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# An investigation of the 661.3 nm diffuse interstellar band in Cepheid spectra

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## ABSTRACT

We have investigated the diffuse interstellar band (DIB) at 661.3 nm seen in the spectra of Cepheid stars. After removal of the blending lines of ionized yttrium and neutral iron, we determined the equivalent widths (EWs) of the DIB and used these values to investigate the  $E(B - V)$ -DIB EW relation. The relation found from Cepheids matches that found in B stars. This relation can help to find the reddening for newly discovered Cepheids without extensive photometric data, and thus determine their distances. The relation between  $E(B - V)$  and the DIB EW does not yield precise reddening values. It is not a substitute for better photometric or spectroscopic methods. At best, it is indicative, but it provides some information that may not be otherwise available. Defining  $R^* = E(B - V)/\text{DIB EW}$ , which we consider to be the analogue of  $R = E(B - V)/A_v$ , we investigated the Galactic longitudinal dependence of  $R^*$  assuming that the DIB EW value is representative of the interstellar absorption  $A_v$ . We found that there is an apparent increase of the  $R^*$  value that corresponds to the abnormal absorption seen towards Cygnus constellation. Finally, we constructed a 2D map of the DIB EW distribution in the Galactic disc basing on our rather limited sample of 253 spectra of 176 Cepheids.

**Key words:** stars: variables: Cepheids-ISM: lines and bands-ISM: molecules-ISM: structure.

## 1 INTRODUCTION

Diffuse interstellar bands (DIBs) are absorption features seen in the spectra of many astronomical objects in the visible and infrared wavelength regions. The total number of these features exceeds 400. These bands are observed in absorption in star light crossing translucent clouds and the carriers of only three such features have been proposed; none of them certain. The origin of the DIBs is as puzzling as since their first detection, more than 90 years ago. The central wavelengths of DIBs are not readily identified with any known atomic or molecular spectral lines. The profiles of DIBs are not just Gaussians as shown for the first time by West-

erlund & Krelowski (1988) which may suggest their molecular carriers. Moreover, precisely determined DIB profiles (Galazutdinov, LoCurto & Krelowski 2008b), showing a specific substructure pattern each, should facilitate their carrier's identification. The better-substantiated hypothesis is that DIBs arise from absorption produced by polycyclic aromatic hydrocarbons (PAHs), although Cox (2011) and Salama & Ehrenfreund (2014) doubt this statement and no specific PAH has been identified until recently (Salama et al. 2011). The other possibility is that carbon chain molecules, similar to those observed in star-forming regions, may carry DIBs. but this idea also has no clear proof (Motylewski et al. 2000). Two DIBs, observed in the near-infrared, were tentatively ascribed to the bucky ball ( $C_{60}^+$ ) molecule (e.g. Foing & Ehrenfreund 1994; Campbell et al. 2015). Nevertheless there is an indication that this identification was proposed but not finally proven. Recently it has been demonstrated

