Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

Mon. Not. R. Astron. Soc. **401,** 1308–1314 (2010) doi:10.1111/j.1365-2966.2009.15729.x

Doppler splitting in diffuse interstellar bands

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Accepted 2009 September 16. Received 2009 September 16; in original form 2009 July 23

ABSTRACT

We demonstrate evident Doppler splitting in the profiles of many narrow diffuse interstellar bands (DIBs). Their components are compared with those of atomic and molecular lines of interstellar origin. It is shown that it is likely that the species that shares both wavelength shifts and strength ratios of the Doppler components seen in the DIB profiles is the CH radical. Because of this profile resemblance, it is recommended that CH lines can be used to shift spectra to the rest velocity frame for interstellar features, especially to determine the DIB rest wavelengths on the basis of the CH line at 4300.3132 Å in the spectrum of HD 147889. Our results strongly support a molecular origin of diffuse bands.

Key words: ISM: molecules.

1 INTRODUCTION

The phenomenon of Doppler splitting inside profiles of interstellar lines was recognized many years ago (see e.g. Beals 1938). The discovery demonstrated that the interstellar medium is not homogeneous but consists of distinct clouds. However, the first spectral features observed as originating in a number of clouds along the same line of sight were Ca II and later Na I lines, which are intrinsically very narrow. A small difference between the radial velocities of two clouds situated along the same sightline can easily be detected. The question whether a similar Doppler splitting is observable in profiles of diffuse interstellar bands (DIBs) remained open much longer, as their intrinsic widths are much greater than those of Na I and Ca II and a possible splitting is much more difficult to detect.

It was only in 1982 that Herbig and Soderblom demonstrated convincingly that Doppler splitting occurred inside the 6196 DIB – commonly considered to be the narrowest strong DIB. The profile proved to be partially resolved, and the components were found to mimic the radial velocities found in interstellar gas lines (especially in KI ones). Herbig and Soderblom also demonstrated that in cases of broader features one can expect a broadening rather than an evident splitting. This result was based on the spectrum of the heavily reddened star HD 183143, often used to search for as yet unknown interstellar features because of its high reddening, rarely observed in an object this bright.

Westerlund & Krełowski (1988) tried to re-construct complex DIB profiles (i.e. those determined in spectra in which one can trace several Doppler components in Na I lines). The method involved an extraction of an 'intrinsic' profile of a given DIB (i.e. observed in some object for which interstellar lines are not split) and the calculation of the shape of a complex one using these intrinsic components, shifted in accordance with those of the observed Na I interstellar lines. In this investigation it was postulated for the first time that strength ratios of DIB components may not mimic those of the Na I lines: some of the Na I Doppler components may not have their counterparts in DIB profiles.

The CH molecule in translucent clouds (known since the publications of McKellar 1940a,b) is closely related to molecular hydrogen (H_2, as shown by Mattila 1986; Weselak et al. 2004), and also to OH (Weselak et al. 2009b). Column densities of the CH molecules are well correlated with intensities of the narrow 5797 DIB (Weselak et al. 2008b).

Many investigations of possible correlations between the strengths of various DIBs have been made, resulting in the concept of 'families' proposed by Krełowski & Walker (1987). In the case of DIBs at 6196 and 6614 Å the correlation based on intensities is tight (Moutou et al. 1999). Two additional DIBs at 5809 and 6660 Å have been also found to be strongly correlated with the 6196 and 6614 DIBs (Weselak et al. 2001). However, mutual correlations between DIBs are always quite tight, and the correlation analysis hardly leads to certain conclusions.

Doppler splitting is expected to be evident only in the spectra of distant and fairly heavily reddened stars, where the velocities of clouds along the sightline span a very broad range. We emphasize that such spectra (i.e. of reasonably high resolution) of heavily reddened, and consequently faint, objects have been very scarce until now. It thus seems important to collect and analyse such spectra in order to check whether one can find Doppler structures inside DIB profiles similar to those observed in identified interstellar features. It is also important to investigate possible spatial correlation between

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Table 1. Observed stars. Columns headings are: Star – HD or BD number and instrument (b, BOES; f, FEROS; h, HARPS); Galactic coordinates (l, b); V, V magnitude; $E(B-V)$, colour excess; Spec/L, spectral and luminosity class; $v\,\sin i$, rotational velocity (km s^{-1}); exposure time (in minutes); and divisor HD number. The telluric line divisors are listed at the bottom.

