High-mass X-ray Binaries: Illuminating the Passage from Massive Binaries to Merging Compact Objects
Proceedings IAU Symposium No. 346, 2019
L. M. Oskinova, E. Bozzo, T. Bulik & D. Gies, eds.

doi:10.1017/S1743921319001339

On the long-term variability of high massive X-ray binary Cyg X-1

Eugenia Karitskaya[1] Nikolai Bochkarev[2], Vitalij Goranskij[2] and Natalia Metlova[2]

[1]Institute of Astronomy RAS, 48 Pyatnitskaya Str., Moscow, Russia.
email: karitsk@yandex.ru

[2]Sternberg Astronomical Institute Lomonosov Moscow State University, Moscow, Russia

Abstract. We continue our study of spectral and photometric variability of Cyg X-1 on the basis of the 45-year long series of multicolor photometric observations and many-year-long series of spectral observations we have accumulated up to now. The mean level of star brightness continues to decrease since 1999 with the variations on smaller time scales superimposed. There is a connection between X-ray and optical changes. The chaotic variations of X-ray flux sometimes reaching to “hard” - “soft” state irregular changes switch on when U brightness decrease and He I λ 4713 Å absorption line depth increase. And inversely - they switch off during U brightness increasing and He I λ 4713 Å absorption line depth decreasing. This may be connected with star size variations, causing outflow gas instability. It is concluded that the fundamental parameters of the supergiant in the system of Cyg X-1 continue to vary on the time scales of years - decades.

Keywords. stars: individual (HD 226868, V1357 Cyg, Cyg X-1), stars: variables: Cyg X-1, stars: fundamental parameters, stars: O-supergiant, stars: spectral variations, stars: photometrical variations

1. Introduction

Cyg X-1 = V1357 Cyg = HDE 226868 is an X-ray binary system (with the orbital period $P = 5.6^d$) whose relativistic component is historically the first candidate to a black hole (BH). It is a prototype of high massive X-ray binaries with a black hole being the brightest one among these objects ($m_V = 9^m$). Cyg X-1 is a microquasar having a jet during its low “hard”- state. The optical component, an O9.7 Iab supergiant, is responsible for about 95% of the system optical luminosity. The X-ray satellite UHURU discovered “hard” - “soft” states of X-ray spectrum. Besides of orbital variation, so called precession variation with $P = 294^d$ (Priedhorsky *et al.* 1983, Kemp, Karitskaya, Kumsiashvili *et al.* 1987), a lot of variability types in X-ray and optical ranges on different time scales (see for example Karitskaya *et al.* 2000, Karitskaya *et al.* 2001) were revealed.

The long-time variability investigations demand long and homogeneous observations. In 1971 V. M. Lyuty started his 35-year long homogeneous photometric series of UBV observations performed at Crimean Laboratory of Sternberg Astronomical Institute (SAI). This multicolor row of observations performed on the same equipment and undergone by the same reduction has permitted to reveal the supergiant light and color variation on the time scale of tens of years (Karitskaya, Lyuty, Bochkarev *et al.* 2006). According to this study the object brightness was slowly increasing between 1985 and 1995, and then decreasing to 2003. The largest variation was in the U band. Comparison of the spectra obtained in 1997 at the Crimean Astrophysical Observatory (the 2.6-meter telescope, resolution R=35000) with the spectra from the Peak Terskol Observatory (the 2-m telescope, R=13000) and BOAO (Korea, the 1.8-m telescope, R=30000) taken in

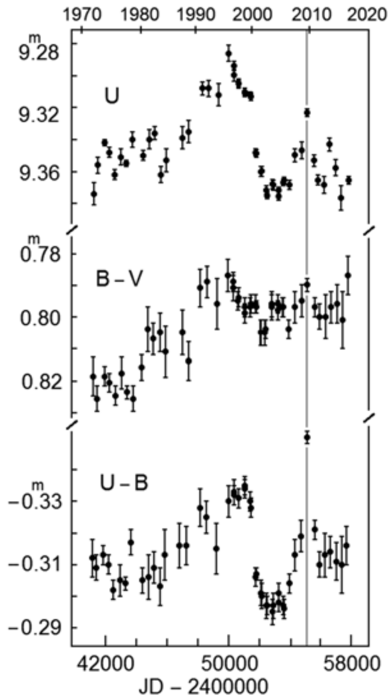

Figure 1. Long-term light curve of Cyg X-1 in U band and in $B-V$, $U-B$ color curves. Points are annualy averaged values. Vertical line marks the strong U-band flare of 2009.

