The Optical Spectrum of an LBV Candidate in the Cyg OB2 Association

V. G. Klochkova and E. L. Chentsov

Special Astrophysical Observatory, Russian Academy of Sciences, Nizhnii Arkhyz, Karachai-Cherkessian Republic, 369167 Russia

Received November 15, 2003; in final form, March 15, 2004

Abstract—We have obtained the first high-spectral-resolution ($R = 15,000$ and 60,000) optical spectra for the extremely luminous star No. 12, identified with the IR source IRAS 20308+4104 in the Cyg OB2 association. We have identified about 200 spectral features at $4552–7939\AA$, including the interstellar NaI, KI lines and numerous DIBs, which are the strongest absorption lines in the spectrum, along with the HeI, CII, and SiII lines. A two-dimensional spectral classification indicates that the star’s spectral type is B5±0.5 Ia*'. Our analysis of the radial-velocity pattern shows the presence of a radial-velocity gradient in the stellar atmosphere, due to the infall of matter onto the star. The strong Hα emission line displays broad Thompson wings and time-variable core absorption, providing evidence that the stellar wind is inhomogeneous, and a slightly blue-shifted P Cygni absorption profile. We conclude that the wind is time-variable.

© 2004 MAIK "Nauka/Interperiodica".

1. INTRODUCTION

Studies of mass loss and elemental-abundance variations in the surface layers are crucial for our understanding of the evolution of massive stars. It is important to establish the evolutionary stage and the star’s luminosity with certainty. One widely used approach to stellar-evolution studies is to investigate stars in clusters and groups: the evolutionary stage, age, and luminosity can be determined fairly reliably for group members, whereas these characteristics are rather uncertain for field stars. It is especially important to study group members that are rare, such as LBV stars or Wolf–Rayet stars. From this point of view, the Cyg OB2 (or V1 Cyg) association, with an age of several million years, is of special importance. The Cyg OB2 association contains a group of high-luminosity stars with correspondingly very high masses (about $100\ M_\odot$), and is so large that the association may be a young globular cluster [1].

According to Massey et al. [2], unveolved O and Of stars have been identified in the association, as well as an LBV candidate—the variable star No. 12 from the list of Schulte [3]. We will refer to this star as Cyg OB2–No. 12.

Cyg OB2–No. 12 is among the brightest OB stars in the IR, due to the presence of circumstellar matter lost by the star via its strong wind [4]. The star is identified with the IR source IRC+40430 = IRAS 20308+4104. For a distance modulus for the star $m-M = 11.2^{m}$, the star’s luminosity is $log(L/L_\odot) = 6.26$ [5] and its bolometric absolute magnitude is $M_{bol} = -11^{m}$ [6]. Massey and Thompson [6] classified the star as B5 Ie, and Souza and Lutz [7] as B8 Ia, whereas Humphreys and Davidson [8] considered it to be one of the Galaxy’s brightest A supergiants. Massey et al. [2] later confirmed the LBV candidate status of Cyg OB2–No. 12 based on its membership in an association whose turnover point is near that for the Milky Way’s most massive stars.

The luminosity of Cyg OB2–No. 12 implied by its association membership indicates that the star is one of the four most luminous stars in our Galaxy (see, for instance, the diagram for S Dor stars presented by van Genderen [9] and Table 2 in the review of de Jager [5]). However, its visible light is strongly attenuated due to the large distance to the association and the presence of strong extinction: the observed magnitudes are $B = 14.41^{m}$, $V = 11.40^{m}$. It was recognized long ago that, apart from being distinguished by its high luminosity, Cyg OB2–No. 12 also displayed very high reddening [10, 11]. Based on their photometric study of a stellar sample in Cyg OB2, Torres-Dodgen et al. [12] estimated the association’s distance modulus to be $m-M = 11.2^{m} \pm 0.2^{m}$ and its distance to be $d = 1.7 \pm 0.3$ kpc, and confirmed that the high interstellar reddening for the association members (with a mean value $E(B-V) = 1.82$) was satisfied by a normal law. The exception is Cyg OB2–No. 12, whose visual extinction exceeds $10^{m}$ (!). Obviously, spectroscopic studies of stars experiencing such a high degree of reddening are possible only thanks to the relatively small distance to the association and the high absolute luminosities of many of its members.
Lozinskaya et al. [13] also emphasized that the compact group of massive stars in the Cyg OB2 association probably possessed the Galaxy’s strongest stellar winds, which are capable of significantly affecting the ambient interstellar gas over some two to three million years.