Star/Obs	l	b	V	$E(B-V)$	Spec/L	$v\sin i$	Exp. time	Divisor
13256 b	132.59	−0.64	8.68	1.35	B1Ia	30	100	218045
147889 h	352.86	−17.04	7.90	1.02	B2III/IV	100	10	116658
168112 f	18.44	+1.62	8.55	1.00	O5.5	120	20	116658
183143 b	53.24	+0.63	6.87	1.28	B7Ia	70	60	120315
219287 b	110.81	−1.18	8.96	1.27	B0Ia	70	120	218045
+58 2580 b	111.51	−1.90	10.01	1.05	B0.5V	45	120	218045
+59 2735 b	112.87	−1.42	9.88	1.39	B0Ib	70	120	218045
116658 h/f			0.97	0.00	B1V	130		
120315 b			1.86	0.00	B3V	160		
218045 b			2.48	0.00	B9.5III	155		

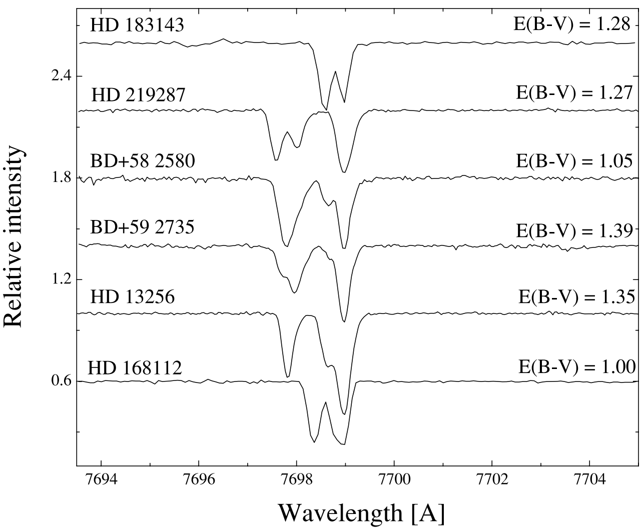

Figure 1. The profiles of the KI 7698-Å interstellar line observed in our targets. Note that the Doppler splitting seen towards HD 183143 (the Herbig and Soderblom target) is 3–4 times smaller.

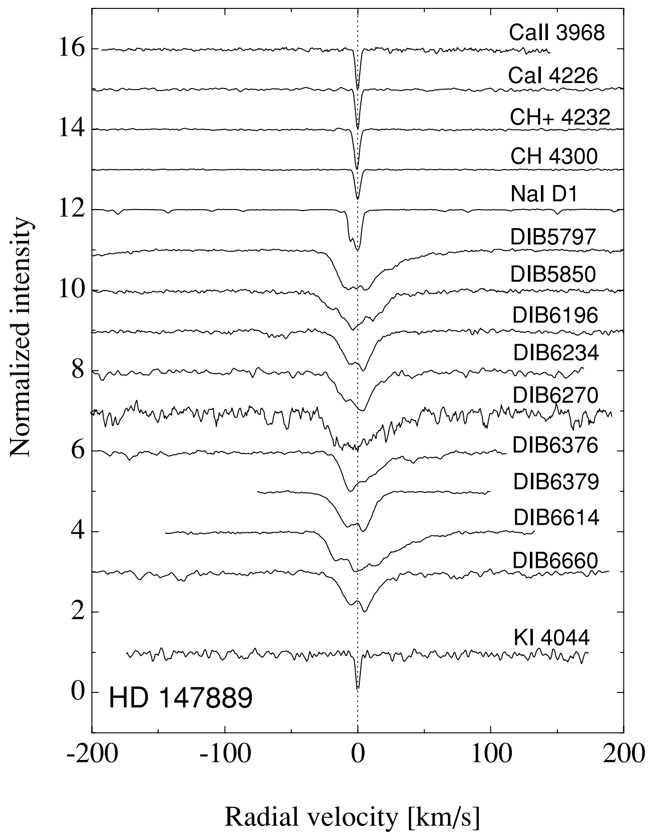

Figure 2. Selected interstellar features observed in the spectrum of HD 147889. Note the narrow interstellar atomic lines. The diffuse band at 6993 Å is not presented as it was not recorded by the HARPS instrument. We present the interstellar KI line at 4044.143 Å instead of at 7699 Å.

