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On the long-term variability of Cyg X-1=V1357 Cyg

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According to our research, the temperature of optical component (O9.7 Iab supergiant) was decreasing and its size was increasing over 7 years (1997–2003). We continue our study of spectral and photometric variability of Cyg X-1 on the basis of the 44-year long series of multicolor photometric observations and many-year-long series of spectral observations that we have accumulated up to now. The photometry performed at the Crimean Station of Sternberg Astronomical Institute (Lomonosov Moscow State University) shows that the variability of the supergiant in this system on the time scale of decades has continued up to now – the mean level of star brightness continues to decrease since 1999 with the variations on smaller time scales superimposed. A remarkable very blue flare 2009 in U-band coinciding with X-ray flare is revealed. Our spectral observations show variations of He I λ 4713 Å absorption line depths. There is a connection between X-ray and optical changes. It is concluded that the fundamental parameters of the supergiant in the system of Cyg X-1 continue to vary. But the conduction of research of these variations is complicated by the possible presence of a variable very hot optically thin gas the evidences of which were revealed.

Keywords: Stars: photometrical variations – stars: X-ray binary – stars: accretion – stars: spectral variations – stars: fundamental parameter variations – stars: X-ray variations – stars: O-supergiant – stars: individual (HD 226868, V1357 Cyg, Cyg X-1)

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 the black hole and 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,

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is responsible for about 95% of the optical luminosity of the system. The remaining 5% is due to the accretion structure (disc and surrounding gas) near the BH. So the great bulk of optical variations refers to the supergiant.

The existence of the X-ray source Cyg X-1 was first suspected by Giacconi et al. (1962) as a result of the first rocket experiment. The X-ray satellite UHURU discovered rapid (on timescale of milliseconds) chaotic variations of the X-ray radiation, and changes of "hard"–"soft" states of X-ray spectrum. After the identification of the X-ray source Cyg X-1 with the B0 star HDE226868 in 1971 (Bolton, 1972) optical observations began to be actively carried out. Besides the orbital variation with $P = 5.6^d$ (Lyuty, Sunyaev, Cherepashchuk, 1973), so called precession variation with $P = 294^d$ (Priedhorsky et al. 1983, Kemp, Karitskaya, Kumsiashvili et al. 1987), many variability types were revealed in X-ray and optical ranges on different time scales (see for example Karitskaya et al. 2000, 2001).

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 fulfilled on the same equipment and undergone by the same reduction has permitted us 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.

A 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 from the the Bohyunsan Optical Astronomy Observatory (BOAO, Korea, the 1.8-m telescope, $R = 30000$) taken in 2003–2004 showed that the He I λ 4713 Å line had become considerably deeper. Non-LTE simulations of this line profile and photometrical variations lead to the conclusion that the star radius has grown by about 1–4% from 1997 to 2003–2004, while the temperature decreased by 1300–2400 K (Karitskaya, Lyuty, Bochkarev et al., 2006). These variations of supergiant's parameter agree with rise of X-ray activity just during the same time. The strong chaotic X-ray flux variations grow sometimes leading to frequent changes of "soft"–"hard" states. The increase in the degree of the Roche lobe filling leads to intensification and instability of the matter outflow towards the X-ray source. Thereby, both photometrical and spectral variations point to supergiant parameter changes on the time scale of tens of years.

2 Broad band photometrical variability

For the continuation of 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 Moscow University. Figure 1 shows the light and color curves representing the object's long-term variability during 45 years. It is easy to see that the drop in brightness starting from 1999 and revealed by Karitskaya, Lyuty, Bochkarev et al., (2006) continues up to now, although separate maxima sometimes take place.

