Diffuse Interstellar Bands

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Diffuse Interstellar Bands (DIBs) are the puzzling spectral features, originated in interstellar clouds, composed mostly of neutral hydrogen. The same clouds are the birthplaces of EXTINCTION and POLARIZATION. Both these phenomena are believed to be caused by interstellar dust grains, oriented in the second case. Despite of these one can observe ATOMIC ABSORPTION LINES as well as some bands, originating in SIMPLE RADICALS composed of the most abundant elements. DIBs are now commonly believed to be carried by some complex molecules, remaining unidentified since nearly 100 years. The paper summarizes the most important observational facts concerning DIBs and comments their relations to other interstellar features.

1 Introduction

There is little doubt if any that the interstellar extinction is caused by small dust particles. However, properties of solid state matter are much more difficult to be determined spectroscopically than those of the matter in gas state. This is why it is important to rely on spectral features originated from interstellar dust and gas. Generally the available observational data concerning the interstellar dust are limited to:

- extinction curve which is a graphic version of the extinction law; in general the extinction grows towards blue – only one maximum is observed near 2200 Å – followed by a minimum near 1800 Å. It is believed that one population of grains cannot account for the whole extinction curve: the visual/infrared segment must be caused by relatively large grains which may be only a source of grey extinction in ultraviolet. Thus the 2200 Å bump is usually related to small graphite grains while the final far–UV rise – to small silicate grains or to polycyclic aromatic hydrocarbons (PAHs)

- total–to–selective extinction ratio, i.e. the factor necessary to "translate" the extinction curve to absolute extinction values and to de-redden a target in practice. This value is heavily variable; the average or "canonical" one being 3.1 (Fitzpatrick & Massa, 2007)

- interstellar polarisation curve. The level of polarization is related to the wavelength of radiation passing a cloud. The polarisation is not an additive phenomenon, in contrast to e.g. extinction. Light beam may get unpolarised while crossing next clouds where grains are oriented in another fashion

- elemental depletions in the interstellar gas. It is well–known since 1973 that abundances of many heavy elements in the interstellar gas are severely below "cosmic abundance"; the only "sink" for these elements may be the interstellar

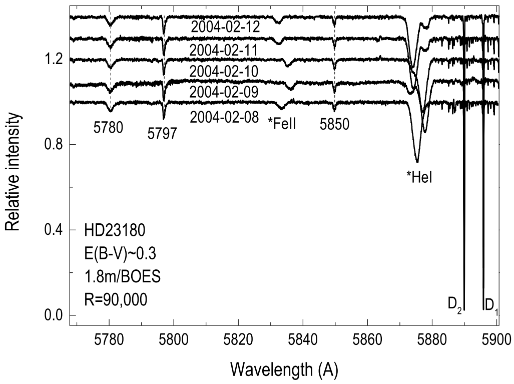

Fig. 1: Five spectra of the spectroscopic binary *o* Per, taken night by night and covering full orbital period. Note the variable radial velocities of stellar HeI and FeII lines as well as the stationarity of interstellar NaI doublet and three DIBs. The profiles of the latter are evidently broad.

dust. An analysis of the depletions may help to determine chemical composition of the dust.

As recently emphasized by Fitzpatrick & Massa (2007) it seems well-established that extinction curves may differ from object to object as well as polarization curves and total-to-selective extinction ratios.

It is certainly interesting to relate spectral features originated in dust with those, revealing interstellar gas (atomic lines, molecular features). Krelowski & Sneden (1994) proposed already a division of interstellar clouds into σ and ζ type objects. This, now commonly accepted division, is based on objects, seen through single clouds, i.e. where no Doppler splitting is observed in atomic or molecular features.

- σ type is characterized by relatively strong broad diffuse bands – DIBs – (5780 and 6284), weak narrow DIBs (5797, 6379) and weak molecular features (of CH, CN or CH^+). The extinction curve is characterized by “slim” 2200 bump and low far–UV extinction growth. Also a higher than “canonical” value (3.1) of the total–to–selective extinction ratio is very likely. We have demonstrated in fig. 7 of Krełowski & Strobel (2012) the extinction curves of HD99264 and HD147889 – the objects which seemingly belong to this class. Our extinction curves clearly resemble those published by Fitzpatrick & Massa (2007).