Table 2. Atomic and molecular data. References: 1, Morton (1991); 2, Carrington & Ramsay (1982); 3, Gredel, van Dishoeck & Black (1993).

Atom/molecule	Position [Å]	Reference
Ca II K	3933.663	1
Ca II H	3968.468	1
K I	4044.143	1
Ca I	4226.728	1
CH^+	4232.548	2
CH	4300.3132	3
Na I D_1	5895.9243	1
K I	7698.974	1

DIB carriers and well-known interstellar lines originating in atoms or simple molecules. This process may shed some light on the physical parameters of the media that allow the formation and/or preservation of DIB carriers in our Galaxy.

2 OBSERVATIONS

Our observations of heavily reddened stars using the BOES echelle spectrograph attached to the 1.8-m telescope of the Bohyunsan Observatory in Korea (b) resulted in several good-quality spectra. A detailed description of the spectrograph is given at http://www.boao.re.kr/BOES/BOESppt3.files/frame.htm. The spectrograph has three observational modes, providing resolving powers of 30 000, 45 000 and 90 000. Our spectra were obtained at the lowest power, allowing observation of relatively faint, heavily reddened objects. In all cases the spectrograph allows us to

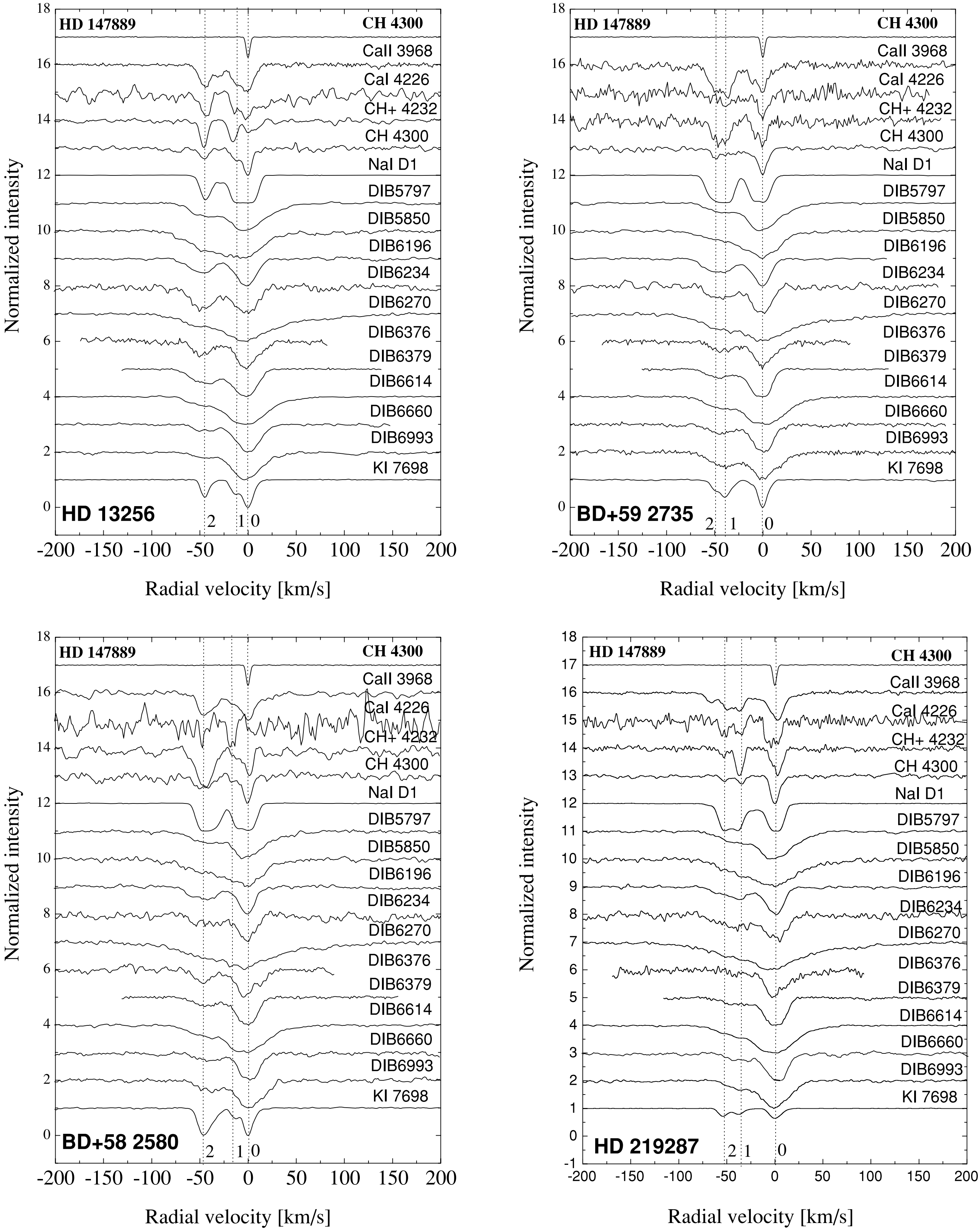

Figure 3. Selected interstellar features observed in the spectrum of HD 13256, BD +59 2735, BD +58 2580 and HD 219287. Note that the DIB components are apparently not related to those of CH^+ and calcium but they are closely related to CH. At the top of each panel we present the CH line at 4300.3132 Å in the spectrum of HD 147889.

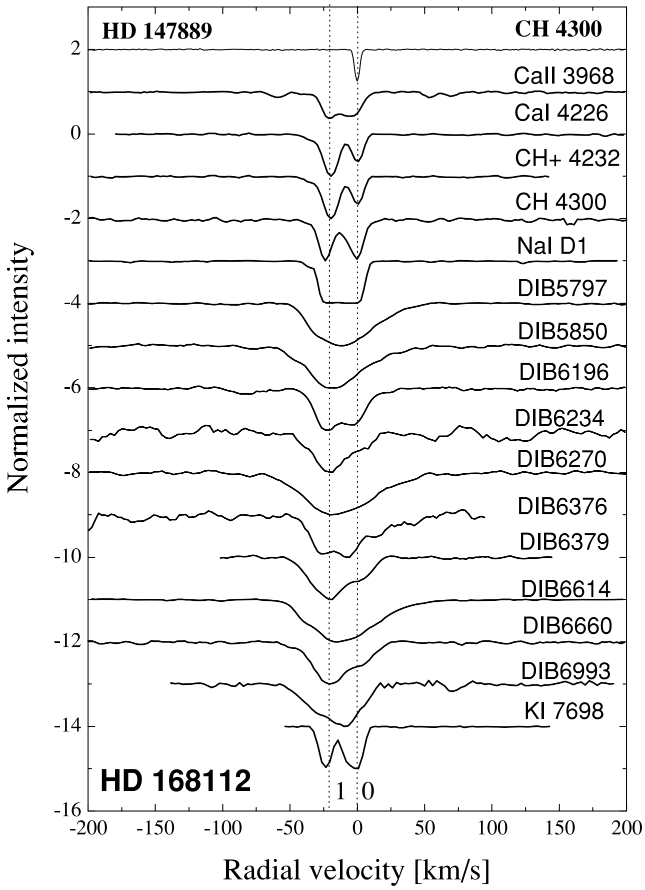

Figure 4. As Fig. 3, but for HD 168112. Some strongly shifted components of atomic lines do not have their counterparts in DIB profiles (Ca II component at −58 km s^{-1}).

record the whole spectral range from ∼3500 to ∼10 000 Å divided into 75–76 spectral orders. The spectrum of HD 168112 was recorded with the FEROS spectrograph (f), fed with the 2.2-m ESO telescope (see http://www.ls.eso.org/lasilla/sciops/2p2/E2p2M/FEROS/). The resolution of these spectra is constant ($R = 48\,000$). This instrument can record the whole available spectral range (∼3700–9200 Å, divided into 37 orders) in a single exposure. The selected stars are listed in Table 1, along with their basic parameters.