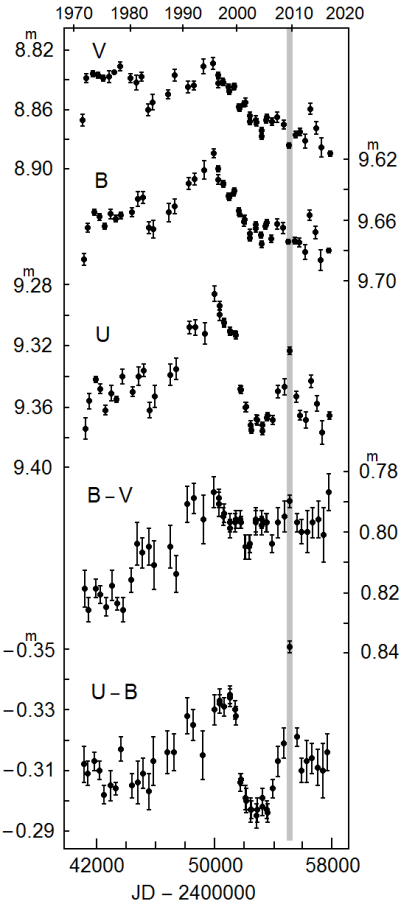


Figure 1 Long-term light curves of Cyg X-1 in the V, B and U bands and in B–V, U–B color curves. Points are annually averaged values. Vertical line marks the strong U-band flare of 2009.

Variations in the U-band are the most significant. The most attractive light curve detail is a very blue flare in 2009 which is remarkably better in the U–B color curve.

Figure 2 represents the long-term variations of orbital light curves for U and V bands during 1996–2016. The points change color gradually from dark red to violet step by step from 1996 to 2016 (see the scale on the right). In the case of V band we can see the mean level decrease, while in the case of U band the blue points corresponding to 2009–2010 years turn out in the middle place of the graph. They represent orbital light curve during the mentioned very blue flare 2009. Evidently the shapes of these light curves conserve the typical two waved appearance.

Figure 3 shows all the observational points after the subtraction of the averaged orbital light curves in three photometrical bands ΔV, ΔB, ΔU. The long-term variations and a very blue flare are clearly visible. The point scattering is caused by observational errors and quick variations.

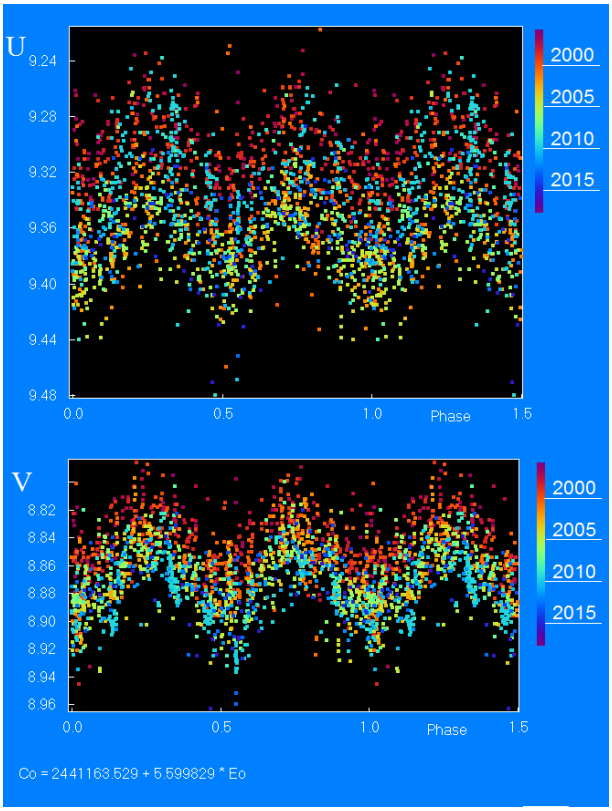


Figure 2 Variations of orbital light curves for U (top) and V (bottom) bands during 1996–2016 observational period. The scales on the right show the gradual change of observational point color from dark red to violet according to time.

3 Comparison of optical and X-ray light curves

Figure 4 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 1.5–12 keV data (http://xte.mit.edu/). RXTE-ASM data after JD 2455200 are affected by instrumental decline before the end of the spacecraft mission. The observations in the same X-ray energy range were prolonged by Monitor of All-sky X-ray Image (MAXI energy band 2–20 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 other. The third panel shows the light curve for 15–50 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 U-band yearly averaged data are given.

