# Diffuse Interstellar Bands Approaching Centenary

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The paper presents in short the history of the investigations of diffuse interstellar bands (DIBs) – the longest standing unsolved problem of the whole spectroscopy. The importance of “peculiar” objects is emphasized as well as a search for the relations of DIBs to other (identified) interstellar spectral features. Some suggestions, concerning possible carriers of diffuse bands are presented as well.

## 1 Statement of the problem

The problem of DIBs is located in a broader subject matter of the physics and chemistry of the interstellar medium (ISM), which consists of atomic gas, molecules, and dust grains. The origin of these bands is as puzzling as since their first detection, more than 90 years ago.

DIBs appeared in the literature more than 90 years ago [1] as described in a nice, recent paper by McCall and Griffin [2]. However, the term “diffuse interstellar bands” was introduced later by P.W. Merrill (1938) who was the first to investigate these puzzling features systematically. At that time only six DIBs were known but their interstellar origin considered as certain. Fig. 1 demonstrates why the features are interstellar – they are stationary as well as NaI interstellar lines in the sharp contrast to stellar lines – and why they are known as “diffuse” – they are much shallower but broader than the NaI lines.

The application of solid state detectors to DIB observations led to discoveries of new features. Currently, the list of known DIBs contains 414 entries [3]; a majority of them – very shallow. Such a rich spectrum cannot share a common carrier; moreover the DIB profiles differ seriously from as narrow ones as about 1 Å (e.g. 6196) to more than 40 Å (e.g. 4430). They bear the name “diffuse” because their profiles are always broader than those of many of the well known atomic/molecular lines, even though the latter are much stronger (Fig. 1).

Nearly all conceivable forms of matter – from hydrogen anion to dust grains – have already been proposed as DIB carriers, so far with no generally accepted success. The abundance of elements in the Universe constrains the chemical composition of the DIB carriers. They ought to be built out of the most abundant elements: H, O, C, N, a small contribution of other elements also cannot be

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V. Grinin et al. (eds) Radiation mechanisms of astrophysical objects. Yerevan: Edit Print, 2017, pp. 105–114.

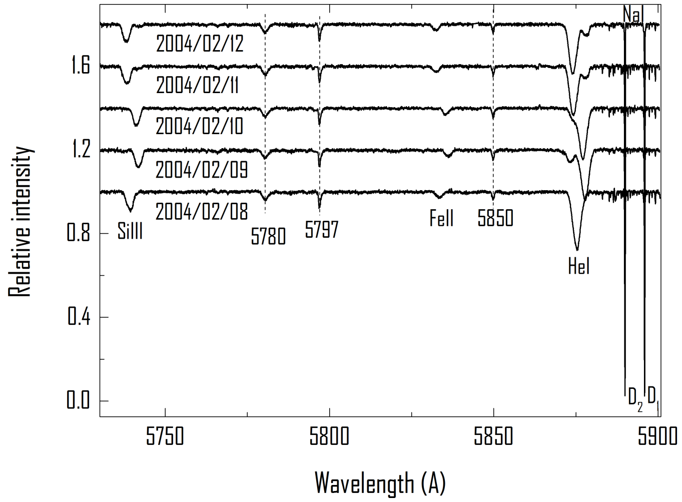

Figure 1: Interstellar NaI lines (right) and three diffuse bands in the spectra of HD 23180 – the spectroscopic binary with a 4.5 day period. Stellar lines (identified) perform the Doppler “dance”. Note that strong interstellar NaI lines are narrower than the indicated DIBs.

