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ANALYSIS OF INTERSTELLAR EXTINCTION TOWARDS THE HYPERGIANT CYG OB2 No. 12

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Abstract. The Cyg OB2 stellar association hosts an entire zoo of unique objects, and among them – an enigmatic star Cyg OB2 No. 12 (Schulte 12, MT 304). MT 304 is enigmatic not only due to its highest luminosity (according to various estimates, it is one of the brightest stars in the Galaxy), but also because its reddening is anomalously large, greater than the mean reddening in the association. To explain the nature of anomalous reddening ($A_V \simeq 10$ mag) of MT 304, we carried out spectrophotometric observations of 25 stars located in its vicinity. We mapped interstellar extinction within the 2.5 arcmin radius and found it to increase towards MT 304. According to our results, the two most reddened stars in the association after MT 304 are J203240.35+411420.1 and J203239.90+411436.2, both located about 15 arcsec from it. Interstellar extinction A_V towards these stars is about 9 mag. Our results favor the hypothesis of the circumstellar nature of reddening excess. In the second part of the paper we present the results of our modeling of MT 282 (B1 IV) and MT 343 (B1 V), which belong to the older population of the association and have ages greater than 10 Myr.

Key words: stars: early-type, atmospheres, fundamental parameters – Galaxy: open clusters and associations: individual (Cyg OB2) – stars: individual : MT 304, MT 343, MT 282

1. INTRODUCTION

The Cyg OB2 association[1], discovered by Münch & Morgan (1953), is now one of the leaders in the number of massive stars among Galactic OB-associations. According to the estimates of Knödlseder (2000), it contains 2600 ± 400 stars and about 100 of them are O-stars located within a one square degree area (Comerón et al. 2002; Wright et al. 2010, 2015). The researchers' interest in individual stars and in the association as a whole is not fading. The stellar population in Cyg OB2 (like Drew et al. 2008; Comerón & Pasquali 2012) as well as interstellar extinction

[1] The Galactic coordinates of Cyg OB2 according to SIMBAD database are $l = 80.22°$and $b = +0.8°$.

(like Guarcello et al. 2012) and the history of star formation (like Wright et al. 2014, 2015) in this association have already been a subject of numerous studies and new papers continue to appear.

Furthermore, Cyg OB2 is one of the closest star-forming regions to the Sun. Many authors estimated the distance to Cyg OB2 using different methods. For example, spectrophotometric measurements of the distance span a range that includes 1.5 kpc (Johnson & Morgan 1954), 2.1 kpc (Reddish et al. 1966), 1.7 kpc (Massey & Thompson 1991; Torres-Dodgen et al. 1991), and 1.45 kpc (Hanson 2003). Kiminki et al. (2015) found the distance to be 1.33 kpc based on their analysis of double-lined spectroscopic binaries. In this paper, like in our previous studies (Maryeva et al. 2013, 2014), we use the distance estimate $d = 1.5$ kpc adopted from Mel'nik & Dambis (2009), where the distance-scale zero point is adjusted by analyzing the line-of-sight velocities and proper motions of OB-associations.

Interstellar extinction toward Cyg OB2 was investigated in several studies (Hanson 2003; Kiminki et al. 2007; Wright et al. 2010, 2015). Compared to other bright stars in the association, MT 304 (Cyg OB2 No. 12, Schulte 12) is significantly more reddened (Klochkova & Chentsov 2004; Chentsov et al. 2013). Sharpless (1957) estimated interstellar extinction toward it as $A_V \simeq 10.1$ mag. This initial estimate is in good agreement with contemporary data (Kiminki et al. 2007; Wright et al. 2015). According to Wright et al. (2015), the interstellar-extinction difference between MT 304 and MT 488, the second most reddened star, is $\Delta A_V = 1.9$ mag. The nature of this excessive absorption remains unclear. Could it originate in a small dense dust cloud, which accidentally happens to be on the same line of sight? Or does it arise in a circumstellar shell?

In this paper we report the results of long-slit spectroscopy and photometry of stars located around MT 304 within 1 arcmin radius. We also summarize the results of modeling of two dwarf star members of this association.

