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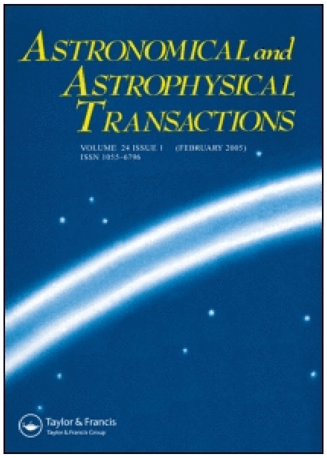

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Results of high-resolution optical spectroscopy investigation of Cyg X-1 = V1357 Cyg

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Results of high-resolution optical spectroscopy investigation of Cyg X-1 = V1357 Cyg

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Selected results of optical high-resolution spectral observations (in 1997 and 2002–2004) are briefly reviewed. A comparison with ASM/RXTE X-ray data is made. The photometric and spectral variations point to supergiant parameter changes on a timescale of tens of years. Line profile non-local thermodynamic equilibrium simulations lead to the conclusion that the star radius increased about 1–4% from 1997 to 2003–2004 and the temperature decreased by 1300–2400 K.

Keywords: X-ray binary; Cyg X-1; Optical spectroscopy; Doppler tomography

1. Introduction

Cyg X-1 = V1357 Cyg/HDE226868 is an X-ray binary system (the orbital period $P = 5.6$ days) whose relativistic component is the first candidate to a black hole (BH). The optical

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component, an O 9.7 Iab supergiant, is responsible for about 95% of the system's optical luminosity. The remaining 5% is due to the accretion structure (the disc and surrounding gas) near the BH. In spite of Cyg X-1 investigations for almost 40 years, which resulted in approximately 1000 publications, more new phenomena in Cyg X-1 continue to be discovered.

Here we present a very brief review of the results obtained on the base of high-resolution optical spectral observations with the echelle spectrographs of the Peak Terskol Observatory (altitude, 3100 m; North Caucasus) 2 m telescope (2002–2004 observations; resolutions $R = 13\,000$ and 45 000), the Bohyunsan Optical Astronomy Observatory (South Korea) 1.8 m telescope (2003–2004 observations; $R = 30\,000$) and the Crimean Astrophysical Observatory 2.6 m telescope (1997 observations; $R = 35\,000$, second order of the diffraction grating).

2. 2002–2004 observations, line and profile variations, supergiant parameters and chemical composition

The 2002–2004 observations cover most of the optical range. The signal-to-noise ratio is $S/N > 100$–200 near Hα. The observations occurred for different states of the Cyg X-1 X-ray spectrum ('hard', 'soft' and transitional). We used the RXTE/ASM X-ray data. The spectra contain the supergiant absorption lines H I, He I and He II, the blend CNO ($\lambda = 4640$ Å), many other lines of heavy elements (C, N, O, Ne, Mg, Si, S, Fe and Zn), and strong emission components of Hα and He II ($\lambda = 4686$ Å) lines with complicated profiles. These profiles show consequent shape variation with the orbital period 5.6 days.

Karitskaya *et al.* [1] described the line profile response to the X-ray flux (2–10 keV) variations. On 13 June 2003 during the 3.7 h interval between the two spectral exposures the X-ray flux increased by a factor of 1.7.

The He II ($\lambda = 4686$ Å) line increased and the Hα line weakened (see figure 2 of [1]). We connect this behaviour with changes in the ionization structure of matter in the system Cyg X-1. A very similar response to the X-ray variation was observed in the case of Cyg X-1 'soft' and 'hard' states in August and December 2002, but such line profile variations did not occur in the case of variations between 'soft' and 'hard' states in 2003–2004. So we suspect the existence of an additional factor affecting the profile formation, *e.g.* variations in the very soft X-ray component during the 'hard' state.

For stellar atmosphere modelling, we used the computer code SPECTR [2] modified in [3, 4]. At present, it permits computation of line profiles of tidally distorted stars, allowing for illumination of the atmosphere by X-ray flux and non-local thermodyamic equilibrium effects for H I, He I, Mg II and Si IV. We find that the model H I, He I and Mg II line profiles correspond to the profiles observed for $T_{\rm eff} = 30\,400 \pm 500$ K and $\log g = 3.31 \pm 0.07$.

In the spectral range $\lambda = 3960$–5880 Å we identified, besides four H lines and one intensive emission line (the He II ($\lambda = 4686$ Å) line), 130 absorption lines and seven unresolvable blends of the ions He I, He II, C II, C III, C IV, N II, N III, O II, O III, Ne II, Mg II, Al III, Si III, Si IV, S III, Fe III and Zn III, which belong to an O supergiant. We found C, N, O, Al, Si, S, Fe and Zn overabundances with respect to the solar abundances. The chemical composition indicates a metallicity ([Fe]/[H] = 0.34 dex) typical of young stars, and also the effects of matter transformation in reactions of the CNO cycle at the main-sequence stage ([N]/[C] = [N]/[O] = 0.7 dex) and of the burning of light elements ([Ne]/[H] = [Si]/[H]= 0.7 dex).

