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# LONG-TERM VARIATIONS OF THE SUPERGIANT IN THE X-RAY BINARY Cyg X-1

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Cyg X-1 is an X-ray binary system (with the orbital period $P = 5\overset{\mathrm{d}}{.}6$) whose relativistic component is the black hole candidate No. 1. More than 30 years passed since the times when the X-ray source Cyg X-1 had been first identified with the star HDE 226868 (Braes & Miley, 1971), its spectroscopic binarity (Webster & Murdin, 1972; Bolton, 1972) and photometric variability (Lyuty, 1972) had been first detected. This time interval is long enough to allow explorations of long-term behavior of the X-ray binary.

As the object's variability amplitude is low, only the homogeneous photometric series of UBV observations acquired at SAI Crimean Laboratory was used for this study (Lyuty, 1985; Kemp *et al.*, 1987; Karitskaya *et al.*, 2001; Lyuty *et al.*, 2006). In order to study intrinsic variability, orbital variations were subtracted.

Figure 1 shows the light curves representing the object's long-term variability. It is easy to see (especially in the U-band) that the objectś brightness is slowly increasing from 1985 to 1995, and then decreasing to a minimum reached in 2003. The brightness minima were observed in 1971 and in 2003–2005. The largest amplitude is $\Delta\mathrm{U} = 0\overset{\mathrm{m}}{.}1$. The B-band curve shows a similar behavior of the object, but with a lower amplitude. The V curve reveals a weak maximum only, and the 2003–2005 minimum is deeper than that of 1971.

The accretion disc cannot be responsible for these brightness variations because its contribution to the object's total luminosity does not exceed 2-4% (Bruevich *et al.*, 1978; Kemp *et al.*, 1987; Bochkarev and Karitskaya, 1988a,b). It is more reasonable to explain the variations with temperature changes in accordance with the variations of the B–V and U–B colors. In 1973, the object's spectrum was classified as O 9.7 Iab (Walborn, 1973). The results of our UBV observations are in agreement with the spectral type O 9.7 Iab,

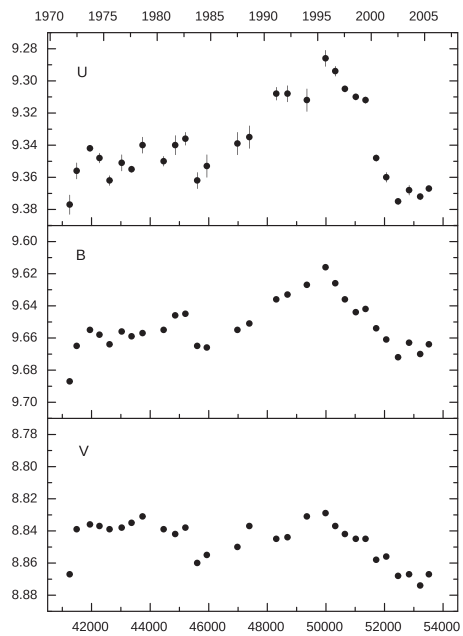


**Figure 1.** Long-term light curves of Cyg X-1 in the U, B and V bands (yearly averages)

the color excess being $E(\mathrm{B}-\mathrm{V}) = 1.05 - 1.06$. The 1995–1999 brightness maximum corresponds to an earlier spectral type, approximately O9.

Figure 2 shows a more detailed U-band light curve (averaged over 60 days); the lower panel gives an RXTE/ASM X-ray light curve (1-day averages). During the transition from the maximal (1995–1999) to the minimal (2003–2005) brightness, the X-ray activity increased. It should be pointed out that the activity maximum took place exactly at the time of the transition (on average, the U-band brightness decreased linearly).

If the supergiant's temperature variations are real, they must affect the spectrum. In 1997, spectroscopic observations were carried out at the Crimean Astrophysical Observatory (the 2.6-m telescope, the second order of the diffraction grating, spectral range $\lambda\lambda 4655 - 4722$Å, resolution $R = 35000$). In 2003–2004, spectra were obtained at the Peak Terskol Observatory (the 2-m telescope, the echelle spectrograph, spectral range $\lambda\lambda 3800 - 7600$Å, $R = 13000$) and at the BOAO (Korea) (the 1.8-m telescope, fiber echelle spectrograph, $\lambda\lambda 3800 - 10000$Å, $R = 30000$).