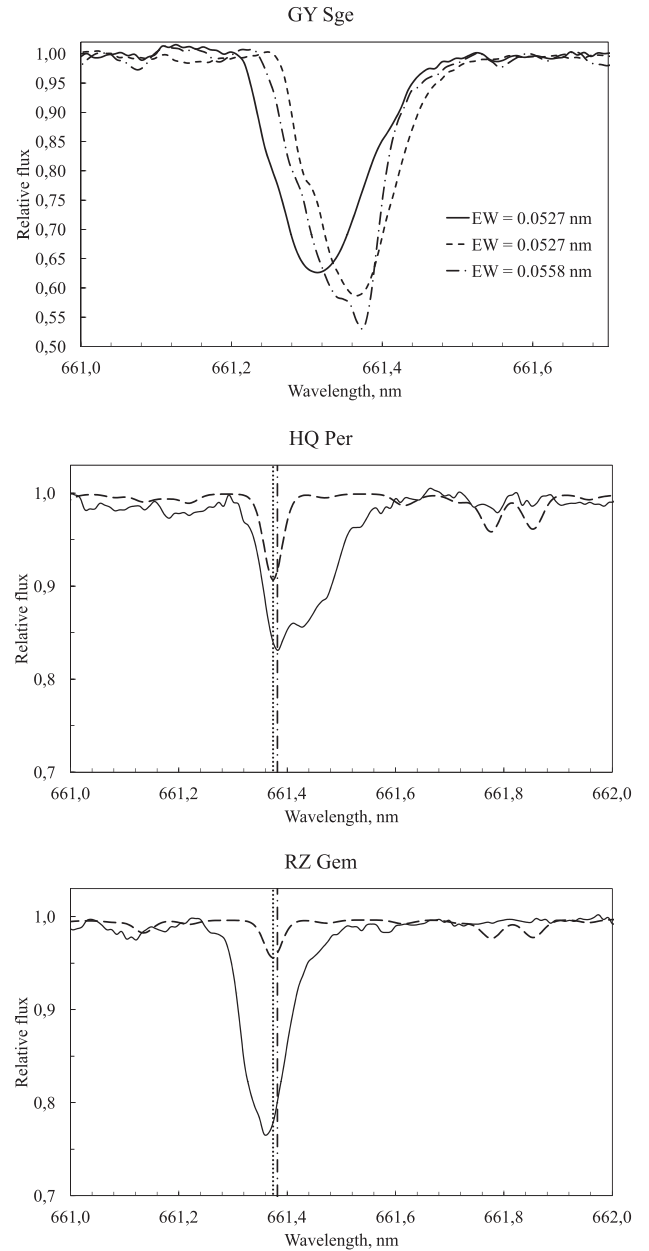
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that DIB profiles (at least some of them) change in unison with the rotational temperature of simple homonuclear molecules  $C_2$  and  $C_3$  (Każmierczak et al. 2009). The relation between temperatures of simple carbon chains and those of DIB carriers may suggest that there is a common chemical history and that the DIB carrier may be polyatomic centrosymmetric (non-polar) molecules as well. This is likely why the earlier attempts to match the electronic spectra of known polar molecules (identified in microwave region of wavelengths) and DIBs failed (Motylewski et al. 2000). In a certain sense, this phenomenon still remains an enigma for astrophysicists. For recent reviews see Cami & Cox (2014).

Doppler-shifted structures within DIBs confirm the existence of non-uniformly distributed matter in interstellar space (Weselak et al. 2010). Hence, a particular interstellar band can exhibit different profiles in different sight-lines (Galazutdinov et al. 2002). The profile differences may be due to different rotational temperatures of the carriers, similar to the differences observed in  $C_3$  (Adámkovic, Blake & McCall 2003). For additional high-resolution studies of the DIB profiles, we refer the reader to Cami et al. (2004), Galazutdinov, Lo Curto & Krelowski (2008a) and Galazutdinov et al. (2008b).

An issue with DIBs is that they are blended with spectral lines of stellar origin. Stellar lines cannot only increase the equivalent widths (EWs) of DIBs, but also distort the DIB shape and the profile boundaries. The probability of a DIB blending with stellar lines in the visible spectrum is low in stars with high effective atmospheric temperature; i.e. O and B. However, this problem can be severe in cooler supergiants and giants; i.e. those with spectral type from F to M. This is well illustrated in Fig. 1 which shows different scenarios of superimposition of stellar spectral lines on the 661.3 nm DIB in the spectra of several Cepheids (recall that the Cepheids are pulsating supergiants predominately of spectral type F and G). It should be noted that similar work where stellar blending lines were taken into account was done by Puspitarini et al. (2015) and Farhang et al. (2015) for cool stars using intermediate and low-resolution spectra.