- ζ type objects demonstrate strong narrow DIBs and molecular features; also the R value (total–to–selective extinction ratio) is likely either canonical or even smaller. The extinction curve is typically characterized by broad and relatively weak 2200 bump and a sharp far–UV rise attributed to relatively small grains or even polycyclic aromatic hydrocarbons (PAHs). Figure 7 of Krełowski & Strobel (2012) confirms the result of Fitzpatrick & Massa (2007) for HD62542 and HD204827. The former object was described as characterized by very weak DIBs by Snow et al. (2002).

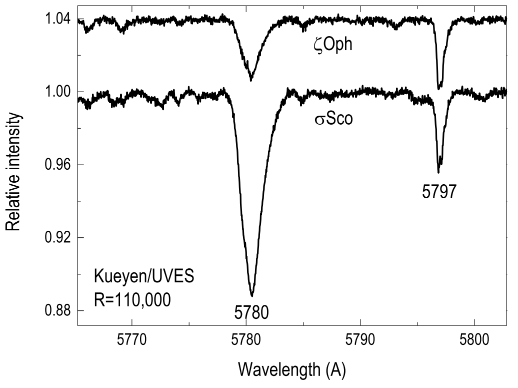

Fig. 2: The major DIBs: 5780 and 5797 in the spectra of two nearby, reddened stars shining through single clouds: HD147165 (σSco) and HD149757 (ζOph). Note the evidently different strength ratio.

ζ type objects are apparently the only ones where the strengths of CN features are comparable to those of CH (see e.g. Krełowski & Strobel (2012); Krełowski et al. (2019). In a vast majority of cases the CH bands are relatively much stronger, especially in σ type objects (Weselak et al. 2008). In ζ type objects the shape of extinction curve suggests a relatively high abundance of small grains.

The above motivate one to establish relations between the extinction curve shapes and relative strengths of interstellar molecular and diffuse bands. The former, as identified, may disclose to us physical parameters of the intervening clouds.

2 Diffuse bands

Diffuse bands have been discovered by Heger (1922) while analyzing early panchromatic photographic plates taken at the Lick Observatory in 1919. Thus they may be considered even as 100 years old. Naturally there are two questions:

- why interstellar?
- why diffuse?

The answers are given in the Fig. 1. The figure presents five spectra of the bright spectroscopic binary, *o* Per, of the period 4.5 days. The spectra have been acquired during five subsequent nights at The Korean National Observatory by G.A. Galazutdinov. The spectral range depicted contains in particular the very strong NaI doublet of interstellar origin, clearly seen to the right of the figure. The stellar lines of HeI and FeII evidently perform the Doppler "dance" due to the binarity of the object. The plot covers one full orbital period. It is evident that one can see at least three spectral features which are stationary, as well as NaI interstellar doublet. Stationarity is considered as a proof of interstellar origin. Moreover, the above mentioned features are evidently broader that the NaI lines, being much stronger. This leads to the name "diffuse".

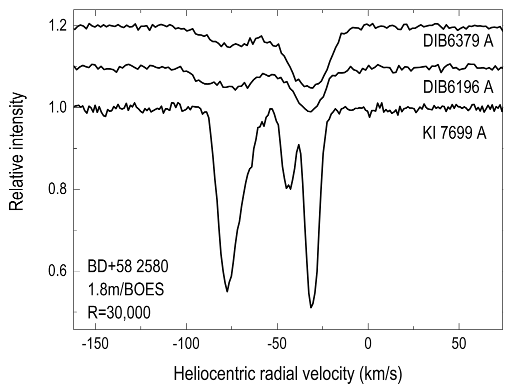

Fig. 3: The Doppler splitting in two narrow DIBs mimics that seen in the interstellar KI line.

