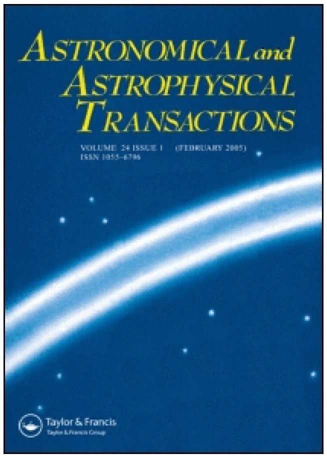

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CYG X-1 = V1357 CYG investigation based on high-resolution optical spectroscopy of 2002–2004

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We report the results of Cyg X-1 spectral monitoring for 2002–2004. A comparison of observed and non-local thermal equilibrium model profiles for H I, He I and Mg II is given, taking into account the tidal distortion of the Cyg X-1 optical component and its illumination by X-ray emission from the secondary component. We set limits on the main characteristics of the optical component, $T_{\rm eff} = 30\,400 \pm 500$K and $\log g = 3.31 \pm 0.07$, and on the overabundances of He and Mg, $[\mathrm{He}]/[\mathrm{H}] = 0.43 \pm 0.06$ dex and $[\mathrm{Mg}]/[\mathrm{H}] = 0.75 \pm 0.15$ dex. The Doppler images were reconstructed by an improved Doppler tomography method on the basis of nine He II ($\lambda = 4686$ Å) profiles from 2003 (the 'soft' X-ray state) and six profiles from 2004 (the 'hard' X-ray state). This allowed us to set limits on the black-hole-to-supergiant mass ratio $(1/4) \leqslant M_{\rm X}/M_{\rm O} \leqslant (1/3)$.

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

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1. Introduction

Cyg X-1 is an X-ray binary system whose relativistic component is the main candidate for a black hole. The optical component, an O 9.7 Iab supergiant, is responsible for about 95% of the system's optical luminosity. As well as the orbital period $P = 5.6$ days, the so-called 'precession' period of 147–294 days and several other periods were found. The nature of these periods remains unclear. The same statement holds for Cyg X-1 sudden transitions from the ordinary 'hard low' state to the 'soft high' state with different hardnesses of the X-ray spectra (in the following these are called the 'hard' and 'soft' state, respectively).

High-precision high-resolution spectroscopy (in particular when combined with photometric, X-ray and radio observations) opens up wide possibilities for analysing the processes of matter outflow from the supergiant, sporadic and quasiperiodic instability of the flows, and the gas flow interaction with the outer parts of the accretion structure. An adequate analysis of high-quality observations should make use of the new methods including the comparison of the observed line profiles with the theoretical profiles, calculated in the non-local thermal equilibrium approximation, taking into account the gas outflow from the stellar atmospheres, illumination by X-ray radiation from the secondary component, and tidal distortion of the X-ray binary optical component.

A list of examples of urgent tasks connected with Cyg X-1 high-resolution optical spectroscopy has been given in [1]. Some results are presented below.

2. Observations

The observations were carried out with the echelle spectrograph of the Peak Terskol Observatory (altitude, 3100 m; North Caucasus) 2 m telescope. The detector was a charge-coupled device camera (Wright Instruments; 1152×1242 pixels). During 29 nights in 2002–2004, 70 spectra were obtained. Each of these covers most of the optical range. The spectral resolution is $R = 13\,000$ or $45\,000$. The signal-to-noise ratio is $S/N > 100$–200 near Hα.

In addition, five spectra were obtained during four nights in 2004 with the fibre echelle spectrograph of the 1.8 m telescope of the Bohyunsan Optical Astronomy Observatory, South Korea ($R = 30\,000$).

The spectral observations were for different states of the Cyg X-1 X-ray spectrum ('hard', 'soft' and transitional). We used RXTE–ASM X-ray data.

3. The spectral observation results

The spectra reveal the supergiant absorption lines, H I, He I, He II, the CNO blend ($\lambda = 4640$ Å), many other lines of heavy elements (C, N, O, Mg, Si, S, Fe, etc.) and strong emission components of the Hα and He II ($\lambda = 4686$ Å) lines with complicated profiles.

We obtained two intensive observational sets, each covering about two orbital periods within the 'soft' (June 2003) and 'hard' (June 2004) states.

Figure 1 shows fragments of the spectra near He II ($\lambda = 4686$ Å) for two 2002 nights and for the June 2003 set. Nine 2003 spectra form a dense observational sequence covering two orbital cycles, allowing us to trace the spectral line variations against the orbital phase, with an almost unchanged 147 day period phase and more or less stable X-ray flux.