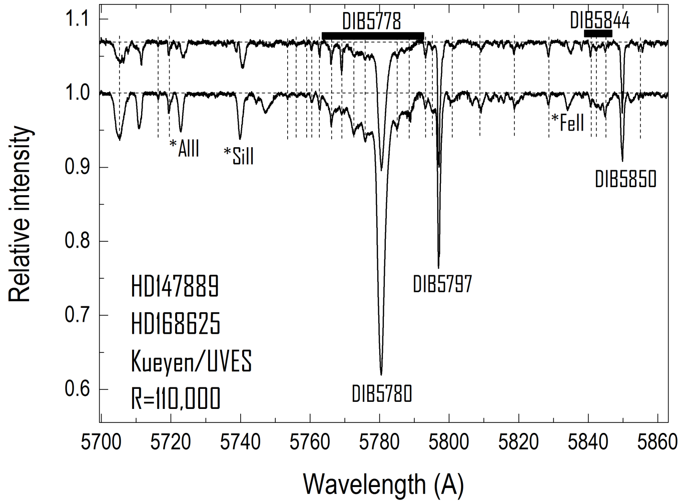

Figure 2: The spectral range in which M.L. Heger found the first two DIBs allows now to trace about 30 features, marked with vertical lines – a vast majority very shallow.

excluded. Among this group of elements carbon is in an exceptional position, since it can form a great number of stable compounds with a linear, planar and spherical structure. Bare carbon chains of 5 to 15 C atoms have been proposed as carriers of diffuse interstellar bands by Douglas [4]. Fulara et al. [5] and Freivogel et al. [6] later extended this hypothesis to the whole class of linear, unsaturated hydrocarbons. The interstellar medium (star forming regions) contains a lot of molecules based on carbon chain skeletons. Their vibrational and electronic transitions cause features in the spectral range full of diffuse bands. Apart from (hydro)carbon chains and polycyclic aromatic hydrocarbons (PAHs), also fullerenes (recently identified in circumstellar shells by [7]) fall in this category having features in visible and near infrared spectral ranges. Unfortunately, the existing spectra of the above mentioned molecules obtained in gas phase experiments (see for reviews [8, 9]) do not match the astrophysical ones. On the other hand, the spectra which have been acquired using the matrix isolation spectroscopy (MIS) cannot be directly compared to the astrophysical spectra. The features in MIS spectra are broadened and wavelength-shifted with respect to the gas phase (the magnitude of the shift remains unknown); the rotational structure is missing. However, the MIS spectra are necessary to determine relative strength ratios of molecular features as the CRDS technique (Cavity Ring Down Spectroscopy) – the method of acquiring gas-phase spectra of molecules – allows only to scan a single feature in a single experiment.

The fine structure (reminiscent of the rotational contours of bands of polyatomic molecules) has been detected in some DIBs [10, 11] giving a strong support to the idea of molecular origin of DIBs.

It is evident that the only way to identify the DIB carriers is to compare observed spectra with those of suspect molecules acquired in gas phase experiments. It is extremely important to keep in mind that what we observe are stellar spectra with interstellar features superimposed. No star is just a lamp, producing continuous spectrum. Stellar spectra contain many atomic lines originating in their atmospheres of the intensities depending on their temperatures, profiles depending on the luminosity class and widths – on rotational speed. This is why not every star allows to separate properly every interstellar feature from its spectrum. The additional problem is the likely present in a majority of targets Doppler splitting of interstellar features. DIB profiles modified in this fashion must not be compared to laboratory ones. This condition shrinks seriously the number of possible targets in which the DIB profiles can be used for such comparison.

The author is collecting high resolution echelle spectra of OB stars since 1993 using different instruments at both hemispheres. The latter is of basic importance for a reliable comparison between laboratory and astrophysical spectra. Very likely the recent attempts to identify neutral PAHs in translucent clouds [12, 13] failed because there are (most likely) a lot of different species in the space and thus abundances of individual PAHs are very small pushing their features below the detection level. Still much higher S/N ratio is necessary to discover ultraviolet PAH features. The very high S/N ratio spectrum of HD 169454 seems to contain the strongest feature of benzo[ghi]perylene (Fig. 3) – one of the investigated PAHs. The evident, neighbour $C_3$ band, is observed for the first time in this object [14]. High resolution echelle spectra allow to observe several spectral features of simple molecular species: CH, $CH^+$, CN, OH, $OH^+$, NH, $C_2$ and $C_3$; recently also SH [15]. It is interesting whether their abundance ratios are similar in all objects or not. The existing data suggest that CH and OH are closely related while NH and $CH^+$ behave in a different fashion [16, 17]. Let's emphasize that the above list allows