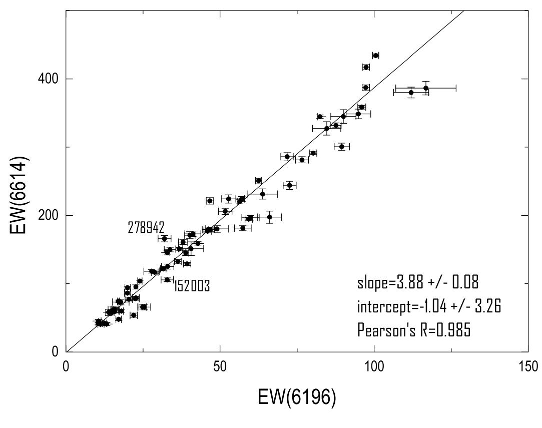

Fig. 4: The tight correlation between 6196 and 6614 diffuse bands. Note the two marked outliers.

Originally all known DIBs have been considered as sharing the same carrier. In fact, their number in 1969 was only 9. Herbig (1975), improving the S/N ratio of the plate recorded spectra, found 39 DIBs plus a few suspects. However, only in 1983, during the European Regional Meeting in Florence, Krełowski presented an evidence that the strength ratio of the major DIBs (shown in Fig. 1) is variable

The above presented result was published later by Krelowski & Walker (1987) and by Krelowski & Westerlund (1988). Many other objects which mimic either σSco or ζOph were found since that time. Strength ratios of many other DIBs were found variable as well.

Since DIBs are interstellar features, their profiles should be Doppler-splitted as those of interstellar atomic and molecular lines, i.e. their profiles may be formed

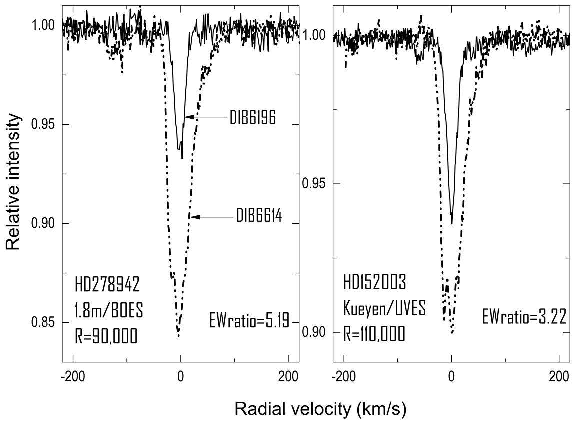

Fig. 5: The variable ration of 6196 and 6614 diffuse bands. These are the two marked in the former figure outliers.

in several clouds along a sightline. However, DIB profiles are broader than those of atomic/molecular lines, which makes a detection of the Doppler splitting much more difficult. This phenomenon was discovered first by Herbig & Soderblom (1982). Naturally they have used the narrowest known strong DIB: 6196. Currently other DIBs are known as Doppler-splitted in several objects (Weselak et al., 2008). One illustration is given in Fig. 3. It is evident that intensities of DIB Doppler components are not related to those of e.g. K I interstellar lines. This is the clear proof that physical parameters of individual clouds may differ seriously.

Since it is now rather clear that DIBs are carried by several different (likely) interstellar molecules, it would be of real importance to divide the known features in between of "families", likely sharing one carrier each. The first important property of a "family" should be tight strength correlations between different members. It is well–known since 20 years that the pair of best correlated strong DIBs is the one: 6196 and 6614 (Moutou et al., 1999). Do they share one carrier?

The correlation is really tight (Fig. 4). The question is whether the observed scatter follows the uncertainties of measurements or is physically grounded? If the former is true the strength ratio of both DIBs should be constant, i.e. the same along every sightline (Krełowski et al., 2016).

Figure 5 proves that the intensity ratios of 6196/6614 in the spectra of two outliers, seen in Fig. 4 are really different. Apparently the scatter, seen in Fig. 4, is not caused by uncertainties of measurements but follows different physical parameters of the intervening clouds.

