Interstellar extinction toward Be/X-ray binary stars

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(Submitted on 21.11.2016. Accepted on 23.01.2017)

Abstract. We report optical spectroscopic observations of the Be/X-ray binaries: MWC 148, LS I +61°303, MWC 656, 4U 2206+54, X Per, γ Cas, V725 Tau, LS V +44 17, V420 Aur and the possible system LSI+59 79. The interstellar extinction is estimated using KI interstellar line and diffuse interstellar bands.

Key words: Stars: emission-line, Be – ISM: lines and bands – binaries: spectroscopic – Stars: individual: MWC 148, LS I +61°303, MWC 656, 4U 2206+54, X Per, γ Cas, V725 Tau, LS V +44 17, V420 Aur and LSI +59 79

1 Introduction

The interstellar space is in fact filled with tenuous gas and dust. The gas and dust along the line of sight dim the starlight. This effect is known as interstellar reddening or interstellar extinction. The knowledge of the physics of the interstellar dust and gas has been developed from observations of the space reddening and the interstellar polarization.

Various constituents of the gaseous interstellar medium absorb radiation at specific combinations of wavelengths. A transition from a state of low excitation to a more energetic state is made possible by the absorption of a photon having an energy equal to the difference in energy of two levels. This forms interstellar absorption lines in the spectra of distant astrophysical objects. The first interstellar lines due to Na and Ca^{+} were discovered by Hartmann (1904) and Heger (1919).

The Diffuse Interstellar Bands (DIBs) are a large number of absorption lines between $\sim$ 4000-10 000 Å. DIBs are first mentioned in the work of Heger (1922). Until now over 400 DIBs in the region between 3900 Å and 8100 Å (Hobbs et al. 2009) are registered. Identifying the carriers of the diffuse interstellar bands (DIBs) is a longstanding challenge in astronomical spectroscopy. Large molecules or their ions appear as likely candidates, however identifications are still actively debated (e.g. Friedman et al. 2011). For example the two bands at 9632 Å and 9577 Å (reported in 1994 by Foing & Ehrenfreund 1994) were suggested to arise from C_{60}^{+} molecules and confirmed by laboratory tests by Campbell et al. (2015). The DIBs at 5797 Å, 6379 Å and 6613 Å are supposed to arise due to large polycyclic aromatic hydrocarbon molecules with more than 40 C atoms, chains of 12-18 C atoms or 30 C rings (Ehrenfreund & Foing 1996). DIBs are best seen in the spectra of O or B stars, because these stars have relatively few intrinsic lines in the their spectra, as opposed to cooler stars. This makes the high-mass X-ray binaries relevant to determine the reddening by the equivalent width (EW) of the DIBs.

The high-mass X-ray binaries contain an early-type (O or B) star with mass $\geq 8\ M_\odot$ and a compact object that orbit each other. The compact object is a neutron star or a black hole. The high-mass X-ray binaries are divided into two classes: Be/X-ray binaries and supergiant X-ray binaries. In the Be/X-ray binaries, the optical companion is a Be star. In the supergiant X-ray binaries the mass donor is a luminosity class I-II star (e.g. Reig 2011).

Here we estimate the interstellar reddening using high-resolution optical spectra towards 9 northern Be/X-ray binaries and one candidate system.

2 Observations

High resolution optical spectra are secured with the fibre-fed Echelle spectrograph *ESpeRo* attached to the 2.0 m telescope of the National Astronomical Observatory Rozhen, located in Rhodope mountains, Bulgaria (Bonev et al. 2017). The spectra are reduced in the standard way including bias removal, flat-field correction, and wavelength calibration. Preprocessing of data and parameter measurements are performed using various routines provided in IRAF. Journal of observations is presented in Table 1, where the date, start of the exposure, exposure time, and signal-to-noise ratio at about λ6600 Å are given.

In Table 2 the measured equivalent widths (EW) of the prominent interstellar features are given. The measurement errors depend on the brightness of the object, S/N ratio achieved, number of the spectra obtained, and the value of EW itself.

