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Diffuse interstellar bands in low E_{B-V} objects

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ABSTRACT
We analyze spectra of slightly reddened, early type stars in which the major diffuse interstellar bands 5780 and 5797 are either strong or weak in relation to E_{B-V}. It is demonstrated that among the low E_{B-V} objects one can find stars obscured by "sigma" as well as "zeta" type clouds. The profiles of the diffuse bands seem not to be dependent on total opacities of interstellar clouds. We discuss also the physical conditions leading to the formation of the diffuse band carriers in low opacity interstellar clouds; the carriers are apparently formed in the media in which one can observe complex velocity fields.

Key words: interstellar extinction – diffuse bands

1 INTRODUCTION

The diffuse interstellar bands (DIBs) are in most of cases observed in spectra of intermediate to high reddening stars i.e. in the objects bright enough to be observed in a reasonable resolution and signal–to–noise. In the well–known paper Herbig (1975) postulated the existence of some DIB residua even in spectra of non–reddened stars. The growth of the S/N ratio available in the spectra acquired during recent years allowed to demonstrate that it is not the case (Herbig 1993). However, the behaviour of the DIBs towards slightly reddened stars is apparently a very interesting problem. Among such objects we should be most likely to find stars seen through only single, individual clouds. Towards more reddened objects we always see several Doppler shifted components in the profiles of interstellar atomic lines: the result of the absorptions taking place in several clouds along each line of sight.

During the 75 years old history of the investigations of the DIBs they have been traditionally correlated with a colour excess, usually E_{B-V}. The observed relations are evident i.e. every DIB correlates with E_{B-V} quite tightly, however there is no doubt that the observed scatter, seen in such relations, is not of instrumental origin but reflects different physical parameters of individual clouds. It is thus interesting to check what is a possible range of a DIB – E_{B-V} ratio in very tiny clouds.

However, in the spectra of slightly reddened stars the interstellar features must be expected to be very weak. Thus a very high S/N ratio is necessary to trace such bands in these spectra. The problem was addressed until now by Kumar, Federman & Vanden Bout (1982), Federman, Kumar & Vanden Bout (1984) and by Kumar (1986). They have discovered DIBs in stars of $E_{B-V} < 0.1$. Their strengths were related to the column densities of the molecular hydrogen.

Since that time it became generally accepted that DIBs originate in some complex interstellar molecules. It is of importance to check whether the correlation between the H_2 molecules and the DIB carriers, found by Kumar and his co–workers holds for clouds more opaque than $E_{B-V} = 0.1$. It is also of importance to check whether the tiny clouds share their spectral properties with those more opaque i.e. whether the DIB strength ratios are also variable among them.

Another interesting problem is that of DIB intrinsic profiles i.e. those free of the Doppler splitting. As mentioned above we are very likely to find such objects among the slightly reddened ones. To address this problem it is necessary to have spectra of very high S/N and also of rather high resolution. It seems also important to compare DIB profiles and intensities observed in spectra from different instruments.

2 THE OBSERVATIONAL DATA

The project, described below is based on the four sets of observational data. Only the slightly reddened stars have

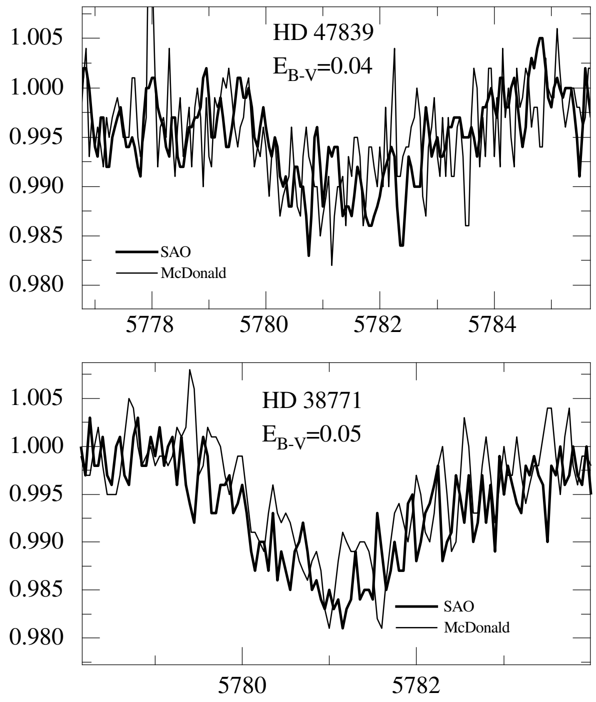


Figure 1. The comparison of the 5780 DIB profiles in SAO and McDonald spectra. The spectra are not shifted to the rest wavelength scale.