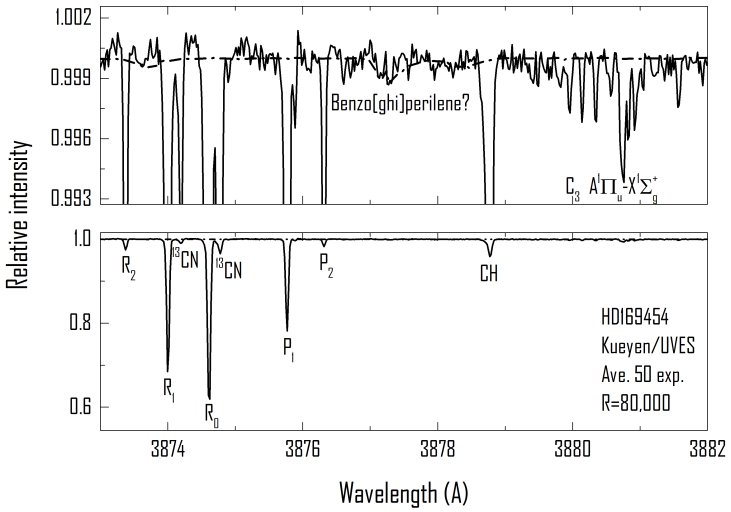

Figure 3: The extremely shallow feature in between of strong CN and CH bands, suggesting the presence of benzo[ghi]perylene in the spectrum of heavily reddened star. The dash-dot line is the laboratory spectrum, courtesy of F. Huisken.

to constrain chemistry of all most important elements: hydrogen, carbon, oxygen and nitrogen. The suggestion that profile widths of (some?) DIBs are related to rotational temperatures of simple carbon centrosymmetric species [18] needs a broader survey.

A comparison of band strength measurements, DIB profile details and their mutual relations require very high resolution, $S/N$ ratio and a broad wavelength range. The necessary observations are very time-consuming and require well-designed procedures of data acquiring and reducing.

## 2 Families of diffuse bands?

The term "families" was used for the first time in the literature in relation to DIBs by Krełowski and Walker [19]. High resolution and high SNR spectra demonstrated that the strength ratio of the major DIBs: 5780 and 5797 changes from object to object. A similar result, confirming the variable DIB strength ratio was published soon after by Josafatsson and Snow [20] confirming that they are not of common origin but belong to different "families" considered as sets of features of common origin. Since 1975 the set of known DIBs was reasonably large [21] which also could suggest diverse origin of the whole DIB spectrum.

The two first objects, in which the variable ratio of major DIBs was observed as early as 1983, are HD 147165 ($\sigma$ Sco) and HD 149757 ($\zeta$ Oph). The result was, however, published a couple of years later [22] for it looked incredible at that time. The terms $\sigma$ and $\zeta$ type clouds, popular now, are rooted in that "ancient" project. The objects were later observed several times and the $\sigma$ and $\zeta$ type clouds were connected not only to the 5780/5797 ratio but also to the shapes

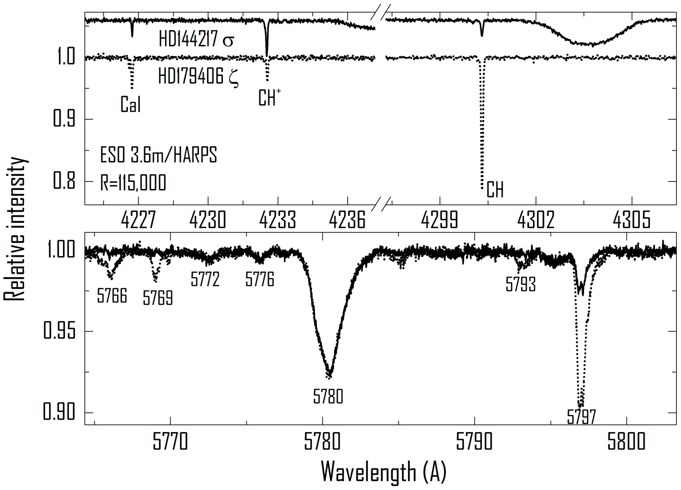

Figure 4: Major DIBs (lower panel) and the bands of simple interstellar radicals, observed in the spectra of HD 144217 and HD 179406 – the typical of $\sigma$ and $\zeta$ type clouds. Note the identical intensity and profile of the 5780 DIB.

