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HIGH-RESOLUTION SPECTROSCOPY OF THE B[e] STAR MWC 645

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ABSTRACT. Optical high-resolution spectroscopic observations of the emission-line star MWC 645 are presented. The spectrum exhibits strong variable double-peaked Balmer emission lines as well as low-excitation emission lines of Fe II, [Fe II], and [O I] which are signatures of the B[e] phenomenon, while lines of helium have not been found. In addition to the emission lines, for the first time we identified absorption lines of neutral metals (e.g., Li I 6708 Å, Ca I 6717 Å, and a number of Fe I and Ti I lines) that indicate the presence of a cool component in the system. The heliocentric radial velocity measured in our best spectrum was found to be -65.1 ± 1.0 km s^{-1} for the emission lines and -23.2 ± 0.4 km s^{-1} for the absorption lines. Using a combination of photometric and spectroscopic data as well as the Gaia EDR3 distance (D=6.5±0.9 kpc), we disentangled the component contributions and estimated their temperatures and luminosities ($\sim$15000 K and $\sim$4000 K, $\log L/L_{\odot} = 3.8\pm0.2$ and 2.8 ± 0.2 for the hot and cool component, respectively).

АНОТАЦІЯ. Представлено оптичні спектроскопічні спостереження високої роздільної здатності зірки лінії випромінювання MWC 645. Спектр демонструє потужні лінії випромінювання Бальмера з подвійними піками, а також лінії випромінювання з низьким рівнем збудження Fe II, [Fe II] і [O I], які є ознаками феномену B[e], в той час як лінії гелію не були знайдені. Крім емісійних ліній, ми вперше ідентифікували лінії поглинання нейтральних металів (наприклад, Li I 6708 Å, Ca I 6717 Å, а також ряд Fe I і Ti I лінії), що вказують на наявність холодного компонента в системі. Виявлено, що геліоцентрична радіальна швидкість, виміряна в нашому найкращому спектрі, становить $-65{,}1\pm1{,}0$ км s^{-1} для ліній випромінювання та $-23{,}2\pm0{,}4$ км s^{-1} для ліній поглинання. Використовуючи комбінацію фотометричних і спектроскопічних даних, а також відстань Gaia EDR3 (D=6,5±0,9 кпк), ми розібрали внески компонентів і оцінили їх температуру та світність ($\sim$15000 K і $\sim$4000). K, $\log L/L_{\odot} = 3,8\pm0,2$ і $2{,}8\pm0{,}2$ для гарячого та холодного компонентів відповідно).

Keywords: circumstellar matter — stars: early-type — stars: emission-line, B[e] — stars, stars — individual: MWC 645.

1. Introduction

The class of B[e]-type stars was introduced by Allen & Swings (1976) and first systematically analyzed Lamers et al. (1998), who suggested to call them objects with the B[e] phenomenon. This class is characterized by the presence of strong Balmer emission lines, narrow permitted and forbidden low-excitation emission lines of Fe II, [Fe II], N II and [O I], and in particular a strong near- to mid-IR excess due to radiation of circumstellar dust in the spectra of B–type stars. These properties are observed in stars with a wide range of masses and evolutionary states. Despite a strong progress in understanding of these complex objects, nature of many of them was not revealed that prompted Miroshnichenko (2007) to introduce a subgroup named FS CMa type objects and suggest that they are binary systems at a post mass-exchange evolutionary stage.

MWC 645 is one of the original objects selected by Allen & Swings (1976) which has not been closely studied. Swings & Allen (1973) studied the blue spectral region of MWC 645 using 20 Å mm^{-1} coudé spectra taken in 1971. They found that all strong emission lines of Fe II and [Fe II] had double-peaked profiles with a radial velocity (RV) of 150 km s^{-1} separation between a stronger red and a weaker blue peak. The profiles of Hγ and Hδ exhibited three components. Swings & Allen (1973) compared the spectrum with that of η Car and found similar low-excitation emission lines, while MWC 645 exhibited almost no emission lines of high excitation. Low-resolution spectra were investigated by Swings & Andrillat (1981). Medium resolution spectra were studied by Jaschek et al.(1996), who found a heliocentric RV of the emission lines to be -76 km s^{-1}. In this paper we report the results of high-resolution spectroscopy of MWC 645 aimed at determining its fundamental parameters and concluding on its nature and evolutionary status.

