Observational analysis of the well–correlated diffuse bands: 6196 and 6614 Å *

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ABSTRACT
We confirm, using spectra from seven observatories, that the diffuse bands 6196 and 6614 Å are very tightly correlated. However, their strength ratio is not constant as well as profile shapes. Apparently the two interstellar features do not react in unison to the varying physical conditions of different interstellar clouds.

Key words: ISM: lines and bands - ISM: molecules.

1 INTRODUCTION
A very recent paper by Oka et al. (2013) demonstrates that profiles of the still unidentified diffuse interstellar bands (DIBs), in particular the very well–correlated ones near 6196 and 6614 Å, may not change in unison (see their Figs. 1 and 2). The rotational temperatures of the polar molecules CH and CH⁺, found in Herschel 36, are as high as about 15K. In this special object the 6614 profile shows a very pronounced extended red wing while the latter is barely seen in 6196. There are several possible explanations for the origin of red wing seen in DIB 6614: Bernstein et al. (2015) offer the hypothesis of accidentally overlapping diffuse bands, Oka et al. (2013) consider a single rotational contour where high rotational transitions being pumped by the nearby irradiation from Her 36. Lastly, Marshall et al. (2015) suggest that “...the extended red tails would arise principally from vibrational hot bands that are red-shifted with respect to the origin band...”

The possible influence of the rotational temperatures of centrosymmetric species (C₂) on some DIB profiles was already suggested by Kązmierczak et al. (2010). This result received a support very recently (Gnaciński & Krelowski (2014); some DIB profile widths have been shown as correlated with the rotational temperature of H₂ – the homonuclear molecule.

The pair of the diffuse bands near 6196 and 6614 Å was found as very well correlated by Moutou et al. (1999). The pair of the diffuse bands near 6196 and 6614 Å was found as very well correlated by Moutou et al. (1999). The intensities of the two DIBs were found as correlated with the Pearson’s coefficient as high as 0.97. The first guess could thus be that 6196 and 6614 Å may form a “family” sharing a common carrier. However, the very high resolution analysis of the profiles of the two DIBs created some doubts (Galazutdinov et al., 2002). Their Fig. 4 demonstrated that while EW’s of 6196 and 6614 do correlate quite tightly, their FWHM’s do not. Apparently the profiles of both DIBs do not react in the same fashion to the varying physical conditions inside interstellar clouds. This fact is also confirmed by differing shapes of both DIB profiles (Galazutdinov, Lo Curto & Krelowski 2008).

The nearly perfect correlation of the two bands was confirmed by McCall et al. (2010) which is better than any other pair of DIBs. Nevertheless, the authors emphasized the need to explain the very different profiles of the 6196 and 6614 diffuse bands if they are of the same origin. Indeed, profile of the former one is much more symmetric and narrow than that of the latter.

 Naturally, it was the very first guess that trying to divide diffuse bands into sets of features carried by the same molecules we should put into one “family” the features which are really well correlated (e.g. Krelowski, Schmidt & Snow (1997)). However, the above mentioned papers expressed some doubts on whether the two nearly perfectly correlated DIBs share the same carrier. The profiles are of very different widths and these widths vary but not in the same way. It is thus important to check whether the observed scatter, seen despite a very high correlation coefficient, follows just measurement errors or has some physical background.

It is commonly believed that the DIB carriers are some complex molecules. The most popularly considered molec-
ular species, being candidates for DIB carriers, are chain molecules, based on a carbon skeleton. They have been observed in star forming regions but the attempts to find them in translucent clouds failed (Motylewski et al. 2000). Another candidate is that of polycyclic aromatic hydrocarbons (PAHs). A kind of their mixture is believed as the carrier of a few emission infrared bands. However, the attempts to identify any specific PAH – this is possible only in the near UV range – failed as well (Salama et al. 2011; 2011). Another possibility – fullerenes – seems to the corresponding CCD cameras, providing the applied slit width was 0.4 and 0.3 arcsecond for the blue and red branches of the spectrograph respectively. These widths satisfy to the 2 pixel criteria for the slit image projection to the corresponding CCD cameras, providing the highest possible resolving power ∼80,000 and ∼110,000 for the blue and red spectrograph branches respectively. Several spectra used in this investigation were acquired using the HARPS spectrograph fed with the 3.6-m La Silla telescope. This instrument offers a very high resolution (R=150,000); the wavelength range is 3,800 – 6,900 Å divided into 72 orders.