2. OBSERVATIONS AND DATA REDUCTION

We performed spectroscopic observations of stars close to MT 304 using the Spectral Camera with Optical Reducer for Photometric and Interferometric Observations (SCORPIO) (Afanasiev & Moiseev 2005, 2011) operated in the long-slit mode with the grism VPHG 1200G and mounted on the the Russian 6-m telescope. Its spectral resolution is ~ 5Å, and spectral range, 4000–5800 Å. All the SCORPIO spectra were reduced using the `ScoRe` package, which was written in IDL language and includes all the standard stages of long-slit data reduction process.

The B- and V-band images of the sky region around MT 304 were acquired on 2013 May 30 using the same SCORPIO focal reducer. The images were bias subtracted and flat-fielded, and aperture photometry was then performed using the SExtractor package (Bertin & Arnouts 1996). We calibrated the instrumental magnitudes of each image using the B- and V-band photometry of selected stars published by Massey & Thompson (1991). Table 1 shows the results of photometry for all stars in our sample.

3. INTERSTELLAR EXTINCTION

Besides Cyg OB2 No. 12 (MT 304), the only stars of our sample that have been previously studied spectroscopically are two: MT 343 (J203250.75+411502.2) and J203231.49+411408.4 (Kiminki et al. 2007; Negueruela et al. 2008). We performed

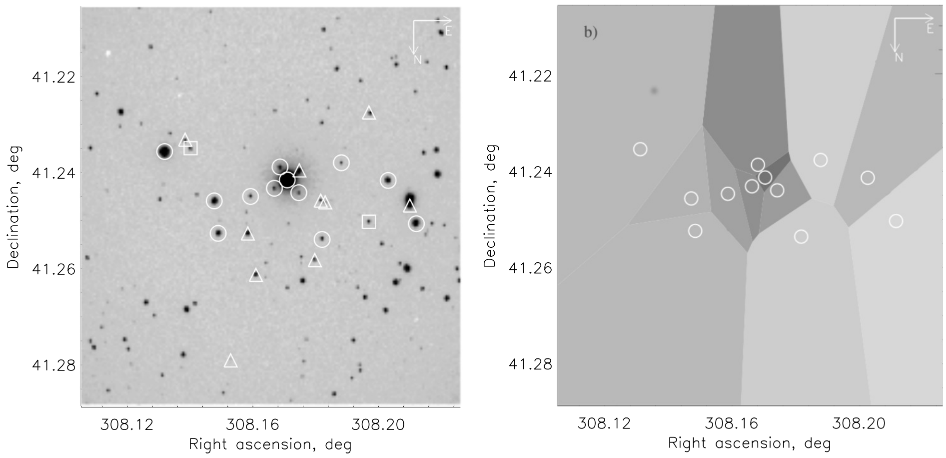

Fig. 1. Left: R-band image of the central part of Cyg OB2 in the vicinity of MT304 acquired with SCORPIO. The circles, triangles and squares mark the member, foreground and background stars, respectively. Right: Voronoi tessellated extinction map (one star per Voronoi cell) for twelve sample member stars (except for USNO-B1.0 1312-0389914) of Cyg OB2.

spectral classification of all stars from our sample and, by combining the results with photometric data, measured interstellar extinction toward them and estimated their distances (see Table 1). We determined the spectral types of stars to within several subtypes. That is why we give in Columns 2 and 3 of Table 1 the lower and upper limits for the spectral type. Columns 4, 5 and 6, 7 give the corresponding lower and upper limits for absolute magnitude M_V and intrinsic color index $(B-V)_0$. In accordance with this logic, Columns 10, 11 and 12, 13 give the upper and lower limits for A_V and heliocentric distance, respectively, for all stars of the sample. It is evident from Table 1 that about half of the stars lie between us and the Cyg OB2 association. Interstellar extinction not only increases with distance but also becomes inhomogeneous at $d > 1$ kpc. Moreover, our sample contains one background star, J203233.44+411406.0, which is located behind the association. Different symbols in Fig. 1 show the foreground stars, association members, and background stars. The A_V estimates listed in Table 1 and the map of interstellar extinction based on these estimates (the right panel in Fig. 1) show that extinction in the association increases toward MT 304. J203240.35+411420.1 and J203239.90+411436.2 are the most reddened stars after MT 304. They are located 13″ and 15″ from MT 304, and extinction A_V toward them is equal to 9.15 mag and 9.03 mag, respectively. It is highly improbable that a small (< 0.5 arcmin) cold dust cloud would lie exactly on the line of sight eclipsing only MT 304. We therefore tend to conclude that anomalous reddening in our case is of circumstellar nature. We suppose that 1.5 to 2 magnitudes are absorbed in the interstellar gas between us and the association, about 6 magnitudes are absorbed inside the association, and two more magnitudes are absorbed by a circumstellar shell with the size of about 0.1 pc.