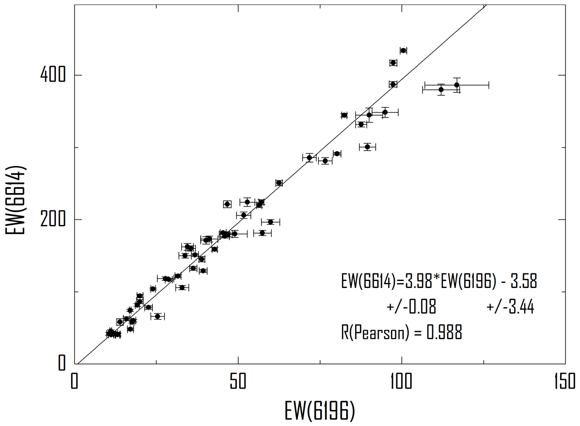

Figure 5: The nearly perfect correlation of the strengths of 6196 and 6614 DIBs.

of extinction curves (see [23]) and to the relative abundances of simple interstellar radicals [24]. Both DIBs and bands carried by simple molecules are depicted in Fig. 4, presenting the two $\sigma$ and $\zeta$ type clouds of similar $E(B-V)$.

Naturally the very first idea was that one “family” members should share the carrier and thus – should be of constant strength ratio. The first DIB survey [25] found a pair that correlates almost perfectly: 6196 and 6614. The former is quite narrow while the latter is quite broad which does not support the idea of common origin. Their equivalent width ratio is nearly 4. This tight correlation was confirmed later by other teams, e.g [26] – it is thus established beyond a reasonable doubt. However, Galazutdinov et al. [11] demonstrated that while the strengths of the two DIBs are well correlated, their FWHMs (full-width half-maxima) are not. Figure 5 presents the above mentioned tight correlation based on spectra from three major world spectrographs: HARPS fed with the

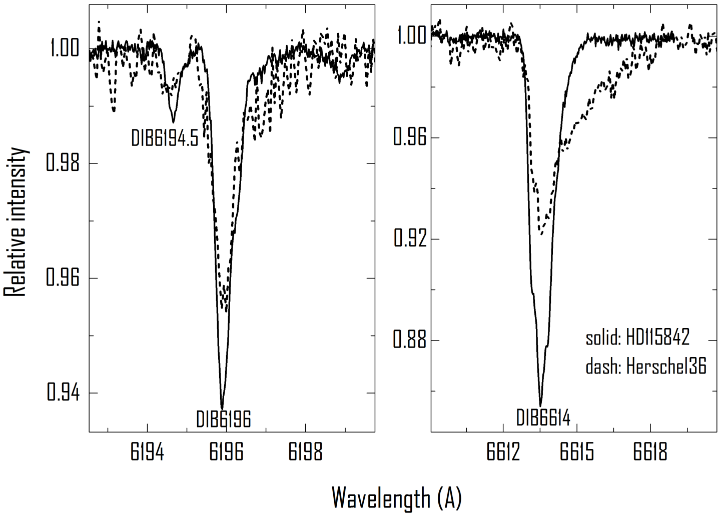

Figure 6: The lack of correlation between FWHM's of 6196 and 6614 DIBs. Note that also some differences of the strength ratio may be physically grounded.

3.6m ESO LaSilla telescope, UVES – attached to the Kueyen mirror of the VLT at Paranal and BOES – fed with the national Korean telescope at Bohyunsan. The very high correlation coefficient is shown. It is, however, a necessary but not a sufficient condition. Analyzing a spectrum of the Herschel 36, it is possible to find more spectacular evidence that FWHMs of the two DIBs do not behave in unison (Fig. 6). Moreover, the scatter, seen in Fig. 5, is very likely caused by different physical conditions inside individual clouds – not by just the measurements' errors.