In Fig. 1 we plot the profiles of the $H\alpha$ emission line, DIBs at λ6613 Å and λ5780 Å, and NaD_1 line. We use only the DIBs in our calculations. $H\alpha$ is given because it is important for the circumstellar disc and NaD lines are the strongest absorption features.

3 Estimates of $E(B-V)$ from interstellar lines

As a first step to evaluate the reddening we use the interstellar line K I λ7699 Å. Munari & Zwitter (1997) derived relations between equivalent width of the interstellar lines of $Na\ I\ D_1,\ D_2$ (5890.0 Å, 5895.9 Å), $K\ I$ (7699 Å) and reddening. In our spectra the interstellar lines NaD_1 and NaD_2 are among the most prominent features, however these lines are (almost) saturated in most of the objects and we use K I line. Using their Table 2, we apply the approximation in the form:

$$E_{(B-V)} = -0.00427 + 3.585\ W_{7699} + 1.765\ W_{7699}^2 \qquad K\ I\ 7699 \qquad (1)$$

The relationship between the interstellar extinction and the equivalent width of the DIBs is given in Herbig (1995), Puspitarini et al. (2013), Kos & Zwitter (2013). We use the relations by Puspitarini et al. (2013) obtained by ordinary least square (OLS*).

$$E_{(B-V)} = 5.1\ W_{6613} + 0.0008 \qquad DIB\ 6613.6 \qquad (2)$$

Table 1. Journal of observations.

Date-obs yyyymmdd	UT start	exp-time	S/N $H\alpha$
MWC 148			
20151224	02:38	40 min	60
20160130	19:43	40 min	84
LS I +61°303			
20150804	00:39	60 min	33
20151223	22:33	60 min	67
MWC 656			
20160621	22:22	30 min	54
20160922	00:53	40 min	32
20160923	20:56	40 min	46
4U2206+54			
2014-01-14	16:12	60 min	26
2014-01-14	16:12	60 min	22
2015-08-04	23:04	60 min	44
2015-12-23	16:40	60 min	80
γ **Cas**			
2014-01-14	00:42	15 min	86
LSV 4417			
2015-12-24	00:03	60 min	56
2016-01-30	20:07	60 min	55
V725 Tau			
2015-12-24	22:17	60 min	110
2016-01-30	16:54	60 min	98
X Per			
2015-12-23	20:51	10 min	114
2015-12-23	23:16	30 min	96
2015-12-24	23:48	10 min	93
V420 Aur			
2016-01-30	21:18	40 min	115
2016-12-11	22:46	40 min	118
LS I +59 79			
2016-06-22	00:10	60 min	27
2016-09-23	23:09	60 min	22

