Medium resolution spectroscopy of the supergiant O3I\textsubscript{f} \*\textsuperscript{*} 
Cyg OB2 \#7

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Abstract

We examine the feasibility of using medium resolution spectra for determining the parameters of atmospheres of hot stars by means of numerical simulations. We chose the star Cyg OB2 \#7 as a test object and obtained its spectrum (\(\lambda/\Delta\lambda = 2500\)) with Russian-Turkish RTT150 telescope. The CMFGEN code was used to construct a model of the atmosphere of Cyg OB2 \#7. For the first time we have detected the NIV \(\lambda\lambda 7103.2 - 7129.2\) lines in the spectrum of this star and used them to determine the physical parameters of the wind. The rate of mass loss measured using the H\textalpha line exceeds the loss rate measured using lines formed in the wind. This indicates that the wind is nonuniform, apparently due to rotation.

Keywords: stellar atmospheres: fundamental parameters: stars of early types: Cyg OB2 \#7

1 Introduction

Since the 1960’s, space based observations made it possible to detect lines with a P Cyg profile in the ultraviolet spectra of O-type stars, which indicated the presence of supersonic winds. This discovery allowed to estimate the mass loss rate due to a stellar wind. Further studies showed that massive stars (> 50 M\textsubscript{\odot}) lose a substantial fraction of their mass (almost half) in the form of wind while on Main Sequence. Later, wind lines (or details of their profiles) were also discovered in high-resolution spectra in the optical wavelength range obtained at ground-based observatories.

The next important step for astrophysics was the discovery of a new method for determining distances using the so-called wind momentum-luminosity relation (WLR) (Kudritzki et al. 1999). However spectral monitoring of selected O-supergiants has shown that the winds from hot stars are inhomogeneous and vary with time (see Owocki (1994) for details). Therefore, to determine their luminosities it is important to obtain averaged, statistically significant characteristics of details of the wind line in spectra of rare O-supergiants. Significant fraction of these stars can only be studied with medium-resolution spectroscopy. Moreover blue parts of their spectra may be attenuated as a result of interstellar and circumstellar extinction.

In this paper we test whether is it possible to reliably determine the atmospheric parameters by modeling medium-resolution spectra. We have chosen the supergiant O3I\textsubscript{f} \*\textsuperscript{*} Cyg OB2 \#7 as a test object. Blue part of its spectrum is significantly absorbed, \(A_v = 5.4\) (Kiminki et al. 2007). The star belongs to the Cyg OB2 association (Klochkova et al. 2011; Klochkova & Chentsov 2004), so we can obtain an independent estimate of its luminosity.

In the next section we present observational data and data reduction process. In Section 3 we describe model calculations and discuss results, comparing these with previous work. The conclusions are considered in Section 4.
2 Observations and data reduction

Observations of Cyg OB2 №7 have been performed on February-March 2012 on the 1.5-m Russian-Turkish RTT-150 telescope at the Tübitak National Observatory, located on Mt. Bakýrlytepe (Turkey). The spectrum was obtained over a wide range of wavelengths (4200-8000 Å) using the TFOSC (Tübitak National Faint Object Spectrograph and Camera) instrument at the Cassegrain focus. The spectral resolution is $\lambda/\Delta\lambda = 2500$. In the overall spectrum the signal-to-noise ratio $S/N = 100$ in the blue part (5000 Å) and 200 in the red part (7000 Å). As noted above, the spectrum of this object is strongly absorbed at shorter wavelengths. Reliable modeling of faint lines requires a fairly high $S/N$ ratio (>100) which, in our case, was realized only in the red for $\lambda > 5000$ Å. Below we study the spectrum in this region. Data were reduced using the DECH software package.

The CIV $\lambda\lambda 5801.3, 5812$, NIV $\lambda\lambda 6214, 6219$ emission lines are present in the spectrum. For the first time the NIV $\lambda\lambda 7103.2−7129.2$ lines were detected in the spectrum of Cyg OB2 №7, they involve a transition from the $1s^22s3d$ to the $1s^22s3p$ state. These emission lines are typical for spectra of early Wolf-Rayet (WR) stars and are used for a spectral classification of nitrogen-rich WR (WN). From published spectra of O-stars in the 7000-8000 Å range we may conclude that the NIV $\lambda\lambda 7103.2−7129.2$ lines are present only in the spectra of O2-O5 supergiants. Modeling shows that these lines are formed only when effective temperature $T_\ast > 38000 K$ (Maryeva et al. 2012).