The spectral data obtained allows only two line profile comparisons: HeII$\lambda$4686Å and HeI$\lambda$4713Å. But as the complex variable HeII$\lambda$4686Å profile is formed mainly outside the supergiant, it cannot be used for the optical component's parameter diagnostic, in contrast to the HeI$\lambda$4713Å absorption line that is formed inside the star's atmosphere. The HeI$\lambda$4713Å line profiles observed in 1997 and 2003–2004 are compared in Fig. 3. Both presented profiles were averaged over 19 nights of observations. In 1997, 20 spectra were obtained during 1.5 months. One spectrum obtained during an X-ray flare was omitted. To construct the 2003–2004 line profile, we used the spectra got during two observational sets (June, 2003 and June, 2004) at the Terskol Observatory and 4 spectra obtained at the BOAO. Fig. 3 shows that the 1997 line depth is exceeded considerably by that of the 2003–2004 line, which points to changes in the supergiant's atmosphere parameters.

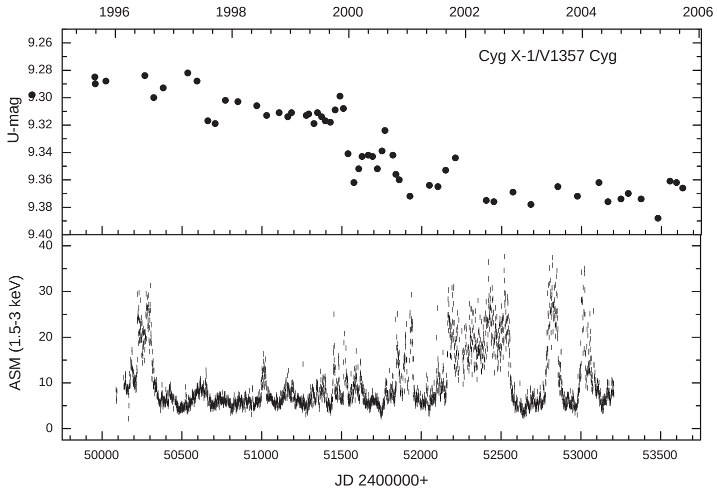


**Figure 2.** Comparison of the long-term light curve of Cyg X-1 (upper panel) with the X-ray light curve as observed by RXTE/ASM, 1-day averages (lower panel)

The 2003–2004 spectra were analyzed by Karitskaya *et al.* (2005). Using many spectral lines of the ions HI, HeI, MgII, we determined the supergiant's atmospheric physical parameters for that time interval: $T_{eff} = 30400 \pm\ 500$ K, log $g = 3.31 \pm\ 0.07$, [He/H] $=$ $0.43 \pm\ 0.06$ dex, [Mg/H] $= 0.75 \pm\ 0.15$ dex. We used a stellar-atmosphere modeling code which included: computation of line profiles of tidally distorted stars, illumination of the atmosphere by hard X-ray flux from the secondary, and non-LTE effects for selected ions. For line-profile simulations, we used Sakhibullin and Shimanskii (1997) computer code, "SPECTR", modified by Ivanova *et al.* (2002), Shimanskii *et al.* (2002).

Figure 3 (left panel) shows the model profile of the HeI$\lambda$4713Å line as derived for the years 2003–2004. To achieve the best coincidence of the computed and the observed 1997 profiles, we varied $T_{eff}$, log $g$, and the macro-turbulent velocity, $V_{\rm macr}$. Two different theoretical profiles corresponding to different $T_{eff}$, log $g$ values are shown in Fig. 3. The two theoretical profiles practically coincide with each other. Therefore, the differences between the observed and theoretical profiles are shown in the right panel of Fig. 3. The regular growth of the differences from the blue to the red wing is due to a feeble P Cyg component affecting the red wing and by unaccounted weak NII absorption blending with the blue wing. In 1997, $V_{\rm macr}$ was found to exceed the value for 2003–2004 by 7 km/s.

