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Spectroscopic families among diffuse interstellar bands

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The inability to identify carriers of the diffuse interstellar bands (DIBs) is one of the longest standing problems in astronomy and astrochemistry. It is debated whether these carriers arise from dust or the gas component of the interstellar medium. Furthermore, different strength ratios of major DIBs along different lines of sight revealed many carriers responsible for DIBs origin. Any attempt to recognize these carriers must involve interdisciplinary collaboration between molecular physicists, chemists and astronomers. One expects that progress in this field will be possible when all known DIBs are divided into families in such a way that only one carrier is responsible for all bands belonging to a given family. Among all known DIBs we can see only few relatively strong bands and big number of rather weak ones. With better quality spectra one can expect to find more weak DIBs. It is very probable that DIBs originated by the same carrier have different intensities; in one spectroscopic family we expect to find stronger bands as well as weaker (and extremely weak) ones. Discovering new very weak DIBs may be therefore crucial when we want to find complete spectroscopic families among DIBs. Extracting spectroscopic families of DIBs is a task to be solved with usage of astronomical spectra of the best quality. After extracting any spectroscopic family, its carrier will be to find by the way of laboratory search supported by quantum chemical considerations. Analysing high resolution optical spectra of reddened stars we tried to find out the first true spectroscopic families among DIBs.

Key words: ISM: lines and bands

INTRODUCTION

The presence of mysterious diffuse absorption structures in the spectrograms of reddened stars has been found many years ago (see [3] for extensive review). The first diffuse interstellar bands (DIBs) were discovered in [2] and then confirmed in [6]. The name "diffuse interstellar bands" is given to all features, observed in the spectra of reddened OBA stars, which remain unidentified. Up to now more than 500 DIBs are known, spanning the wavelength range from 4000 to 13000 Å. The most prominent DIBs include those at 4428, 5780, 5797, 6196, 6203 and 6284 Å. DIBs differ greatly in shapes; from very broad, e.g. 4430 Å, to very narrow, like 6196 Å. Many structures of this kind are extremely weak. Their central depths usually do not exceed 1% of the continuum level of the spectra. Precise measurements of such bands are still very difficult and many research papers deal usually only with the strongest DIBs. During the past years more precise observing techniques were developed and the improved quality of the spectra allowed a deeper analysis of these structures, highlighting more and more details on their behaviour and therefore making DIBs interesting candidates as markers of the physical and chemical processes occurring in the interstellar medium. However, in spite of the higher resolution and the excellent signal-to-noise ratio in the spectra which can be obtained from modern spectrographs, the nature of the carriers of the DIBs still remains a mystery.

THE CARRIERS OF DIBs

The identification of the DIBs' carrier(s) is a problem that has fascinated researchers for very long time. The various proposals are reviewed in [3]. Although very numerous, the DIBs are weak and the sum of their absorptions is very small. The absorbers need not be very abundant. The big number of known DIBs, and their widespread distribution across the optical spectrum, strongly suggest that more than one carrier is involved. Further support for multiple carriers arises from intensity correlations of the features with each other and with reddening, suggesting the existence of several 'families' of DIBs (e.g. [5, 7]). In [5] it was shown that the relative strengths of 5780 Å and 5797 Å DIBs might be quite different in the spectra of different stars.

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They demonstrated that these two DIBs do not have the same carrier. DIBs' origins in dust grains and gaseous molecules have been proposed. Features produced by solid-state transitions in the large-grain population should exhibit changes in both profile shape and central wavelength with grain size, and emission wings would be expected for radii $> 0.1 \mu$m [9]. None of such effects has been observed. There is also a lack of polarization in the features that might link them to the larger aligned grains. If the carriers are solid particles, they must be very small compared with the wavelength. There has been a degree of consensus that the most plausible candidates for the DIBs' carriers are carbonaceous particles that might appear as very small grains or large molecules like PAHs or fullerenes [3]. Ionized species are more probable than the neutral ones because they have stronger features in the visible band. Observations show that the DIBs become relatively weak if they originate inside dark clouds [1] where ionizing radiation is effectively shielded. Identification of specific DIBs with specific species is problematic, as the techniques used to study their spectra in the laboratory introduce wavelength shifts and line broadening [8] and this makes any comparisons between laboratory and interstellar spectra very difficult.

SPECTROSCOPIC FAMILIES OF DIBS

All known DIBs form very inhomogeneous sample. Some of them are relatively strong, contrary to the others which are extremely weak. There are DIBs which are narrow (e. g. 5797 Å), and there are very broad bands (e. g. 4430 Å). This morphological heterogeneity of the observed DIBs indicates, even without the other arguments invoked in previous section, that there are many carriers of DIBs. In 1980s researchers started their attempts to isolate families of DIBs according to their morphological features (e.g. [4]). However, it is expected that some carriers would be closer to identification, when among all known DIBs the spectroscopic families (SF) will be revealed, like multiplets in atomic spectroscopy [11]. Theoretically, SF might be revealed only by analysis of appropriate astronomical spectra. However, the task is not easy, as it was shown in detail in [11]. The main obstacle in isolating SF is the so called "noisy correlation". The nature of interstellar medium is so, that all measurable parameters describing it are partially correlated one with another, even if they have none intrinsic connections. Two quite independent species may produce DIBs and intensities of these DIBs may be reasonably good correlated, when one takes into account spectra of many reddened stars. The ability of the standard statistical methods to isolate SF is very limited. The tight linear correlation, expected between members of the same SF, is effectively hidden by noisy correlation and the measurement errors. Therefore, we still look for more adequate methods of revealing SF. The first trials in this field were performed in [11]. Below we outline the other method, developed recently.