Physical parameters of interstellar clouds can be deciphered from the spectral features of well–identified atoms or molecules. The latter seem to be more important because of the transitions available only in molecular spectra. In 2013 a very peculiar object, namely Herschel 36, was discovered (Oka et al., 2013)). It is still the only known object in the sky showing absorptions from rotationally excited levels of CH^+ and CH interstellar molecules (Fig. 6).

The fact that the first rotationally excited level in CH and CH^+ is evidently

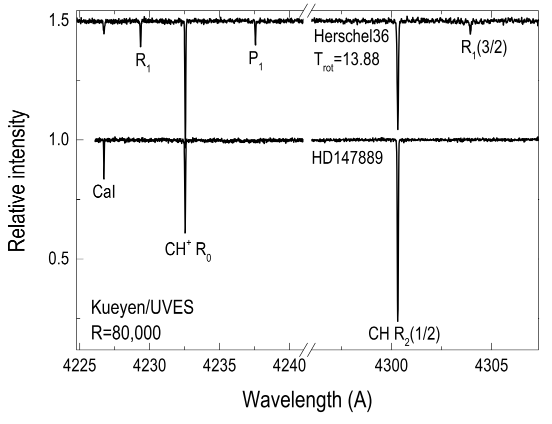

Fig. 6: The CH^+ and CH interstellar absorptions from the rotationally excited level. The rotational temperatures of polar molecules should be close to that of the cosmic background radiation, i.e. below 3K.

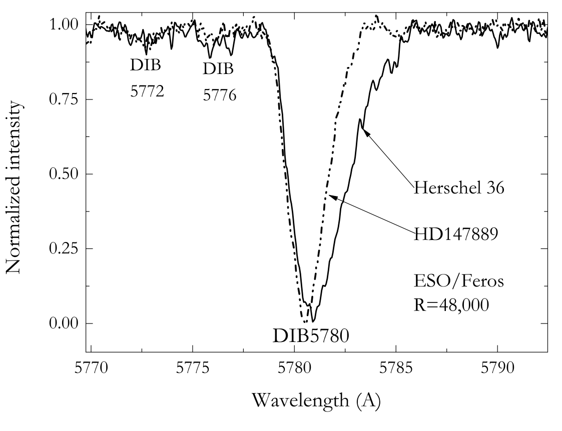

Fig. 7: The 5780 diffuse band in Herschel 36 and in "normal" star HD147889. The DIB is evidently broadened in the case of high rotational temperature. Figure 6 demonstrates that the broadening is not caused by the Doppler splitting.

populated is a very uncommon one. Apparently rotational temperature and other parameters of the intervening cloud are peculiar. Figure 6 shows clearly that the object shines through a single cloud as no Doppler splitting is seen in the UVES high resolution spectrum.

Does the latter influence intensities or profiles of diffuse bands? Herschel 36 was observed using several instruments (2.2m/Feros – ESO, Kueyen/UVES – Paranal, Magellan Clay/MIKE) with the same results. Let's compare DIB profiles in this and other object (HD147889) where the rotational temperature is low (Fig. 7).

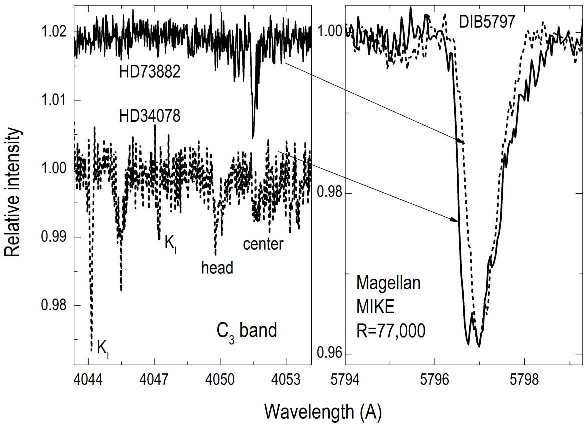

Fig. 8: The evidently different C_3 band towards two targets. HD73882 is characterized by very low rotational temperature (lack of the bandhead) while HD34078 shows the highest ever observed C_3 rotational temperature.