2. Observations

The spectroscopic observations of the MWC 645 were obtained at the 2.7 m Harlan J. Smith telescope of the McDonald Observatory (Texas, USA, spectral resolving power R = 60,000) with the Tull coudé spectrograph TS2 (Tull et al., 1995), 2.1 m telescope of the Observatorio Astronomico Nacional San Pedro Martir (OAN SPM, Baja California, Mexico, R = 18,000) with a REOSC spectrograph, 6 m telescope of the Special Astrophysical Observatory of the Russian Academy of Sciences (SAO RAS, Nizhnij Arkhyz, Russia, R = 60,000) with the NES échelle spectrograph (Panchuk et al., 2017), and the 3.6 m Canada-France-Hawaii Telescope (CFHT, Mauna Kea, HI, USA, R = 65,000) with the ESPaDOnS spectropolarimeter (Manset & Donati, 2003). The spectra were reduced with the *echelle/slit* package in IRAF program except for the CFHT data, which were reduced with the Upena and Libre-ESpRIT software packages (Donati et al., 1997). A total of 13 high-resolution spectra were taken between 2004 and 2016.

3. Spectral analysis

The optical spectrum of MWC 645 exhibits emission and weak absorption lines including diffuse interstellar bands (DIBs). The strong permitted and forbidden emission lines in the spectrum of MWC 645 are represented by hydrogen (Balmer and Paschen series), Fe II, Cr II, Ti II, Ca II, O I, [Fe II], and [O I]. RVs of both the emission and absorption lines were determined by fitting the line profiles to a Gaussian. The spectral lines were identified using a catalog by Coluzzi (1999) and the equivalent widths (EW) were measured by integration in the continuum normalized spectra.

Figure 1 shows strong variations of the Hα line profile in the spectrum of MWC 645. It contains a very intense wide blue and a narrow red peak that have a RV of -232.5 ± 5.6 km s^{-1} and -17.8 ± 3.4 km s^{-1}, respectively. RVs of some emission lines are shown in Table 1, which lists RVs of Fe II(42) 4923.90 Å, Fe II(42) 5018.43 Å, Fe II(49) 5197.57 Å, [Fe II](19) 5333.65 Å, Na I(1) 5889.95 Å and 5895.92 Å, [O I](1) 6300.23 Å and 6363.88 Å lines. A region of a high-resolution spectrum with some emission lines is shown in Fig. 2. The average RV was found to be -65.1 ± 1 km s^{-1} for the emission lines, and -23.2 ± 0.4 km s^{-1} for the absorption lines.

The absorption lines include such DIBs as 5780, 5796, 6613 Å and the lines of Na I at 5889 and 5895 Å. Using a relationship between the EW of the DIB at 5780 Å and the color-excess E$(B-V)$ from Herbig (1993), we estimated an interstellar extinction of $A_V = 3.1\times\mathrm{E}(B-V) \approx 2.9$ mag. Due to the presence of strong emission lines and a circumstellar free-free and bound-free continuum, it was difficult to detect absorption lines and determine their parameters. Nevertheless, some absorption lines were detected for the first time. In order to identify them, we used an optical spectrum of the B[e] type binary system MWC 623, which contains a hot and a cool component (Zickgraf 2001), for comparison. The spectra of MWC 645 and MWC 623 shown in Fig. 3 were obtained at CFHT in 2008 and 2015, respectively.

The absorption lines of the stars MWC 645 and MWC 623 were compared with models calculated with the code *SPECTRUM* by Gray & Corbally (1994). Comparing these spectra, we identified lines of neutral metals (Li I, Ca I, Fe I, Ti I, etc.) that are characteristic of a cool component (see Fig. 3). From the emission-line content in the spectrum of MWC 645