Additional spectra were collected with the aid of the Magellan/Clay telescope at the Las Campanas Observatory (Chile) using the MIKE spectrograph (Bernstein et al. 2003) with a 0.35×5 arc sec slit. The resulting high resolution spectrum (R∼65,000) is an average of several individual exposures, achieves the high S/N ratio (∼1000) and covers the

2 OBSERVATIONS

The UVES spectra of our targets were collected at the 8-m UT2 telescope (Paranal Observatory, ESO, Chile). We used our own observations as well as those available from the public ESO archive. The spectra were carried out in two standard modes DIC1(346+580) and DIC2(437-860) covering the whole wavelength range ∼3050 - ∼10400 Å some of them with a gap between ∼5770 - ∼5830 Å due to the inaccurate set-up of the optical elements of spectrograph.

The applied slit width was 0.4 and 0.3 arcsecond for the blue and red branches of the spectrograph respectively. These widths satisfy to the 2 pixel criteria for the slit image projection to the corresponding CCD cameras, providing the highest possible resolving power ∼80,000 and ∼110,000 for the blue and red spectrograph branches respectively.

\[ \begin{array}{cccccc}
\text{Star} & \text{EW(6196)} & \text{EW(6614)} & \text{Star} & \text{EW(6196)} & \text{EW(6614)} \\
bd59456b & 52.8±2.3 & 224.2±6.0 & 114470f & 15.8±1.3 & 60.4±2.7 \\
bdo0594b & 40.2±1.7 & 171.1±5.1 & 14470h & 18.6±3.1 & 57.8±5.2 \\
bodo4220b & 89.5±2.5 & 300.7±5.2 & 16.2±1.0 & 59.8±1.1 & 161056a \\
bdo4227b & 84.6±4.6 & 327.4±9.9 & 145037u & 72.6±2.1 & 244.0±6.0 \\
CD-324348u & 82.4±0.8 & 344.6±2.5 & 145502f & 15.0±0.6 & 58.9±1.9 \\
CygOB27b & 90.0±4.1 & 344.8±9.9 & 147165b & 18.0±0.7 & 60.1±1.8 \\
CygOB28ab & 94.9±4.0 & 348.7±7.0 & 147165u & 17.6±0.6 & 58.0±1.5 \\
CygOB211b & 112.0±5.7 & 380.0±7.8 & 17.8±0.2 & 58.9±1.0 & 168257u \\
CygOB212b & 116.8±9.8 & 386.4±9.9 & 147889b & 46.2±2.0 & 179.5±3.4 \\
15785b & 46.7±1.2 & 221.3±4.8 & 147889u & 45.4±0.9 & 181.6±1.5 \\
23180 & 15.3±1.6 & 61.8±5.1 & 25.0±1.4 & 179.7±2.6 & 20.0±1.0 & 76.5±1.6 \\
2373 & 61.4±4.1 & 149757h & 10.5±0.7 & 41.8±1.9 & 194839h & 66±1.3 & 197.5±9.0 \\
6804u & 87.6±1.7 & 332.0±3.5 & 149757u & 11.2±0.8 & 40.7±1.5 & 203532h & 14.9±0.8 & 58.4±1.1 \\
7388u & 17.1±0.9 & 48.1±1.8 & 10.8±0.3 & 41.1±0.5 & 204872h & 41.2±0.2 & 173.1±4.0 \\
7834u & 76.2±2.1 & 281.4±4.6 & 151932u & 31.6±0.9 & 121.8±2.1 & 207198h & 33.9±0.2 & 125.2±3.7 \\
8007u & 80.2±1.2 & 291.3±3.9 & 152003u & 32.9±2.0 & 105.8±2.9 & 210839h & 32.9±0.8 & 145.5±3.2 \\
130432u & 17.0±0.3 & 74.4±1.6 & 152233h & 22.6±1.2 & 78.3±2.4 & 226868b & 49.0±3.8 & 180.2±4.9 \\
114213u & 38.9±0.9 & 145.2±3.7 & 152233m & 22.7±1.1 & 79.3±2.1 & 228712b & 57.4±2.7 & 181.4±3.6 \\
115842u & 39.8±0.9 & 151.0±2.0 & 22.7±0.1 & 78.9±0.5 & 228779b & 71.8±2.1 & 285.9±6.0 \\
125241u & 57.1±0.8 & 224.3±3.4 & 152236u & 36.3±1.1 & 132.5±2.6 & 229059b & 63.8±4.8 & 231.4±7.5 \\
142486u & 56.4±0.8 & 220.2±3.4 & 152236u & 39.3±1.2 & 129.0±2.1 & 254777b & 51.7±2.2 & 206.0±4.5 \\
144217 & 13.2±0.8 & 40.9±2.0 & 152249h & 20.0±1.0 & 86.4±2.7 & 278422b & 32.9±2.1 & 166.0±4.6 \\
144217u & 11.1±0.3 & 45.6±1.5 & 152249u & 19.2±0.6 & 81.5±1.9 & Hersch36 & 40.6±4.1 & 151.3±9.9 \\
114±0.7 & 43.9±2.3 & 19.4±0.4 & 83.1±2.3 \\
144218h & 14.1±3.1 & 57.4±8.6 & 154368u & 33.8±1.9 & 150.0±3.3 \\
\end{array} \]
broad wavelength range $\sim 3600 - \sim 9400 \, \text{Å}$) with the lack of gaps between spectral orders.