2003-2004 showed that the He I λ 4713 Å line had became considerably deeper. Non-LTE simulations of this line profile and photometrical variations lead to the conclusion that the star radius has grown by about 2% from 1997 to 2004, while the temperature decreased by about 2000 K (Karitskaya, Lyuty, Bochkarev *et al.* 2006). These variations of supergiants parameter agree with the rise of X-ray activity just during the same time. The strong chaotic X-ray flux variations grow and sometimes leading to frequent changes of soft-hard states. The increasing of the degree of the Roche lobe filling leads to intensification and instability of the matter outflow towards the X-ray source. Therefore, both photometrical and spectral variations point to supergiant parameter changes.

2. Broad band photometrical variability

For continuation our study of Cyg X-1 long-term variability after the death of V. M. Lyuty, the unique homogeneous photometric UBV series was extended by N. V. Metlova up to now with the same equipment on the 60-cm telescope at the Crimean Station of the Moscow University. The long-term variability light curves for UBV see in Karitskaya, Bochkarev, Goranskij *et al.* (2017) and Karitskaya, Bochkarev, Goranskij *et al.* (2018). The largest variation is in the U band so Fig. 1 shows U light and color curves representing the object long-term variability during 45 years. The brightness drop starting from 1999 and revealed by Karitskaya, Lyuty, Bochkarev *et al.* (2006) continues up to now, although separate maxima sometimes take place. The most interesting feature is a very blue flare in 2009 which is pronounced better in the $U-B$ color curve.

3. Comparison of optical and X-ray light curves

Fig. 2 compares the long-term U-band light curve with the X-ray variations in time between 1996 and 2016. The upper panel shows the RXTE-ASM $1.5 \div 12$ keV

https://doi.org/10.1017/S1743921319001339 Published online by Cambridge University Press