## 3 Rest wavelengths

Rest wavelengths of DIBs are necessary to identify these puzzling features. However, having no identification we must not have the laboratory wavelengths of any spectral line or band. It is natural that the observed wavelengths of interstellar features are Doppler shifted because of the relative motions of interstellar clouds, the Sun and the Earth. One can shift the wavelength scale of any spectrum to that of some interstellar identified line; this may allow to determine the laboratory wavelengths of unidentified features providing they share the place of origin with the chosen identified line. This may be complicated because not all identified interstellar lines or bands share the same radial velocity.

Seemingly the only proper way to determine rest wavelengths of DIBs is to find an object (or a couple of objects) where radial velocities of all identified lines or bands are identical and their profiles – free of the Doppler splitting. Such objects are very scarce. They should be reasonably bright to allow acquiring high $S/N$ spectra and reasonably heavily reddened to make the tracing of weak DIBs possible. The additional difficulty follows the fact that DIB profiles are not just Gaussians and thus their central wavelengths may not coincide in different publications. This is broadly discussed in the paper by Bondar [27] where the rest wavelengths of 336 DIBs are determined using high quality spectra of 10 stars. However, even this method may not always lead to proper results. The example is the Orion Trapezium [28] where the observed DIBs are apparently red-shifted.

There is no explanation of this effect. Anyway it creates possible doubts on how far the wavelengths of DIBs, shifted to the rest wavelength frames of interstellar lines, are equal to the laboratory ones.

## 4 Profiles of diffuse bands

As mentioned above, the intrinsic profiles of diffuse bands are not just Gaussians; the profiles are not only quite broad but also asymmetric with possible substructures inside. Since the first such analysis [29] it was established that practically all narrow diffuse bands demonstrate some substructure patters, suggesting their molecular origin. It was demonstrated clearly in the paper by Galazutdinov et al. [11]. The profiles of very well correlated 6196 and 6614 DIBs apparently change from object to object where no Doppler splitting is observed in identified lines. The influence of the Doppler splitting on the observed DIB profiles was demonstrated, e.g., by Westerlund and Krełowski [30]. This mechanical broadening makes difficult a comparison of observed and laboratory DIB profiles.

It seems reasonable that changes of DIB profiles are results of different rotational temperatures of their carriers if the latter are molecules as well. It is much easier to find differences in rotational temperatures of centrosymmetric molecules as such temperatures may cover a very broad range [31].

Herschel 36 is a very specific object – the only such one in the sky. Oka et al. [32] found the CH and $CH^+$ molecules in its spectrum to be rotationally excited. The exceptionally high rotational temperatures of the simple, polar radicals are apparently related to severely broadened profiles of some DIBs (Fig. 7). However, not all profiles are broadened; for example that of the 5850 DIB is free of any visible broadening.

Another unique object in the sky is HD 34078 (AE Aur). Adamkovics et al. [31] found the exceptionally high rotational temperature of the $C_3$ molecule in this object. The object seems extremely interesting as the spectral features in its spectrum, carried by simple interstellar radicals, decline with time. Despite of this the profiles of diffuse bands seem to be broadened and their gravity centers – blue-shifted [33]. Also in this case one can expect that the rotational temperatures of the DIB carriers may be responsible for the observed changes of profiles.

The star taken for comparison is HD 27778. Apparently, the 5797 profile resembles that, observed by Oka et al. [32] in 9 Sgr. It is interesting that the DIB is broadened in HD 34078 as well but it looks also blue-shifted. The rotational components of $CH^+$ and CH are not observed in HD 34078 and so the rotational temperature of these species is apparently lower than in Herschel 36.