been selected for this purpose. In many cases the same object has been observed using more than one instrument. It is of importance to compare data from different sources to make sure that the weak features traced in our spectra are real and that their intensities can be measured with a reasonable accuracy.

The main set of data considered here are the spectra acquired at the Russian Special Astrophysical Observatory (SAO), with the aid of the new coude echelle spectrometer fed with the SAO 1m telescope (Musaev 1993). With the Wright Instruments CCD 1242x1152 matrix (pixel size 22.5μm x 22.5μm) the spectrometer covers in a single exposure the range ∼3500 Å – ∼10100 Å with the resolution R=40,000. The relatively small size telescope is proper for this kind of project as we are interested in acquiring spectra of very bright stars. Our reduction of the echelle spectra was made using the DECH code (Galazutdinov 1992). This program allows flatfield division, bias/background subtraction, one–dimensional spectrum extraction from the 2–dimensional images, correction for the diffuse light, spectrum addition, excision of cosmic ray features, etc. The DECH code also allows location of a fiducial continuum, measurements of the line equivalent widths, line positions and shifts, etc. The spectral range, covered in every exposure, contains strong and well–identified atomic interstellar lines: CaII, CaI, NaI and KI. This allowed us to determine precisely the radial velocities of the intervening interstellar clouds with a high precision.

The other spectra have been acquired by one of us (JK) at the McDonald Observatory in Texas. The set of collected spectra contains data for ∼80 objects – OB stars, more or less reddened. All the spectra, covering the wavelength range from ∼5600Å to ∼7000Å with the resolution of 60,000, have been acquired with the Sandiford echelle spectrograph installed at the Cassegrain focus of the 2.1 m telescope. For the data acquiring and reducing techniques see Krełowski & Sneden (1993). The set of the McDonald spectra contains the data for many reddened objects as well as for a few objects considered as unreddened standards which are in fact very slightly reddened and which are to be considered in this paper.

Table 1. Basic stellar data

HD	Sp/L	V	B-V	E(B-V)	Observatory
5394	B0IVe	2.39	-0.10	0.16	CFHT, PdM
14633	O8.5V	7.47	-0.21	0.07	CFHT
20336	B2.5V	4.80	-0.11	0.08	SAO
21428	B3V	4.67	-0.09	0.09	SAO
22928	B5III	2.99	-0.11	0.04	SAO
24760	B0.5V	2.88	-0.17	0.07	SAO, McD
38771	B0Iab	2.06	-0.17	0.05	SAO, McD
47839	O7Ve	4.66	-0.25	0.04	SAO, McD
87015	B2.5V	5.66	-0.19	0.00	McD
87901	B7V	1.35	-0.11	0.02	PdM
89353	B9Ib-II	5.34	0.24	0.24	McD
91316	B1Ib	3.85	-0.14	0.05	SAO
132742	B9.5V	4.92	0.00	0.04	PdM
138485	B3V	5.50	-0.14	0.04	SAO
149438	B0V	2.82	-0.25	0.01	McD
164353	B5Ib	3.97	0.02	0.10	SAO
164852	B3IV	5.27	-0.08	0.10	SAO
166182	B2IV	4.35	-0.15	0.06	SAO, PdM
214680	O9V	4.90	-0.22	0.06	CFHT

Other observations have been performed with the aid of the 2.03 m. Bernard Lyot Telescope of the Pic du Midi Observatory in July 1995, February 1996 and in April 1997. The instrument used is the echelle spectrograph MUSICOS, fed by an optical fiber. It allows to cover in two exposures the whole visible range (3850-9100 Å). The resolution of these spectra is ∼32,000 (Baudrand & Böhm, 1992). They allow also to observe all possible atomic lines, but two exposures in two different spectral regions are required. One can find in this set of data also a few stars of very low E_{B-V}.