We selected the $R = 30\,000$ spectra of five objects for which the differences between the radial velocities of the clouds situated along their sightlines are especially large. Fig. 1 shows the profiles of the interstellar KI 7698-Å line with the characteristic Doppler components. This profile observed towards HD183143 – the target of Herbig and Soderblom – is shown for comparison. It is thus demonstrated that our set of targets is characterized by the Doppler splitting being 3–4 times larger than that seen by Herbig & Soderblom (1982). The selected objects thus offer a very good chance to see the Doppler components resolved to a degree mainly depending on the resolving power in the case of DIBs that are not intrinsically as narrow as 6196 – the DIB selected by Herbig & Soderblom (1982).

In addition to the above-mentioned KI line, our echelle spectra contain several quite strong but narrow diffuse bands (5797, 5850, 6196, 6234, 6270, 6376, 6379, 6614, 6660 and 6993) as well as the atomic lines of Na I and Ca II and the molecular features of CH and CH$^+$ presented in Table 2. We moved the spectra to the rest velocity frame after determining the radial velocities from the profiles of the KI line. We used the strong, extremely red-shifted components as the reference ones. We have not analysed the possible Doppler structure of broader DIBs, such as 5780 or 6284. The intrinsic widths of these features make the search for Doppler components useless. The largest observed splitting (in the KI line) is about 50 km s^{-1}, and the FWHM of 5780 is about 110 km s^{-1}. We have not even tried to analyse profiles of very broad diffuse bands, such as 4430. For reference, we added in Fig. 2 the spectrum of one heavily reddened object, HD 147889, for which Doppler splitting is not seen for either the atomic or the molecular lines. The profiles of DIBs seen in this spectrum are thus intrinsic; that is, they depend only on the physical parameters of the single, obscuring cloud. The spectrum of HD 147889 was obtained using the HARPS instrument (h), fed with the 3.6-m ESO telescope in Chile (see http://www.ls.eso.org/lasilla/sciops/3p6/harps/). This spectrograph allows us to cover the range ∼3800 – ∼6900 Å with a resolution of $R = 115.000$. As the KI line at 7698 Å is not covered by the HARPS instrument range we present another KI line, at 4044.143 Å, in Fig. 2. The HARPS range does not cover the 6993 DIB either.

3 RESULTS AND DISCUSSION

The selected spectral features, atomic, molecular and diffuse, are depicted in Figs 3 and 4. In these figures the features are compared on the radial velocity scale in the following order (from bottom to top): KI (7698 Å), 6993 Å, 6660 Å, 6614 Å, 6379 Å, 6376 Å, 6270 Å, 6234 Å, 6196 Å, 5850 Å, 5797 Å, Na I (D$_1$), CH (4300 Å), CH$^+$ (4232 Å), CaI (4226 Å) and Ca II (H). Only the radial velocity scale allows a direct comparison of the profiles, which makes it possible to check whether the components at a given velocity are in all features seen along a given line of sight. At the top of each plot of Figs 3 and 4 we present the narrow CH line at 4300.3132 Å in the spectrum of HD 147889. The spectrum of each star presented in Figs 3 and 4 was shifted based on the position of the CH A–X (0, 0) band at 4300.3132 Å in each case. Positions of the CH components observed towards heavily reddened stars are presented in Table 3. To obtain the positions of each Gaussian component we performed an analysis as in Weselak et al. (2009a).

The Doppler splitting, clearly visible in Fig. 1, is also observed in most of the DIB profiles. Such an evident Doppler splitting of DIBs is demonstrated here for the first time. We can trace the splitting even

Table 3. Positions of CH components towards translucent clouds.

