Linear and circular spectropolarimetry of diffuse interstellar bands^{★,★★,★★★}

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ABSTRACT

Context. The identification of the carriers of diffuse interstellar bands (DIBs) remains one of the long-standing mysteries in astronomy. The detection of a polarisation signal in a DIB profile can be used to distinguish between a dust or gas-phase carrier. The polarisation profile can give additional information on the grain or molecular properties of the absorber.

Aims. To measure the polarisation efficiency of the carriers of the diffuse interstellar bands.

Methods. In order to detect and measure the linear and circular polarisation of the DIBs we observed reddened lines of sight showing continuum polarisation. For this study we selected two stars HD 197770 and HD 194279. We used high-resolution ($R \sim 64\,000$) spectropolarimetry in the wavelength range from 3700 to 10 480 Å with the ESPaDOnS échelle spectrograph mounted at the CFHT.

Results. High S/N and high resolution Stokes V (circular), Q and U (linear) spectra were obtained. We constrained upper limits by a factor of 10 for previously observed DIBs. Furthermore, we analysed ~ 30 additional DIBs for which no spectropolarimetry data has been obtained before. This included the 9577 Å DIB and the 8621 Å DIB. The former is attributed to the C_{60}^+ fullerene, which could become aligned in a magnetic field. The latter shows a tight correlation with the amount of dust in the line-of-sight and therefore most likely may show a polarisation signal related the aligned grains.

Conclusions. The lack of polarisation in 45 DIB profiles suggests that none of the absorption lines is induced by a grain-type carrier. The strict upper limits, less than $\sim 0.01\%$, derived for the observed lines-of-sight imply that if DIBs are due to gas-phase molecules these carriers have polarisation efficiencies which are at least 6 times, and up to 300 times, smaller than those predicted for grain-related carriers.

Key words. astrochemistry – polarization – dust, extinction – ISM: lines and bands – ISM: molecules

1. Introduction

The diffuse interstellar bands (DIBs) are more than 300 absorption lines in the optical spectrum that reside in the interstellar medium (Merrill 1934; Herbig 1995). See for example Hobbs et al. (2008) for a recent DIB inventory. DIBs are ubiquitously present throughout the Galaxy and they have been detected also in other galaxies (Ehrenfreund et al. 2002; Sollerman et al. 2005; Cox et al. 2006, 2007b; Cox & Patat 2008; Cordiner et al. 2008a,b). Not a single carrier has been identified unambiguously yet. Their relative large widths argue against atoms and di-atomic molecules in the gas-phase. And although their

intensity is related to the extinction by dust grains their (spectral) properties and behaviour are more consistent with large gas-phase molecules (see also the review by Sarre 2006). In particular the substructure in several DIB profiles indicates that the carrier(s) are large gas phase molecules (Sarre et al. 1995; Ehrenfreund & Foing 1996; Cami et al. 2004). DIBs respond to the local environmental conditions, in particular to the effective strength of the UV field (e.g. Cami et al. 1997; Cox et al. 2006). Their strength variation could reflect the local charge state balance of the carrier molecules (Ruiterkamp et al. 2005; Cox & Spaans 2006). Therefore, specific groups of stable UV resistant molecules (such as PAHs, fullerenes and carbon chains) are commonly postulated carrier candidates (Herbig 1995). Interstellar grains are known to become aligned when situated in a magnetic field which is evidenced by linear and circular continuum polarisation (e.g. Serkowski 1965). The linear continuum polarisation can be described by the following empirical relation:

$$P(\lambda) = P_{\max} \exp(-K \ln^2(\lambda_{\max}/\lambda)), \quad (1)$$

with $K(\lambda_{\max}) = (1.66 \pm 0.09)\lambda_{\max} + (0.01 \pm 0.05)$ (Serkowski 1965; Coyne et al. 1974; Whittet et al. 1992). The wavelength

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** Appendices are available in electronic form at <http://www.aanda.org>

*** Intensity and polarisation spectra are only available at the CDS via anonymous ftp to [cdsarc.u-strasbg.fr](ftp://cdsarc.u-strasbg.fr) (130.79.128.5) or via <http://cdsarc.u-strasbg.fr/viz-bin/qcat?J/A+A/531/A25>

dependency of the polarisation is mainly determined by the composition and size of the dust particles. The polarisation efficiency, $P(\lambda)/A(V)$, is a function of various factors, such as porosity and shape (Voshchinnikov & Das 2008).