The comparison between the observed ($\Delta$U $= 0.065 \pm\ 0.003$, $\Delta$B $= 0.031 \pm\ 0.003$, $\Delta$V $= 0.029 \pm\ 0.003$) and computed UBV brightness variations shows that the size of the star increased slightly, by $1 - 4\%$ from 1997 to 2003–2004. The changes of the radius point to slight changes in log $g$ ($< 0.04$). Besides, the photometric and spectral variations can be described together only assuming that $T_{eff}$ was higher in 1997, being in the $31300 - 32300$ K range, than in 2003–2004, and the gravity in 1997 was log $g = 3.33 - 3.36$. The bolometric luminosity was by $14 - 24\%$ higher in 1997 than in 2003–2004. So the case with log $g = 3.06$ shown in Fig. 3 does not agree with photometric data.

So, from 1997 to 2003–2004 the radius of the star increased by $1 - 2\%$, that is, the degree of the Roche lobe filling, and consequently of the matter outflow toward the X-ray source, have increased. This is in agreement with the X-ray activity growth in that time interval (see Fig. 2). Moreover, the temperature decrease can lead to decreasing star-wind velocity, that is, to the increase of the portion of matter captured by the X-ray component, which may prove to be another factor keeping up X-ray activity of the system Cyg X-1.

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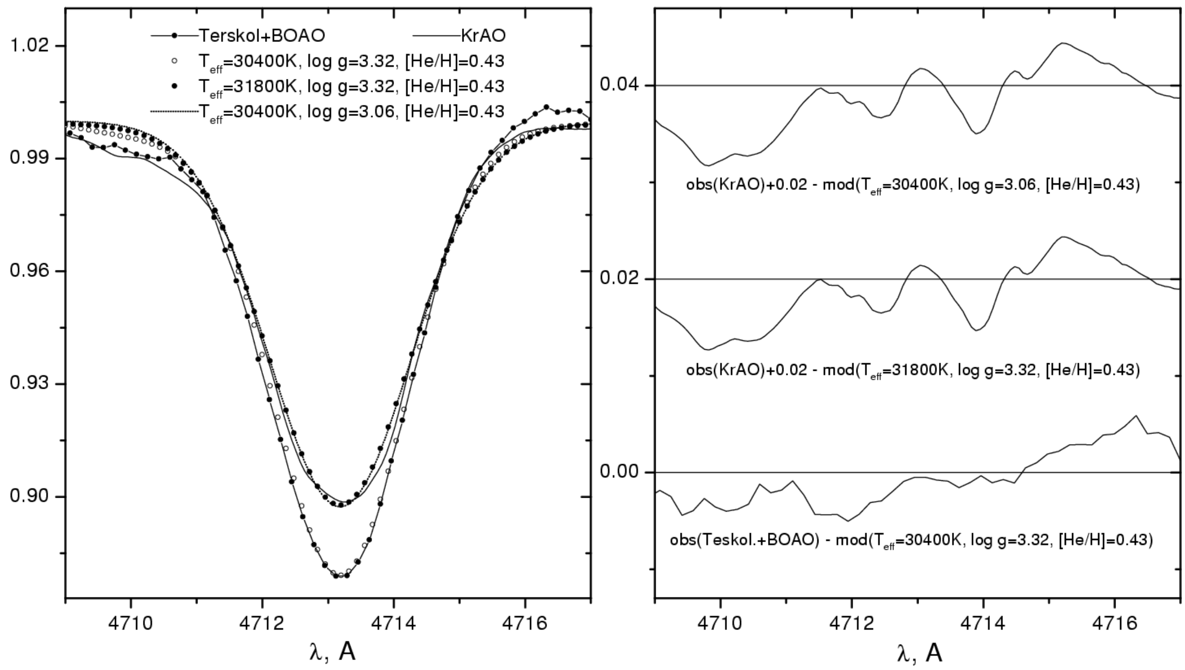


**Figure 3.** *Right:* Comparison of HeI$\lambda$4713Å line profiles observed in 1997 and 2003–2004 with the theoretical ones. The case with log $g = 3.06$ disagrees with photometric data. *Left:* The deviations of the observed profiles from the theoretical ones.

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