Several segments of the spectra of OB stars have also been acquired with the Canada-France-Hawaii Telescope (CFHT) in September 1989. The telescope fed the coudé spectrograph which formed the spectra in the silicon diode array detector system. The system yields an effective (two pixel) spectral resolution of 0.14 Å (about 7.5 km·s^{-1}) at 5780 Å. The procedure for data acquisition and reduction using this system has already been described by Snow & Seab (1991). The spectra cover the yellow spectral range (5760–5905 Å). In this range we observe two prominent diffuse bands near 5780 and 5797 Å as well as the two strong lines of the neutral sodium D_1 and D_2.

3 RESULTS

Table 1 lists the object considered in this paper together with their spectral types, luminosity classes and the colour

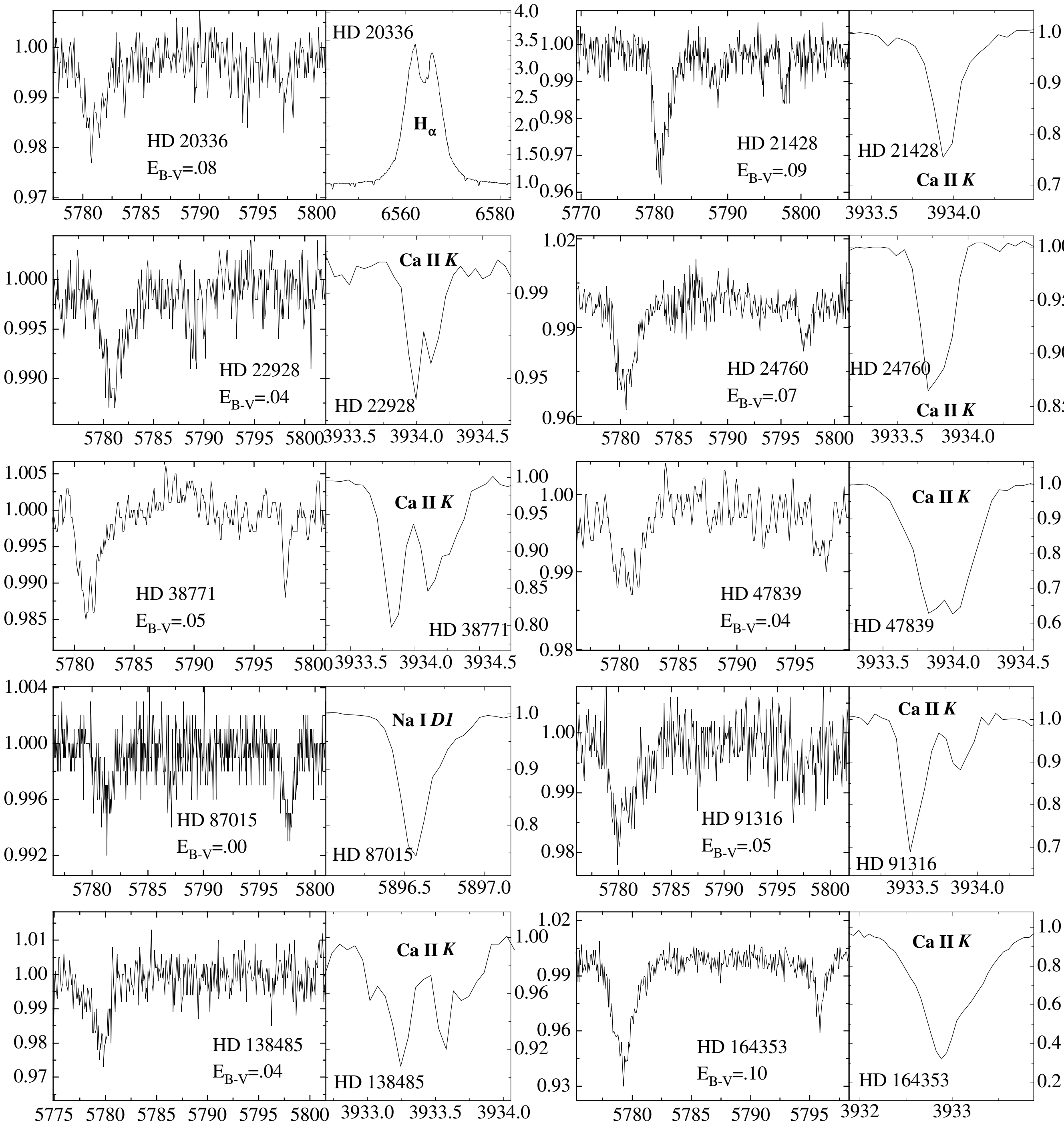
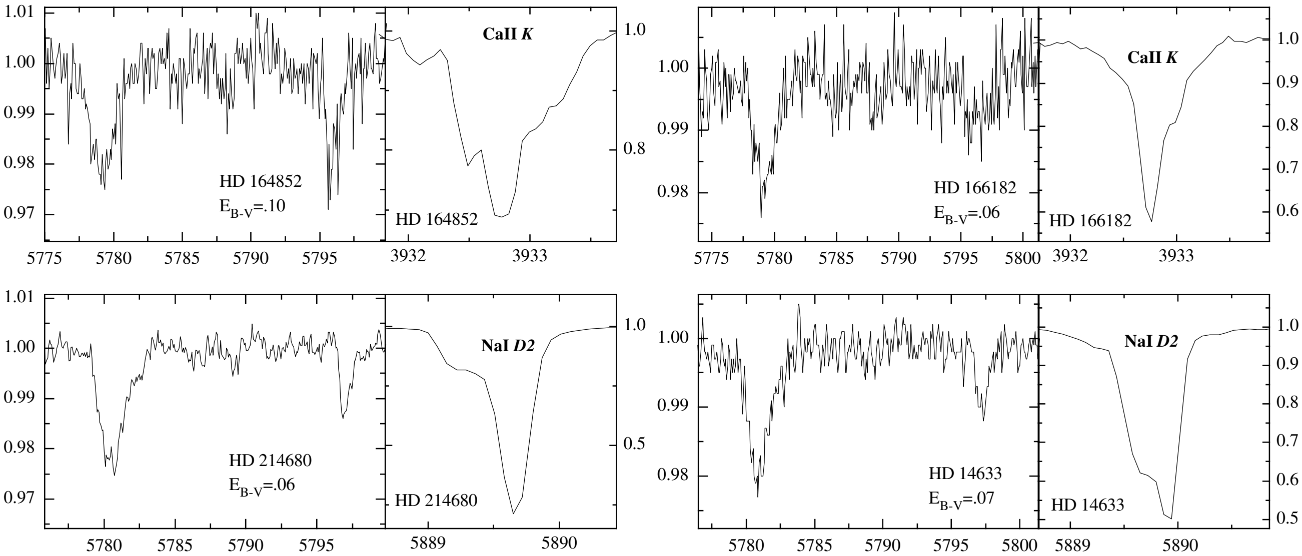


Figure 2. The diffuse interstellar bands 5780 and 5797 observed in our program star spectra. Note the varying strength ratio of the two features. The wavelengths are not shifted to the rest wavelength scale.*(continued on next page)*

excess. The observed colours have been taken from the SIMBAD database; the intrinsic colours – from the paper of Papaj, Krełowski and Wegner (1993). Most of the determined E_{B-V}'s are so small that they are not much larger from typical errors of this parameter which are very likely to be of 0.03 among the early type stars which are not easy objects to be properly classified, especially while rotating very fast. Thus we can hardly expect a tight correlation between E_{B-V} and the DIB strength.