For example, it has been well established that the silicate features at 9.7 and 18.5 μm show an excess of polarisation (Aitken et al. 1998; Smith et al. 2000). Also ice-features show polarisation (3.1 μm O–H stretching mode of water ice; Hough et al. 1996, or ice features near 4.6–4.7 μm show polarization due to CO and CN-bearing species; Chrysostomou et al. 1996). These detections have been taken as evidence for alignment of core/mantle grains in molecular clouds. Thus, polarization of the 3.4 μm C–H feature is expected if it is due to carbonaceous mantles on silicate cores. However, no polarisation has been detected for the 3.4 μm feature (Chiar et al. 2006). Adamson et al. (1999) obtained an upper limit of $\sim 0.06 \pm 0.13\%$ for Δp , which is a factor 5 below the predicted value for $\Delta p_{9.7}/\tau_{3.4}$ of 0.4%.

Several theoretical and experimental studies predict that also large (ionized) molecules, such as PAHs and fullerenes, can align, via for example the Barnett effect, under certain physical conditions (see e.g. Ballester et al. 1990; Rouan et al. 1992; Lazarian 1994; Wolff et al. 1997). Depending on the polarisation (i.e. parallel versus perpendicular) of the incident light changes can be seen in the electronic absorption spectra of large molecules that have some intrinsic asymmetry. A summary of different proposed alignment mechanisms is given in Cox et al. (2007a). Therefore, the polarisation signal across a DIB profile could provide further constraints on the (molecular) properties of their carriers. Spectropolarimetry of diffuse bands has been limited to about ten lines-of-sight and only nine individual DIBs, although no DIB polarisation has yet been detected. Recent studies include those by Adamson & Whittet (1992, 1995); Somerville (1996), and Cox et al. (2007a, but see also references therein for earlier work). The most recent and comprehensive study involved three sightlines and six DIBs (Cox et al. 2007a). This study set the most stringent detection limits, between 0.01 and 0.14%, for linear and circular polarisation of 6 narrow DIBs. These values exclude classical grains as carriers of the $\lambda\lambda$ 5780, 5797, 6613 and 6284 DIBs. That the 6379 and 6613 $\text{\AA}$ DIBs originate from (classical) grains could only be marginally excluded from previous polarisation measurements. This lack of line polarisation of DIBs implies that the DIB carriers are not embedded in or attached onto large – silicate – grains (i.e. those that produce optical extinction and polarisation), but might still be related to smaller – carbonaceous – grains, i.e. those that produce the far-UV extinction. The current constraint on the line polarisation is still consistent with a gas phase carrier for which the polarisation signal could be very weak.

The aim of the present study is to ascertain whether or not the DIB carriers can give rise to an observable polarisation and what that means for their identity. There is not a priori way of knowing if and which DIB carriers are related to grains or molecules, and therefore each DIB could or could not give rise to significant line polarisation predicted for grains or very weak polarisation from molecules. Note that only a few DIBs exhibit a strong correlation with each other thus indicating that the majority of the DIBs have different, though possibly physically/chemically related, carriers (Cami et al. 1997; McCall et al. 2010). We present new observations for two lines-of-sight previously studied but with an order of magnitude higher sensitivity and for many more additional individual DIBs not included in spectropolarimetry studies before. In particular, our study includes also weak DIBs and DIBs in the near-IR.

Table 1. Target and line-of-sight information (from literature).

ID	HD 197770	HD 194279
RA (J2000) ^a	20:43:13.68	20:23:18.16
Dec (J2000) ^a	+57:06:50.4	+40:45:32.6
Spectral type ^a	B2 III	B1.5 Ia
distance (pc)	$\sim 440^g$	1100 ⁱ
B (mag) ^a	6.594	7.92
V (mag) ^a	6.341	7.09
$E_{(B-V)}$ (mag)	0.58 ± 0.04^c	1.21
A_V (mag)	1.61 ± 0.14^c	3.9
R_V	$2.8^d, 2.77 \pm 0.15^c$	$3.2^d, 3.25 \pm 0.03^e$
P_{max} (%)	$3.83^b, 3.81^f$	2.77
λ_{max} (μm)	$0.49^b, 0.51^f$	0.58
P_{max}/A_V (%/mag)	2.4	0.71
P_{max}/τ_V^h	0.026	0.008

Notes. ^(a) From Simbad. ^(b) From Clayton et al. (1995). ^(c) From Valencic et al. (2004). ^(d) Computed from $R_V = 5.5\lambda_{\text{max}}$ (Serkowski et al. 1975). ^(e) From Wegner (2003). ^(f) From Wolff et al. (1993). ^(g) From Dobashi et al. (1994). ^(h) The optical depth $\tau_V = A_V/1.086$. ⁽ⁱ⁾ Spectroscopic parallax distance (McCall et al. 2002); see also Sect. 3.2.2.