Even though it is easier to study the structure of DIBs in the spectra of hot stars, we set ourselves the more difficult task to analyse interstellar bands in Cepheid spectra. We have two aims in this work. Our first goal is to plot the colour excess  $E(B - V)$  for our program stars against the DIB absorption EW, and use that calibrating correlation to estimate the colour excess values in future analyses of Cepheids for which  $E(B - V)$  values are not known or for which no colour information is available.  $E(B - V)$  values for the Cepheids used here are more secure than for most field stars. The values given in Table 1 are quoted from Luck & Lambert (2011). The primary source adopted in that work was the values of Fouqué et al. (2007) derived in the determination of the Cepheid period–luminosity relation. Our second goal relates to the distribution of extinction in the Galactic plane. The Cepheid pulsation period–luminosity relation allows the determination of the distance to these stars with what is assumed to be of the great accuracy, so we can attempt to construct a map of the DIB absorption distribution in the Galactic disc, and thus determine the positions of the interstellar clouds where interstellar bands are formed. This process obviously assumes that the Cepheid distance is the upper limit to the distance of the matter contributing to the DIB absorption. The distance to Galactic Cepheids currently requires accurate  $E(B - V)$  values and the total-to-selective extinction ratio; the latter is very uncertain – varying from 2.0 to 6.5 (Fitzpatrick & Massa 2007). In the near future, parallax measures of most Cepheids should become available and make Cepheid distances much more secure.



**Figure 1.** Typical examples of DIB profiles observed in the spectra of several program Cepheids. The solid line is the observed profile, while the dashed line is a synthetic spectrum showing the relative strengths and positions of intervening stellar features. Vertical lines show the positions of the yttrium  $Y\ II$  (dotted) and iron  $Fe\ I$  (dash-dotted) blending lines. Note that the stellar features at 661.8 nm are present. No attempt was made to fit these lines in detail (by correction of the oscillator strengths for these lines or by tuning the corresponding elemental abundance) as they have no influence on the DIB extraction.

## 2 SPECTRAL MATERIAL

We used spectra of Northern hemisphere Cepheids obtained by REL – one of the co-authors of this paper, with the High Resolution Spectrograph of the Hobby-Eberly Telescope at the McDonald Observatory of the University of Texas at Austin (Texas, USA) with the resolving power of 30 000, a typical signal-to-noise ratio of about 100, and wavelength range of 435–780 nm. A total of 253 Cepheid spectra were used in the research. These spectra were used to determine stellar parameters and chemical compositions in an

**Table 1.** List of observed stars, their parameters and DIB EWs (only header of the table is showed). The full table is available in electronic form.

Name	Date	Phase	$T_{\text{eff}}$ (K)	$\log g$	$V_t$ ( $\text{km s}^{-1}$ )	$d$ (pc)	$l$	$b$	$E(B - V)$	EW(Y+Fe) (nm)	EW DIB 661.3 (nm)
AA Gem 1	2010-11-08	0.422	5141	1.2	3.9	3662	184.59	2.70	0.309	3.10E-03	1.38E-02
AA Gem 2	2010-11-22	0.658	5190	1.5	5.9	3662	184.59	2.70	0.309	6.47E-03	9.14E-03
AA Mon	2009-01-14	0.841	5797	2.3	4.9	4014	217.03	-0.43	0.792	6.06E-03	2.62E-02
AA Ser	2010-04-19	0.342	5045	1.3	3.5	1963	30.79	1.74	1.603	1.41E-02	3.95E-02

investigation of the elemental abundance distribution in the Galactic disc (see Luck & Lambert 2011; Andrievsky, Luck & Korotin 2014; Korotin et al. 2014). Some characteristics of the program stars can be found in Table 1.

