DIB and Na D_1 line parameters.

	M 33		MW *EW*s (mÅ)	
	v (km s^{-1})	*EW* (mÅ)	β^1 Sco	MW Avg.@$E_{B-V}^{\mathrm{M\,33}}$
4428	-144^{f}	<1550		595
5705	-143^{+15}_{-15}	46^{+18}_{-18}	23	26
5780	-130^{+15}_{-19}	282^{+36}_{-38}	142	112
5797	-142^{+13}_{-14}	92^{+22}_{-22}	35	34
6196	-144^{f}	<31	12	12
6203	-155^{+19}_{-33}	133^{+23}_{-32}	57	37
6269	-120^{+14}_{-14}	45^{+18}_{-18}	26	
6283	-144^{f}	488^{+90}_{-27}	330	249
6613	-130^{+5}_{-4}	137^{+14}_{-14}	43	47
Na D_1	-144^{+2}_{-2}	384	147	

^{f} Denotes velocities held fixed during fitting.

The radial velocities and equivalent widths of the strongest DIBs were measured using the least-squares fitting technique described by Cordiner et al. (2008). DIB profiles observed towards β^1 Sco (Cordiner 2006), convolved with the DEIMOS spectral point spread function, were shifted and scaled to obtain the best fit to the observed DIBs. The observed DIB spectra and fitted profiles are shown in Fig. 2.

For the $\lambda\lambda$5780, 5797, 6203 and 6613 DIBs, the radial velocities and equivalent widths were allowed to vary in the fits. For the λ6196 and λ6283 DIBs, the radial velocities were fixed at the M 33 Na I radial velocity and only the equivalent widths were allowed to vary. A telluric absorption component (shown in Fig. 2) was also included for λ6283. For λ5705 and λ6269, the DIB profiles were assumed to be Gaussian. DIB radial velocities and *EW*s are shown in Table 2. The λ5797 *EW* is the sum of the λ5797 and overlapping (broad) λ5795 DIBs, which cannot be separated at the observed resolving power. The radial velocities of all measured DIBs agree closely with the Na D-line radial velocity, which is consistent with previous high resolution studies of the Galactic and extragalactic ISM (such as those by Sollerman et al. 2005 and Cox et al. 2006, 2007), and the low resolution study of M 31 by Cordiner et al. (2008). However, it should be noted that the velocity of the M 33 interstellar clouds may differ from the fitted Na I radial velocity due to stellar contamination of the Na Dlines.

There is evidence for a Lorentzian-shaped absorption feature (with *FWHM* $\approx$ 18 Å), centered close to 4426 Å, which we interpret as possibly being caused by the λ4428 DIB in M 33. However, the low *S/N* and presence of several stellar lines in this region prevents the precise measurement of this feature. The upper limit on the M 33 λ4428 *EW* is 1.55 Å.