2. Spectropolarimetric observations

For the present study we obtained new spectropolarimetry data with ESPaDOnS at the Canadian-French-Hawaiian Telescope (CFHT). The data were taken on 8–9 July and 21–25 July 2008 under good seeing ($\leq 1''$) conditions. ESPaDOnS is a high-resolution high-efficiency 2-fiber echelle spectrograph with polarising capabilities. The dispersion for the spectropolarimeter is about 64 000, covering a wide spectral range, from 3700 to 10 480 $\text{\AA}$ with only a few small gaps in the near-infrared. We selected two reddened targets, HD 197770 and HD 194279, for an in-depth study of the interstellar line polarisation. A summary of line-of-sight properties is provided in Table 1. Exposure times amounted to 3040 and 5840 s for each final Stokes Q , U and V spectrum (each consisting of four sub-exposures taking at different positions of the retarder) for HD 197770 and HD 194279, respectively.

The observations were automatically reduced with Upena, which is CFHT's reduction pipeline for ESPaDOnS. The Upena data reduction system uses Libre-ESPRIT which is a purpose built data reduction software tool (Donati et al. 1997). We choose to opt for continuum normalized spectra (we are looking for line variation) and to apply both the heliocentric velocity correction and the radial velocity correction from telluric lines. Thus we obtain total intensity Stokes I spectra as well as Stokes Q/I , and U/I (linear), and V/I (circular) spectra normalized to a zero mean (i.e. the spectra are sensitive to line polarisation only). The achieved signal-to-noise ratio (S/N) varies across the spectrum, but is about 700 and 1200 in the red range, for HD 194279 and HD 197770, respectively. In addition to the shape of the SED, the reduced S/N at the longest wavelengths is also due to the lower efficiency of the instrument (mainly the detector) and at the shortest wavelengths due to stronger extinction by dust.

3. Results and discussion

3.1. Polarisation and total intensity line profiles

The polarisation efficiency of an absorption line can be written generally as (adapted from Greenberg & Hong 1974; Martin & Angel 1974; Somerville 1996):

$$\Delta P(\lambda) = f_P(\lambda) P(\lambda) \Delta\tau(\lambda)/\tau(\lambda) \quad (2)$$

Table 2. Upper limits on the DIB carrier polarisation efficiency factor f_P . See text for details.

DIB ^a	Upper limits on the polarisation efficiency factor f_P							
	HD 197770	HD 194279	DIB	HD 197770	HD 194279	DIB	HD 197770	HD 194279
4428.19	~0.033	~0.070	4979.61	0.15	0.39	7045.89	0.06	0.11
5705.08	0.056	0.068	5844.92	0.09	0.16	7061.05	0.03	0.05
5780.48	0.007	0.008	5849.81	0.02	0.03	7062.68	0.07	0.07
5797.06	0.005	0.010	5973.81	0.08	0.24	7069.55	0.03	0.07
6195.98	0.010	0.024	5975.75	0.03	–	7077.86	–	0.14
6203.05	0.019	0.024	6027.68	–	0.24	7119.71	0.03	0.06
6269.85	0.015	0.017	6065.28	0.05	0.15	7375.87	–	0.17
6283.84	0.017	0.006	6089.85	0.02	0.07	7385.89	0.08	0.14
6379.32	0.005	0.010	6113.18	0.02	0.08	7405.71	0.10	0.25
6613.62	0.003	0.007	6139.98	0.04	0.13	7559.41	0.08	0.10
6660.71	0.010	0.033	6234.01	0.04	0.08	7832.89	0.02	0.06
6993.13	0.014	0.015	6244.46	0.07	0.17	7862.43	0.07	0.23
7224.03	0.013	0.007	6308.80	–	0.14	8026.25	0.04	0.03
8620.41	0.11	0.029	6317.86	–	0.07			
9577.00	–	~0.095	6425.66	0.03	0.07			
			6456.01	0.07	0.06			

Notes. ^(a) DIB central wavelengths from [Hobbs et al. \(2008\)](#) are with respect to K I. Central wavelength for 8620 DIB from [Munari et al. \(2008\)](#) and for 9577 DIB from [Herbig \(1995\)](#). For DIB non-detections the upper limits could not be derived (“–”).

where $\tau(\lambda)$ and $P(\lambda)$ are the continuum optical depth and the continuum polarisation. $\Delta\tau(\lambda)$ (i.e. $\ln(I_c/I_\lambda)$) is the observed change in optical depth across the line profile and $f_P(\lambda)$ is the polarisation efficiency factor across the line profile. $P(\lambda)$ can be computed from Eq. (1) if $P_{\max}$ and K are known. Therefore, with $\tau_\lambda = A_\lambda/1.086$ we can write the previous as

$$\Delta P(\lambda) = f_P(\lambda) \Delta\tau(\lambda) 1.086 P(\lambda)/A(\lambda) \quad (3)$$