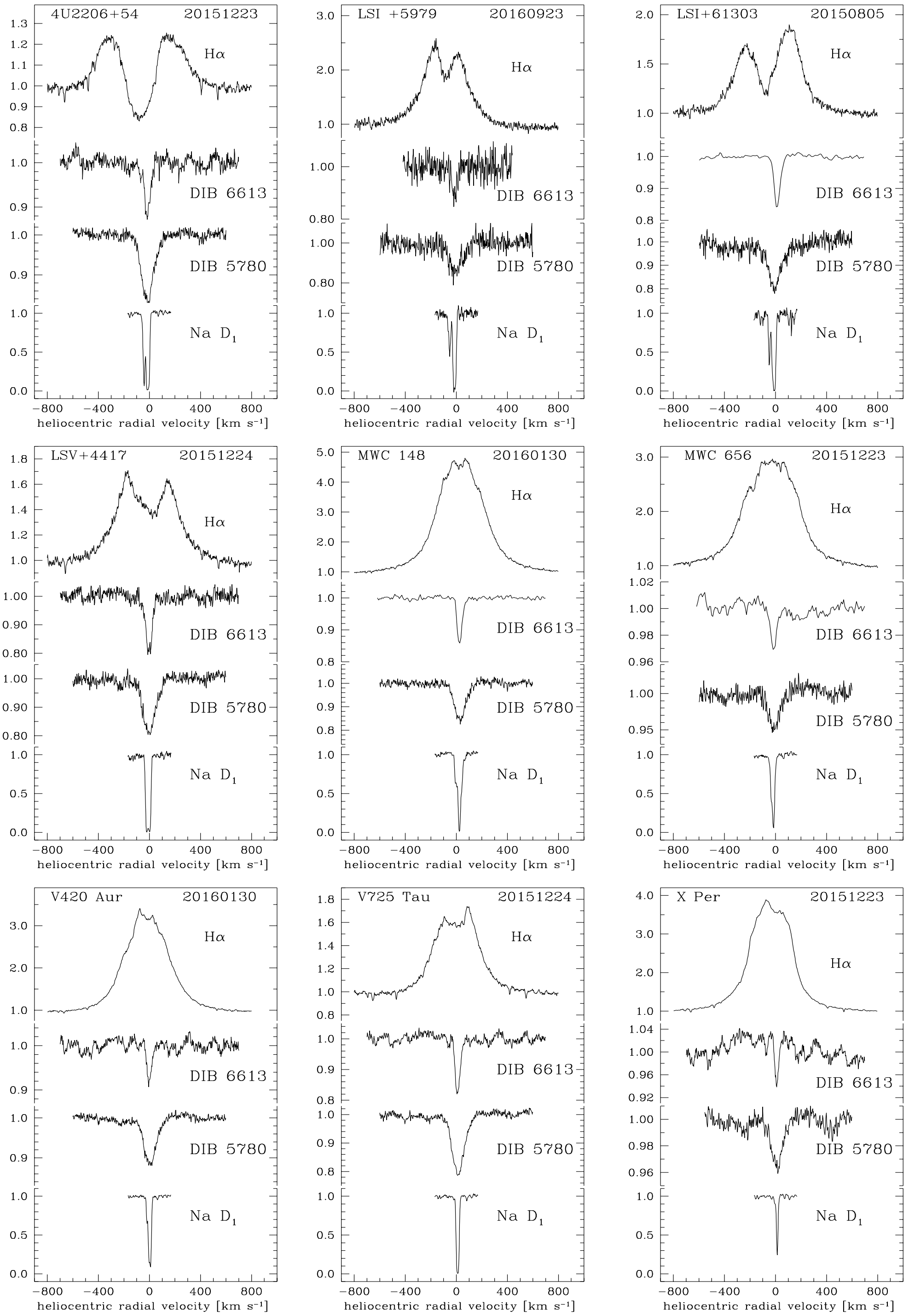

Fig. 1. Profiles of the $H\alpha$ emission line, DIBs at λ 6613 Å and λ 5780 Å, and NaD_1 line.