### 3 METHOD

The DIB at the wavelength 661.3 nm was selected as an object of the study. Its central rest wavelength is 661.356 nm (Galazutdinov et al. 2000), and its full width at half-maximum is a bit more than 0.1 nm (Galazutdinov et al. 2002). In the Cepheid spectra, in most cases this DIB is superimposed on two stellar absorption lines, namely ionized yttrium (661.373 nm) and neutral iron (661.382 nm) lines. In a few cases, the DIB falls within the spectral region where the 661.135 nm absorption line of very weak neutral carbon lies. Stellar lines coincident with a DIB will increase the measured DIB EW, but not the intrinsic DIB EW. In no case does the DIB extend blueward to the strong Fe I line at 660.911 nm. In contrast to weak lines of carbon and iron, the ionized yttrium line is strong enough in the spectra of supergiants; therefore, a correct measurement of the EW of the DIB at 661.356 nm is not feasible unless the blending lines of stellar origin are removed.

We have developed a method that enables performing such a procedure. Our methodology was briefly explained in Kashuba et al. (2015). The method consists of several steps.

(1) The accuracy of oscillator strengths of the yttrium, iron and carbon blending lines must be checked. These values are required to calculate the synthetic spectrum of a star in the vicinity of the 661.356 nm band. Preliminary values of  $\log gf$  for the lines were taken from the Vienna Atomic Line Database (<http://vald.astro.uu.se/>). The oscillator strengths for the yttrium 661.373 nm and iron 661.382 nm lines were then updated using the solar spectrum (Kurucz et al. 1984) and the iron and yttrium abundances from Grevesse, Noels & Sauval (1996). The resulting values are  $\log gf = -1.32$  for the yttrium line and  $\log gf = -5.8$  for the iron line.

(2) The atmospheric parameters (effective temperature  $T_{\text{eff}}$ , surface gravity  $\log g$ , microturbulent velocity  $V_t$  and [Fe/H]) of the program stars from the study by Luck & Lambert (2011) were used to calculate the fragments of synthetic spectra of Cepheids containing the 661.356 nm DIB. The atmospheric models of the target stars were generated using the ATLAS9 code (Kurucz 1993). The synthetic spectra were calculated using the software of Tsymbal (1996). The macro-turbulent velocity for each star (reported by Luck & Lambert 2011) was refined using the observed profile of the 660.911 nm iron line which is out of the range of the interstellar band at 661.356 nm. The yttrium and iron abundances were taken from the study of Luck & Lambert (2011).

(3) The processing of the observed spectra in the region of the target DIB (namely, accurate continuum level placement, selection of the reference wavelengths and line identification) was carried out using the DECH20 software package (Galazutdinov 1992). The

normalized region of the observed spectrum of each target star, containing both stellar lines and interstellar band, was divided by the calculated synthetic spectrum for that star. This gives the ‘undistorted’ profile of the DIB at 661.356 nm for the spectra of each of the target Cepheids.

(4) Having obtained the rectified DIB profile, the DIB EW is derived by direct integration. These values can be found in Table 1 (EWs of the DIB and blending Y II and Fe I lines in nm).