Component	HD 147889 [km s^{-1}]	HD 13256 [km s^{-1}]	HD 168112 [km s^{-1}]	HD 219287 [km s^{-1}]	BD+592735 [km s^{-1}]	BD+582580 [km s^{-1}]
0	0 ± 1	0 ± 1	0 ± 2	0 ± 1	0 ± 2	0 ± 1
1		−13 ± 2	−24 ± 3	−34 ± 3	−39 ± 3	−17 ± 2
2		−46 ± 2		−52 ± 2	−48 ± 2	−46 ± 2

Table 4. Comparison of DIB positions in the recent literature. References: (1) Jenniskens & Désert (1994); (2) Galazutdinov et al. (2000); (3) Tuairisg et al. (2000); (4) Weselak, Schmidt & Krełowski (2000); (5) Hobbs et al. (2008); (6) this work in the spectrum of HD 147889, with FWHM in the last column. The symbol (:) denotes an uncertain position. Remarks on errors in shift on the basis of interstellar lines of: *a*, Ca II, Na I, KI, CH and CH^+ (many objects); *b*, Ca II K (many objects); *c*, Ca II, CaI, CH and CH^+ towards BD+63 1964; *d*, Na D_1 and D_2 (many objects); *e*, KI line at 7699 Å towards HD 204827 (error in the case of narrower DIBs); *f*, CH line at 4300.3132 Å towards HD 147889.

Survey	(1) [Å]	(2) [Å]	(3) [Å]	(4) [Å]	(5) [Å]	(6) [Å]	(6) [Å]
Error	0.22^a	0.03^b	0.05^c	0.10^d	0.03^e	0.01^f	FWHM
DIB5797	5797.11	5796.96	5797.08	5796.97	5797.06	5796.973 ± 0.017	0.80±0.03
DIB5850	5849.78	5849.80	5849.81	5849.85	5849.81	5849.817 ± 0.011	0.65±0.05
DIB6196	6196.19	6195.96	6195.99	6196.05	6195.98	6195.963 ± 0.012	0.49±0.02
DIB6234	6234.27	6234.03	6234.01	6234.05	6234.01	6234.008 ± 0.013	0.51±0.02
DIB6270	6270.06	6269.75	blend	6269.86	6269.85	6269.692 ± 0.019	0.62±0.03
DIB6376	6376.07	6375.95	blend	6376.10	6376.08	6375.998 ± 0.018	0.60±0.04
DIB6379	6379.27	6379.29	6379.22	6379.46:	6379.32	6379.242 ± 0.005	0.57±0.03
DIB6614	6613.72	6613.56	6613.63	6613.52	6613.62	6613.567 ± 0.020	1.07±0.06
DIB6660	6660.64	6660.64	6660.62	6660.70	6660.71	6660.655 ± 0.007	0.52±0.02
DIB6993	6993.18	6993.18	–	–	6993.13	–	–

in broader profiles; it is shown for the first time inside the strong 5797 and 6614 DIBs. Only the profiles of 5850 and 6270 DIBs proved to be too broad to allow a demonstration of separate Doppler components in their profiles. We emphasize that any improvement in instrumental resolution will not be able to resolve such profiles; they are intrinsically too broad.

Figs 3 and 4 show clearly that the strength ratios of DIB Doppler components do not mimic those of atomic and/or molecular lines. An analysis of our four plots leads to the conclusion that DIB profiles resemble most closely that of the CH 4300-Å line. Other atomic and molecular features usually either show some additional components or their strength ratios are completely different from those of DIBs. It is thus possible that DIB carriers are spatially correlated with the CH radical. This conclusion is of importance: the CH features can be used to determine radial velocities of interstellar clouds, and exact wavelengths for the DIBs can be read directly from the measurements. Such shifted spectra should allow precise measurements of the rest wavelengths of numerous diffuse bands. However, the sample of objects in which the Doppler splitting can be traced in DIB profiles remains very small, and thus the conclusions inferred cannot be considered as absolutely certain. It is difficult to fit single-cloud (intrinsic) DIB profiles to the Doppler-split, complex ones. In each case the procedure involves too many free parameters.

Quite strong Doppler components, as seen in profiles of the lines of ionized species, have no counterparts in the DIB profiles (CH^+ in the case of HD 13256 in Fig. 3). Apparently the carriers of observed, narrow DIBs (with FWHMs in the range 20–40 km s^{-1}, except for the broader 6614 DIB, which has a FWHM equal to 50 km s^{-1}) are not abundant in environments in which the ionization level is high. This fact supports a molecular origin of diffuse bands.