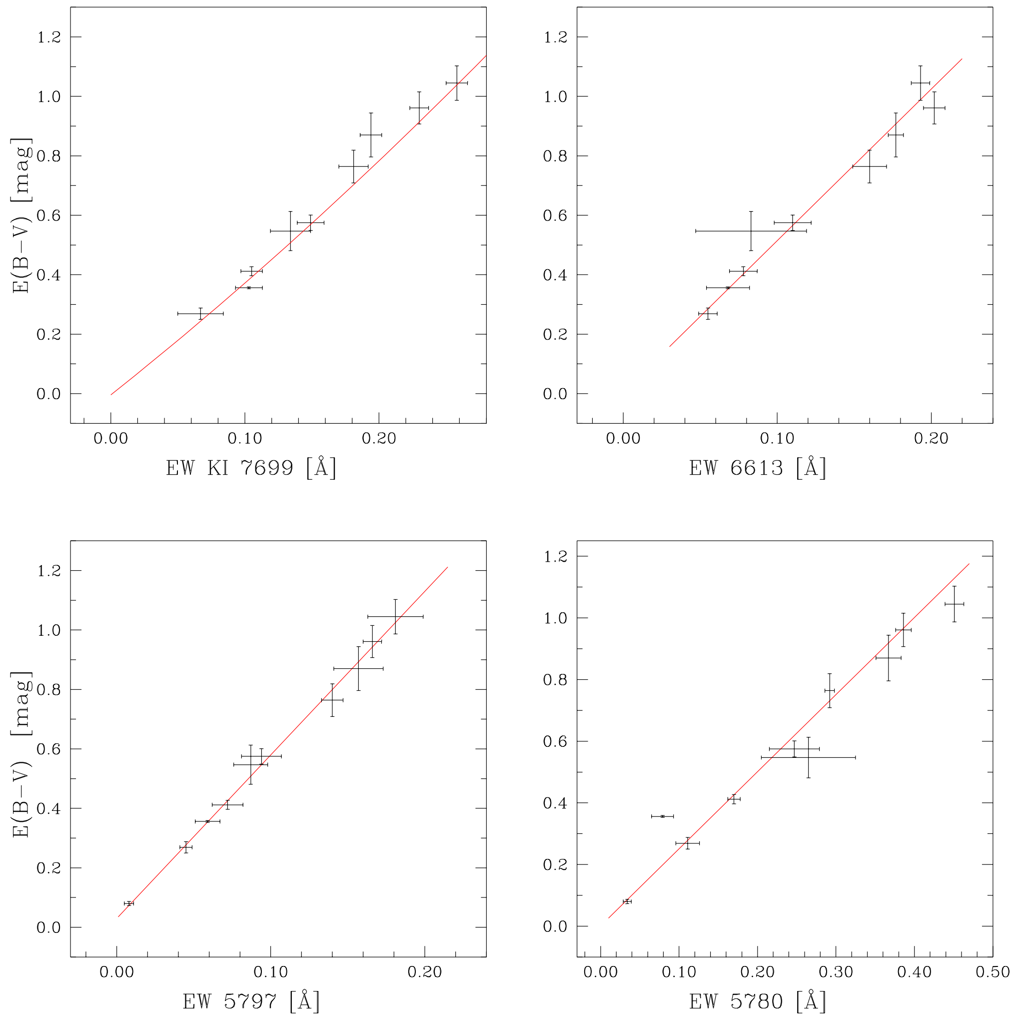

Fig. 2. The calculated average interstellar extinction E(B-V) versus equivalent width of KI λ7699 Å, DIB λ6613 Å, DIB λ5797 Å and DIB λ5780 Å. The solid lines represent Eq.1, Eq.2, Eq.3 and Eq.4, respectively.

$$E_{(B-V)} = 6.3\,W_{5797} + 0.0203 \qquad DIB\ 5797.0 \tag{3}$$

$$E_{(B-V)} = 2.3\,W_{5780} + 0.0086 \qquad DIB\ 5780.3, \tag{4}$$

where W is in Å.

In Table 3 are given E(B-V) calculated using the above equations. In Table 4 are given the average values of E(B-V) and 1-σ standard deviation of the mean.

Table 2. Equivalent widths of the interstellar absorption features.

Object	EW7699 [Å]	EW6613 [Å]	EW5797 [Å]	EW5780 [Å]
MWC 148	0.181 ± 0.011	0.160 ± 0.011	0.140 ± 0.007	0.292 ± 0.006
LS I +61°303	0.194 ± 0.008	0.177 ± 0.005	0.157 ± 0.016	0.367 ± 0.016
MWC 656	0.067 ± 0.017	0.055 ± 0.006	0.045 ± 0.004	0.111 ± 0.015
4U 2206+54	0.134 ± 0.015	0.083 ± 0.036	0.087 ± 0.011	0.265 ± 0.060
γ Cas	—	—	0.008 ± 0.003	0.034 ± 0.005
LS V +44 17	0.230 ± 0.007	0.202 ± 0.007	0.166 ± 0.006	0.386 ± 0.010
V725 Tau	0.258 ± 0.008	0.193 ± 0.006	0.181 ± 0.018	0.451 ± 0.012
X Per	0.103 ± 0.010	0.068 ± 0.014	0.059 ± 0.008	0.079 ± 0.014
V420 Aur	0.105 ± 0.008	0.078 ± 0.009	0.072 ± 0.010	0.170 ± 0.008
LSI +59 79	0.149 ± 0.010	0.110 ± 0.012	0.094 ± 0.013	0.247 ± 0.032

Table 3. Interstellar reddening E(B-V) estimated from the individual equivalent widths.