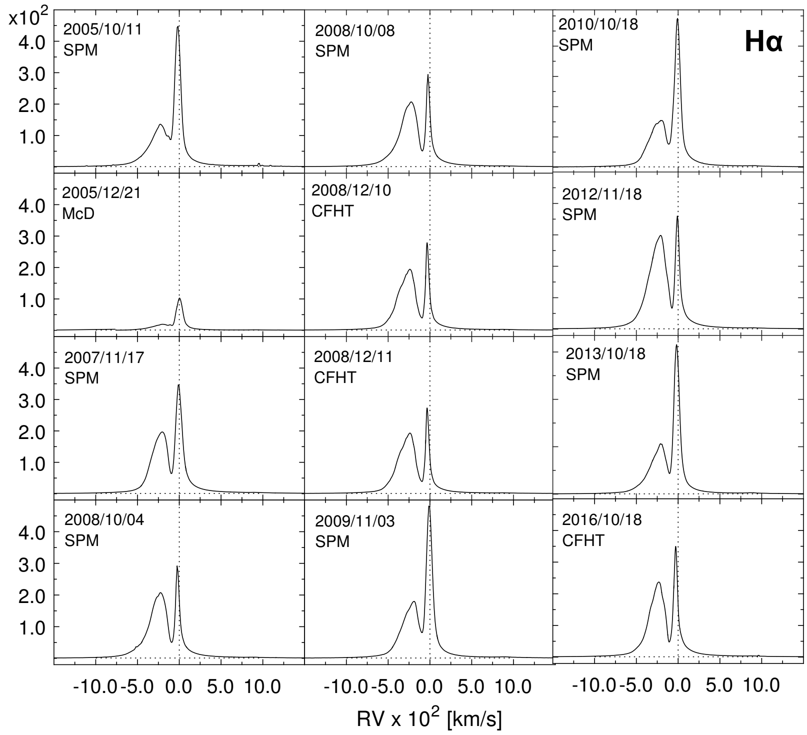

Figure 1: Variations of the Hα line in the spectrum of MWC 645. Horizontal dotted lines show the continuum level across the line profiles, and vertical dotted lines show the laboratory position of the Hα line. The intensities are normalized to the local continuum and shown in units of hundreds, and RVs are shown in km s^{-1}.

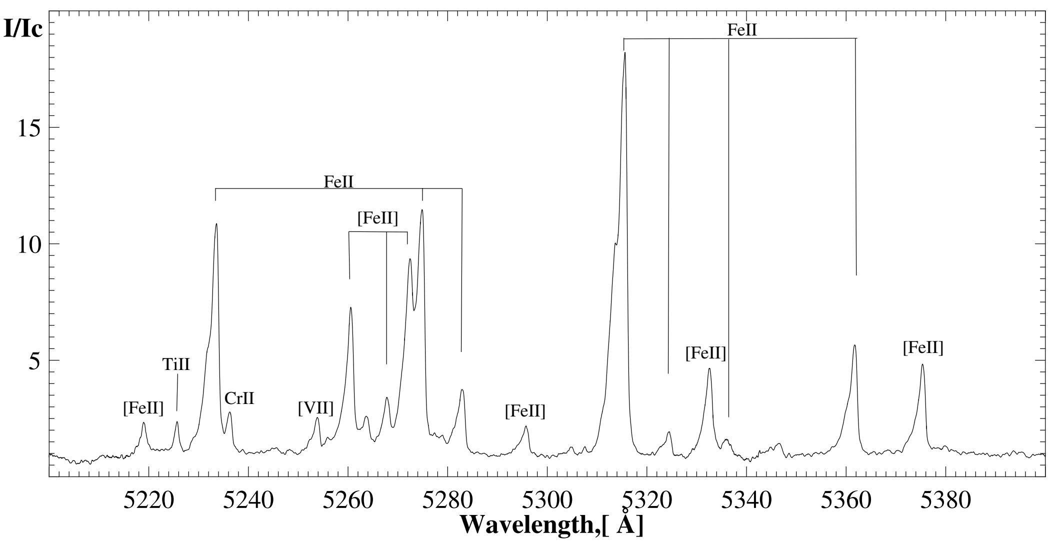

Figure 2: Part of a high-resolution CFHT spectrum of MWC 645 (R = 65,000). The intensity is normalized to the continuum, the wavelength scale is heliocentric.