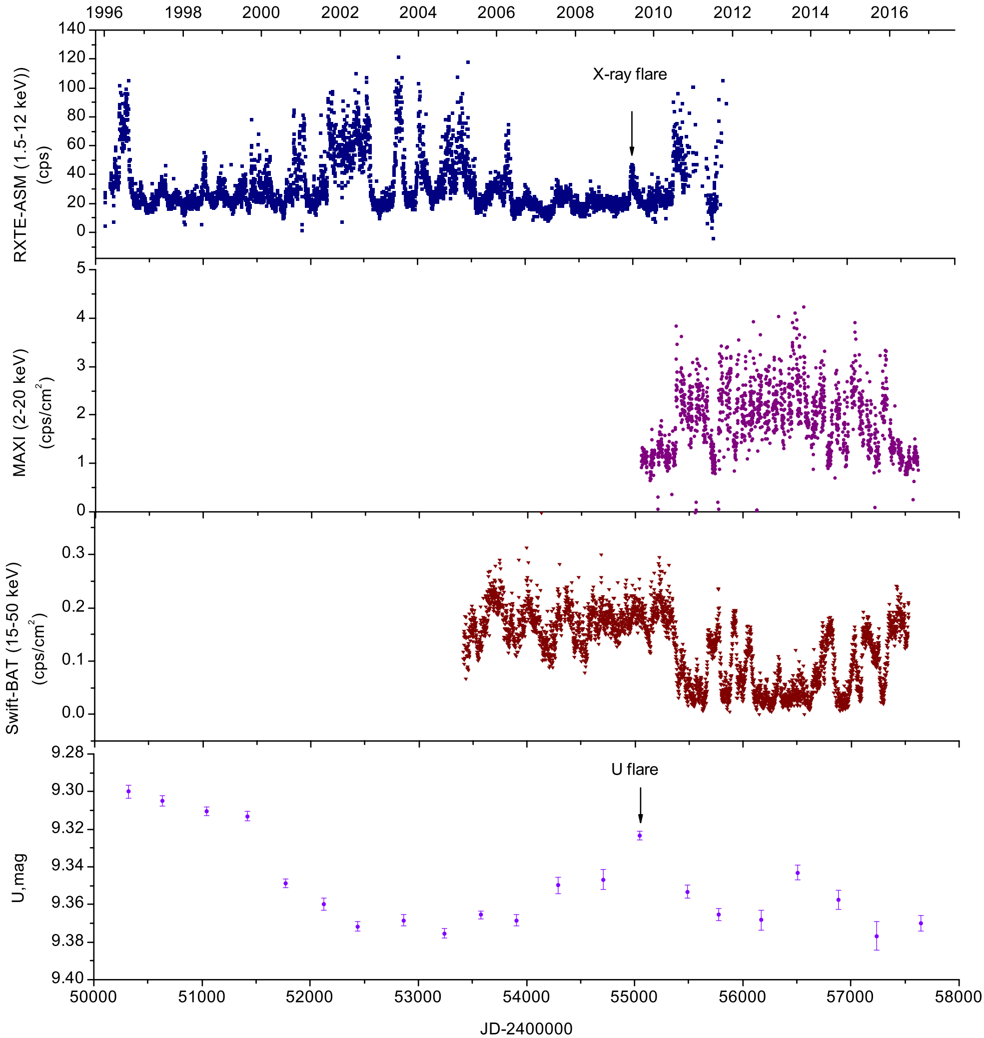

Figure 2. X-ray (RXTE-ASM, MAXI, Swift-BAT) and U-band light curves of Cyg X-1 from 1996 to 2016. The U-band data are yearly averaged. The X-ray flare coinciding with the U-band flare of 2009 is marked (see Karitskaya, Bochkarev, Goranskij *et al.* 2018).

data (http://xte.mit.edu/). RXTE-ASM data after $JD2455200$ are affected by instrumental decline before the spacecraft mission finishing. The observations in the same X-ray energy range were prolonged by Monitor of All-sky X-ray Image (MAXI energy band $2 \div 20$ keV). The second panel shows the data from this cosmic equipment (http://maxi.riken.jp/top/ index.php?cid=1&jname=J1958+352). It is very important to compare them with the hard X-ray data because of their different behavior - the light curves anti-correlate to each others. The third panel shows the light curve for $15 \div 50$ keV obtained by Swift gamma-ray burst satellite and Burst Alert Telescope (Swift-BAT) (http://swift.gsfc.nasa.gov/results/ transients/). On the lowest panel, the yearly averaged data in U-band are given.

In Fig. 2 we can see time intervals with chaotic variations of X-ray flux sometimes reaching to "hard" - "soft" state irregular changes. Earlier the transition from ordinary low "hard" state to high "soft" state occurred only once per several years. We can see at least two such events, in 2000 and 2010. They are coincide with U band brightness

https://doi.org/10.1017/S1743921319001339 Published online by Cambridge University Press

decreasing. For 2000 year it was noted by Karitskaya, Lyuty, Bochkarev *et al.* (2006). Inversely - when the brightness in the U band begins to grow, the X-ray activity turns off. In the time interval $JD2454000 \div 2455000$ the source was in quiet "hard" state while U-band brightness was increasing. After $JD2455000$ U-band brightness began to fall and the X-ray instability (chaotic variations of X-ray flux) appeared. This small U-band brightness growth was followed by a relative stabilization at the "soft" state, and than, the U-band brightness began to fall and X-ray instability is resumed.

