Detection of diffuse interstellar bands in M31

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Received 21 December 2007 / Accepted 22 January 2008

ABSTRACT

Aims. We investigate the diffuse interstellar band (DIB) spectrum in the interstellar medium of M31.

Methods. The DEIMOS spectrograph of the W. M. Keck observatory was used to make optical spectroscopic observations of two supergiant stars, MAG 63885 and MAG 70817, in the vicinity of the OB78 association in M 31 where the metallicity is approximately equal to solar.

Results. The \( \lambda \lambda 5780, 5797, 6203, 6283, 6613 \) DIBs are detected in both sightlines at velocities matching the M 31 interstellar Na I absorption. The spectra are classified and interstellar reddens are derived for both stars. Diffuse interstellar band (DIB) equivalent widths and radial velocities are presented.

Conclusions. The spectrum of DIBs observed in M 31 towards MAG 63885 is found to be similar to that observed in the Milky Way. Towards MAG 70817 the DIB equivalent widths per unit reddening are about three times the Galactic average. Compared to observations elsewhere in the Universe, relative to reddening the M 31 ISM in the vicinity of OB78 is apparently a highly favourable environment for the formation of DIB carriers.

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

1. Introduction

Today, more than 300 diffuse interstellar bands (DIBs) are known but the carriers have remained unidentified since their discovery almost 100 years ago. It is debated whether the DIB carriers arise from the dust, the gas, or the large-molecule component of the interstellar medium (see the review by Sarre et al. 1995; Ehrenfreund & Foing 1996) that they are caused by large gas-phase molecules. The interaction between gas-phase species (atoms and molecules), UV radiation and dust grains may be crucial in the formation of large (\( \geq 250 \) atom) molecules in space which are likely candidates for the carriers of the DIBs (see e.g. Salama et al. 1996; Ruitenkamp et al. 2005).

In interstellar environments distinct from those found in the Milky Way (MW), previous research on the relationships between atoms, molecules, dust and DIBs has focused on the Large and Small Magellanic Clouds (e.g. Ehrenfreund et al. 2002; Cox et al. 2006, 2007; Welty et al. 2006). The behaviour of the DIB carriers was analysed with respect to the higher gas-to-dust ratios, lower metallicities, lower \( RV \) and stronger interstellar radiation fields of these environments. Beyond the Magellanic Clouds, studies are sparse, confined to sightlines probed by sufficiently bright supernovae (e.g. Rich 1987; Sollerman et al. 2005) or background quasars (e.g. York et al. 2006).

M 31 presents the opportunity to study the effects on the DIB carriers of the unique chemical and physical conditions found in this Local Group galaxy. This letter presents spectra of two supergiant stars in M 31 and we report the first unambiguous detection of DIBs in M 31. The observed DIB properties are discussed in relation to those in other galaxies and the interstellar conditions of M 31.

2. Observations

Seventy-two bright stars in and around the M 31 OB 78 association (van den Bergh 1964) were observed in November 2003 using the Keck DEIMOS spectrograph. Two angles of the 1200 G grating were used to cover the region from approximately 3500 to 9000 Å with a resolving power \( R = 3300 \). 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". Wavelength calibration accuracy was confirmed using the Na D sky emission lines whose central wavelengths were found to be accurate to within \( \pm 5 \) km s\(^{-1}\). Reduced spectra were Doppler-corrected to the LSR frame. Table 1 shows the co-ordinates and photometry of MAG 63885 and MAG 70817. These targets were selected for analysis in this letter due to their prominent DIBs. The rest of the DEIMOS data will be presented in a future article (Cordiner et al. 2008).

1 Initially the red and blue spectra were both reduced using the spec2d pipeline. However, the wavelength scale of the blue spectra (\( \sim 3500–6000 \) Å) was found to be erroneous so these were re-reduced manually in IRAF using the twodspec routines.
Table 1. Observed M 31 stars. Target numbers from Magnier et al. (1992). Co-ordinates and photometry from Massey et al. (2006). Derived stellar spectral classifications and radial velocities \((v_r)\) are shown. M 31 \(E_{B-V}\) values were calculated using intrinsic colours from Johnson (1966) and have been corrected for Galactic foreground reddening (see Sect. 3.4).