In Fig. 4, we can see that at the end of the 1990s the time intervals appeared with often irregular changes of "hard"–"soft" states. Earlier the transition from the

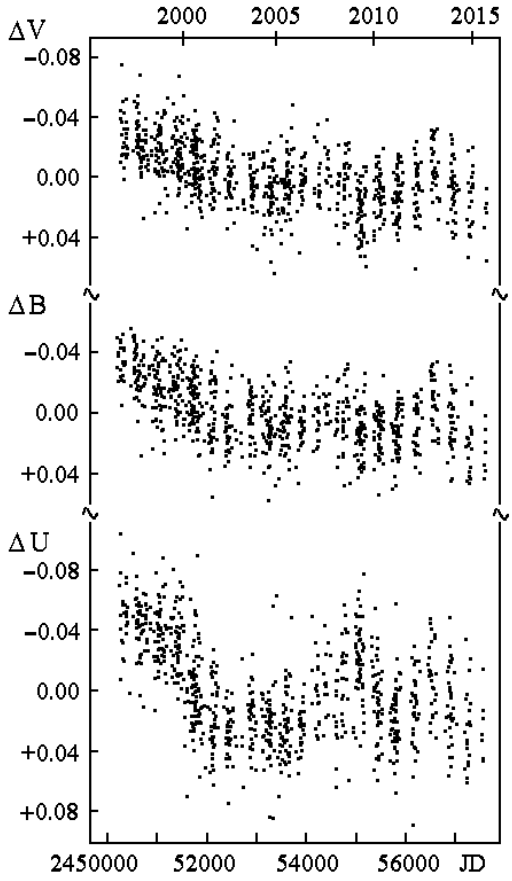


Figure 3 Long-term light curves of Cyg X-1 plotted for the period between 1996 and 2016 and extracted for V, B and U bands after orbital light variation subtraction from each observational point.

ordinary low "hard" state to high "soft" state occurred only once per several years. As it was noted by Karitskaya, Lyuty, Bochkarev et al. (2006) this change of behavior is connected with the beginning of brightness decay. This connection between X-ray and optical variations continues up to now. When the brightness in the U band is decreasing, the X-ray activity switches on. We can see in Fig. 4 at least two such events, in 2000 and 2010. Inversely – when the brightness in the U band begins to grow, the X-ray activity turns off. In the time interval JD 2454000–2455000 the source was in quiet "hard" state while U-band brightness was increasing. After JD 2455000 the 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 then, the U-band brightness began to fall and X-ray instability is resumed.

The situation is similar to that described by Karitskaya, Lyuty, Bochkarev et al. (2006) and is explained by supergiant parameter variation. When the temperature