### 4 DIB EWS

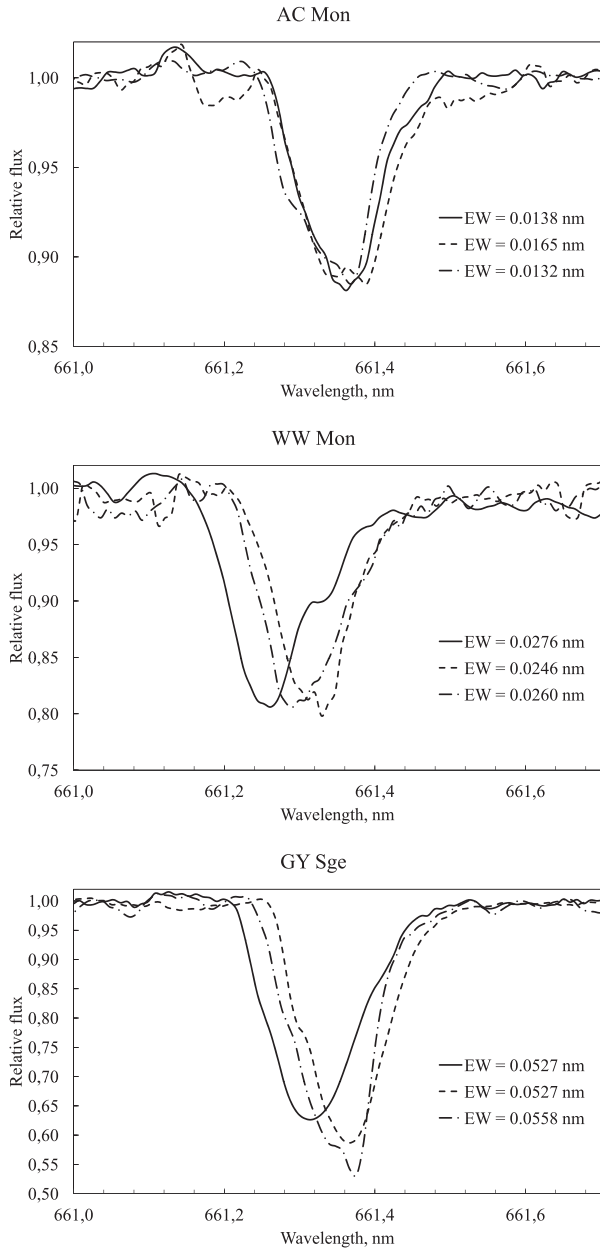
Before recovering DIB EWs and profiles, it is necessary to consider how accurate the extractions are. In the case of a single spectrum, this is essentially impossible as the background spectrum can only be inferred from the computed synthetic spectrum. That spectrum is subject to numerous uncertainties: the parameters of the Cepheid at the phase of observation and the abundances of the intruding species being the primary concern. These uncertainties are discussed in Luck & Lambert (2011) and Luck (2014). Our expectation would be that a reasonable uncertainty would be of the order of 20 per cent – that is, a line with a computed depth of 10 per cent would range between 8 and 12 per cent in depth for the allowed range of parameters and abundances. For weaker stellar lines in strong DIBs the DIB extraction should be secure. However, there will be cases where this uncertainty is a problem.

In this study, there are 62 Cepheids with two or more spectra obtained at different phases. The first is to compare the extracted EWs, and the second is to consider how well the extracted profiles compare between the different extractions.

To examine the EWs, we use as our metric the total range in DIB EW divided by the average value. That is, the (maximum EW – minimum EW)/(average EW). The mean value for the metric is 14 per cent over the 62 stars. To put this in context, the 661.356 nm DIB EW in B stars shows an uncertainty that averages 18 per cent (McCall et al. 2010) when computed in a fashion similar to that used here. It appears that our extractions give accuracies comparable to those found in B stars, a rather surprising finding given the lack of background problems in those stars.

Profiles of the 661.356 nm DIB in B stars have been published by McCall et al. (2010). The B star profiles show some variation but overall are not dissimilar to the profiles seen in these Cepheids. In Fig. 2, we show the DIBs extracted from three different Cepheids each having three observations. The integrated EW average for these three stars is AC Mon 0.0145 nm with an uncertainty of 10 per cent, WW Mon at 0.0261 nm ( $\pm 11$  per cent) and GY Sge at 0.0537 nm ( $\pm 6$  per cent).

The source of the spread in the EWs is immediately apparent – the profiles are different from extraction to extraction for the same Cepheid. This is disconcerting as it is assumed that the DIB arises in interstellar space along the line of sight and thus should be invariant. An alternate view would be that while the overall structure and strength of the DIB remains constant, small variations in the DIB