Table 1. Interstellar extinction towards, and the distances to, stars in the vicinity of MT 304. Here the absolute magnitudes M_V and intrinsic color indices $(B-V)_0$ are adopted from Schmidt-Kaler (1982).

SDSS	Spectral type		M_V, [mag]		$(B–V)_0$, [mag]		B, [mag]	V, [mag]	A_V, [mag]		d, [kpc]	
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
Foreground stars												
J203250.25+411448.4	G8 V	G9 V	+5.5	+5.7	+0.74	+0.775	14.68	13.7	0.72	0.615	0.31	0.3
J203247.28+411339.0	K0 V	K7 V	+5.9	+8.1	+0.81	+1.33	18.53	17.08	1.94	0.38	0.7	0.5
J203247.17+411501.0	G8 IV	K0 IV	+3.1	+3.1	+0.84	+0.91	21.63	18.68	6.33	6.1	0.7	0.8
J203243.84+411446.5	K0 V	K2 V	+5.9	+6.4	+0.81	+0.91	20.89	19.18	2.7	2.4	1.3	1.2
J203243.49+411445.1	K7 V	M2 V	+8.1	+9.9	+1.33	+1.49	19.62	18.02	0.8	0.3	0.7	0.4
J203243.01+411529.9	M2 V	M5 V	+9.9	+12.3	+1.49	+1.64	19.35	17.7	0.47	0	0.3	0.1
J203241.84+411422.14	G8 V	K1 V	+5.5	+6.15	+0.74	+0.86	16.01	15.02	0.8	0.4	0.6	0.5
J203238.51+411541.2	G8 V	K0 V	+5.5	+5.9	+0.74	+0.81	17.3	16.14	1.16	1.25	0.75	0.7
J203237.89+411509.7	F0 V	F1 V	+2.7	+3.15	+0.3	+0.325	16.64	15.41	2.79	2.71	1.0	0.8
J203236.58+411644.7	K1 V	K7 V	+6.15	+8.1	+0.86	+1.33	22.4	20.44	3.3	1.9	1.6	1.2
J203233.07+411359.6	F8 V	G2 V	+4.0	+4.7	+0.52	+0.63	18.93	17.43	2.94	2.6	1.25	1.05
Association members												
J203250.75+411502.2[a]	B1 V	B2 V	–3.2	–2.45	–0.26	–0.24	16.38	14.41	6.68	6.62	1.5	1.12
J203248.62+411429.8	B1 V	B2 V	–3.2	–2.45	–0.26	–0.24	17.85	15.54	7.7	7.64	1.6	1.2
J203245.07+411416.5	B8 V	A1 V	–0.25	+1.0	+0.11	+0.01	21.13	18.86	7.16	6.8	2.5	1.6
J203243.61+411513.9	B5 V	B7 V	–1.2	–0.6	–0.17	–0.13	19.8	17.56	7.2	7.0	2.0	1.6
J203241.80+411439.2	B5 V	B9 V	–1.2	+0.2	–0.17	–0.07	21.7	18.94	8.78	8.5	1.9	1.1
J203240.89+411429.6[b]	B5 Ia-0		–8.4		–0.08		14.7	11.52	9.78		1.1	
J203240.35+411420.1	B2 V	B5 V	–2.45	–1.2	–0.24	–0.17	20.57	17.76	9.15	8.94	1.6	1.0
J203239.90+411436.2	B5 V	B6 V	–1.2	+0.9	–0.17	–0.15	21.58	18.74	9.03	9.00	1.5	1.35
J203238.09+411441.8	B5 V	B7 V	–1.2	–0.6	–0.17	–0.13	20.85	18.24	8.4	8.2	1.7	0.8
J203235.63+411509.6	B1 V	B2 V	–3.2	–2.45	–0.26	–0.24	18.14	15.82	7.75	7.7	1.8	1.3
J203235.33+411445.3[c]	B1 V	B1 IV	–3.2	–3.8	–0.26		17.29	14.9	7.94		1.0	1.4
J203231.49+411408.4	O7.5 Ib-IIf		–6.3	–5.8	–0.31	–0.32	15.12	12.9	7.6	7.62	2.0	1.6
USNO-B1.0 1312 -0389914	B7 V	A2 V	–0.6	+1.3	–0.13	+0.05	19.19	17.27	6.15	5.61	2.2	1.2
Background stars												
J203233.44+411406.0	B5 V	B7 V	–1.2	–0.6	–0.17	–0.13	20.48	18.26	7.16	7.04	2.9	2.3