<table>
<thead>
<tr>
<th>Target</th>
<th>RA (2000)</th>
<th>Dec (2000)</th>
<th>(B - V) (mag)</th>
<th>Sp. type</th>
<th>(E_{B-V}) (mag)</th>
<th>(v_r) ((\text{km s}^{-1}))</th>
<th>S/N</th>
</tr>
</thead>
<tbody>
<tr>
<td>65885</td>
<td>00:40:30.47</td>
<td>+40:35:03.8</td>
<td>16.380 (\pm) 0.003</td>
<td>B9 Ia</td>
<td>0.326 (\pm) 0.003</td>
<td>-544 (\pm) 150</td>
<td>7018</td>
</tr>
<tr>
<td>7018</td>
<td>00:40:35.46</td>
<td>+40:36:44.6</td>
<td>18.282 (\pm) 0.003</td>
<td>F2 I</td>
<td>0.431 (\pm) 0.003</td>
<td>-543 (\pm) 80</td>
<td>6885</td>
</tr>
</tbody>
</table>

Fig. 1. Observed continuum-normalised Na D spectra (histograms) with best-fitting models overlaid (red curves). Velocity scale at the top is relative to the Na D1 rest wavelength. The M 31 and Galactic (MW) absorption components are labelled.

3. Analysis and results

3.1. Interstellar sodium D

The observed Na D lines (see Fig. 1) show two clearly separated absorption components due to interstellar gas at velocities consistent with the Galactic and M 31 ISM (around radial velocities of 0 and \(-550 \text{ km s}^{-1}\) respectively). The spectra were modelled using VAPID (Howarth et al. 2002) and each absorption component was accurately reproduced with a Gaussian interstellar cloud model. The fits are plotted in Fig. 1 and the mean radial velocities and equivalent widths (EWs) of the M 31 D1 absorption components are given in Table 2.

3.2. Diffuse interstellar bands

We searched the spectra for all DIBs with central depths greater than 0.05 in Fig. 6 of the DIB survey by Jenniskens & Desert (1994). Scaled to the reddening of our targets, this central depth limit corresponds to \(-1\sigma\) of the spectral Poisson noise. The \(\lambda\lambda 5780, 5797, 6203, 6283\) and 6613 DIBs were detected at M 31 velocities in the spectra of MAG 63885 and MAG 70817. \(\Delta l 196\) was tentatively detected towards MAG 70817. The \(\lambda\lambda 4501, 4726, 5705, 5849, 6269, 6376, 6379, 6445, 6532, 6660, 6993\) 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.

To simultaneously measure the DIB radial velocities and equivalent widths, Galactic DIB templates were fitted to the observed spectra using a non-linear least-squares algorithm. The Galactic templates were derived from high resolution, high S/N spectra of \(\beta^1\) Sco (see Cordiner 2006). These were shifted to the interstellar rest frame and convolved with a Gaussian interstellar cloud model then with the instrumental spectral PSF and rebinned to the wavelength scale of the DEIMOS spectra. This technique minimises statistical errors in the measurement of the equivalent widths and velocities of weak DIBs but assumes that the intrinsic M 31 DIB profiles and rest wavelengths closely match those of \(\beta^1\) Sco. If this is not the case, unknown systematic errors could occur, but we find no evidence to suggest that M 31 DIB profiles differ at all from those of \(\beta^1\) Sco. Observed DIB spectra and fitted profiles are shown in Fig. 2.

For the \(\lambda\lambda 5780, 6283\) and 6196 DIBs the radial velocities and equivalent widths were allowed to vary in the fits. A telluric absorption component (derived from a high-resolution spectrum of the unreddened fast-rotator \(\alpha\) Gru (see Cordiner 2006), degraded to \(R = 3300\), was also included for \(\lambda\lambda 6283\) to account for the prominent band-head of atmospheric O2 between 6278 and 6286 \(\text{Å}\). For the \(\lambda\lambda 5779, 6196\) and 6203 DIBs only the equivalent widths were allowed to vary while the DIB radial velocities were fixed at the M 31 Na I radial velocities. In all cases, there is excellent agreement between the fitted and observed DIB profiles. DIB radial velocities and EWs are shown in Table 2. The radial velocities of all measured DIBs closely match the Na I radial velocities, consistent with previous high-resolution studies of the Galactic and extragalactic ISM (such as those by Sollerman et al. 2003; Megier et al. 2005; and Cordiner 2006).