The situation for 2000 year is described by Karitskaya, Lyuty, Bochkarev *et al.* (2006) being explained by supergiant parameter variation. When the temperature was decreasing, the supergiant radius was increasing approaching to the critical Roche lobe. It results to unstable material flowing between the components and resuming the X-ray activity.

In Fig. 2 we can see already mentioned very blue flare 2009. It is interesting that it coincides with an X-ray flare. This flare observed only in the U band is probably an evidence of an appearance of the very hot gas in the Cyg X-1 system.

4. He I absorption line variation

The variability of photospheric spectral line depths found in the available high-resolution spectra is also in agreement with above mentioned idea - the variation of supergiant fundamental parameters. In the papers Karitskaya, Bochkarev, Goranskij *et al.* (2017) and Karitskaya, Bochkarev, Goranskij *et al.* (2018) we have demonstrated the He I λ4713 Å line profile variations during 1997 - 2014 by using precise high resolution spectra. They where obtained on different instruments - at the Crimean 2.6 meter telescope (1997), at the observatories BOAO and Peak Terskol (2003-2004), at the 6-meter telescope of the SAO RAS (2005-2013), at 3.6 meter telescope CFHT (Hawaii) with the ESPaDOnS spectrograph (Sep 12, 2014). The first spectra from Crimean 2.6 meter telescope in 1997 were obtained in a very narrow spectral range, where He I λ4713 Å was the only one among absorption photospheric lines. Therefore we study behavior of this line. The depth variations of the line (up to 30%) are visible.

We revealed a general tendency of the line profile depth variations. During U brightness decrease the He I λ 4713 Å absorption line depth increases. And inversely - during U brightness increase the line depth is getting shellower. During the 1997 – 2004 U-band brightness decay, the He I λ 4713 Å line profile became deeper. By using model calculation in the paper Karitskaya, Lyuty, Bochkarev *et al.* (2006) it is explained by decreasing of the supergiant surface temperature: the lower is the temperature – the stronger is this photospheric absorption line. The profile depth on 12.11.2005 is approximately the same as when U brightness is in at minimum of the light curve. In 2006–2008 the line depth is decreasing while U-brightness is growthing and reaching maximum. The line profiles observed in 2013 with the 6-m BTA/NES and in 2014 with the CFHT/ESPaDOnS show the biggest depths although U-band light curve has small maximum.

Fig. 3 presents the comparison of changes in the depth of the He I λ4713 Å absorbtion line with the brightness variations in the U band in 2015. We used our low-resolution spectral observations conducted at the SAO RAS 1-m telescope with the UAGS spectrograph (the range 3850–5200 Å, R= 2000, $S/N \sim 200 - 300$). The advantage of these observations in respect to the observations with the 6-m telescope is in their frequency and regularity allowing a better comparison of the variability in line profiles with the brightness variability. The low panel of Fig. 3 presents ΔU light curve for 2015 after orbital light curve subtraction from U photometrical data. The point scattering is caused by observational errors and quick variations. Anti-correlation may be noticed, which is consistent with conclusion by Karitskaya, Lyuty, Bochkarev *et al.* (2006) on the variability of the fundamental parameters of the optical component. The moment of the

https://doi.org/10.1017/S1743921319001339 Published online by Cambridge University Press