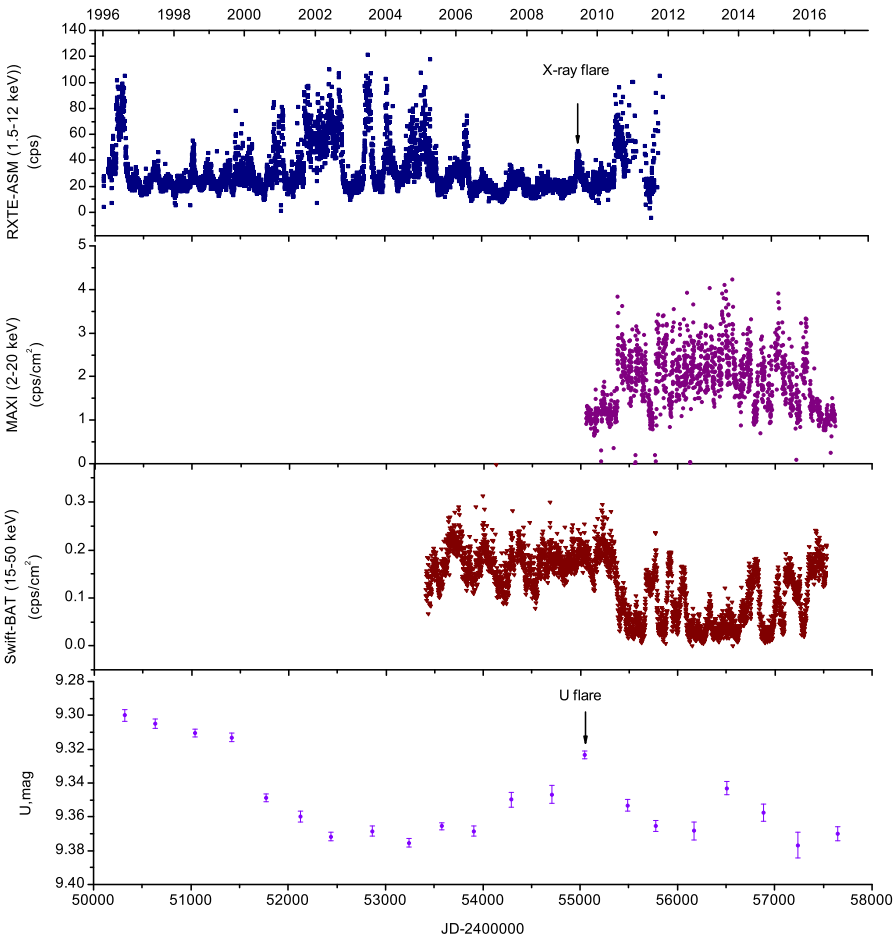


Figure 4 X-ray (RXTE-ASM, MAXI, Swift-BAT) and U-band light curves of Cyg X-1 from 1996 to 2016. The U-band data are yearly averaged. The X-ray flare coinciding with the U-band flare of 2009 is marked.

was decreasing, the supergiant radius was increasing approaching to the critical Roche lobe. It was stimulating the flow of unstable material and resuming the X-ray activity.

In Fig. 4, we can see the already mentioned very blue flare 2009. It is interesting that it coincides with X-ray flare. In Fig. 5, it is shown in more detail. This flare observed only in the U band is probably evidence of the appearance of very hot gas in the Cyg X-1 system.

4 He I λ 4713 Å absorption line variation

The variability of photospheric spectral line depths found in the available high-resolution spectra is also in agreement with the above mentioned idea.

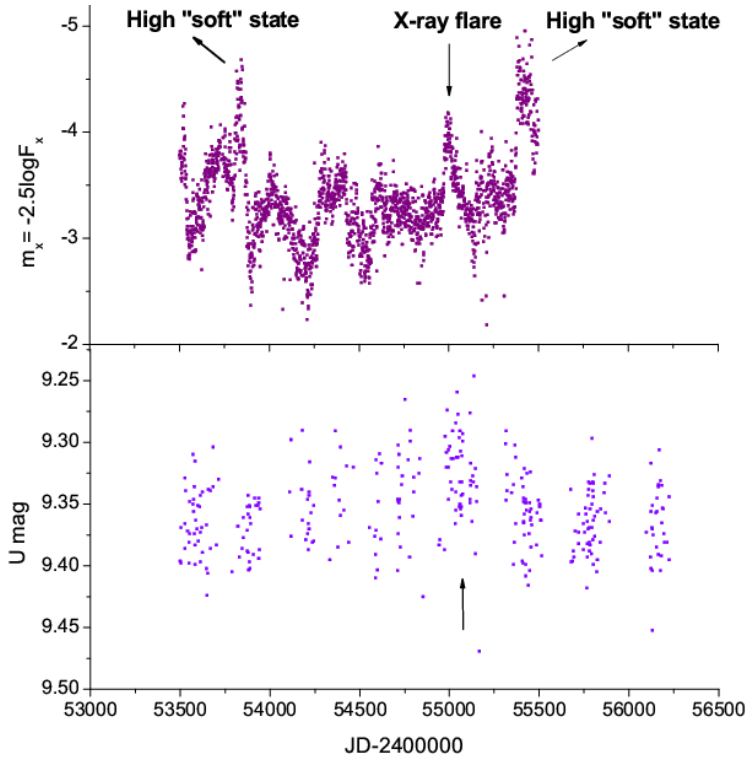


Figure 5 X-ray RXTE-ASM and U-band light curves of Cyg X-1. Very blue U-band flare 2009 and X-ray flare coinciding with it are marked.