Table 2. Summary of best-fitting DIB equivalent widths (EW/\(\text{mÅ}\)) and LSR radial velocities (\(\text{v} / \text{km s}^{-1}\)) for MAG 63885 and MAG 70817. \(f\) denotes values held fixed during fitting. Statistical (68th percentile) DIB velocity errors are less than \(\pm 10 \text{ km s}^{-1}\). The M 31 Na I radial velocities and D1 line EWs are also shown, including an estimated contribution due to stellar photospheric Na I in square brackets. EWs for \(\beta^1\) Sco (\(\text{EW}_{\beta^1} = 0.22\)) and Galactic mean \(\text{EW}/\text{EW}_{\beta^1}\) data (normalised to \(\text{EW}_{\beta^1} = 0.14\)) are also given (data from Herbig 1993; Thorburn et al. 2003; Mege 2005; and Cordiner 2006).

<table>
<thead>
<tr>
<th>MAG 63885</th>
<th>MAG 70817</th>
<th>(\beta^1) Sco</th>
<th>MW Avg.</th>
</tr>
</thead>
<tbody>
<tr>
<td>EW</td>
<td>(v)</td>
<td>EW</td>
<td>(v)</td>
</tr>
<tr>
<td>5780</td>
<td>190 (\pm) 16</td>
<td>-539</td>
<td>271 (\pm) 17</td>
</tr>
<tr>
<td>5797</td>
<td>44 (\pm) 5</td>
<td>-550 (\pm) 26</td>
<td>58 (\pm) 26</td>
</tr>
<tr>
<td>6196</td>
<td>3 (\pm) 3</td>
<td>-550 (\pm) 12</td>
<td>29 (\pm) 12</td>
</tr>
<tr>
<td>6203</td>
<td>94 (\pm) 11</td>
<td>-550 (\pm) 16</td>
<td>121 (\pm) 16</td>
</tr>
<tr>
<td>6283</td>
<td>260 (\pm) 11</td>
<td>-575</td>
<td>541 (\pm) 21</td>
</tr>
<tr>
<td>6613</td>
<td>63 (\pm) 3</td>
<td>-564</td>
<td>74 (\pm) 11</td>
</tr>
</tbody>
</table>

NaD1 736 \(\pm\) 04 846 \(\pm\) 300 -550 145 7 147

2 A synthetic average of their observed DIB spectra (normalised to \(E_{B-V} = 1.28\)).

3 Our DEIMOS observations contained no telluric standards by which to perform a conventional telluric division.
3.3. Stellar spectral types

Spectral types and stellar radial velocities for the target stars are presented in Table 1. Analysis of luminous B-type supergiants in M 31 finds chemical abundances comparable to those in the solar neighbourhood (e.g. Trundle et al. 2002), so Galactic standards are appropriate. The spectra were classified with reference to the Galactic standards from Evans & Howarth (2003), with luminosity classes assigned on the basis of the Hγ equivalent widths (Evans et al. 2004).

Stellar radial velocities are the mean results from manual measurements of the cores of the Hα Balmer line and the Paschen lines. Statistical errors on the measured radial velocities are less than ±5 km s⁻¹.

We searched Galactic stellar spectra of the same spectral types as our targets for the presence of lines overlapping the detected DIBs. No significant contamination of the λλ6196, 6203, 6283 or 6613 DIBs is expected. The λλ5780 and 5797 may suffer contamination of up to about 5 and 2 mÅ respectively as a result of overlapping lines of Fe i.

3.4. Foreground gas and dust

LAB H i data (Kalberla et al. 2005) for the nearest survey point in the direction of our sightlines shows N(H i) = 5.91 × 10¹⁹ cm⁻² over the velocity range of Galactic gas (from -300 to 100 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 = 0.06 mag towards our targets, identical to the value given by the foreground dust map of Schlegel et al. (1998).

The Galactic foreground Na i column densities measured towards MAG 63885 and MAG 70817 are 3.7 × 10¹² and 1.9 × 10¹² cm⁻² respectively, which correspond to reddenings of 0.12 and 0.08 mag (Hobbs 1974). However, there may be contamination of the Galactic Na i profiles near v = 0 due to sky-line subtraction residuals. Using a foreground reddening of 0.06, corrected M 31 E_B-V values are given in Table 1.