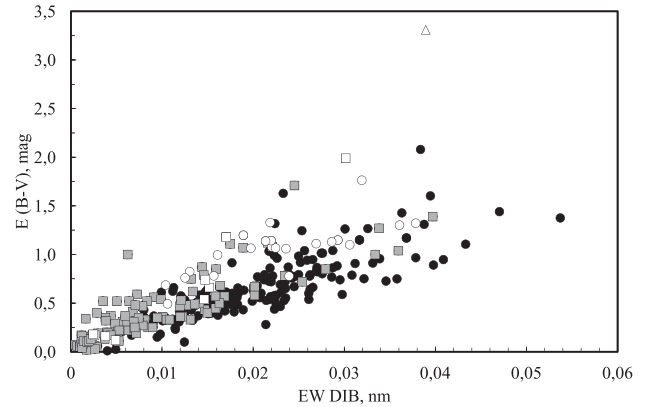
**Figure 2.** DIB extractions for three Cepheids. The wavelength scale is the photospheric rest frame for the Cepheid. The pulsation leads to velocity changes which are reflected in the DIB position relative to the assumed rest frame. See text of Section 4 for discussion of the profiles and their integrated EW.

are triggered by Cepheid dynamic events. While possible, this would be difficult to confirm given the uncertainties in the DIB extraction and the dynamic nature of Cepheid pulsation.

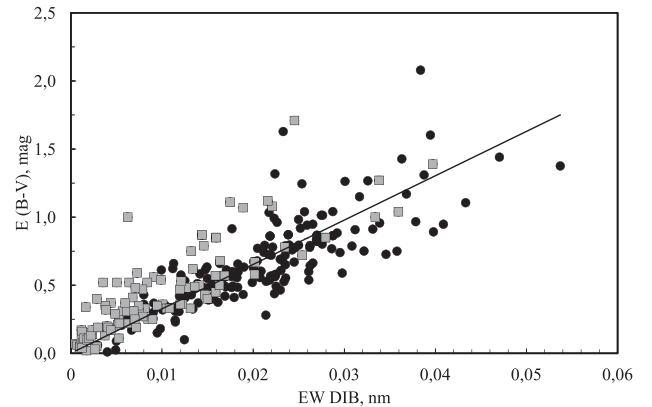
This discussion serves as a caveat emptor for the reader as we proceed with a modest interpretation of DIB strengths following the model of B star DIB interpretation relative to reddening.

## 5 RESULTS

The first item to be investigated is the correlation between the 661.356 nm DIB equivalent and the line of sight reddening. The general correlation of some DIB EWs and interstellar reddening was perhaps first shown by Merrill & Wilson (1938). Herbig (1975)



**Figure 3.**  $E(B - V)$  value versus DIB 661.356 nm EWs for Cepheids (filled circles – all program Cepheids except for Cepheids towards Cygnus constellation; open circles – Cygnus Cepheids) and B stars (grey filled squares – program B stars except for B stars towards Cygnus constellation, open squares – Cygnus B stars). Open triangle – hot star (Cyg OB2 #12 – Schulte 12 = HIP101364) with anomalous reddening (it was not used in statistics).



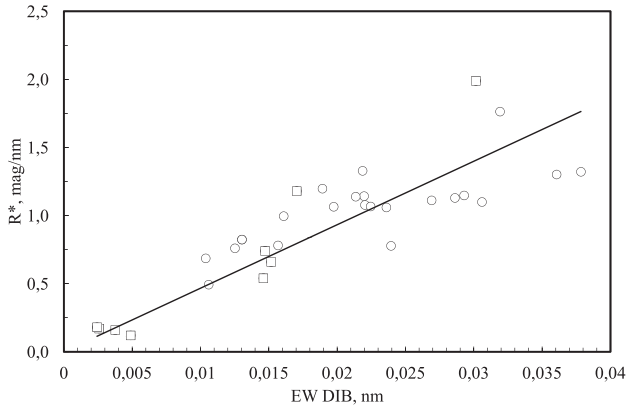
**Figure 4.** The correlation between the colour excess on the EW of the DIB at 661.356 nm for all program Cepheids (filled circles) except for Cepheids situated towards the Cygnus constellation, and B stars (grey squares).

showed that the 661.356 nm DIB correlates with  $E(B - V)$ . Later Moutou et al. (1999), Vos et al. (2011), Friedman et al. (2011), Raimond et al. (2012), Xiang, Liu & Yang (2012) and Puspitarini, Lallemand & Chen (2013) continued the study of correlation between reddening and DIB characteristics.