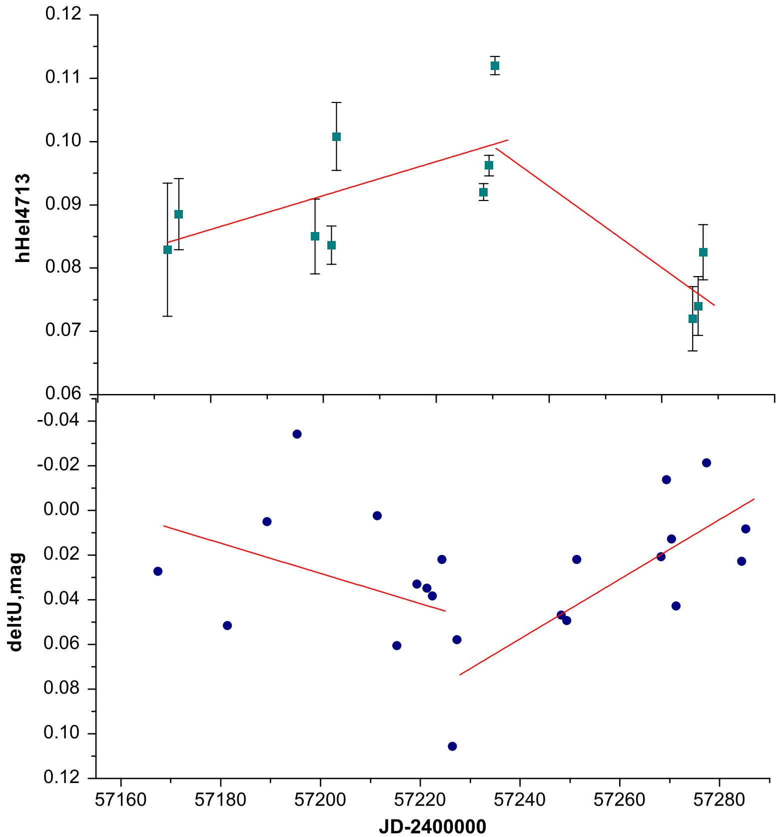

Figure 3. Comparison of the U-band brightness with the He I λ 4713 Å line profile depth variations observed at the SAO RAS 1-m telescope in 2015. U-band photometrical data are presented after averaged orbital light curve subtraction (see Karitskaya, Bochkarev, Goranskij *et al.* 2018).

U-band brightness minimum appears to be a turning point, after which the radius of the supergiant began to decrease and the temperature to rise.

5. Conclusions

As a result of our multi-year study of the photometric and spectral variability of Cyg X-1, we have established that the mean level of star brightness continues to decrease since 1999 with the variations on smaller time scales superimposed.

We revealed a very blue flare in 2009 observed only in the U band. It is probably an evidence of appearance of a very hot gas in the Cyg X-1 system. It coincides with the X-ray flare.

Our precise high resolution spectral observations and with the SAO RAS 1-meter telescopes show variations of absorption line depths up to 30%. There is a connection between X-ray and optical changes. The chaotic variations of X-ray flux sometimes reaching to "hard" - "soft" state irregular changes switch on when U brightness decrease and He I λ 4713 Å absorption line depth increase. And inversely - they switch off during U brightness increasing and He I λ 4713 Å absorption line depth decreasing.

All above mentioned facts suggest that the fundamental parameters of the supergiant in the system of Cyg X-1 continue to vary. When the temperature of the optical component (9.7Iab supergiant) was decreasing, its size was increasing approaching to the critical

Roche lobe. It was stimulating the unstable material flow and initiating the X-ray activity. Inversely - when the temperature was increasing the supergiant getting smaller, moving away from the critical Roche lobe, and the X-ray activity stops. But the conduction of research of these variations was complicated by a possible presence of a variable optically thin gas, the evidences of which were revealed.

References

Karitskaya, E. A., Goranskij, V. P., Grankin, E. N., & Melnikov, S. Yu. 2000, *Astron. Let.*, 26, 22

Karitskaya, E. A., Voloshina, I. B., & Goranskii, V. P. *et al.* 2001, *Astron. Reports*, 45, 350

Karitskaya, E. A., Lyuty, V. M., Bochkarev, N.G. *et al.* 2006, *IBVS*, No.5678, 1

Karitskaya, E. A., Bochkarev, N. G., Goranskij, V.P. *et al.* 2017, *ASP Conf. Ser.*, 510, 408

Karitskaya, E. A., Bochkarev, N. G., Goranskij, V.P. *et al.* 2018, *AApTr*, 30, 421

Kemp, J. C., Karitskaya, E. A., Kumsiashvili, M. I., *et al.* 1987, *Soviet Astron.*, 31, 170

Priedhorsky, W. C., Terrell, J., & Holt, S. S. 1983, *ApJ*, 270, 233