where $f_P(\lambda)$ is the unknown polarisation efficiency parameter and $A(\lambda)$ is the extinction curve which depends on A_V and R_V (see e.g. [Cardelli et al. 1989](#); [O’Donnell 1994](#); [Fitzpatrick 1999](#); [Fitzpatrick & Massa 2007](#)). [Voshchinnikov & Das \(2008\)](#) derive $P(\lambda)/A(\lambda) \propto \lambda^\epsilon$, with $\epsilon = 1.41$ for HD 197770 (from 1000 Å to 1 μm), which matches with the power-law index of 1.4 computed for $P(\lambda)/A(\lambda)$ using Eq. (3) and the $R_V = 2.8$ extinction curve (see [Fitzpatrick & Massa 2007](#)). Applying the same procedure to HD 194279 gives $\epsilon \sim 1.32$ in the optical. Thus, the expected polarisation signal ΔP for a DIB depends on its wavelength. For example, compared to the red DIBs near 5500 Å (e.g. V band) the near-infrared DIBs (~7500 Å) are then predicted, for the same f_P , to give rise to a polarisation signal a factor ~1.5 stronger. For grain related polarisation the efficiency is predicted to be a constant for a given transition, thus the polarisation profile would have the same shape as the optical depth profile. [Martin & Angel \(1974\)](#) estimated for grain related carrier that $f_P \approx 1.0$ –1.8. We can also write: $f_P = \frac{\Delta P}{\Delta\tau_\lambda} \frac{\tau}{P}$.

However, we have no a priori information on the polarisability efficiencies of the DIB carriers, which would scale with the amount of material (i.e. column density) and could be much higher for carriers of the weak DIBs. The measured equivalent width (or central depth) is proportional to both column density N and oscillator strength f . For example, a weak DIB could be a result of a small oscillator strength, f (or small abundance), of the particular electronic transition, while the polarisation efficiency, f_P could be large relative to the line strength (or abundance). Or vice versa, a strong DIB could be due to a carrier with a large oscillator strength but with a small polarisation efficiency; i.e. the ratio f_P/f is not known for any of the DIB carrier candidates. Thus, we stress the importance of investigating both strong and weak bands for polarisation features.

Intensity and polarisation spectra of CH, CH⁺, CN, C₂, C₃, Na I, Ca I, Ca II, K I are shown in Figs. B.1 and B.2. Measurement of interstellar line strengths are given in Table B.1. The polarisation spectra of the (di)atomic absorption lines do not reveal any line polarisation.

To exploit the large spectral range and high quality of the spectra obtained it is possible to explore the line polarisation of not just the strongest DIBs but also those of moderate and weak strength, at both optical and near-infrared wavelengths. First we focus on the strongest known diffuse bands. From the survey of HD 183143 by [Herbig \(1995\)](#) we select all DIBs with central depths larger than 7%, however we omit some of the very broad bands (i.e. at 5778, 6177, and 6533 Å) as these are too difficult to detect in our echelle spectra. This cut-off is somewhat arbitrary but at least ensures that all well-studied DIBs are included (Table 2). Figures 1 and 2 show the observed line polarisation computed as follows:

$$\Delta P = \sqrt{\frac{1}{3}[(P_m + Q/I)^2 + (P_m + U/I)^2 + (P_m + V/I)^2]} - P_m \quad (4)$$

for the 15 strong DIBs at $\lambda\lambda 4428, 5705, 5780, 5797, 6196, 6203, 6269, 6283, 6379, 6613, 6660, 6993, 7224, 8621$, and 9577 toward HD 197770 and HD 194279. Individual V , Q and U spectra are shown in Figs C.1 and C.2.

Complementary to previous polarisation studies and to account for the possible strong alignment/polarisation signal of weak(er) DIB carriers (see previous section) we include also a selection of these in this work. We select sixteen DIBs of moderate and weak strength confirmed by several previous DIB surveys ([Jenniskens & Désert 1994](#); [Tuairisg et al. 2000](#); [Hobbs et al. 2009](#)). In addition, we selected also 13 near-infrared DIBs for analysis. In our selection we avoided DIBs that might be contaminated by either stellar or telluric lines, strong adjacent DIBs, or those that are too weak to be detected in the most reddened sightline towards HD 194279. See Table 2 and Figs. A.1 to A.4 for the list of DIBs and the corresponding intensity and polarisation ΔP spectra. Again, the corresponding Q , U , and V spectra are shown in Figs. C.3 to C.6.

Fig. 1. Total normalized intensity I and polarisation ΔP spectra of 15 strongest DIBs toward HD 197770. The ΔP spectra are scaled 10 $\times$ and displaced vertically for display. DIB rest wavelengths from Hobbs et al. (2008), corrected for radial velocity of K I, are shown as dashed vertical lines.

Fig. 2. Total normalized intensity I and polarisation ΔP spectra of 15 strongest DIBs toward HD 194279. The ΔP spectra are scaled 10 $\times$ and displaced vertically for display. DIB rest wavelengths from Hobbs et al. (2008), corrected for radial velocity of K I, are shown as dashed vertical lines.