While dealing with very weak spectral features it is of basic importance to make sure they are not of instrumental origin (Krełowski & Sneden 1993). Fortunately some of the targets listed in Table 1 have been observed both using the SAO and McDonald telescopes and spectrometers. Fig. 1 compares the 5780 DIB profiles acquired using both instru-



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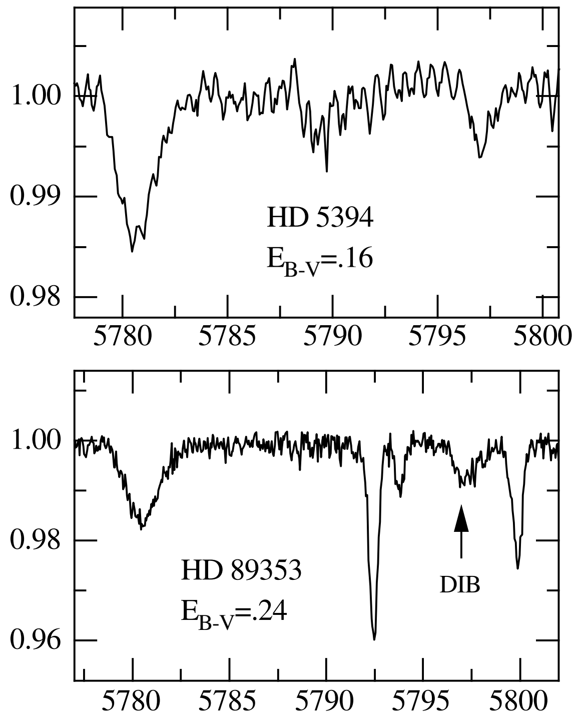

Figure 3. The diffuse interstellar bands observed in the two targets in which their intensities are very low in relation to E_{B-V}.

ments. It is evident that the profiles are identical and thus the presence of DIBs in spectra of slightly reddened stars is proved beyond a doubt.

Fig. 2 presents the spectral range containing the two major DIBs: 5780 and 5797 in all our targets. We attempted at adding the profiles of the CaII K line as far as possible as these lines are apparently very sensitive to the presence of inter– or circumstellar velocity fields. In fact the Doppler split which could hardly be expected in cases of such small E_{B-V}'s is clearly seen in our spectra. However, the spectral range of the CaII H and K lines is available only in SAO and Pic du Midi spectra. In the McDonald or CFHT stuff we could analyse only interstellar NaI D_1 and D_2 lines. In the spectrum of HD 20336 one can hardly observe the Doppler splitting in either CaII or NaI lines but the presence of the outflow of the matter is proved by the profiles of the H_α line which proves the presence of a circumstellar disk. In the spectrum of HD 21428 the CaII lines do not show two components but the assymmetry of their profiles suggests the presence of different velocities inside the matter situated along the sightline towards this object. The same is observed in the NaI profiles in the spectrum of HD 87015.

It is interesting whether the major DIBs, observed in spectra of slightly reddened stars, show the same phenomenon as that observed in moderately reddened objects by Krełowski & Walker (1987) and Krełowski & Westerlund (1988) – the variable strength ratio. In Fig. 2 it is clearly demonstrated that the 5780/5797 intensity ratio is different while observed in spectra of HD 22928 or HD 138485 from one side and HD 164852 or HD 87015 from the other one. The first two are, in accordance to the classification proposed by Krełowski & Sneden (1995), "sigma" type objects (i.e. characterized by a high 5780/5797 strength ratio) whereas the others are apparently "zeta" type ones with the relatively strong 5797 DIB. Several intermediate cases can be observed as well.

Among our objects DIBs are very strong (in relation to E_{B-V}) in spectra of HD 164353, HD 21428 and HD 24760. This result can be considered as very convincing as we compared the spectra from SAO, Pic du Midi and CFHT in HD 164353 and from SAO and McDonald in HD 24760. It is interesting to mention that the atomic NaI lines are also relatively strong towards these targets i.e. very strong in comparison to E_{B-V} as well as DIBs. It is, however, ill–advised to try to build any correlation between the strengths of the DIBs depicted in Fig. 2 and E_{B-V} as the latter is usually