REVEALING SF – NEW METHOD

We tested a new method of extracting SF of DIBs [10]. This method may be summarized as follows:

1. We measure equivalent widths (EWs) of all accessible DIBs in the spectra of two different target stars. These stars should be moderately reddened and they should be sufficiently far away one from another on the sky, to have slightly different chemistry in the corresponding interstellar clouds. Such restriction should minimize the influence of the noisy correlation. We get series of measurements:

   EW_1^1, EW_2^1, EW_3^1, …, EW_n^1 (for the first star, n is the number of measured DIBs)
   EW_1^2, EW_2^2, EW_3^2, …, EW_n^2 (for the second star)

2. We count the ratios of kind: $\mathrm{R}_i = \mathrm{EW}_i^1/\mathrm{EW}_i^2$, (where $i = 1, \ldots, n$) and we draw the diagram with R_i on vertical axis and i on horizontal one (Fig. 1).
3. We look on the diagram for groups of DIBs with almost the same R. If the commonly used assumption is valid that intensity ratio for two DIBs originated by the same carrier should be constant (independently on the direction to target star), points in the diagram with the same value of R should correspond to DIBs belonging to the same SF. Searching one diagram we may expect to find many SF, each for the other value of R.

Ratios R defined above have much smaller errors than the direct ratios of type $\mathrm{r}_{k,i}^m = \mathrm{EW}_k^m/\mathrm{EW}_i^m$ ($m = 1 \ldots n$), which were of common use before, since they avoid dividing very big numbers (EW for strong DIBs) over very small numbers (EW for weak DIBs). Furthermore, our method needs in principle only spectra for two stars instead of a few dozens stars needed by other methods. Actually, we use different pairs of spectra to confirm results achieved for one pair of target stars.

To test our method we used the echelle spectra taken by spectropolarimeter NARVAL coupled with Telescope of Barnard Lyot (TBL) at Pic du Midi Observatory. We got spectra with S/N ratio of about 2,000 and with resolution R of 67,000. For given pair of target stars observations were done during the same night to have the same atmospheric conditions. Observations with different

Table 1: The details concerning observed stars. In rows HD number is followed by spectral type, magnitude, reddening, air mass and the date of observation. First two items are for comparison stars.

HD	Sp	m(v)	E(B-V)	air mass	date
35497	B7 III	1.68	0.00	1.08	13.03.2010
120315	B3 V	1.85	0.02	1.02	23.06.2010
23180	B1 III/B3 V	3.82	0.30	1.25	12.03.2009
				1.70	13.03.2010
24760	B0.5 V/A2 V	2.9/3.9	0.10	1.27	13.03.2010
149757	O9 V	2.56	0.29	1.70	23.06.2010
184915	B0.5 III	4.96	0.22	1.90	23.06.2010
210839	O6 I	5.04	0.54	1.10	23.06.2010

air mass helped us to decide which weak absorption lines are telluric in their origin and which are extraterrestrial. To distinguish interstellar lines from weak stellar lines we observed moderately reddened spectroscopic binary (HD 23180) during two subsequent nights. We observed also practically non-reddened comparison stars, which were helpful to indicate telluric lines. In Table 1 we summarize the details concerning the observed stars. To minimize errors for ratio R we limited our measurements only to well confirmed DIBs which were additionally quite good visible in our spectra. Resulting diagrams look like the one presented in Figure 1.

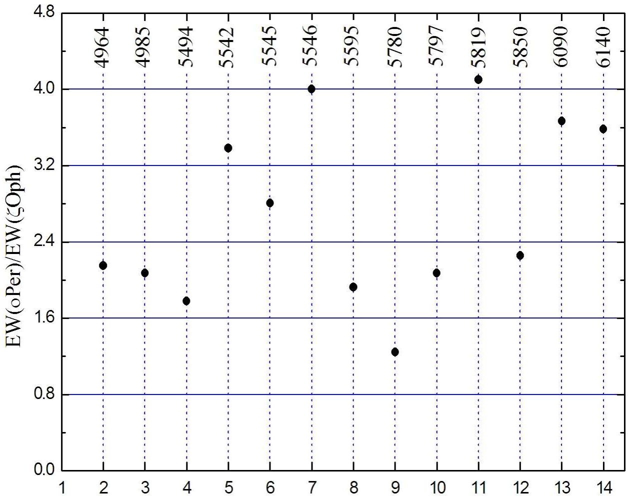

Fig. 1: R_i/i diagram for the pair of stars: *o*Per (HD 23180) – ζOph (HD 149757). On the top DIBs' names (in common notation – the profile wavelengths in Å) are written. On the bottom we have *i*-numbers describing individual DIBs.

FINAL REMARKS

Interdisciplinary study of the problem of SF seems to be of crucial importance to identify the carriers of DIBs. The first trials of revealing SF with different complementary methods seem to be promising. When looking at the Figure 1 we can see that DIBs 5546 Å and 5819 Å tend to belong to the same SF with R=EW(*o*Per)/EW(ζOph) of about 4. Similarly, DIBs 4895 Å and 5797 Å seem to represent the other SF, with the ratio R of about 2. However, before qualifying DIBs as the same SF members one has to check whether they show the same tendency for other pairs of stars. To exploit successfully the presented method we need spectra of very high original S/N ratio. Spectra, averaged from many spectrograms, taken in different time, may be slightly contaminated by residuals of weak telluric lines which are not fully removed when using traditional reduction procedures.

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