A big portion of the data was collected at the ICAMER (North Caucasus, Russia) observatory, with the aid of the coudé échelle spectrograph MAESTRO (Musaev 1999) fed by a 2-m telescope. These spectra may be obtained in two operating modes of the instrument, with resolving powers respectively of 45,000 and 120,000. In this paper we used only the high ($R=120,000$) resolution.

We have measured our selected diffuse bands’ equivalent widths also in the spectra collected at the McDonald Observatory in 1993 by one of us (JK). The Sandiford échelle spectrograph allows the resolution as high as $R=60,000$ and the wavelength range $5,650 – 7,000 \, \text{Å}$ is divided into 27 orders.

Several targets have been observed using the Feros spectrograph, fed with the 2.2-m telescope. The resolution of this instrument is $R=48,000$ and the spectral range covers $3,700 – 9,000 \, \text{Å}$. The latter is divided into 37 orders.

Lastly, our sample includes seven spectra obtained through the fibre-fed échelle spectrograph BOES (Kim et al., 2007) installed on the 1.8-m telescope at the Bohyunsan Observatory (South Korea). In this case the resolution may be either 30,000; 45,000 or 90,000; the wavelength range is always $3,800 – 10,000 \, \text{Å}$ divided into 76 orders.

All spectra were processed and measured in a standard way using both IRAF (Tody 1986) and our own DECH codes.

3 RESULTS

Oka (2013) demonstrated that profiles of both 6196 and 6614 (especially the latter) may change seriously while the rotational temperatures of CH or CH$^+$ are extraordinarily high, forming the extended red wings. Our sample of high S/N ratio targets shows that similar extended red wings may be observed in relatively many objects though not as evident as in Herschel 36. We have selected three spectra of HD179406, HD147889 (mentioned as differing seriously in $T_{\text{rot}}$ of C$_2$ by Kaźmierczak et al. 2010) and Herschel 36 to compare the DIB profiles. The result is shown in Fig. 1. Apparently HD179406 is the case of low rotational temperatures of molecular species and HD147889 is somewhere in between of HD179406 and Herschel 36. We would like to draw attention to a comparison of two spectra of HD147889 and HD179406: one from HARPS and one from UVES – both of very high S/N ratio. The DIB profiles are not identical in both these sources. Apparently the extended red wings develop with the growing rotational temperatures of molecular species. In the case of 6196 the DIB core is broadened when $T_{\text{rot}}$ grows but the extended red wing is relatively shallow while in the case of 6614 it is very pronounced.

Our measurements of the equivalent widths of both DIBs in our sample of high S/N ratio spectra are given in Table 1. Equivalent width error estimations are based on use of equation 7 from Vollmann & Eversberg (2006). The method neglects possible continuum placement errors, though hard to expect sufficient incorrectness in case of relatively narrow DIBs like 6196.