It is interesting that the profiles of certain narrow DIBs are practically identical when compared on the scale of radial velocities. Among the subset of 6993, 6660, 6379, 6234 and 6196 DIBs the differences between profiles are practically negligible. It seems that the carriers of these DIBs are mutually spatially correlated but also that their physical structure is very probably similar.

The problem of precise DIB positions in spectra of translucent clouds still exists in the literature (see Hobbs et al. 2008; Galazutdinov, Lo Curto & Krełowski 2008). Typically, differences do not exceed 0.5 Å in the case of strong DIBs. In Table 4 we present a comparison of DIB positions presented in this work with those taken from the literature. We also present typical errors in position in the case of each DIB survey, along with the method applied to the position measurement in each case; that is, we note the atomic and/or molecular lines that were used to shift spectra to obtain the exact position of the DIBs for each survey. It is difficult to ascertain why differences of up to 0.5 Å in position in the case of some strong DIBs arise between surveys. We note, however, that profiles of strong DIBs are in many cases asymmetrical (Westerlund & Krełowski 1988) and it is difficult to find the exact DIB position.

We also obtained precise DIB positions in the spectrum of HD 147889 shifted on the basis of the CH line at 4300.3132 Å. To perform this analysis we used the centre of gravity in the case of each observed band. In the last column of Table 4 we present the FWHM of each DIB as measured in the spectrum of HD 147889.

We observe that many other evidently narrow DIBs seem to show a similar Doppler structure in our spectra. Their profiles are very shallow, which makes their individual presentation difficult. We thus compared the averaged profile of 11 such features, situated at wavelengths (in Å) of 4964, 5494, 5513, 5910, 5923, 6089, 6140, 6426, 6445, 6689 and 7367, with that of the above-mentioned five stronger DIBs. The result is shown in Fig. 5. It is striking that the two averaged profiles are identical. It seems that all the conclusions concerning the relatively strong, narrow (FWHM ∼ 20–30 km s^{-1}) DIBs apply also to most weaker diffuse bands. This result is consistent with those of Weselak et al. (2008b). Apparently, the CH is better spatially correlated with narrow DIBs such as 5797.

The Doppler splitting in DIBs is the result of several clouds observed towards a target star. This phenomenon is very well observed in the case of Ca II K and H lines at 3933 and 3968 Å. It is also possible to obtain the distance to a target star based on measured equivalent widths of Ca II lines (see Megier et al. 2005). In Table 5 we present our results on distance (in parsecs) based on the formulae $d = 2.78\ W(K) + 95$ and $d = 4.58\ W(H) + 102$, where W(K) and W(H) are the equivalent widths of Ca II K and H lines at 3933 and 3968 Å, respectively. In each case the result was averaged to obtain the distance based on K and H lines of Ca II. We compared our results with those presented in the literature and found this method to give results consistent with those of Munari & Zwitter (1997) in

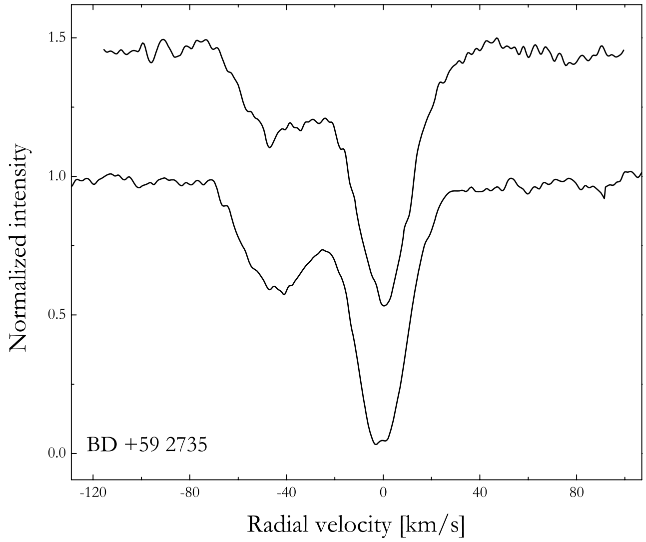

Figure 5. The identical averaged DIB profiles observed towards BD +59 2735. The lower profile involves the 6993, 6660, 6379, 6234 and 6196 relatively strong DIBs, whereas the upper one involves 4964, 5494, 5513, 5910, 5923, 6089, 6140, 6426, 6445, 6689 and 7367. Note the rms in normalized intensity with amplitude close to 0.1 in each case.