3 Modeling results

We have used the CMFGEN atmosphere code (Hillier & Miller 1998) to determine the physical parameters of the atmosphere of Cyg OB2 №7. This code solves radiative transfer equation for objects with spherically symmetric extended outflows using either the Sobolev approximation or the full comoving-frame solution of the radiative transfer equation. CMFGEN incorporate a line blanketing, the effect of Auger ionization and clumping. Every model is defined by a hydrostatic stellar radius $R_\ast$, luminosity $L_\ast$, mass-loss rate $\dot{M}$, filling factor $f$, wind terminal velocity $v_\infty$, stellar mass $M$, and by the abundances $Z_i$ of included elementary species.

Using the model of the star AV 83 (O7 Iaf +) calculated by Hillier et al. (2003) as the seed model we have adjusted its parameters to reproduce the observed spectrum of Cyg OB2 №7 and gradually changed the parameters of the model ($L_\ast$, $R_\ast$ and $\dot{M}$).

In our calculations we assumed that:

- the volume filling factor $f_\infty$ is equal to 0.1, as in the initial model;
- $\beta$–law for wind velocity and $v_\infty = 3080$ km s$^{-1}$ (a value taken from Herrero et al. (2001));
- H, He, C, N, O, S, Si, P, and Fe were included in calculations;
- the abundances of S, Si, P, and Fe are solar abundances;
- the abundances of H, He, C, N, and O are the same as in the initial model, $([X(N)/X(N)_\odot]) \sim 3$, $[X(C)/X(C)_\odot] = 0.08$, $[X(O)/X(O)_\odot] = 0.09$.

We used photometric data for an exact determination of the luminosity. The model flux was recalculated for the distance of Cyg OB2 association (1.5 kpc, Mel'nik & Dambis (2009)). Then we added interstellar absorption using the IDL program FM-UNRED (W. Landsman) which uses the absorption curves calculated by Fitzpatrick [12]. The value $A_v = 5.4$ is taken from Kiminki et al. (2007). Then, the simulated spectra were convolved with V-band sensitivity filters. The resulting fluxes were converted to magnitudes and compared to the photometrical data ($V = 10.55$, Simbad data base).

\footnote{www.tug.tubitak.gov.tr/rtt150_tfosc.php}
Figure 1: Left: A comparison of the observed Hα + HeII λ6560 (solid line) spectrum with the models reported here. The dotted line is a model with β = 1 and $\dot{M}_{\text{cl}} = 2 \times 10^{-6} M_\odot$/year and the dashed curve, with $\beta = 1$ and $\dot{M}_{\text{cl}} = 2.5 \times 10^{-6} M_\odot$/year. Another line, HeII λ6527, is seen to the left of Hα and DIB λ6613 to the right. Right: A comparison of the theoretical and observed profiles of Hα + HeII λ6560 from Herrero et al. (2002).

As a result, we constructed a best-fit model. Its parameters are: $L_* = (1.1 \pm 0.1) \times 10^6 L_\odot$, $R_* = 16.5 R_\odot$, $T_* = 44 \pm 1 kK$ and $\beta = 1$. $R_*$ is the radius of the star, corresponding to the inner boundary of the atmosphere lying approximately at $\tau \sim 20$, and $T_*$ is the effective temperature at radius $R_*$, which is related to the luminosity by $L_* = 4\pi R_*^2 \sigma T_*^4$. The mass loss rate is $\dot{M}_{\text{cl}} = (3 \pm 0.5) \times 10^{-6} M_\odot$/year. The unclumped mass loss rate ($\dot{M}_{\text{uncl}}$) is related to the clumped rate ($\dot{M}_{\text{cl}}$) by $\dot{M}_{\text{uncl}} = \dot{M}_{\text{cl}} / \sqrt{\beta}$.

Figure 1 shows comparison between the calculated and observed Hα + HeII λ6560 profiles. The rotational velocity of the star is $V \sin i = 105$ km s$^{-1}$ (Herrero et al. 2002). In order to account for the star’s rotation and the spectral resolution of the instrument ($\Delta \lambda = 2\text{Å}$), we convolved the calculated spectrum with a Gaussian of FWHM=2.65Å.

In order to describe the profiles of the CIVλλ5801.3, 5812 and NIV λλ7103.2 − 7129.2 wind lines, we had to construct a model with slower acceleration of wind, corresponding to larger values of $\beta$ ($\beta = 2$) and a lower mass loss rate $\dot{M}_{\text{cl}} = (3 \pm 2) \times 10^{-7} M_\odot$/year (Figure 2).