A notable exception is one of the two spectra obtained on 13 June 2003, within an X-ray flare. During the 3.7 h interval between the two spectral exposures the X-ray flux increased

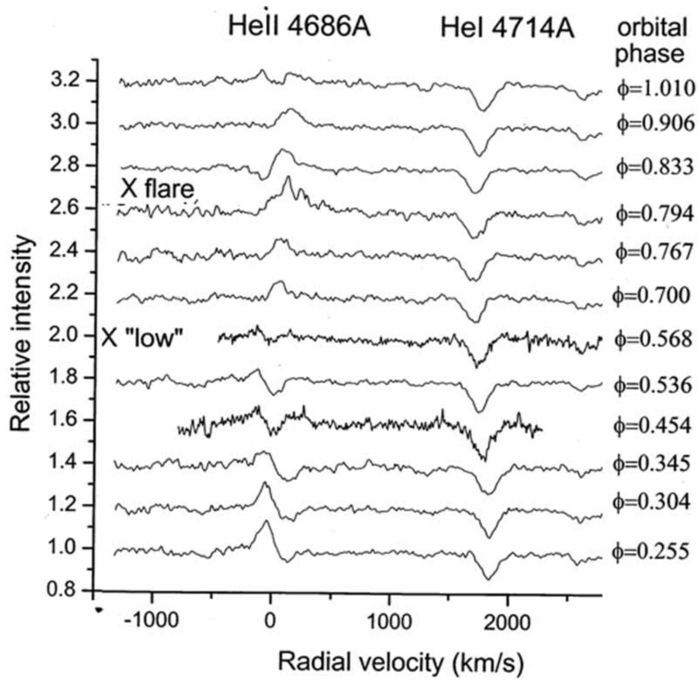

Figure 1. Variations in the He II ($\lambda = 4686$ Å) and He I ($\lambda = 4714$ Å) profiles in June 2003, and August and November 2002. The spectrum corresponding to the X-ray flare on 13 June 2003 (X flare) and the spectrum from 28 November 2002 corresponding to the Cyg X-1 'hard low' state ('X low') are labelled.

by a factor of 1.7. This yields an opportunity to study the impact of the X-ray radiation on the spectral line features. Figure 2 shows the variations in the He II ($\lambda = 4686$ Å) and Hα profile during that X-ray flare; the He II ($\lambda = 4686$ Å) line becomes stronger and the Hα line weakens. We connect such behaviour with changes in the ionization structure of matter in the Cyg X-1 system.

Differences in the line profiles of the two 2002 spectra (figure 1) obtained for similar orbital phases and different Cyg X-1 states (the 'soft' state on 24 August 2002 and the 'hard' state on 28 November 2002) could seemingly be interpreted in a similar way. However, on comparing the observational sets of June 2003 (the 'soft' state) and June 2004 (the 'hard' state) we found no significant difference between the He II line profiles obtained during these two sets for the same orbital phases. This indicates the influence of some additional factors, e.g., variations in the very soft X-ray radiation component during the 'hard' state upon the He II ($\lambda = 4686$ Å) and Hα profile formation.

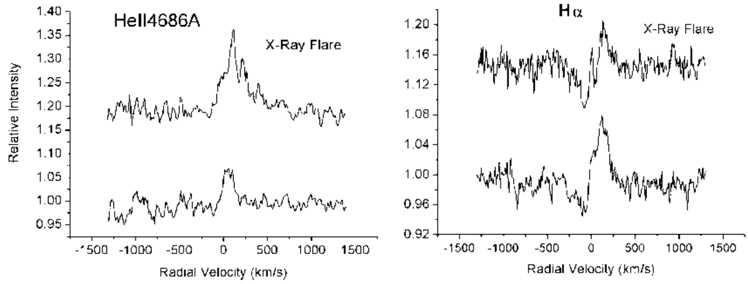

Figure 2. X-ray flare impact on the He II ($\lambda = 4686$ Å) and Hα profiles. The line profiles of 13 June 2003, before the X-ray flare (lower profiles) and 3.7 h later, during the flare (upper profiles), are shown.

4. Line profile simulation and comparison with observations

For simulations we used the computer code SPECTR reported by Sakhibullin and Shimanskii [2] and modified by Ivanova *et al.* [3], Shimanskii *et al.* [4] and Ivanova *et al.* [5]. The code is based on the original Kurucz code for stellar atmosphere modelling but includes computation of the line profiles of tidally distorted stars, illumination of the atmosphere by the hard X-ray flux from the secondary component and non-local thermal equilibrium effects for selected ions. To simulate the influence of X-ray illumination on O-supergiant spectral line profiles we used 'soft' and 'hard' Cyg X-1 X-ray spectra from the work of Zdziarski and Gierlinski [6].

As a result of an analysis of the observed V1357 Cyg light curves and spectra we conclude the following.