Figure 6 demonstrates He I λ 4713 Å line profile variations during 1997–2014. For this purpose we show several profiles from Fig. 3 by Karitskaya et al.(2017) obtained in 2005–2013 with the NES echelle spectrograph at the 6-meter telescope of the SAO RAS, $R \simeq 60000$ and signal-to-noise ratio $S/N \geq 330$. We add one profile which was obtained on Sep. 12, 2004 at 3.6 meter telescope CFHT (Hawaii) with the ESPaDOnS spectrograph, $S/N \simeq 700$ and $R = 65000$. For comparison, Fig. 6 includes the profiles obtained in 1997 with the Crimean 2.6 meter telescope and the profiles obtained in 2003–2004 at the observatories BOAO and Peak Terskol, each of them averaged over 19 nights (see Fig. 3 by Karitskaya, Lyuty, Bochkarev et al., 2006). Note that in contrast to the other shown line profiles of 2005–2014, they are reduced to laboratory wavelength. The depth variations of the line (up to 30%) are visible.

The comparison of Fig. 6 and Fig. 4 permits us to see a general tendency of line profile depth variations. During 1997–2004 U-band brightness decay, He I λ 4713 Å the line profile became deeper. In Karitskaya, Lyuty, Bochkarev et al. (2006), it is explained by the decrease in the supergiant surface temperature: the lower the temperature – the stronger this photospheric absorption line. The profile depth on 12.11.2005 is approximately the same when U brightness remains in minimum of light curve. In 2006–2008 the line depth is decreasing while U-brightness grows and reaches maximum. The line profiles observed in 2013 with the 6-m BTA/NES and in 2014

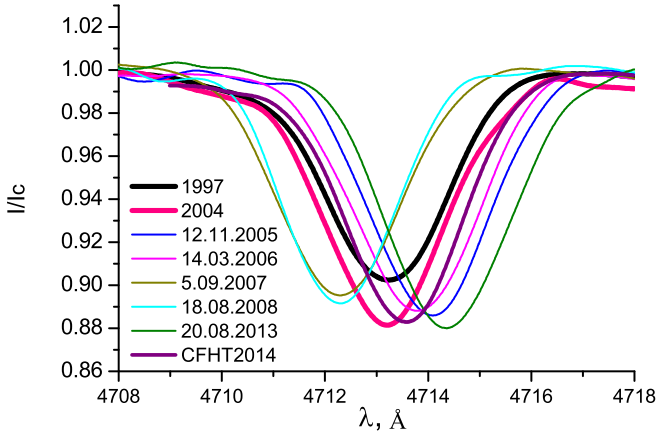


Figure 6 Comparison of examples of the line profiles He I λ 4713 Å observed with the 6-m telescope in 2005–2013 (thin lines), with the CFHT in 2014 (moderate line) with those observed at the Crimean Observatory (bold black) in 1997 and at the BOAO and Terskol observatories (bold pink) in 2003–2004. Smoothing was done by convolution with the Gaussian profile, FWHM 1 Å.

with the CFHT/ESPaDOnS show the biggest depths although U-band light curve has small maximum.

There is no direct correspondence between depth of this line and U-band magnitude, but is a tendency only. May be it is connected with an appearance of "third light". It can be a variable emission of thin hot gas in this binary system. For example the blue flare observed in 2009 by us (see, e.g., Fig. 5) may be explained by such gas appearance. Its proper quantity could create additional emission which reduced absorption line depths. And in the next years this gas disappeared, additional light vanished and the profile became corresponding to the light level observed in the early 2000s.

The variable hot gas component (or stellar wind?) produces additional variable emission line components superimposing on the line profiles and distorting them. The example of such a profile variation has been demonstrated in Fig. 1 by Karitskaya & Bochkarev (2015) for H_β line using the observations obtained near orbital phase $\phi = 0.0$ with the 6-m telescope on Aug 11, 2006 and on Sep 24, 2007 when the gas component appeared.