Object	E(B-V) 7699 [mag]	E(B-V)6613 [mag]	E(B-V)5797 [mag]	E(B-V)5780 [mag]
MWC 148	0.704±0.043	0.819±0.054	0.802±0.038	0.731±0.014
LS I +61°303	0.760±0.031	0.910±0.025	0.894±0.090	0.917±0.040
MWC 656	0.236±0.059	0.286±0.006	0.274±0.022	0.279±0.037
4U 2206+5	0.515±0.056	0.428±0.182	0.508±0.060	0.662±0.150
γ Cas	———	——-	0.075±0.014	0.085±0.012
LS V +44 17	0.903±0.029	1.033±0.036	0.943±0.034	0.965±0.024
V725 Tau	1.038±0.031	0.990±0.033	1.025±0.097	1.127±0.031
X Per	0.384±0.038	0.353±0.071	0.355±0.044	0.199±0.035
V420 Aur	0.397±0.030	0.401±0.048	0.424±0.056	0.426±0.019
LSI +59 79	0.574±0.037	0.567±0.061	0.548±0.073	0.611±0.081

4 Objects and results

MWC 148 (HD 259440) consists of a B0Vpe star and a compact object, most probably a $\approx 4\ M_{\odot}$ black hole with $P_{orb} = 321$ d (Aragona et al. 2010; Casares at al. 2012; Zamanov et al. 2017). For this star Friedemann (1992) estimated E(B-V)=0.85 from the 217 nm band. We measure a lower value of $E(B-V) = 0.764 \pm 0.055$.

LS I +61°303 (V615 Cas) consists of a B0.5Ve star and most probably a neutron star with a mass $\approx 1.6\ M_{\odot}$(Zamanov et al. 2017) with $P_{orb} =$ 26.496 d (Gregory 2002) and $e = 0.54$ (Aragona et al. 2010). For this object Hutchings & Crampton (1981) give $E(B-V) = 0.93$. Howarth (1983)obtained $E(B-V) = 0.75 \pm 0.1$ using 2200 Å extinction bump. Steele et al. (1998) estimated $E(B-V) = 0.70 \pm 0.40$ from Na I D_2 and $E(B-V) = 0.65 \pm 0.25$ from diffuse interstellar bands. For LS I +61°303 we measure $E(B-V) = 0.870 \pm 0.074$.

MWC 656 (HD215227) consists of a B1.5-B2IIIe star and a black hole with $P_{orb} = 60.37$ d and $e = 0.40$ (Williams et al. 2010; Casaraes at al. 2012). For this star Williams et al. (2010) give a low value E(B-V)=0.02. Casares et al. (2014) estimated E(B-V)=0.24. We estimate $E(B-V) =$ 0.269 ± 0.019, higher than the value by Casares et al. (2014).

4U 2206+54 (LS III +54 16) consists of a O9.5Vep donor star and a neutron star (Ribó et al. 2006) with $P_{orb} = 9.57$ d, and $e = 0.30$ (Stoyanov et al. 2014). For this object Reig & Fabregat (2015) gives $E(B-V) =$ 0.51 ± 0.03. Our result is very similar, $E(B-V) = 0.547 \pm 0.066$.

γ **Cas** has $E(B-V) = 0.07$ derived from the 2200 Å extinction bump and from the position in the Galaxy (Beeckmans & Hubert 1980; Harmanec 2002). Chevalier & Ilovaisky (1998) give $E(B-V) = 0.05$. Our result is $E(B-V) = 0.080 \pm 0.007$.

LS V +44 17 (RX J0440.9+4431) consists of a B0.2Ve star (Reig et al. 2005) with $P_{orb} = 150.0 \pm 0.2$ d (Ferrigno et al. 2013). For this star there are two values of the extinction $E(B-V) = 0.65 \pm 0.05$ (Reig et al. 2005) and $E(B-V) = 0.91 \pm 0.03$ (Reig & Fabregat 2015). Our value is $E(B-V) = 0.961 \pm 0.054$.