(i) The surface potential of an O star has a value of about 1.05 of its Roche lobe. This means that the star fills about 95% of its Roche lobe linear size. In terms used by Bochkarev *et al.* [7] this means that the Roche lobe filling factor $\mu \approx 0.95$.
(ii) The non-sphericity effects produce additional Doppler line shifts with an amplitude of up to $7\,\mathrm{km\,s^{-1}}$, distorting the V1357 Cyg radial velocity curve, in agreement, at least qualitatively, with the results discussed by Abubekerov *et al.* [8].
(iii) A chromosphere with a temperature excess of up to 5000 K appears in the 'soft' state only.
(iv) The supergiant illumination almost does not affect the H I, He I, Mg II and C II absorption line intensities and profiles in either of the X-ray spectrum states.
(v) The model H I, He I and Mg II line profiles coincide with the observed profiles (figure 3) at $T_{\mathrm{eff}} = 30\,400 \pm 500\,\mathrm{K}$ and $\log g = 3.31 \pm 0.07$ (instead of $T_{\mathrm{eff}} = 32\,000\,\mathrm{K}$ and $\log g = 3.18$ as in the work of Herrero *et al.* [9]) and $[\mathrm{He}]/[\mathrm{H}] = 0.43 \pm 0.06$ dex and $[\mathrm{Mg}]/[\mathrm{H}] = 0.75 \pm 0.15$ dex.

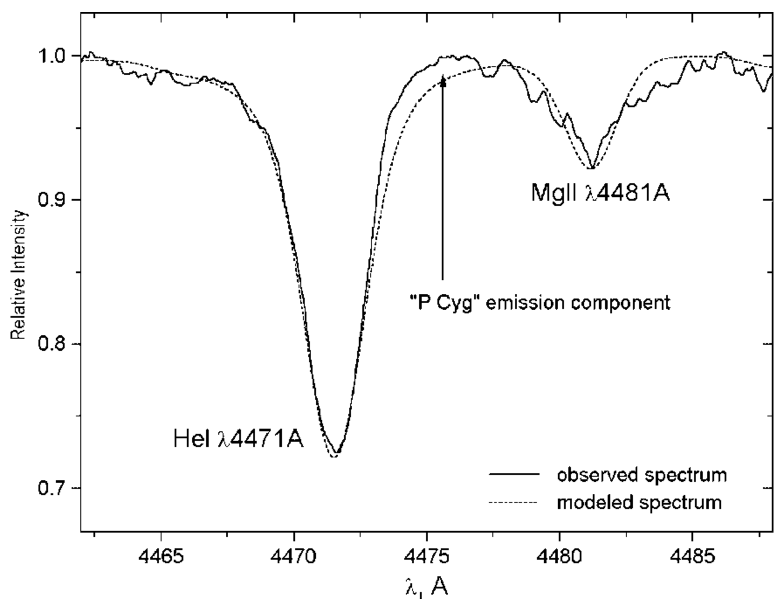

Figure 3. The comparison of observed and model Cyg X-1 spectra. The solid curve shows the observed spectrum fragment averaged over two orbital phases $\phi = 0.43$ and $\phi = 0.55$. The dashed curve is the model spectrum.

(vi) The observed profiles of HeI ($\lambda = 4387, 4471, 4713, 4921$ and 5876 Å) (figure 3) are a superposition of the photosphere absorption and P Cyg red emission components. The latter becomes brighter, the stronger the absorption. The emission components are produced by the O-supergiant hot stellar wind in layers with a continuum optical depth $\tau < 0.01$.

(vii) Only the weak absorption lines (such as He I ($\lambda = 4713$ and 5015 Å), Mg II ($\lambda = 4481$ Å) and O II ($\lambda = 4591$ Å) should be used for Doppler shift measurements.

5. Doppler tomography

For Doppler tomography we used the method developed by Agafonov [10], on the basis of a radioastronomical approach. The main features of the reconstruction are deconvolution in the image space with the introduction of a synthesized beam (equivalent to a summarized transfer function) and the removal of the distortions in the summarized image (after back projection) caused from the side lobes of this beam using the CLEAN algorithm. The method has been developed specially for a small number of irregularly distributed observations.

Figure 4 shows the tomography map of Cyg X-1 which we constructed using nine He II ($\lambda = 4686$ Å) profiles of the June 2003 observational set when the X-ray source was in the 'soft' state. Figure 5 shows the tomography map that has been constructed on the basis of six profiles from 2004 (the 'hard' X-ray state). In both cases, the observational sets used were obtained during two orbital periods. As already mentioned in section 2, short intensive sets yielded information on different orbital phases with a more or less stable state of the system.

Doppler tomograms show the two-dimensional distribution of the spectral intensity in velocity space. The negative values correspond to absorption line components (in our case, produced by the supergiant); the positive values are emissions from the surrounding matter.