Table 1: Derived properties of Cyg OB2 №7.

| Model | $T_*$ [kK] | $R_*$ [R_\odot] | $T_{\text{eff}}$ [kK] | $R_{2/3}$ [R_\odot] | $L_*$ [$10^6 L_\odot$] | $\dot{M}_{\text{uncl}}$ [$10^{-6} M_\odot$/year] | $v_\infty$ [km/s] | $\beta$ |
|-------|------------|-----------------|----------------------|----------------------|---------------------|-----------------------------------------------|-----------------|-------|
| Model1 | 45 | 16.5 | 44.5 | 16 | 1 | 7.9 | 3080 | 1 |
| (Hα) | | | | | | | | |
| Model2 | 45 | 16.5 | 44.5 | 17 | 1 | 0.95 | 3080 | 2 |
| (NIV, CIV) | | | | | | | | |
| Cyg OB2 7 * | 45.5 | 14.6 | 0.813 | 9.86 | 3080 | 0.9 |

* – The data were taken from (Herrero et al. 2002)
We now compare our results with earlier studies of Cyg OB2 №7. Herrero et al. (2002) studied its spectrum over a wide range of wavelengths (4000-6700 Å) using the FASTWIND code (Santolay-Rey, Puls & Herrero 1997; Puls 2005) which includes the blanketing effect. Their results for the Hα line are shown on the right panel of Figure 1. Table 1 lists the parameters of our models and the parameters obtained by Herrero et al. (2002). $R_{2/3}$ is the radius at which the optical depth $\tau$ becomes equal to 2/3 and $T_{\text{eff}}$ is the effective temperature of the object at $R_{2/3}$ (assuming radiative equilibrium). From the table it can be seen that our estimates for the Hα line are in good agreement with the earlier measurements Herrero et al. (2002). Note that the nitrogen and carbon emission lines were not modelled in Herrero et al. (2002), so that the differences we have found in the parameters derived from the Hα line and the wind lines do not contradict earlier results.

The rotation of early-type stars with radiatively driven winds leads to interesting effects, the most prominent is the tendency to concentrate the outflowing material toward regions near the equatorial plane. This results in a deviation from a spherically symmetric shape and possibly the formation of an outflowing disk (Lamers & Cassinelli 1999). Disks of this kind have been discovered in B[e] and Be stars (Zickgraf et al. 1985). Asymmetric winds were found in objects that are evolutionary related to O-stars: Luminous Blue Variables (LBV) (Groh et al. 2006, 2010) and Wolf-Rayet stars (Harries et al. 1998). Moreover numerical calculations Groh et al. (2008) have shown that density of the wind of qWR star HD 45166 varies with latitude. We assume that the difference between the model describing Hα and the one describing CIV and NIV lines is related to a latitudinal inhomogeneity of the supergiant wind due to its rotation ($V \sin i = 105$ km s$^{-1}$).

4 Conclusions

We studied one of the hottest stars in our Galaxy Cyg OB2 №7 by spectrum obtained on the RTT150 telescope. Using non-LTE code CMFGEN we estimate its parameters (bolometric luminosity, stel-
lar radius, mass loss rate, wind velocity, elementary abundances). The atmosphere of this object is rich with nitrogen. We have shown that the wind of Cyg OB2 №7 is inhomogeneous. Therefore Cyg OB2 №7 is yet another star with density of wind depending on latitude.

The good agreement between the parameters of Cyg OB2 №7 found here and those determined from spectra over a wide range of wavelengths (Herrero et al. 2002) indicates that medium-resolution spectra in the red can be used to obtained fairly accurate estimates for the parameters of the atmospheres of hot stars when used in combination with reliable codes such as CMFGEN. Spectra of hot stars at red wavelengths contain lines formed in a stellar wind. Thus, when a red-sensitive detector is available, medium-resolution spectra can be used to study the strong photospheric lines, as well as features of the wind by monitoring its spectral variability.

O. Maryeva thanks John D. Hillier for his excellent program CMFGEN, used here to analyze the data, and S. V. Karpov for help with the calculations. O. M. was supported by the “Kadry” program (state contract 14.740.11.0800) and the Russian Foundation for Basic Research (grants RFFI-11-02-00319-a, 12-07-00739-a). R. Zh. thanks the Russian Foundation for Basic Research (grant RFFI-10-02-01145), Tubitak, and KFU for partial support in using the RTT-150 telescope.

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