V725 Tau (1A 0535+262) consists of a B0IIIe star (Janot-Pacheco et al. 1987) and a neutron star with $P_{orb} = 111.0 \pm 0.4$ d (Giovannelli et al. 2015) and $e = 0.47$ (Finger et al. 1994). For this star Reig et al. (2015) give $E(B-V) = 0.77 \pm 0.04$. The reddening to the object was determined from the 2200 Å feature to be $E(B-V) \approx 0.75$ (Giovannelli et al. 1981). We estimate a higher value $E(B-V) = 1.045 \pm 0.058$.

X Per consists of a B0Ve star (Lyubimkov et al. 1997) and a neutron star. Delgado-Martí et al. (2001) find $P_{orb} = 250.3$ d and $e = 0.11$ by pulse time analysis of the 837 s pulsations. We find $E(B-V) = 0.356 \pm 0.003$, in agreement with the value $E(B-V) = 0.35$ (Viotti et al. 1982). Our result is based on three lines, because DIBλ5780 gives a lower value and is not used (see Table 2 and 3).

V420 Aur (MWC 107) harbours a B0IVpe star (Everall et al. 1993). The interstellar reddening is $E(B-V) = 0.42 \pm 0.05$ (Everall et al. 1993; Chevalier & Ilovaisky 1998). Our value is $E(B-V) = 0.412 \pm 0.015$

LS I +59 79 is a B1/2Vnne star (McCuskey et al.1974). The LS I+59 79 position is remarkably consistent with the X-ray and γ-ray sources 1RXS J013326.9+592946 and 3FGL J0133.3+5930, respectively. This object has been recently confirmed as a binary system with an orbital period of 1.94 d based on photometric observations (see Martí et al. 2015 and references therein). However, its X-ray or γ-ray binary nature remains to be confirmed yet. We include it in this work to assist in future studies. For LS I+59 79 we measure $E(B-V) = 0.575 \pm 0.026$.

Table 4. The average values of the interstellar extinction toward 9 Be/X-ray binaries.

Object	E(B-V) [mag]	Reference	E(B-V) (this work) [mag]
MWC 148	0.85	Friedemann(1992)	0.764 ± 0.055
LS I +61°303	0.65	Steele at al. (1998)	0.870 ± 0.074
MWC 656	0.24	Casares et al.(2012)	0.269 ± 0.019
4U 2206+54	0.51	Reig & Fabregat (2015)	0.547 ± 0.066
γ Cas	0.05	Chevalier & Ilovaisky (1998)	0.080 ± 0.007
LS V +44 17	0.91	Reig & Fabregat (2015)	0.961 ± 0.054
V725 Tau	0.77	Reig et al. (2015)	1.045 ± 0.058
X Per	0.35	Viotti et al. (1982)	0.356 ± 0.003
V420 Aur	0.42	Everall et al. (1993)	0.412 ± 0.015
LSI +59 79	—	—	0.575 ± 0.026

As an illustration of our results, in Fig. 2 the calculated interstellar extinction $E(B-V)$ versus the equivalent width of KI λ7699 Å, DIB λ6613 Å, DIB λ5797 Å and DIB λ5780 Å are plotted. It is visible that the deviation of the points from the solid lines is of the order of the estimated error.

Conclusions: We estimate the interstellar extinctions toward 9 Be/X-ray binaries and one possibly related system. In most cases the results are in agreement with published values which means that the applied technique is relevant and the measured extinction should provide useful input for theoretical modeling.

Acknowledgments: This research was partially supported by the Bulgarian National Science Fund of the Ministry of Education and Science under grant DN 08-1/2016. RZ and JM acknowledge partial support from the grant AYA2016-76012-C3-3-P from the Spanish Ministerio de Economía y Competitividad (MINECO). JM also acknowledges support from Consejería de Economía, Innovación, Ciencia y Empleo of Junta de Andalucía under excellence grant FQM-1343 and research group FQM-322, as well as FEDER funds. We also thank the anonymous referee for the useful suggestions that improved the paper.

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