3.2. Environmental conditions of the sightlines

In this section we review the physical conditions of the interstellar medium towards HD 197770 and HD 194279.

3.2.1. HD 197770

HD 197770 is an evolved, spectroscopic, eclipsing binary with two B2 stars (e.g. Clayton 1996). It lies on the edge of a large

area of molecular clouds and star formation in the Cygnus region, at the edge of Cyg OB7 and Cep OB2 (Gordon et al. 1998), at a distance of ~ 440 pc (Dobashi et al. 1994).

The interstellar medium in front of HD 197770 has also been studied extensively, in particular because it is currently one of two sightlines (the other being HD 147933-4) for which a polarisation feature (at level of 0.4% and efficiency $\Delta p / \Delta \tau = 0.0017$) corresponding to the 2175 Å UV bump has been detected

(Clayton et al. 1992; Somerville et al. 1994; Kim & Martin 1994; Martin et al. 1995; Wolff et al. 1997) as predicted by Draine (1989). Clayton et al. (1992); Wolff et al. (1997) assigned the polarisation of the UV bump to small aligned graphite disks, while other authors favour silicate grains (Kim & Martin 1994). The sightline shows a high continuum linear polarisation of almost 4% in the optical (see also Table 1).

The dust grains in this interstellar cloud are aligned, where $P_{\max}/\tau_V$ is 0.026, which is close to optimal alignment (0.032; Serkowski et al. 1975).

From optical spectroscopy we observe strong CH and CN absorption lines, but a weak CH⁺ line. Column densities of Ca I, Fe I, CH, CH⁺, CN and C₂ for the main velocity component at -3 km s^{-1} have been reported by Hanson et al. (1994) and are consistent with our values (Table B.1). The atomic and molecular line profiles show a single strong narrow component at a heliocentric velocity of -17 km s^{-1} . The CN and CH lines are narrow, with *FWHM* of ~ 0.07 to $0.09 \text{ \AA}$, while CH⁺, Ca I, and Ca II are a little broader, with *FWHM* of ~ 0.16 to $0.20 \text{ \AA}$.

Both the 5797 and 5780 Å DIBs are weak, per unit reddening, with respect to the Galactic average. However, the strength ratio of 5797 over 5780 is relatively high ($W(5797)/W(5780) = 0.58$), typical of a translucent (ζ -type) diffuse cloud. This is also indicated by the low CH⁺/CH ratio of 0.11 (lower than 0.5 is typical for a quiescent medium, no shocks). Previously, Wolff et al. (1993) invoked quiescence for this sightline to efficiently align the UV bump grains.

In summary, this sightline probes a *single dense quiescent interstellar cloud*.

3.2.2. HD 194279

HD 194279 (Cyg OB9) is associated to the NGC 6910 cluster which has a distance between 1.7–2.1 kpc (Underhill 1956; Trumpler 1930). McCall et al. (2002) report a spectroscopic parallax distance of 1.1 kpc, while Gyul’Budagyan et al. (1994) derived a distance of 740 pc for the Cyg OB9 association. The sightline toward HD 194279 shows a more complex structure with components at -16.1 , -9 and -2.6 km s^{-1} . It shows multiple strong components in both CH and CH⁺ whereas the CN line is very weak. The CH⁺, CH and CN lines have similar *FWHM* of 0.20, 0.22, and $0.17 \text{ \AA}$, respectively. To explain high CH⁺ abundances in the diffuse ISM both shocks and a strong UV field are invoked in cloud models (Spaans 1996). The C₂ transitions are detected, originating from the coldest component only. It thus appears that HD 194279 probes several diffuse clouds which in superposition cause significant reddening.

The dust grains in this interstellar cloud are not efficiently aligned as illustrated by a very low value for $P_{\max}/\tau_V = 0.008$, which is far from optimal alignment.

The $W(5797)/W(5780)$ ratio in this line-of-sight is 0.32, which is close to the average Galactic value of ~ 0.26 (Vos et al., in prep.). Also the $W(\text{CH}^+)/W(\text{CH})$ ratio, of 1.36, is intermediate, a sign of a slight enhanced production of CH⁺ in this sightline. From the line profiles of the atomic and molecular lines it is clear that this line-of-sight probes multiple diffuse cloud components, for which the entire sightline gives average Galactic values for DIB strengths and molecular line ratios.

In summary, this sightline probes an *average of diffuse interstellar clouds*.