4. Discussion

DIB equivalent widths in the Milky Way correlate with E_B-V (Herbig 1995). Given the signal-to-noise and the limited reddening of our target spectra, only the strongest known Galactic DIBs were detected in M 31. Other M 31 DIBs (including those listed in Sect. 3.2) are expected in our spectra around or below the limit of detectability.

The DIB equivalent widths observed in M 31 toward MAG 63885 are consistent with those typically observed in Galactic sightlines with the same reddening, as highlighted by comparison with the similarly-reddened β¹ Sco (see Table 2). Towards MAG 70817 the observed DIBs are stronger per unit E_B-V by a factor of about 2–5 compared with Galactic-mean data. Figure 3 shows that the λ₅₇₈₀ EW/E_B-V for MAG 63885 is among the larger values observed elsewhere in the Universe and for MAG 70817 λ₅₇₈₀ EW/E_B-V is significantly greater than any other sightline plotted.
Detailed information is sparse, but M 31 appears to be similar to the Milky Way in terms of the average interstellar gas-to-dust ratio (Nedialkov et al. 2000; Bresolin et al. 2002) and the metallicity in the vicinity of our targets (Trundle et al. 2002). There is, however, evidence for a difference in the properties of the interstellar dust grains and the interstellar UV radiation field. A different star formation history and low rate of star formation (1/10th of MW; Walterbos & Braun 1994) has been measured in M 31, and the surface radiation flux was found to be poor in UV (Cesarsky et al. 1998; Pagani et al. 1999). The fact that strong DIBs are observed under these conditions may be in contradiction to the hypothesis that UV radiation is required for the production of the carriers (see Herbig 1995; Kendall et al. 2002, for example). However, MAG 63885 and MAG 70817 are near to the OB78 association where the abundance of early-type stars may result in a strong interstellar UV radiation field.

The M 31 2175 Å UV extinction bump has been found to be weak and narrow (Bianchi et al. 1996; Hutchings et al. 1992) and a peculiar extinction law was observed by Massey et al. (1995) in the anomalously low average colour-excess ratio \( E(B-V) / E(B-V) \). Accepting current theories of dust grain extinction (see review by Draine 2003), the evidence is consistent with a different distribution of dust grain sizes and compositions compared to the Milky Way average. In particular, there may be a lack of small graphitic dust grains (see also Xu & Helou 1994). In that case, the observation of strong DIBs implies that the carriers are not closely associated with the small grains believed to be responsible for the shape of the UV extinction curve.

5. Conclusion

The \( A_{\text{L}5780}, 5797, 6283, 6203 \) and 6613 DIBs were detected towards MAG 63885 and MAG 70817 at velocities corresponding (within 25 km s\(^{-1}\)) to the mean M 31 interstellar Na I absorption. \( A_{\text{L}5166} \) and \( A_{\text{L}4430} \) were also tentatively detected.

The M 31 DIB spectrum towards MAG 63885 is consistent with that observed in the Galaxy. Towards MAG 70817 the DIBs are about a factor of three stronger per unit reddening than the Galactic average. The high DIB strengths might be related to differences in the M 31 interstellar UV extinction curve and radiation field compared to the Galaxy. Further studies will be required to determine if the two sightlines examined here are representative of the general M 31 DIB behaviour.

A planned instrument for the Hubble Space Telescope, the “Cosmic Origins Spectrograph” will be able to provide essential information on the UV properties of M 31 sightlines to further examine these possibilities. However, the connection between DIBs in M 31 and the atomic and molecular content (e.g. Na, K, Ca, CH\(^+\), CH, CN and C\(_2\)) of the diffuse medium can only be properly addressed with high resolution, high signal-to-noise optical spectroscopic observations.

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Sarre, P. J. 2006, Molec. Spectrosc., 238, 1

Fig. 3. \( \lambda \lambda 5780, 5797, 6283, 6203 \) and 6613 DIBs were detected towards MAG 63885 and MAG 70817 at velocities corresponding (within 25 km s\(^{-1}\)) to the mean M 31 interstellar Na I absorption. \( A_{\text{L}5166} \) and \( A_{\text{L}4430} \) were also tentatively detected.