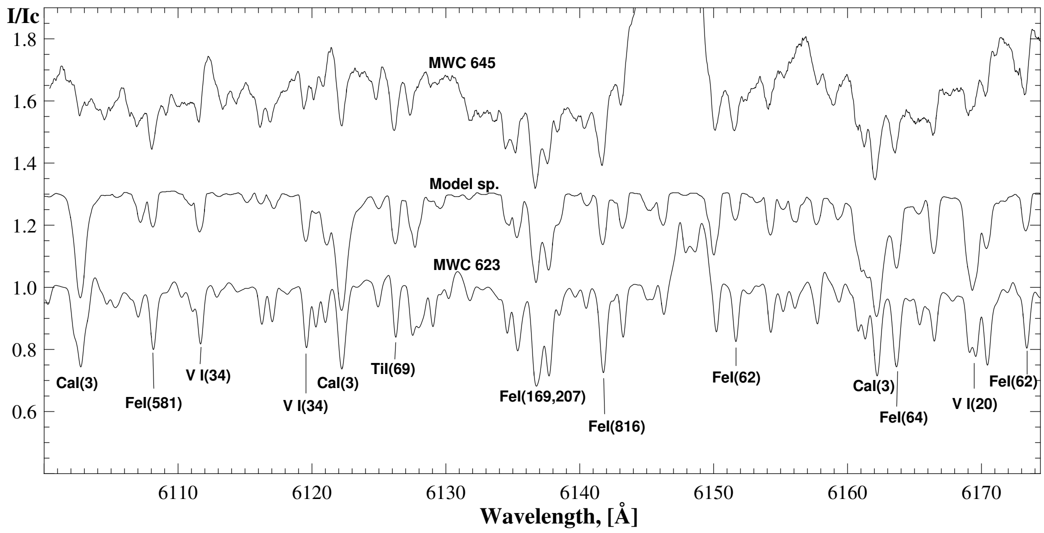

Figure 3: Comparison of absorption lines of the stars MWC 645 and MWC 623 with a model calculated with the code *SPECTRUM* by Gray & Corbally (1994). Identified absorption lines are marked with the element ID, ionization state, and multiplet number.

we suggest that an effective temperature of the hot component is T_{eff} = 15000 K. From the line profiles, we estimated a rotational velocity is $v \sin i$ =150 km s^{-1} for the hot component. Parameters of the cool component (T_{eff} = 4000 K and $v \sin i$ = 20 km s^{-1}) were estimated from the detected absorption lines and their widths.

3.1. Spectral Energy Distribution

The spectral energy distribution (SED) data of MWC 645 were taken from different sources, which included both ground- and space-based photometric data. The SED part in the optical spectral region was modeled with as a sum of a hot and a cool star model atmospheres taken from Kurucz (1994) with effective temperatures of T_{eff} = 15000 K and T_{eff} = 4000 K, respectively (see Fig. 4). The best fit was found for 10% contribution of the cool component and 90% contribution of the hot component. The object's SED in the IR region shows hints for an emission peak at 10 microns and another broad peak at 18 microns which indicate the presence of an optically-thin dusty shell that mainly consists of silicate particles.

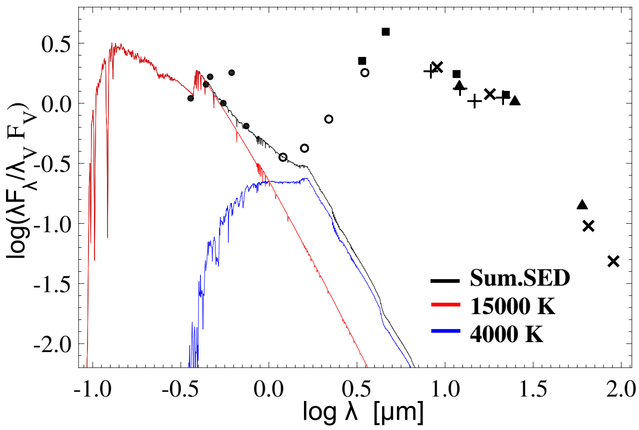

Figure 4: Spectral Energy Distribution of MWC 645 corrected for the interstellar reddening. Symbols: filled circles - optical photometry, open circles - near-IR photometry (JHKL), squares - WISE data, pluses - MSX data, crosses - AKARI data, and filled triangles - IRAS data. The model atmospheres from Kurucz (1994) for the system components are shown by the blue and red solid lines, while the sum of the two models is shown by the black solid line.

4. Conclusions

Figure 5 shows a Hertzsprung-Russell diagram with positions of some FS CMa objects and the components of the MWC 645 system. The luminosity of the system components was calculated using the GAIA EDR3 distance (D = 6.5±0.9 kpc, Bailer-Jones et al. 2021) and found to be log $L/L_\odot = 3.8 \pm 0.2$ and log $L/L_\odot = 2.8 \pm 0.2$, respectively, taking into account the relative component contributions reported above.