3.3. DIB polarisation limits

Previously, Cox et al. (2007a) provided linear polarisation 2σ detection limits per *FWHM* of 0.04–0.14% for HD 197770 for the $\lambda\lambda 5780$, 5797, 6196, 6283, 6379, and 6283 DIBs. Corresponding polarisation detection limits per Å (PDLA) are 0.06 to 0.19%. Or alternatively, $f_{\max}$ are 0.31, 0.44, 0.45, 0.18, 0.47, and 0.68 resp. Circular line polarisation for these DIBs gave 2σ (per $0.1 \text{ \AA}$) limits of 1.0–2.5% for HD 197770.

In this work we derive new upper limits on the polarisation efficiency f_P (i.e. similar to $f_{\max}$ in Cox et al. 2007a) for 45 strong, weak and near-infrared DIBs (see Table 2). $f_P(\lambda_{\text{peak}})$ is computed from Eq. (3) adopting $P(\lambda)/A(\lambda) = P_{\max}/A_V$, $\Delta P(\lambda) = 2\sigma_{\Delta P}$ (the standard deviation per pixel on ΔP), and $\Delta\tau_{\text{peak}} = \ln(1/(1 - \text{centraldepth}))$. The new constraints on the level of line polarisation are given in Table 2.

In this work we investigate two different types of interstellar clouds that show evidence of interstellar polarisation due to dust grains. In neither of these two environments do we detect polarisation significant signals, with detection limits on f_P of about 0.02 for the strongest DIBs toward HD 197770. For example, for the 8621 DIB we derive $f_P < 0.11$. The strength of this DIB is known to be strongly correlated to the amount of interstellar dust and has been thus suggested to be related more directly to grains than other DIBs (Wallerstein et al. 2007; Munari et al. 2008). The theoretical f_P for a classical grain carrier is a factor 10 higher than this new limit. The 9577 DIB, attributed to the C₆₀⁺ fullerene, also does not reveal line polarisation, with $f_P < 0.1$ (towards HD 194279). For the weak DIBs we obtain upper limits on f_P of ~ 0.02 to ~ 0.2 towards both sightlines. Again these limits suggest a non-grain related carrier. The near-infrared DIBs suggest f_P values between 0.02 to 0.10 for these bands (for the HD 197770 sightline; factor of two less stringent for the HD 194279 sightline). These low levels for the polarisation efficiency exclude typical “classical” dust grains as carriers, and thus strongly reinforce the idea that all DIB carriers are gas-phase molecules. In particular, polycyclic aromatic hydrocarbons (PAHs) and fullerenes are proposed as candidates for the DIB carriers (See recent assessment by Salama et al. 1996). The presence of these large molecules in the ISM has been confirmed from their mid-infrared emission features in various astrophysical environments (Salama 2008; Tielens 2008).

Recently, Sironi & Draine (2009) investigated the polarised infrared emission by PAHs upon anisotropic irradiation by UV photons and the subsequent alignment of the angular momentum and the principal axis of the PAH molecule. Conservation of the angular momentum and partial memory retention of UV photon source direction leads to partial polarisation (of not more than few %) of the infrared emission. This is an extension of the notion put forward by Léger (1988) that infrared emission features resulting from in-plane and out-of-plane modes should have orthogonal polarization directions. Additionally, Tolkachev and collaborators have shown from theoretical and experimental work that large molecules can show polarisation signatures in fluorescent emission excitation lines (e.g. Tolkachev 1994; Tolkachev & Blokhin 2009). In the case of PAHs, it would be interesting to quantitatively assess the polarization efficiency that is associated with the electronic absorption of these molecules and their ions when aligned in an external magnetic field and compare this value to the values of f_P derived from the observations. Recent advances in quantum chemical calculations of PAH polarizability (Marques et al. 2007) should help make it possible to quantify the polarization that is associated with a population

of PAH molecules or ions. Studies are ongoing in this direction and will be reported elsewhere.

4. Conclusion

The results presented in this study show that:

1. The Polarisation Detection Limit per Å in % (i.e. $PDLA = 2\sigma_{\Delta P}(\text{per pixel})/\sqrt{1./\text{pixelsize}(\text{\AA})} \times 100.0$) for the DIBs in the red and green spectral range (i.e. between 5700 and 7000 Å) have typical values between 0.004 and 0.010%, an order of magnitude improvement with respect to previous limits.
2. None of the 45 DIBs measured and analysed in this work show unambiguous evidence for line polarisation of the DIBs.
3. For the strongest DIBs towards HD 197770 the obtained upper limits on the polarisation efficiency factor are at least a factor 10 smaller (and in some cases more than 300 times smaller) than those expected for classical grains.
4. For all 45 DIBs the derived f_P is significantly less than 1, the lower limit predicted for carriers related to classical grains.