Notes in Col. (1) : *a* – J203250.75+411502.2 is MT 343; *b* – J203240.89+411429.6 is MT 304; *c* – J203235.33+411445.3 is MT 282.

Table 2. Physical parameters of MT 282 and MT 343 estimated using CMFGEN.

Star	Spectral type	$\log L/L_\odot$	$T_{\rm eff}$ [kK]	$R_{2/3}$ [$R_\odot$]	M_* [$M_\odot$]	$\log g$ [cm s^{-2}]	V_∞ [km s^{-1}]
MT 282	B1 IV	4.4	25	8.42	<26	4.0	2230
MT 343	B1 V	4.3	26	6.7	<16.4	4.0	2230

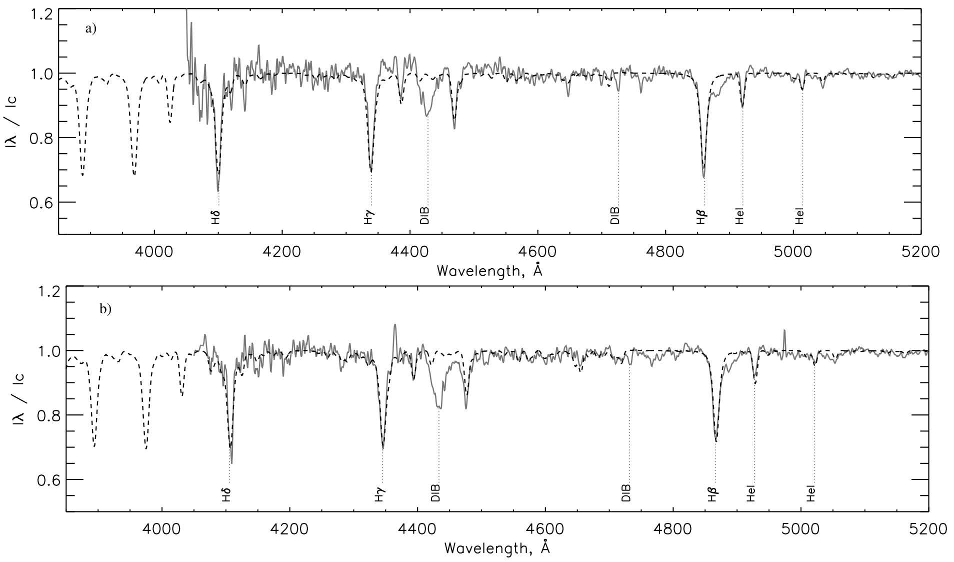

Fig. 2. Comparison of the observed continuum-normalized spectra of MT 282 (top) and MT 343 (bottom) with the CMFGEN-model (the dashed line).

4. MODELING USING CMFGEN

The large magnitude range of stars studied, $V = 13 - 20$ mag, made it possible to significantly reduce the difference in absorption between MT 304 and other members of the association. Moreover, the quality of our spectra for the two brighter stars, MT 282 (J203235.33+411445.3, $V = 14.9$, signal-to-noise ratio in the spectrum $S/N = 50$) and MT 343 (J203250.75+411502.2, $V = 14.4$, $S/N = 70$) allowed us to conduct a more detailed investigation of these stars using numerical simulation.