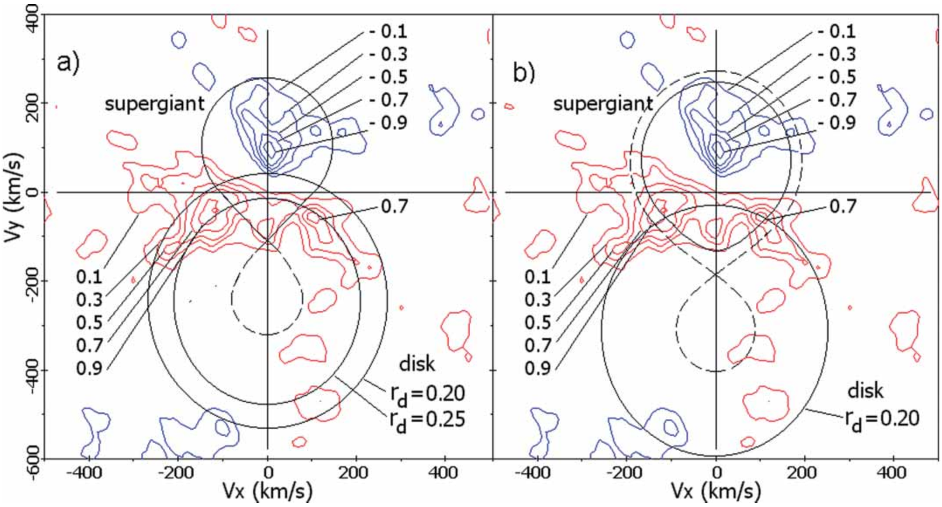

Figure 4. Doppler tomogram of Cyg X-1 in He II ($\lambda = 4686$ Å), based on nine spectra of June 2003 (the 'soft' state) from figure 1. The spectrum corresponding to the moment of X-ray flare was not included; data for about the same X-ray fluxes were used. The thin red curves are isophots of the emission region (in relative units). The blue curves are isophots of the absorption region. The black dashed curves show the Roche lobes for the extreme cases: (a) mass ratio $q = (1/3)$; (b) mass ratio $q = (1/4)$. The black solid curves show the optical component with the Roche lobe filling factors (a) $\mu = 1$ and (b) $\mu = 0.95$ for the two cases. The ovals represent the accretion discs with different r_d.

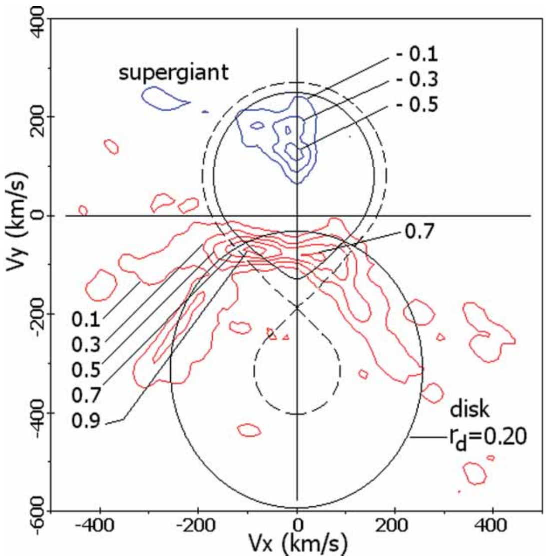

Figure 5. Doppler tomogram of Cyg X-1 in He II (λ = 4686 Å), based on six spectra obtained during the set of June 2004 which was 10 days long and which were in the 'hard' X-ray state. The notation is the same as in figure 4(b).

The upper part of the negative isoline region of figures 4 and 5 corresponds to the supergiant back part. It should fall within the Roche lobe. This restriction yields the upper limit of the component mass ratio $q = M_X/M_O$, where M_X and M_O are the masses of the X-ray and optical components respectively. The star should almost fill its Roche lobe ($\mu = 95\%$ of its linear size), which yields the lower limit for q. So we obtain $(1/4) \leqslant q \leqslant (1/3)$. Figures 4(a) and (b) show these two extreme cases. The Roche lobes are drawn for $q = (1/3)$ in figure 4(a) and for $q = (1/4)$ in figures 4(b) and 5. The Roche lobes conserve their shape in the velocity space because of their solid-body rotation.

The rotating matter of the accretion disc corresponds to the lines outside the black-hole Roche lobe as a result of the motion of the matter relative to the Roche lobe. These lines are not circles but ovals because the rotation of the matter is not Keplerian. Figure 4(a) shows two ovals corresponding to the disc radii $r_d = 0.2$ and 0.25 in units of the distance between the mass centres of the components. Figures 4(b) and 5 show the outer part of the accretion disc with $r_d = 0.2$. The emission may come from the outer regions of the accretion disc heated by hot supergiant emission, from the 'hot line' discussed by Kuznetsov *et al.* [11] and/or from the accretion stream (focused stellar wind).

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