Apparently the growth of the CH^+ and CH rotational temperatures may lead to physical broadening of (some) DIB profiles. Unfortunately in the existing spectra the S/N ratio is too low to estimate rotational temperatures of homonuclear molecules, such as C_2 or C_3 as the bands of them are really shallow. We can try to do this using another targets.

Figure 8 depicts two targets where the rotational temperatures of C_3 differs seriously. HD34078 shows the highest, ever observed this rotational temperature (Adamkovics et al. 2003). It is evident as the band contains the bandhead, formed out of rotationally exited levels as high as 20 – 25. HD73882, where only the lowest rotational levels are populated, was not considered in the latter paper but the C_3 band in its spectrum is practically identical to that, observed in HD169454, where the rotational temperature, according to Ádámkovics et al. (2003) is extremely low.

The same difference in C_3 profiles is depicted in Fig. 9 using spectra from Kueyen/UVES. The plot was, however, made to demonstrate another important phenomenon. Some diffuse bands may not necessarily change profiles with rotational temperature but to change central wavelengths. The spectra, depicted in Fig. 9, are shifted to the rest wavelength velocity frame using the identified features. This is clearly seen while comparing the bands of C_2 and C_3 as well as K I lines. Nevertheless the depicted DIBs clearly do not share the same wavelengths!

The observed wavelength shifts are thus not Doppler shifts: they follow different physical parameters of the intervening clouds. An analysis of this phenomenon in possibly big samples may shed light on the problem of DIB carriers' identification.

3 Conclusions

The above considered material may lead us to the following conclusions:

- DIBs are certainly not carried by atomic species; atomic spectra are sufficiently

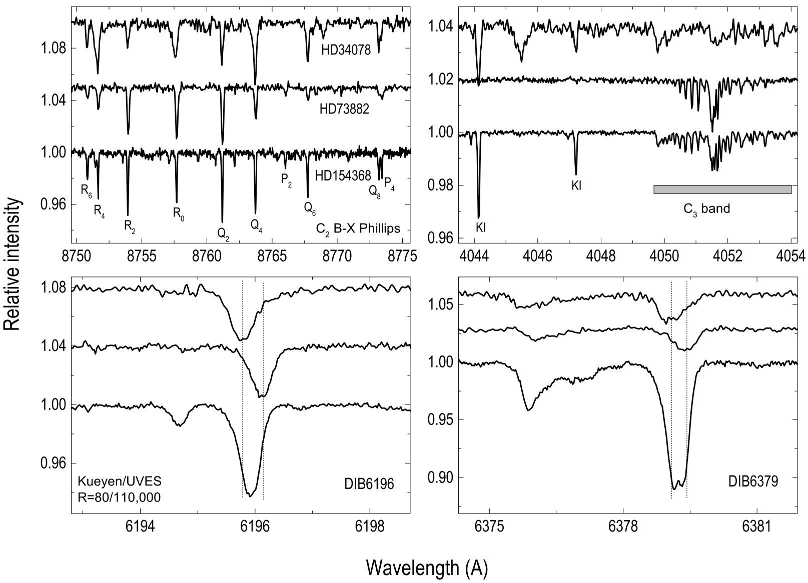

Fig. 9: The depicted spectra are all shifted to the rest wavelength velocity frame. In fact C_2 and C_3 lines, as well as K I ones clearly coincide with laboratory positions. However, the central wavelengths of the depicted DIBs differ evidently.

well-known to leave such a hypothesis valid. Atomic lines, if interstellar, are very sharp

- Dust is almost certainly not the carrier too. Impurities in bulk material of grains may be revealed by broad absorption features but their profiles must show a specific shape which is not observed
- In between of the sizes of atoms and grains one can expect more or less complex molecules. They are now commonly believed to be the DIB carriers, though remaining unidentified. If the molecules are relatively large their rotational constants are small and we must not expect to resolve individual rotational transitions
- Blends of rotational lines may be observed as substructures in DIB profiles.

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