We determined the stellar parameters using CMFGEN code (Hillier & Miller 1998) developed for computing spherically symmetric model atmospheres for stars with extended winds. We adopted the surface gravity, terminal wind velocity, and mass-loss rate of $\log g = 4$, $V_\infty = 2.65\,V_{\rm esc}$, and $\dot{M} = 1 \cdot 10^{-8}$, respectively. The fact that the stars considered are members of the Cyg OB2 association with known distance (see Introduction) allowed us to accurately determine their luminosities. Table 2 lists the computed atmospheric parameters and Fig. 2 shows the corresponding best-fit models. Our modeling demonstrates that MT282 is brighter than

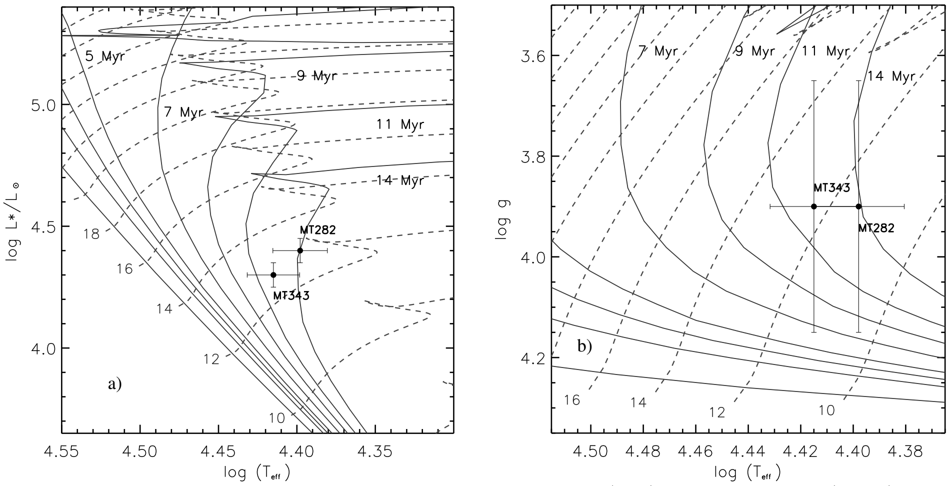

Fig. 3. Location of MT 282 and MT 343 on the HR (left) and $\log g$, $T_{\rm eff}$ (right) diagrams. Evolutionary tracks (the dashed lines) and isochrones (the dashed-dotted lines) are adopted from Ekström et al. (2012).

MT 343 and suggests that MT 282 is a star of luminosity class IV. This conclusion is further corroborated by the difference in line intensities (absorption lines in the spectrum of MT 282 are weaker than in that of MT 343).

Fig. 3 shows the location of the stars studied on the Hertzsprung-Russell (HR) diagram as well as evolutionary tracks and isochrones adopted from the Geneva database (Ekström et al. 2012). Most of the stars in Cyg OB2 have ages between 4–5 Myr (Wright et al. 2015) and therefore, according to our measurements, MT 282 and MT 343 belong to the older population of Cyg OB2.

5. CONCLUSIONS

We performed long-slit spectroscopy and photometry of 25 stars with V-band magnitudes in the range from 13 to 20 and located in the neighborhood of the unique hypergiant MT 304. We conclude, based on our constructed interstellar reddening map, that the maximum extinction in the association is about 8 mag. The excess reddening of MT 304 forms in a circumstellar shell with the radius of some tenths of a parsec. J203240.35+411420.1 and J203239.90+411436.2 are the most reddened stars after MT 304. These stars are located $13''$ and $15''$ from MT 304, and have a total extinction A_V of 9.15 mag and 9.03 mag, respectively. The shell of MT 304 probably also affects J203240.35+411420.1 and J203239.90+411436.2.

We modeled B1-type stars MT 282 and MT 343 and convincingly demonstrated that they belong to the older population of the association, having ages > 10 Myr.

For more details and discussions, see our forthcoming papers (Maryeva et al. 2016a,b).

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