![Figure 1. The extended red wings of the considered DIBs growing in unison with $T_{\text{rot}}$ of identified species.](http://gazinur.com/DECH-software.html)

![Figure 2. The tight relation between 6196 and 6614 diffuse bands. A few departing points are labeled with the stellar HD or BD numbers. For HD34078 we plotted measurements from UVES, MIKE and Maestro. Linear fit done with including errors for both coordinates, see Fasano & Vio(1988).](http://gazinur.com/DECH-software.html)

It is important to emphasize that the extended red wings are incorporated into the integrated profiles if present. This set of data is especially reliable as we have selected from our database only the best spectra, i.e. with S/N ratio exceeding 250 and where the DIB profiles are not contaminated with stellar lines. Our sample contains thus 80 spectra; some of the targets have been observed using more than one instrument. We consider the fact that equivalent widths, measured using different instruments, coincide inside the one sigma errors, as very important. They prove that all measurements can be repeated with the same result. The correlation plot is demonstrated in Fig. 2.

Fig. 2 clearly supports the conclusions of the above mentioned papers – that the correlation between both DIBs is nearly perfect. However, it seems interesting to compare the departing points and so – to check whether they really do not follow the main stream because of the measurements’ errors or the strength ratios of 6196 and 6614 in these targets are really different.

1. [http://gazinur.com/DECH-software.html](http://gazinur.com/DECH-software.html)
There are some evidently departing points which represent HD34078 (weak DIBs but three different spectra) and HD15785 where both DIBs are strong and the BOES spectrum is of very high quality. The profiles of both diffuse bands are shown in the radial velocity scale Fig. 3. Another departing star - HD169454, is represented by two points: one based on UVES and one on MIKE spectra, both of very high quality.

Fig. 3 demonstrates that the strength ratio of the two DIBs under consideration really varies from target to target. Apparently there are two different carriers causing these DIBs though they must be related in a way – their abundances ratios are similar but not identical. This seems to support the conclusions of Galazutdinov et al. (2002) that the FWHM’s of the DIBs do not correlate and the recent result of Oka et al. (2013) which demonstrates evident extended red wing in 6614 while the latter is barely seen in 6196. This extended red wing seems to appear in HD34078 and thus the object may be a transition one between typical objects with low rotational temperatures of molecules and the extreme object – Herschel 36. It is worth to mention that the $T_{rot}$ of the CN molecule in this object (HD34078) is as high as 4.0K (Krelowski et al., 2012). It is interesting that the point, representing Herschel 36 in Fig. 3 is situated exactly at the average relation. The observed 6196/6614 strength ratios seemingly do not depend on rotational temperatures of identified molecular species.

Fig. 3 allows to select other pairs of targets situated at both sides of the average relation. We also demonstrate the same as in Fig. 3 effect for Cyg OB2 11 and HD168625 and for HD278942 and HD152003 – Fig. 4 and Fig. 5. The plots clearly support the conclusion that the two DIBs’ ratios really differ from object to object. Apparently the physical scatter is not related to the changes of DIB profiles. The profiles apparently depend on rotational temperatures of the carriers while the strength ratios – on their abundances.

4 CONCLUSIONS

Our analysis of the 6196 and 6614 Å diffuse bands leads to the following conclusions:

- profiles of both diffuse bands change with the rotational temperature of identified species; the growing $T_{rot}$ results with the extended red wings
- both considered DIBs correlate almost perfectly (with the Pearson’s correlation coefficient 0.98); the average 6614/6196 strength ratio being 3.88±0.13
- the observed scatter is not a result of measurement’s errors, i.e. the difference is higher than uncertainty of individual measurements; the 6614/6196 strength ratios are proved to be variable
- the variable strength ratio is not related to the observed profile changes; apparently both DIBs are caused by different carriers but their abundances are pretty closely related.

Apparantly the very first idea, expressed by Krelowski & Walker (1987) and by Krelowski & Westerlund (1988),...
that all DIBs do not share the same carriers but can be divided into several “families” cannot be helpful while trying to identify DIB carriers. An analysis of DIB profiles, pioneered by Westerlund & Kre’sowski (1988) is necessary as well. As yet it was not possible to find any pair of DIBs being certainly carried by the same species. Seemingly all stronger DIBs which can be reliably measured in statistically meaningful samples of objects are carried by a different molecule each.

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