the case of HD 13256, 219287 and BD+58 2580, +59 2735, and of Chentsov (2004) in the case of HD 183143. It was also possible to obtain the distance to cloud clumps, present in the spectra of stars as blue-shifted components of the Ca II lines (see Figs 3 and 4). A typical distance to a clump is of the order of 1 kpc in the case of three stars, HD 219287, BD+58 2580, +59 2735, which are close together in Galactic coordinates (see Table 1). The distance to a cloud clump in the case of HD 13256 is close to 0.7 kpc. Based on the distances in Table 5 we conclude that cloud clumps observed towards HD 13256, 219287, BD+58 2580 and 59 2735 are located in the local arm of our Galaxy (Becker 1963; Humpreys 1976). However, spectra of higher quality are necessary to solve this problem completely.

We conclude that the phenomenon of Doppler splitting, resembling that observed in the spectral features originating in simple molecular species, is apparently a common property of a vast majority of observed diffuse interstellar bands which are thus very probably carried by some species of CH. Most of these species carry rather narrow features of strikingly similar widths. They do not populate clouds with relatively high ionization levels. This confirms the conclusions of Megier et al. (2005). According to that paper, the interstellar medium is fairly uniformly filled with ionized species (Ca II), whereas neutral gases, molecules and dust grains very probably occupy small, dense clumps. Additional observations of heavily reddened objects in our Galaxy may shed some light on the phenomenon presented in this paper. The number of cases in which the Doppler splitting of DIBs is observed does not allow us to perform statistical analyses.

ACKNOWLEDGMENTS

The authors acknowledge financial support from the Polish State Committee for Scientific Research (grant N203 012 32/1550).

Table 5. Results on distances towards stars based on Ca II lines and towards cloud clumps based on a blue-shifted blend of Ca II components. We present HD/BD number, equivalent widths of Ca II K and H lines (W(Ca II_K), W(Ca II_H)), distances calculated on the basis of Ca II K and H lines and distance to the star (d). In column (d^{Lit}) we compare our results on distance with those of (*a*) Munari & Zwitter (1997) and (*b*) Chentsov (2004). In the last column we present results on distance to the cloud clumps based on a blue-shifted blend of Ca II components (d(B)).

Star	W(Ca II_K) [mÅ]	W(Ca II_H) [mÅ]	d(Ca II_K) [pc]	d(Ca II_H) [pc]	d [pc]	d^{Lit} [kpc]	W(B Ca II_K) [mÅ]	W(B Ca II_H) [mÅ]	d(B Ca II_K) [pc]	d(B Ca II_H) [pc]	d(B) [pc]
HD 13256	611 ± 12	419 ± 13	1794 ± 128	2021 ± 162	1907 ± 206	1.7[a]	204 ± 15	138 ± 14	662 ± 137	734 ± 166	698 ± 215
HD 168112	479 ± 13	305 ± 16	1427 ± 131	1499 ± 175	1463 ± 219	–					
HD 183143	695 ± 23	400 ± 14	2027 ± 159	1934 ± 166	1981 ± 230	2.0[b]					
HD 219287	712 ± 21	504 ± 26	2074 ± 153	2410 ± 221	2242 ± 269	2.4[a]	390 ± 18	240 ± 12	1179 ± 145	1201 ± 157	1190 ± 214
BD+58 2580	602 ± 19	371 ± 17	1769 ± 148	1801 ± 180	1785 ± 233	1.4[a]	304 ± 17	221 ± 16	940 ± 142	1114 ± 175	1027 ± 226
BD+59 2735	613 ± 25	351 ± 16	1799 ± 165	1710 ± 175	1754 ± 240	1.9[a]	361 ± 24	234 ± 18	1099 ± 162	1174 ± 184	1136 ± 245

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