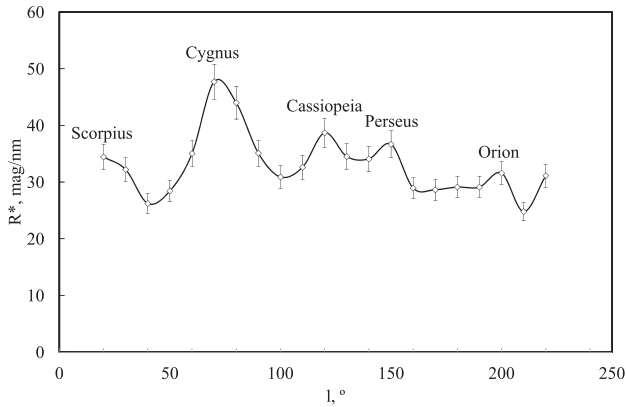
In Figs 3–5, the reddening  $E(B - V)$  is shown as a function of DIB EWs for the sample of Cepheids and the B star sample of McCall et al. (2010).

The scatter in these figures is quite large, but the same problem we can see in Maiz-Apellaniz (2015) and van Loon et al. (2013), who remarked upon the huge spread in DIB EW at a given  $A_V$ .

There are several salient points about this plot. First, as expected, the DIB EWs do correlate with  $E(B - V)$ . Secondly, the Cepheid data, on the whole, are consistent with the B star data. The Cepheid DIB EWs extend to larger values than do the B star values, but it appears both types of stars following the same relation for the bulk of the data. Thirdly, there is a bifurcation in the relation for both the Cepheid and B star data. Some stars have anomalously high  $E(B - V)$  value for a given DIB EW. As it turns out, all deviating points for the Cepheids correspond to Cepheids from the Cygnus region (open circles and open squares in Fig. 3). The non-Cygnus



**Figure 5.** The same as Fig. 4 but for Cepheids towards the Cygnus constellation.



**Figure 6.**  $R^* = E(B - V)/\text{DIB EW}$  versus Galactic longitude.

Cepheid and B stars data can be characterized by the follow relation (EW DIB is given in nm):

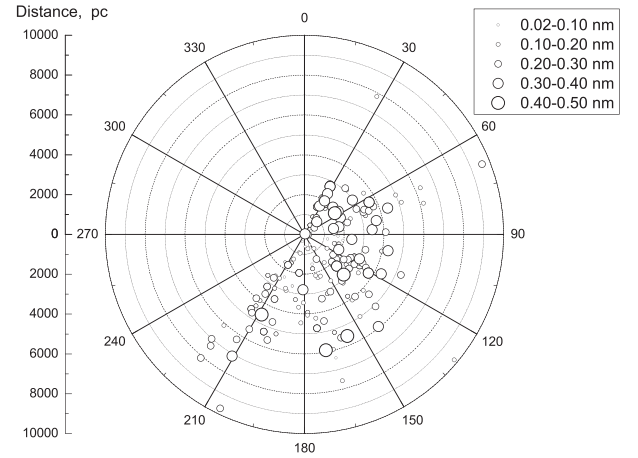
$$E(B - V) = 32.6(\pm 1.1)\text{EW DIB (nm)},$$

for the Cygnus associated Cepheids and B stars the relation is following:

$$E(B - V) = 46.6(\pm 2.4)\text{EW DIB (nm)}.$$

To obtain these relations, we forced the linear fit to cross the origin of the coordinate system as  $E(B - V)$  must equal to 0 when the DIB EW is 0 (although it is not obvious, DIB EW can be non-zero even if  $E(B - V) = 0$ , see discussion in Bailey et al. 2015, 2016, and Galazutdinov et al. 1998).