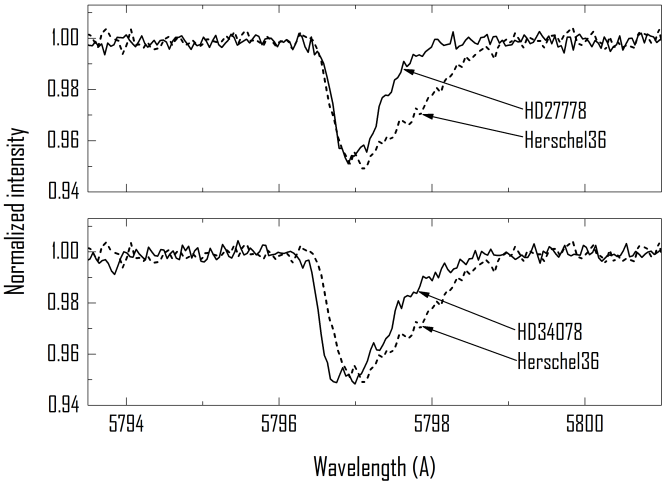

Figure 7: 5797 DIB profiles broadened in the spectra of Herschel 36 and HD 34078. The comparison of HD 27778 with Herschel 36 closely resembles Fig. 3 of [32]. Apparently the DIB is broadened in HD 34078 but not as much as in Herschel 36. The spectra of HD 34078 and HD 27778 are from MIKE ($R = 67\,000$) while that of Herschel 36 from Feros ($R = 48\,000$). All spectra are shifted to the rest wavelength velocity frame using the KI 7699 Å line.

“Peculiar” cases, like AE Aur or Herschel 36, are extremely interesting because they do reflect some specific situations which can take place only in individual clouds (likely homogeneous environments). Unfortunately such cases are extremely rare; it is of basic importance to hunt for more such “peculiar” objects – perhaps they will allow to understand the physics and chemistry leading to the formation of the DIB spectrum.

## 5 Identification propositions

The first proposition of a DIB identification, but signed with a question mark, is the $CH_2CN^-$ molecule proposed as the carrier of the 8037 Å DIB by Cordiner and Sarre [34]. This feature is located in the wavelength range severely contaminated with telluric lines and fringes. Thus it is very difficult to check whether the identification is reliable because the profile of it is clearly seen only in a few objects and no more its features are proposed.

Recently we found a very weak DIB which coincides with the electronic, gas-phase band of $HC_4H^+$; this finding [35] supports DIB molecular origin. The identification was disputed by Maier et al. [36]; this fact clearly demonstrates the necessity of close cooperation between experimentalists and observers. The lack of the latter leads to obvious confusions. The wavelength of the above mentioned feature may be a bit floating due to different rotational temperature of the carrier. Unfortunately, the band is so weak that a proper statistics of observations is hardly available.

Another overlap between a lifetime broadened absorption spectrum, recorded through a hydrocarbon plasma and a stronger DIB at 5450 Å was reported by [37]; an identification of the carrier was not possible yet. If l-$C_3H_2$ can produce the 5450 Å DIB, as proposed by Maier et al. [38] then the carrier is unacceptably abundant; moreover the second l-$C_3H_2$ feature, near 4883 Å is clearly of another origin [39].

The recently published by Campbell et al. [40] gas phase spectra of the $C_{60}{}^{+}$ reactivated the dormant idea of this species to be the carrier of two near infrared DIBs: 9577 and 9632. According to the authors the cation of $C_{60}{}^{+}$ exhibits four relatively strong spectral lines centered at 9365.9, 9428.5, 9577.5 and 9632.7 Å with relative intensity 0.2, 0.3, 1.0 and 0.8, respectively, and the wavelength precision not worse than 0.1Å. However, the authors did not collect big enough sample of spectra allowing a comparison with the laboratory data. The strength ratio of both strong, observed features may seriously differ from the laboratory predictions; moreover the ratio is apparently variable if observed in a pretty big sample of targets. Also the rest wavelengths of both DIBs do not match the laboratory ones inside the possible errors.

*Acknowledgments.* The author is very indebted to Dr. G.A. Galazutdinov for very helpful discussions. The paper was financially supported by the grant 2015/17/B/ST9/03397 of the Polish National Science Center.

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