Figure 7 presents the comparison of changes in the depth of the He I λ4713 Å absorption 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. 7 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. For example, the fast variability of photospheric line depth was also reported in OB and A giants and supergiants by Kholtygin et al.(2016). Anti-correlation may be noticed, which is

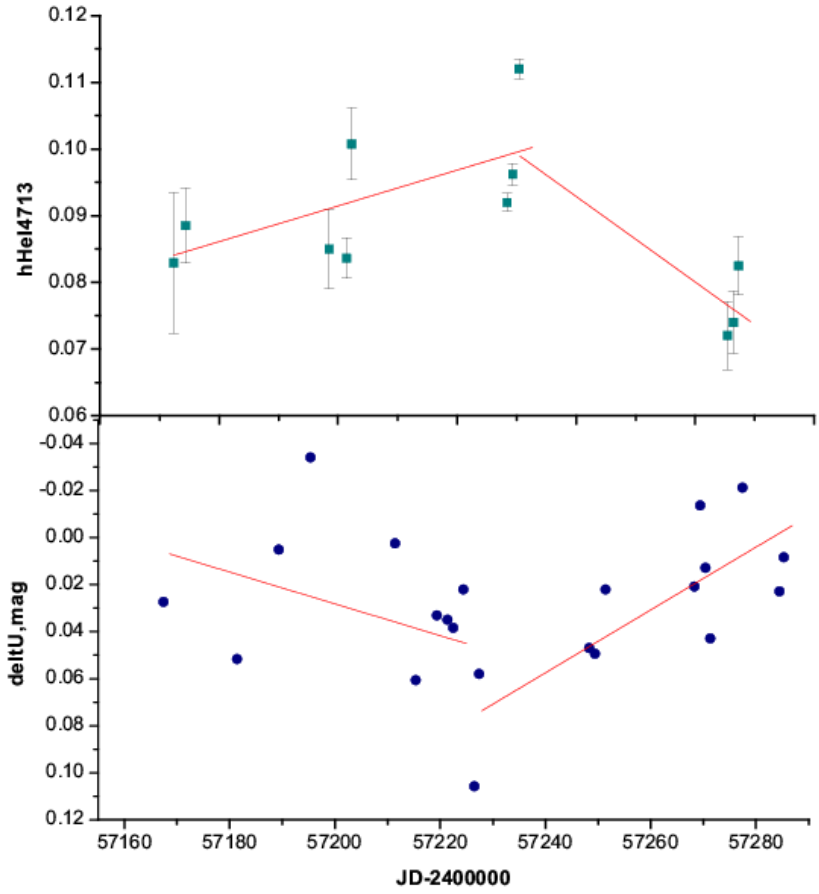


Figure 7 Comparison of the U-band brightness with the He I λ 4713 Å line profile depth variations observed at the SAO RAS 1-m telescope in 2015. U-band photometrical data are presented after averaged orbital light curve subtraction.

consistent with the conclusion by Karitskaya, Lyuty, Bochkarev et al. (2006) on the variability of the fundamental parameters of the optical component. The moment of the U-band brightness minimum appears to be a turning point, after which the radius of the supergiant began to decrease and the temperature began to rise.

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 has continued 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 the appearance of a very hot gas in the Cyg X-1 system. It coincides with the X-ray flare.

Our spectral observations with the 6 meter and 1 meter telescopes of the SAO RAS show variations of absorption line depths. There is a connection between X-ray and optical changes, the X-ray instability (chaotic variations of X-ray flux) appeared when the brightness in the U band is decreasing. Inversely – when the brightness in the U band begins to grow, the X-ray activity turns off. A general tendency of line profile depth variations was revealed. During U-band brightness decay He I λ 4713 Å line profile became deeper, and inversely – when the brightness in the U band begins to grow, this line profile became shallower. But it is a tendency only and there is no direct correspondence.

All of the 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 (O9.7 Iab 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 radius was 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 the possible presence of a variable optically thin gas, the evidences of which were revealed.

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