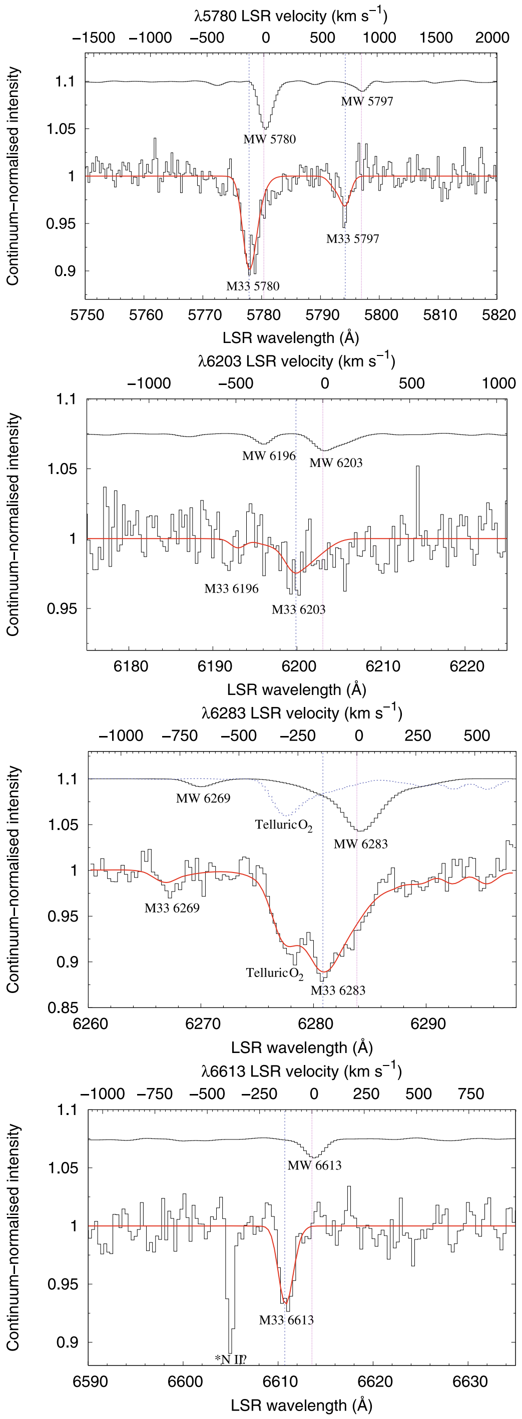

Fig. 2. Continuum-normalised spectra of the observed DIBs (lower black histograms). Fitted model DIB profiles are overlaid (thick red curves). Velocity scales at the top are relative to the Galactic DIB rest wavelengths published by Galazutdinov et al. (2000). The DIB rest wavelengths and blue-shifted M 33 DIB wavelengths are plotted with vertical dotted and dashed lines. Spectra of β^1 Sco are plotted as a reference for Galactic DIB wavelengths and profiles, shifted vertically for display purposes (upper black histograms). A telluric O_2 spectrum is shown for the 6283 Å region (dotted blue line).

Statistical equivalent width and DIB velocity error estimates were derived using the same method as Cordiner et al. (2008). To account for errors introduced into the fits due to the blending of MW and M 33 DIB components for $\lambda\lambda$4428, 5780 and 6283 DIBs, a Milky Way component was also included. The *EW*s of these MW components were varied between zero and the value that corresponded to the least-squares fit. The resulting M 33 DIB parameter ranges are included in the errors quoted in Table 2.

3.4. Foreground gas and dust

LAB H I data (Kalberla et al. 2005) for the closest survey point in the direction of the target imply that $N(\mathrm{H\,I}) = 4.3\times10^{20}$ cm^{-2} for the velocity range of the Galactic foreground gas (from −60 to 50 km s^{-1}). Equation (7) of Burstein & Heiles (1978) is used to calculate the foreground reddening for lines of sight at latitudes away from the Galactic plane, which yields E_{B-V} = 0.03 mag towards our targets. The foreground reddening derived by Schlegel et al. (1998) from COBE and IRAS maps is 0.042 mag.

We measure a Galactic foreground Na I column density towards J013346.96 + 303642.8 of 2.8×10^{12} cm^{-2}, which corresponds to $E_{B-V} \sim 0.10$ mag (Hobbs 1974). However, there is considerable scatter in the relationship derived by Hobbs (1974) and there is likely to be contamination of the Na I profile close to $v = 0$ due to sky-line subtraction residuals. We therefore adopt a foreground reddening of 0.04 ± 0.02 mag, which results in a foreground-corrected reddening of $E^{\mathrm{M\,33}}_{B-V} = 0.22 \pm 0.04$ mag.

4. Discussion

DIB equivalent widths in the Milky Way correlate with E_{B-V}, and many DIBs have *EW*s that correlate with each other (Herbig 1995). In terms of the relative strengths of the detected DIBs and their (Doppler-shifted) wavelengths, the observed M 33 DIB spectrum is consistent with that observed in the Galaxy and in M 31 (by comparison with Cordiner et al. 2008). Only the strongest known Galactic DIBs were detected in M 33, which is as expected given the signal-to-noise and the low reddening of the target.

The observed DIBs are stronger by a factor of about two compared with those observed towards our chosen Galactic reference target β^1 Sco. The β^1 Sco sightline has $E_{B-V} = 0.22$, which is identical to the $E^{\mathrm{M\,33}}_{B-V}$ value for J013346.96 + 303642.8. As shown in Table 2, the β^1 Sco DIBs are about as strong as the Galactic average per unit E_{B-V}. The MW Avg.@$E^{\mathrm{M\,33}}_{B-V}$ values in Table 2 were calcualted by taking the average of EW/E_{B-V} for each DIB in the data published by Herbig (1993), Thorburn et al. (2003), Megier et al. (2005), and Cordiner (2006), then scaling by a factor of $E^{\mathrm{M\,33}}_{B-V} = 0.22$. Figure 3 shows that the M 33 $\lambda\lambda$5780, 6283 and 6613 EW/E_{B-V} values are similar to the upper limit to the spread of values observed in the MW, and are almost as large as observed towards MAG 70817 in M 31 (the upper left (blue) square in the plots). In the Milky Way, such strong DIBs (per unit reddening), are rarely, if ever, observed. The Galactic target HD 164 402 has a λ5780 *EW* among the largest known for its reddening (E_{B-V} = 0.22, *EW*(5780) = 187 mÅ) (Herbig 1993), which is still significantly lower than found here. Such large DIB strengths are remarkable, but cannot be considered as indicative of the properties of DIBs throughout M 33 because this target was selected from the observed set due to its strong DIBs. In the direction of the observed target, the 21 cm H I emission maximum is at about −150 km s^{-1} (Warner et al. 1973), which is consistent with the measured Na I and DIB velocities.