In summary, none of the diffuse bands of varying strengths and widths exhibit a polarised absorption spectrum, neither for the dense cloud, with efficient grain alignment, in the line-of-sight towards HD 197770, nor the diffuse clouds averaged along in the line-of-sight toward HD 194279. Thus, we postulate it is likely that none of the DIB carriers measured in our study are directly related to grain-like carriers. This includes the 8621 Å DIB for which a very good correlation with dust reddening has been observed. Also, if DIB carriers are indeed related to large gas-phase molecules, it appears that these do indeed not align efficiently in the diffuse ISM and/or have a low polarisation efficiency.

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Appendix A: Polarisation (ΔP) and total intensity I spectra for weak and near-infrared DIBs

Fig. A.1. ΔP (top) and normalised intensity (bottom) spectra of 16 weak DIBs toward HD 197770. The ΔP spectra are scaled 10x and displaced vertically for display.

Fig. A.2. ΔP (top) and normalised intensity (bottom) spectra of 16 weak DIBs toward HD 194279. The ΔP spectra are scaled 10 $\times$ and displaced vertically for display.

Fig. A.3. ΔP (top) and normalised intensity (bottom) spectra of 13 near-infrared DIBs toward HD 197770. The ΔP spectra are scaled 10x and displaced vertically for display.

Fig. A.4. ΔP (top) and normalised intensity (bottom) spectra of 13 near-infrared DIBs toward HD 194279. The ΔP spectra are scaled 10 $\times$ and displaced vertically for display.

Appendix B: Atomic, molecular and DIB line profiles, equivalent widths and central depths

Fig. B.1. Normalised I and P ($5\times$) spectra of atomic and molecular transitions as a function of heliocentric velocity (in km s^{-1}) toward HD 197770. From top left to bottom right Na I D, K I, CH, CH+, Ca I, Ca II, and CN. The dashed vertical lines indicate the interstellar radial velocity.

Fig. B.2. Normalised I and P ($5\times$) spectra of atomic and molecular transitions as a function of heliocentric velocity (in km s^{-1}) toward HD 194279. From top left to bottom right Na I D, K I, CH, CH+, Ca I, Ca II, and CN. The dashed vertical lines indicate the interstellar radial velocity.

Fig. B.3. C₂ (2–0) Phillips band toward both sightlines. Line strengths are given in Table B.1. For HD 194279 the strong Hydrogen Paschen line at 8750.47 Å has been removed (no C₂ lines detectable), and furthermore, the 8764.4 Å DIB is clearly present in this line-of-sight.

Table B.1. Equivalent widths (mÅ) for interstellar atomic and diatomic lines observed for the two lines-of-sight.

	HD 197770	HD 194279 ^a
CN (3874.6 Å)	20.0 ± 0.3	4.9 ± 0.2
CN (3873.8 Å)	4.1 ± 0.2	–
Fe I (3719.9+3859.9)	3.7 ± 0.8, 2.8 ± 0.5	9.6 ± 4, 8.2 ± 1
Ca II K	186 ± 1	720 ± 1.5
Ca II H	96.5 ± 0.5	397 ± 3
CH ⁺ 4232.3 Å	3.0 ± 0.3	46.8 ± 0.3
Ca I	8.0 ± 0.3	11.9 ± 0.7
CH (4300.3 Å)	26.6 ± 0.1	34.4 ± 0.3
K I (4044 Å)	1.0 ± 0.1	1.0
K I (4047 Å)	0.6 ± 0.2	1.0
C ₂ (2,0):		
R(0)	0.9 ± 0.1	1.5 ± 0.1
R(2)	2.1 ± 0.1	2.2 ± 0.1
R(4)	1.8 ± 0.1	–
R(6)	1.6 ± 0.1	–
R(8)	1.1 ± 0.1	–
P(4)	0.9 ± 0.1	0.55
P(6)	0.9 ± 0.1	–
P(8)	0.9 ± 0.1	0.95 ± 0.15
P(10)	0.7 ± 0.1	–
Q(2)	2.3 ± 0.1	3.6 ± 0.1
Q(4)	2.8 ± 0.1	2.2 ± 0.1
Q(6)	2.8 ± 0.1	2.4 ± 0.1
Q(8)	1.7 ± 0.1	1.3
Q(10)	1.2 ± 0.1	0.97 ± 0.1

Notes. ^(a) Non-detections are indicated by “–”, and indicate either the line is too weak or contaminated by stellar lines or instrumental artifacts.

Table B.2. Equivalent widths (in mÅ) for DIBs in Table 2.