The data from the two intensive observational sets, each covering about two orbital periods within 'soft' (June 2003) and 'hard' (June 2004) states, allowed us to construct, on the basis of the He II ($\lambda = 4686$ Å) line profiles [1], Doppler tomography maps (images in the velocity field) of Cyg X-1 for those time intervals (see figures 4 and 5 in [1]).

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We used the method developed by Agafonov [5], based on the radioastronomical approach.

We can see an absorption region connected with the supergiant and an emission region. The emission may come from the outer regions of the accretion disc, which were heated by the hot supergiant, from the 'hot line' discussed by Kuznetsov *et al.* [6] and/or from the accretion stream (focused stellar wind).

A new method of parameter determination through the Doppler tomogram was proposed and tested. The Doppler images and Roche lobe model allowed us to set a limitation on the BH-to-supergiant-mass ratio of $1/4 < q < 1/3$ [1].

3. Long-term supergiant variations in the Cyg X-1 binary system

Both photometric and spectral variations indicate parameter changes for the supergiant on a timescale of tens of years [7, 8]. We used a homogeneous photometric series of *UBV* observations over 35 years acquired at the Crimean Laboratory of the Sternberg Astronomical Institute. Concerning photometric variations the contribution to this volume by Lyuty [7] should be consulted.

The object brightness slowly increased from 1985 to 1995 and then decreased to a minimum which was reached in 2003. Brightness minima were observed in 1971 and in 2003–2005. The largest amplitude was recorded in the U band ($\Delta U = 0.1$). During the transition from maximum (1995–1999) to minimum (2003–2005) brightness, the X-ray activity increased. In 1997, high-resolution spectra were obtained at the Crimean Astrophysical Observatory ($R = 35\,000$; $\lambda = 4655$–4722 Å). So we can compare the behaviours of the He I ($\lambda = 4713$ Å) and He II ($\lambda = 4686$ Å) lines in 1997 and 2003–2004. The spectral data obtained allow the comparison of only two line profiles: He II ($\lambda = 4686$ Å) and He I ($\lambda = 4713$ Å). However, as the complex variable He II ($\lambda = 4686$ Å) profile is formed mainly outside the supergiant,

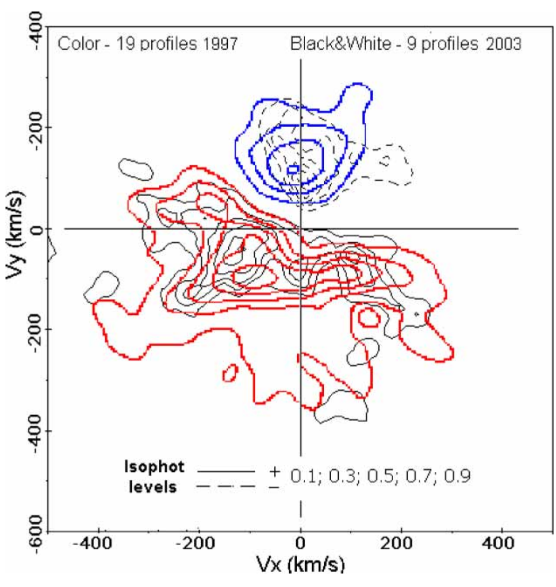

Figure 1. Doppler tomogram of Cyg X-1 for the He II ($\lambda = 4686$ Å) line, based on 19 spectra obtained in August 1997 (colour) in comparison with that obtained in June 2003 from figure 4 of [1] (black and white). The red curves and the black solid curves are isophots for the emission region (in relative units). The blue curves and the black dashed curves are isophots for the absorption region (in relative units).

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it cannot be used for the optical component's parameter diagnostic, in contrast with the He I ($\lambda = 4713$ Å) absorption line that is formed inside the star's atmosphere. Comparison of the observed and non-local thermodyamic equilibrium simulated photometric variations and the He I ($\lambda = 4713$ Å) line profiles leads to the conclusion that the star radius has increased by about 1–4% from 1997 to 2003–2004 and the supergiant effective temperature decreased by 1300–2400 K [8].

The 19 He II ($\lambda = 4686$ Å) line profiles corresponding to 19 nights of observations in 1997 (one spectrum obtained during an X-ray flare was omitted) allowed us to construct a Doppler tomography map of Cyg X-1 for August 1997 when Cyg X-1 was in a 'hard' state. Figure 1 shows a comparison of the tomography maps for August 1997 and June 2003. In 1997 the size of the emission region was larger in the velocity field but the absorption region was about the same and conforms to the q limitation. It is in qualitative agreement with our results because the ultraviolet photon flux ionizes He I with a strong dependence on the temperature of the supergiant.

The increase in the radius of the star from 1997 to 2004–2004 leads to an increase in the degree of Roche lobe filling. So we may expect intensification of the matter outlet towards the X-ray source. The conclusion is in agreement with the X-ray activity growth in that time interval. Moreover, the temperature decrease can lead to a decrease in the wind velocity of the star, *i.e.* to an increase in the portion of matter captured by the X-ray component, which may prove to be one more factor that maintains the X-ray activity of the system Cyg X-1.

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