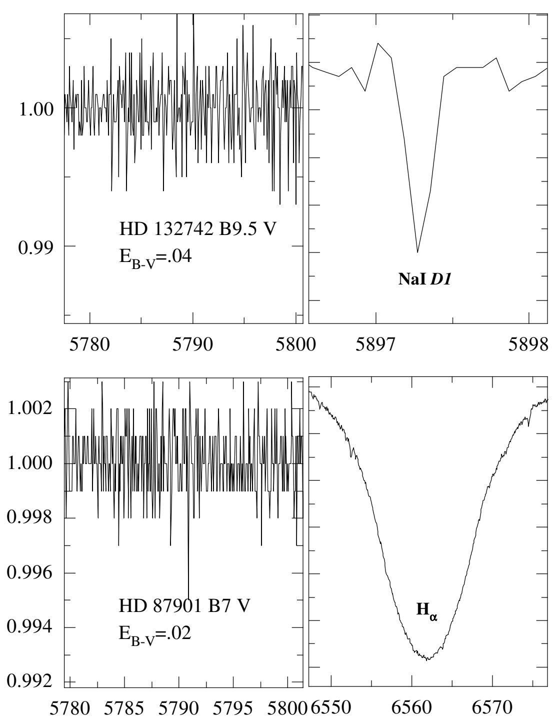

Figure 4. The lack diffuse interstellar bands in the spectra of slightly reddened late B type dwarfs.

not greater than the expected error of this parameter resulting from incorrect Sp/L determination.

In contrast to what is observed in HD 164353, HD 21428 and HD 24760 the same DIBs are very weak in spectra of HD 89353 and HD 5394 (Fig. 3). Both these objects are relatively heavily reddened (Table 1) but the DIBs appear much weaker than in other objects of the Table 1 which are characterized by E_{B-V}'s smaller by a factor 2 – 3. The latter supports the idea that the DIBs do not originate in dust grains as their intensities are completely not related to the dust absorption and scattering.

All the objects shown in Fig. 2 are very hot stars, usually hotter than B3. One may expect strong mass outflows in vicinities of such stars propelled by the strong flux of far–UV photons. The observed profiles of interstellar lines are most probably created in this way as it is dificult to accept that many clouds can be observed along the sightlines towards very bright (=nearby) stars. For this reason we decide to search for DIBs in spectra of slightly reddend late B dwarfs where the far–UV flux is substantially reduced. As shown in Fig. 4 spectra of such stars, despite a similar reddening, are free of diffuse interstellar bands.

The profiles of DIBs observed in slightly reddened stars are compared to those seen in the "standard" object HD 144217 (Westerlund & Krełowski 1988). It is evident that the shape of the profiles in the slightly reddened objects is the same as in HD 144217 (Fig 5). The latter result is consistent with that of Westerlund & Krełowski (1989) for the slightly reddened star HD 157246 in which only the 5780 DIB was found as e.g. in our HD 22928.

Table 2 contains the measurements of the DIB intensities together with those of the H_2 column densities taken from Savage et al. (1977). It is evident that the ratios of the DIB strengths to E_{B-V} differ by a factor of ∼5. However, the data collected in Table 2 do not support the suggestion of Kumar (1986) that DIB intensities are related to H_2 column densities.

Table 2. Measurements

HD	E_{B-V}	lg($N(H_2)$)	5780	5797
5394	0.16	<17.51	29.0	10.0
14633	0.07	<19.11	45.0	12.5
20336	0.08	—	41.0	5.0
21428	0.09	—	88.0	16.5
22928	0.04	19.30	31.0	0.0
24760	0.07	19.53	68.0	18.0
38771	0.05	15.68	27.0	6.5
47839	0.04	15.55	34.0	13.5
87015	0.00	—	8.5	6.8
87901	0.02	<14.98	0.0	0.0
89353	0.24	—	35.0	12.0
91316	0.05	15.61	48.0	5.0
132742	0.04	—	0.0	0.0
138485	0.04	—	39.0	0.0
149438	0.01	14.50	22.0	0.0
164353	0.10	20.26	129.0	36.0
164852	0.10	—	51.0	26.0
166182	0.06	—	43.0	19.0
214680	0.06	19.22	51.0	11.0

4 DISCUSSION

Diffuse interstellar bands are observed in very tiny clouds of very low E_{B-V} i.e. in the environments which give almost no protection against the penetration of the energetic UV photons. However, even such tiny clouds can be clearly divided into "sigma" or "zeta" objects. DIBs behaving like narrow (5797) or broad (5780) can originate in clouds of very low E_{B-V}. This may be due to either the fact that DIB carriers are not destructed or ionized by the UV photons or due to their formation in such low E_{B-V} clouds.