J013346.96+303642.8 is 3.0′ (730 pc) from the centre of M 33 (assuming a distance of 840 kpc). Observations of H II regions in M 33 by Magrini et al. (2007) indicate that the metallicity at this radius is approximately solar. This suggests

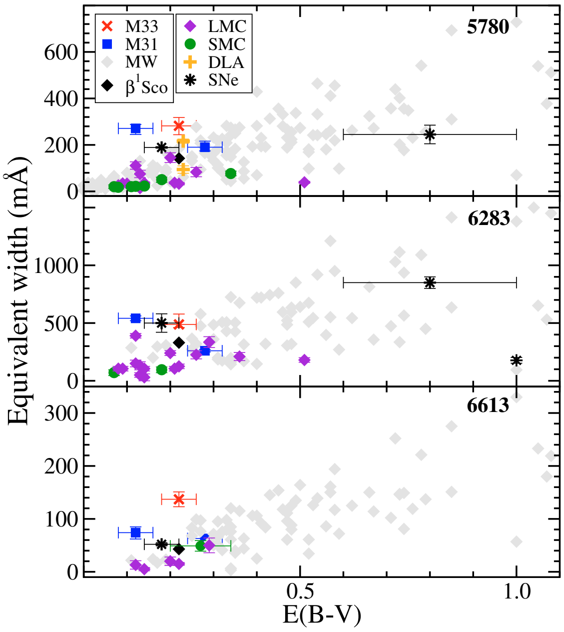

Fig. 3. $\lambda\lambda$5780, 6283 and 6613 equivalent widths vs. reddening for different galaxies. Milky Way data (from Herbig 1993; Thorburn et al. 2003; Megier et al. 2005; Cordiner 2006), are shown as grey diamonds. Data are shown for M 33 (this work), M 31 (Cordiner et al. 2008), the LMC and SMC (Welty et al. 2006), DLAs (York et al. 2006; Ellison et al. 2008) and supernovae in NGC 1448 and NGC 2770 (Sollerman et al. 2005; Thoene et al. 2008).

that the metallicity of the M 33 ISM along the line of sight to this star should be comparable with that in the solar neighbourhood. Thus, an explanation other than metallicity may be required to explain the large DIB strengths.

The GALEX map of M 33 (Thilker et al. 2005) shows that the observed star is close to (within 0.4′/96 pc) a small cluster of UV-bright stars. It has been suggested that UV radiation is required for the production of DIB carriers (see Herbig 1995; Kendall et al. 2002), which may explain why the DIBs along this sightline are strong. This hypothesis could be tested by observing DIBs along sightlines that traverse UV-bright sources with varying impact parameters. Figure 2 shows that the observed ratio of λ5780 to λ5797 DIB strengths is similar to that of β^1 Sco and that this M 33 sightline is therefore of "σ" type (Weselak et al. 2000). This designation may be considered as evidence that the interstellar gas is relatively diffuse and quite strongly UV-irradiated (see e.g. Cami et al. 1997), although not to such a degree as to cause nebular emission, which tends to be associated with weaker DIBs (Snow et al. 1995). High resolution spectroscopic observations of interstellar Ca I, Ca II, CH, and CN near-UV absorption lines would provide a further probe of the UV field strength along this sightline; in this respect, the upper limits to the column densities of these species derived from our spectra are inconclusive.

5. Conclusion

The $\lambda\lambda$5705, 5780, 5797, 6203, 6269, 6283, and 6613 DIBs have been detected in M 33 towards the A3 Ia star J013346.96 + 303642.8 at velocities corresponding (within 25 km s^{-1}) to the mean M 33 Na I absorption velocity. This constitutes the first reported detection of DIBs in the M 33 galaxy. Both the λ4428 and λ6196 DIBs are tentatively detected. The overall spectrum of DIBs observed in M 33, including the strength ratios between different DIBs, is found to be similar to that observed in the Milky Way. However, in this line-of-sight, the DIBs measured are up to about a factor of two stronger per unit reddening than towards the Galactic reference target β^1 Sco (which has the same reddening, E_{B-V} = 0.22). The $\lambda\lambda$5780, 6283 and 6613 equivalent widths per unit E_{B-V} are among the highest observed in any galaxy. The high DIB strengths may be due to differences between the gas/dust composition or interstellar radiation field of M 33 and the Galaxy. Further observational and theoretical studies of the chemical and physical properties of the ISM along this sightline will be required to determine what may be causing such strong DIBs.

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