One of our goals was to be able to determine the reddening of a star from the DIB EW. Let us assume that the DIB EW can be considered a proxy for the total absorption  $A_V$  in the corresponding direction. Then, we can write  $E(B - V) = R^* A_V \sim R^* \cdot \text{DIB EW}$ . In Fig. 6, we show the binned dependence between  $R^* = E(B - V)/\text{DIB EW}$  and Galactic longitude  $l$  using the total Cepheid sample. The binning was performed within each  $10^\circ$  of  $l$ . A clear maximum of  $R^*$  seen at about  $60^\circ$  corresponds to anomalous absorption in the direction of Cygnus constellation. This is also the region where the blue hypergiant Cyg OB2-12 (HIP 101364) lies. Cyg OB2-12 is the B star in Fig. 3 at  $E(B - V)$  of about 3.3 but of an anomalously low 661.356 nm DIB EW. This further reinforces the idea that the Cygnus lines of sight have peculiar reddening and/or  $R$  values. This is not a new finding as Johnson & Morgan (1955) were perhaps



**Figure 7.** 2D map of the 661.356 nm DIB absorption distribution in the Galactic disc.

the first to note this effect. Other peaks are relevant to Scorpius, Cassiopeia, Perseus and Orion directions.

As the last item, we show in Fig. 7, a radial plot of distance versus DIB EW. What is remarkable about this plot is the intermixing of DIB EW in close longitude proximity. As an example, at  $210^\circ$  there are a number of stars at a heliocentric distance of about 10 kpc with small DIB EW but sitting between them and the Sun are numerous Cepheids with larger DIB EW and hence, larger reddening. This could indicate that the intervening material is very patchy and the exact line is critical, or that these stars lie at different distances from the plane and thus exhibit different extinction, or perhaps both ideas are in play. The counter argument to the off-the-plane idea is that Cepheids are young massive objects which help define the plane. This result needs further exploration.

Similar complexity of the spatial distribution of DIBs was also seen in the works of van Loon et al. (2009), as well as Bailey et al. (2015) and Farhang et al. (2015) who applied this procedure to the nearest few hundred pc to stars with parallax distance measurements. Kos et al. (2014) and Zasowski et al. (2015) presented projected maps of the DIB absorption field in the Galactic plane. In addition van Loon et al. (2013) mapped the 6614 Å DIB using hundreds of stars in a region within the Large Magellanic Cloud.

## 6 CONCLUSION

We performed an investigation of the 661.356 nm DIB profile in 253 spectra of 176 Cepheids. After removal of the blending  $Y_{II}$  line the EW of each DIB was calculated for each spectrum. We constructed the dependence between a colour excess  $E(B - V)$  of each program star and EW of the DIB seen in its spectrum. Such a calibrated relation can help to estimate at present unknown  $E(B - V)$  values for some Cepheids (including those recently discovered), and thus to more or less correctly estimate their heliocentric distances.

The proposed method cannot yield accurate  $E(B - V)$  values for individual stars, but as a statistical method it can offer useful estimates, in particular in the absence of other means, to determine extinction towards distant Cepheids.

We investigated the longitudinal dependence of  $R^* \sim E(B - V)/\text{DIB EW}$  assuming that the DIB EW value is a representative characteristic of the interstellar absorption  $A_V$ . We found that there is an apparent increase of the  $R^*$  value that corresponds to the abnormal absorption seen towards Cygnus constellation.

Our 2D map of the 661.356 nm DIB absorption in the Galactic disc indicates that there is not a simple relation between DIB strength and heliocentric distance because the interstellar matter is distributed in a very patchy fashion.

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## SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

**Table 1.** List of observed stars, their parameters and DIB EWs (only header of the table is showed). (<http://www.mnras.oxfordjournals.org/lookup/suppl/doi:10.1093/mnras/stw1344/-/DC1>).

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