The object has a circumstellar dusty envelope that contains small silicate particles and produces a strong infrared excess. The spectroscopic study made possible to estimate the temperatures of the stellar components. We found neither emission nor absorption lines

Table 1: RVs of some emission lines in the spectra of MWC 645

Date	HJD	Fe II 4923.92	Fe II 5018.43	Fe II 5197.57	[Fe II] 5333.65	Na I 5889.95	Na I 5895.92	[O I] 6300.23	[O I] 6363.88
10/07/2004	3286.424	–	–	–	−60.2	−136.1	−102.9	−58.1	−64.6
10/12/2005	3655.633	−29.3	−44.5	−43.2	−60.7	−82.7	−79.0	−47.6	−42.4
12/21/2005	3725.595	−23.2	−35.5	−27.6	−41.6	−58.2	−49.0	–	−19.8
11/17/2007	4421.634	−24.4	−36.1	−34.0	−47.2	−147.9	−127.9	−36.2	−38.7
10/04/2008	4744.632	−57.3	−42.7	−66.9	−57.4	−119.3	−84.1	−45.7	−52.8
10/08/2008	4748.635	−57.9	−44.5	−64.0	−62.4	−99.0	−83.6	−48.1	−56.1
12/10/2008	4810.699	−62.8	−54.0	−63.4	−61.9	−81.1	−88.7	−60.0	−63.6
12/11/2008	4811.699	−54.9	−52.8	−66.9	−64.1	−83.2	−89.7	−59.5	−64.1
11/03/2009	5139.665	−41.5	−42.7	−36.3	−62.4	−65.9	−60.2	−31.9	−38.2
10/18/2010	5487.748	−22.0	−35.5	−32.3	−48.4	−57.7	−58.2	−25.7	−29.7
11/18/2012	6250.611	−48.8	−42.1	−56.5	−56.8	−86.2	−79.0	−32.4	−40.1
10/18/2013	6583.705	−47.0	−50.5	−43.8	−61.3	−82.7	−78.5	−40.0	−43.8
10/18/2016	7679.500	−52.5	−50.5	−56.5	−57.9	−138.2	−95.8	−54.8	−60.3

Column information: (1) - the date of the observation (Month/Day/Year); (2) - Heliocentric Julian Date (JD−2450000); (3)–(10) - heliocentric RVs in km s^{-1}. The second row contains laboratory wavelengths of the lines in Å.

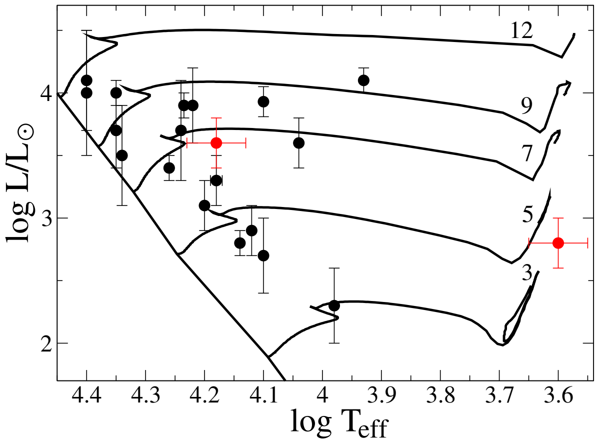

Figure 5: HR diagram with positions of FS CMa objects with known parameters. Evolutionary tracks for single rotating stars and indicated initial masses (Ekström et al. 2012) are shown. Possible places of components of the MWC 645 are marked by the red dots.

of He I, which may be filled with the circumstellar continuum, and derived the hot component temperature of 15 000 from the SED fitting. We identified lines of neutral metals in the object's optical spectrum which should not be present in the spectrum of a B-type star and assumed that these lines belong to a cool component, thus making MWC 645 a binary system. By comparing spectra of MWC 645 and MWC 623 (a binary system of the FS CMa type) we identified lines of neutral metals (Li I 6708Å, Ca I 6717Å, Fe I, Ti I, etc.) that characterize the cool component. We estimated the temperature of the cool component to be ∼ 4000 K from the identified absorption lines and the SED fitting. Finally, MWC 645 can be classified as a FS CMa type object based on its binary nature and the system components' positions in the HR diagram.

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