Cyg OB2—No. 12 is one of the few late B stars known to radiate thermal radio emission [4]. The variability of its radio flux is surprising [14]. White and Becker [15] estimated the mass-loss rate to be $4 \times 10^{-5} M_\odot/\text{yr}$, which is unusually high for a normal supergiant, but consistent with the extreme luminosity of Cyg OB2—No. 12. According to the criterion suggested by Humphreys and Davidson [8], a mass-loss rate that high indicates that Cyg OB2—No. 12 is an LBV star. Through his modeling of the IR spectral energy distribution, Leitherer et al. [16] estimated the star’s effective temperature to be $T_{\text{eff}} = 13 600$ K and the envelope’s electron temperature to be $T_e = 5000$ K. The combination of a hot atmosphere and a cool, dense envelope found for Cyg OB2—No. 12 is not unique: such structures are known for S Dor stars [17].

The light from Cyg OB2—No. 12 is polarized [18]. The broadband polarimetry of Schulz and Lenzen [17] at 0.3–1.1 $\mu$m displayed linear polarization exceeding 10%, providing evidence for a nonspherical distribution of the circumstellar material, and hence for a nonspherically symmetrical stellar wind.

The accumulated observations show that Cyg OB2—No. 12 is a crucial object for studies of late evolutionary stages for massive stars, creating the need for high-resolution optical spectroscopy that would make it possible to classify the spectrum, and thereby refine estimates of the star’s fundamental parameters and the characteristics of its stellar wind.

2. OBSERVATIONS AND DATA REDUCTION

Our spectroscopic observations of Cyg OB2—No. 12 were acquired with the 6 m telescope of the Special Astrophysical Observatory (Russian Academy of Sciences) using echelle spectrographs. Our first set of observations, obtained on June 12, 2001 using the PFES spectrometer [19] with a 1040 $\times$ 1170-pixel CCD chip at the primary focus, yielded a spectrum in the interval 4542–7939 $\AA$ with a resolution of $\lambda/\Delta \lambda \sim 15 000$ (20 km/s). A second set of observations was obtained on April 12, 2003 at the Nasmyth focus using the NES spectrograph [20] equipped with an image slicer [21]. We obtained a spectrum in the range 5273–6764 $\AA$ with a resolution of $\lambda/\Delta \lambda \sim 60 000$ (5 km/s) using a 2048 $\times$ 2048-pixel CCD chip.

We used the PFES spectrometer to acquire spectra of bright, luminous B stars for use in spectral classification (see Section 3.1 for details). We eliminated cosmic-ray traces via a median averaging of two consecutive exposures. The wavelength calibration was performed using the spectrum of a ThAr hollow-cathode lamp. We recorded the spectrum of the hot, rapidly rotating star HR 4687, which has no narrow lines, each night for use in subtracting the telluric absorption spectrum.

The preliminary reduction of the CCD images of our echelle spectra (removal of cosmic rays, background subtraction, wavelength calibration, and extraction of the spectral orders) was performed using the MIDAS (98NOV) ECHELLE package. The final reduction (continuum normalization, measurements of radial velocities and equivalent widths for various spectral features) was done using the DECH20 program package [22].

3. DISCUSSION OF THE RESULTS

3.1. General Description of the Spectrum and Spectral Type of Cyg OB2—No. 12

The main features of Cyg OB2—No. 12 are evident even in low-resolution spectra [10]: it is an early-type, very luminous star with very strong H$\alpha$ emission and extremely strong diffuse interstellar bands (DIBs). The Na D1,2 sodium-doublet lines display no obvious peculiarities. Wendker and Altenhoff [4] note that the H$\alpha$ profile is probably variable.

Our high-resolution spectra enabled us for the first time to make detailed line identifications, classify the spectrum, and measure radial velocities. Table 1 presents identifications for the spectral features observed on June 12, 2001 and April 12, 2003, along with their equivalent widths $W_\lambda$, residual intensities $r$, and heliocentric radial velocities $V_r$. Figures 1 and 2 display fragments of the spectra of Cyg OB2—No. 12 and of the hypergiant HD 168625 (B6Ia+, $M_v = -8.5$). The spectrum of HD 168625 was taken on June 19, 2001 with the PFES spectrometer. These spectra are very similar, demonstrating that the stars have similar temperatures and luminosities. In addition, DIBs are equally well represented in these spectra and have similar intensities. The strongest of them, the 5780 and 5797 $\AA$ bands, dominate in Fig. 1, but even the weak DIBs at 5766, 5773 $\AA$, etc. have comparable intensities to the stellar NII, AIII, and SiII absorption. The DIBs at 6376 and 6379 $\AA$ in Fig. 2 are almost as deep as the SiII (2) absorption.

The vast majority of spectral features are shallow absorption lines with depths of 0.02–0.03 of the continuum level, whose depths, equivalent widths, and