It is interesting that among the slightly reddened stars we rarely observe the K CaII interstellar line profile without any Doppler splitting. Typically two components are seen; sometimes only the shape of profile may suggest the presence of two or more clouds along the sightline. This may be either due to the presence of two well–separated clouds i.e. separated by a substantial distance or to a velocity field inside a single cloud or a complex.

The latter possibility seems to be more likely. It is difficult to imagine several clouds along the sightline towards a nearby object like our targets. In such a case the Doppler splitting, observed in the CaII lines may reflect some macroscopic motions of the interstellar matter. Do they influence in a way the formation of the DIB carriers? The answer is seemingly – yes. In the quite environments of the late B stars DIBs are not observed while E_{B-V} is low as in cases of hotter stars. In cases of low E_{B-V} we observe DIBs only in spectra of very hot or very luminous stars. This may explain the "luminosity effect" already postulated in DIB intensities by Krełowski & Strobel (1981).

One possible scenario is the following: the DIB carriers

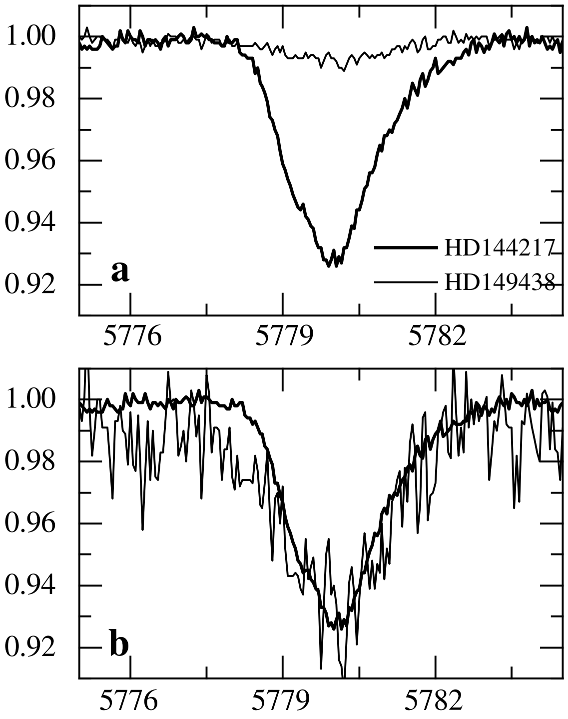

Figure 5. The identical profile of the 5780 DIB observed in the spectra of Hd 144217 ($E_{B-V} = 0.17$) and HD 149438 ($E_{B-V} = 0.01$). **a**) original spectra, **b**) both spectra normalized to the same central depth.

(complex molecules) are much more likely to be formed on grain surfaces than in the gas phase in the low density ISM clouds. However, the molecule formed inside a grain mantle may be optically inactive e.g. due to the existence of some chemical bonds between the carrier and the bulk grain material. In the presence of a fast gas flows (or shocks) the DIB carriers can be liberated from the grain mantles by the energetic collisions and give birth to the observed features.

The above scenario may also permit an interpretation of the lack of very weak DIBs towards certain targets. This may be due to the lack of any mechanism liberating the DIB carriers from grain surfaces. In such a case we can observe relatively high extinction but not the DIBs. The lack of any DIBs in the low E_{B-V} clouds may be due to the complete destruction of grain mantles either by collisions with gas atoms or by energetic photons. The most resistant grain cores can still produce some extinction even in such cases.

The another possibility is the DIB carriers formation under the influence of far–UV photons, typically emitted by very hot stars. However, the very hot stars of our sample are usually also characterized by complex profiles of interstellar atomic lines. The intense far–UV flux may be the “engine” of the flows of matter.

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