DIB	HD 197770	HD 194279	Equivalent widths			DIB	HD 197770	HD 194279
			DIB	HD 197770	HD 194279			
4428.19	–	–	4979.61	4.5 ± 0.5	8 ± 0.5	7045.89	2 ± 1	9 ± 1
5705.08	27 ± 1	95 ± 3	5844.92	2.5 ± 0.5	6 ± 0.5	7061.05	4 ± 1	14 ± 1
5780.48	141 ± 2	472 ± 2	5849.81	27 ± 1	66 ± 4	7062.68	2 ± 1	12 ± 1
5797.06	82 ± 1	149 ± 3	5973.81	3.5 ± 0.5	3 ± 0.5	7069.55	8 ± 1	31 ± 2
6195.98	27.1 ± 0.5	55 ± 2	5975.75	6 ± 0.5	–	7077.86	–	7 ± 1
6203.05	64 ± 2	222 ± 2	6027.68	–	18 ± 1	7119.71	22 ± 1	34 ± 1
6269.85	40 ± 2	128 ± 3	6065.28	5 ± 0.5	9.5 ± 0.5	7375.87	(1 ± 1)	8 ± 1
6283.84	–	–	6089.85	12.5 ± 0.5	18 ± 0.5	7385.89	2 ± 1	7 ± 1
6379.32	74 ± 2	192 ± 2	6113.18	17 ± 0.5	18 ± 0.5	7405.71	2.5 ± 1	4 ± 1
6613.62	125 ± 1	208 ± 2	6139.98	7.5 ± 0.5	9 ± 0.5	7559.41	2 ± 1	9 ± 1
6660.71	28 ± 1	31 ± 2	6234.01	9 ± 0.5	16 ± 0.5	7832.89	8.5 ± 1	22 ± 1
6993.13	33 ± 1	95 ± 2	6244.46	9 ± 1	–	7862.43	(1.5 ± 1)	(4 ± 1)
7224.03	51 ± 2	246 ± 3	6308.80	–	(31 ± 3)	8026.25	(2 ± 1)	32 ± 1
8620.41	28 ± 1	247 ± 3	6317.86	–	(83 ± 5)			
9577.00	–	(~ 120)	6425.66	10 ± 1	15 ± 1			
			6456.01	17 ± 1	29 ± 2			

Table B.3. Central depths cd (with respect to the normalized continuum) for DIBs in Table 2.

DIB	HD 197770	HD 194279	Central depths			DIB	HD 197770	HD 194279
			DIB	HD 197770	HD 194279			
4428.19	~ 0.03	~ 0.08	4979.61	0.005	0.010	7045.89	0.005	0.013
5705.08	0.011	0.036	5844.92	0.006	0.013	7061.05	0.013	0.028
5780.48	0.071	0.210	5849.81	0.034	0.072	7062.68	0.005	0.021
5797.06	0.101	0.168	5973.81	0.007	0.008	7069.55	0.012	0.020
6195.98	0.069	0.090	5975.75	0.019	–	7077.86	–	0.012
6203.05	0.033	0.085	6027.68	–	0.011	7119.71	0.0145	0.025
6269.85	0.033	0.078	6065.28	0.011	0.013	7375.87	(0.0025)	0.013
6283.84	0.030	0.23	6089.85	0.026	0.028	7385.89	0.005	0.012
6379.32	0.121	0.183	6113.18	0.025	0.022	7405.71	0.004	0.008
6613.62	0.135	0.179	6139.98	0.014	0.014	7559.41	0.004	0.014
6660.71	0.049	0.045	6234.01	0.016	0.022	7832.89	0.014	0.025
6993.13	0.042	0.101	6244.46	0.009	0.009	7862.43	0.005	0.006
7224.03	0.049	0.199	6308.80	–	0.013	8026.25	0.007	0.04
8620.41	0.007	0.057	6317.86	–	0.023			
9577.00	–	~ 0.03	6425.66	0.017	0.020			
			6456.01	0.008	0.025			

Appendix C: Stokes I , U , Q , and V spectra for the selected DIBs

Fig. C.1. Stokes V , U , Q and I spectra (top to bottom) of 12 strong DIBs toward HD 197770. The Q , U , V spectra are scaled $5\times$ and displaced vertically for display.

Fig. C.2. Stokes V , U , Q and I spectra (top to bottom) of 12 strong DIBs toward HD 194279. The Q , U , V spectra are scaled $5\times$ and displaced vertically for display.

Fig. C.3. Stokes V , U , Q and I spectra (top to bottom) of 16 weak DIBs toward HD 197770. The Q , U , V spectra are scaled $5\times$ and displaced vertically for display.

Fig. C.4. Stokes V, U, Q and I spectra (top to bottom) of 16 weak DIBs toward HD 194279. The Q, U, V spectra are scaled 5× and displaced vertically for display.

Fig. C.5. Stokes V, U, Q and I spectra (top to bottom) of 13 near-infrared DIBs toward HD 197770. The Q, U, V spectra are scaled 5× and displaced vertically for display.

Fig. C.6. Stokes V, U, Q and I spectra (*top to bottom*) of 13 near-infrared DIBs toward HD 194279. The Q, U, V spectra are scaled 5× and displaced vertically for display.