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THE INFRARED VARIATIONS OF CYG X-1 (V1357 CYG), 1995–2007

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We present the results of our long-term ($\sim$13 years) J and K photometry of the X-ray binary Cyg X-1. The object's JK variability amplitudes were less than $0^{\rm m}_{.}2$. The J and K orbital light curves are appreciably asymmetric in quadratures. The secondary minimum is deeper, in comparison to the primary, and it is probable that the star becomes hotter at secondary minima. The ratio of average radii of the supergiant in quadratures and in minima is $\sim$1.02 if the temperature of the optical component does not change during its orbital motion. We estimate the interstellar extinction as $E(B-V) = 1^{\rm m}_{.}025 \pm 0^{\rm m}_{.}006$ and the distance to the star, as $d = (2.44 \pm 0.04)$ kpc. The luminosity and radius of the optical component are respectively $\sim 2.8 \cdot 10^5 L_\odot$ and 21 $R_\odot$. The JK variations of the X-ray binary Cyg X-1 in 1995–2007 can be explained with orbital ellipsoidal variations of the optical component (hot supergiant HD 226868), accompanied with long-term JK variations on a time scale of 11.5 years with an amplitude of $0^{\rm m}_{.}06$–$0^{\rm m}_{.}07$. In 1995–2007, the JK brightness fluctuations probably had a 294-day periodicity with an amplitude of no more than $0^{\rm m}_{.}03$–$0^{\rm m}_{.}05$.

1 INTRODUCTION

Cyg X-1 is one of the best-studied X-ray sources since its discovery in 1965 (Bowyer et al. 1965). Webster & Murdin (1972) identified the source with the O9.7Iab supergiant HD 226868 and found an orbital period of 5.6 days. On the basis of the analysis of data from the X-ray satellite UHURU, together with radio and optical observations, Tananbaum et al. (1972) suggested that the invisible component of the X-ray binary Cyg X-1 was a black hole. Optical variations of the supergiant were investigated by Lyuty (1972) and Lyuty et al. (1973). They calculated parameters of the binary, confirmed that the source Cyg X-1 was the first black-hole candidate, and explained variations of the optical component with its ellipsoidal shape, changing aspect during orbital motion.

Since then, the orbital period ($\sim 5.6^{\rm d}$) was reliably identified in the binary's brightness variations and the existence of several periods (from dozens of days to hundreds of days; see, for example, Kemp et al. 1978; Priedhorsky et al. 1983) was suspected.

Despite extensive studies of Cyg X-1 in the recend decades, the IR variability of the source was reliably established only in the early 1990s (Leahy & Ananth 1992). The cited authors discovered fluctuations of the J and K brightness with an amplitude of $0^{\rm m}_{.}3$ during the orbital motion and explained the near-IR radiation from the system as due to the accretion disk.

The first cycle of our JK photometry of Cyg X-1 was performed in 1984–1994 (Nadzhip et al., 1996). From the analysis of these observations together with optical photometry of Cyg X-1, we concluded that the variations of the binary's J and K brightness were ellipsoidal.

The results of our JK photometry of Cyg X-1 acquired in 1995–2007 are presented in this paper.

2 OBSERVATIONS

Our JK photometry of Cyg X-1 was performed at the 1.25-m telescope of the Crimean Laboratory of the Sternberg Astronomical Institute using a photometer with a liquid-nitrogen-cooled InSb detector. The photometer was mounted at the Cassegrain focus of the telescope; the exit aperture was $\sim 12''$. The star BS 7615 from the Johnson et al. (1966) catalog served as a photometric standard. The results of our photometry of Cyg X-1 between June, 1995 and September, 2007 and their uncertainties are presented in Table 1.

3 RESULTS AND DISCUSSION

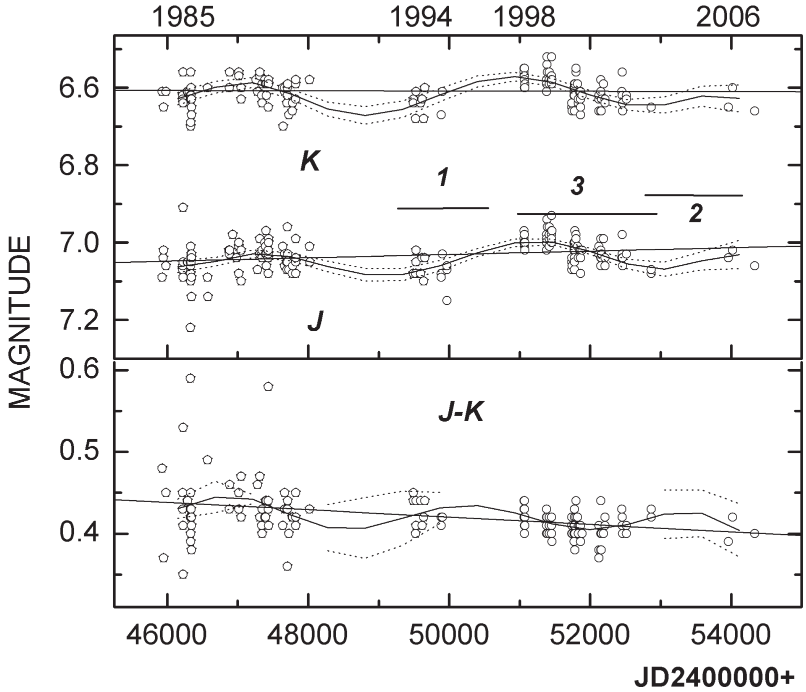

Figure 1. The 1984–2007 JK light curves and $J-K$ color curve of Cyg X-1. The straight lines are linear fits. The solid and dotted curves are fits to eighth-order polynomials and their confidence intervals. The lines 1, 2, and 3 show approximal time intervals of the maximum (line 1) and minimum (line 2) in the optical brightness and in the X-ray source activity (line 3).

Characteristic Features of the JK Brightness Variations of Cyg X-1 in 1995–2007

Variations of the J and K magnitudes and $J-K$ color of Cyg X-1 are presented in Fig. 1 for the whole time interval covered with our observations (1984–2007). The observations of 1984–1994 are plotted as asterisks; circles are observations of 1995–2007. The straight lines are linear fits of the observations. The results of our J and K photometry of 1984–1994 were discussed earlier (Nadzhip et al. 1996). The following qualitative features of the J and K magnitude and $J-K$ color variations are apparent from Table 1 and Fig. 1:

– the amplitudes of fluctuations of the J and K brightness did not exceed $0^{\mathrm{m}}.2$ during 1995–2007;

– the average K-brightness level almost did not vary between 1984 and 2007, but the J brightness has probably increased (see Fig. 1, straight lines). This has led to a decrease of the $J-K$ color index in 2006–2007 compared to 1984–1985 (the straight line in the bottom part of Fig. 1).

It is easily apparent from the JK light curves (Fig. 1) that the brightness of Cyg X-1 decreased during 1990–1994, then it increased to a maximum near 2000 and again decreased to 2003. We attempted to fit the J and K brightness fluctuations observed in 1984–2007 to polynomials of different order (from 2 to 9). As a result, the narrowest confidence intervals were found for curves of the eighth order, they are shown in Fig. 1 as solid curves (the dashed lines are boundaries of the confidence intervals). The periodic component having a time scale of 4000–4300 days ($\sim$ 11.5 years) and an amplitude of $\sim 0^{\mathrm{m}}.06-0^{\mathrm{m}}.07$ in the K filter is visible well enough.

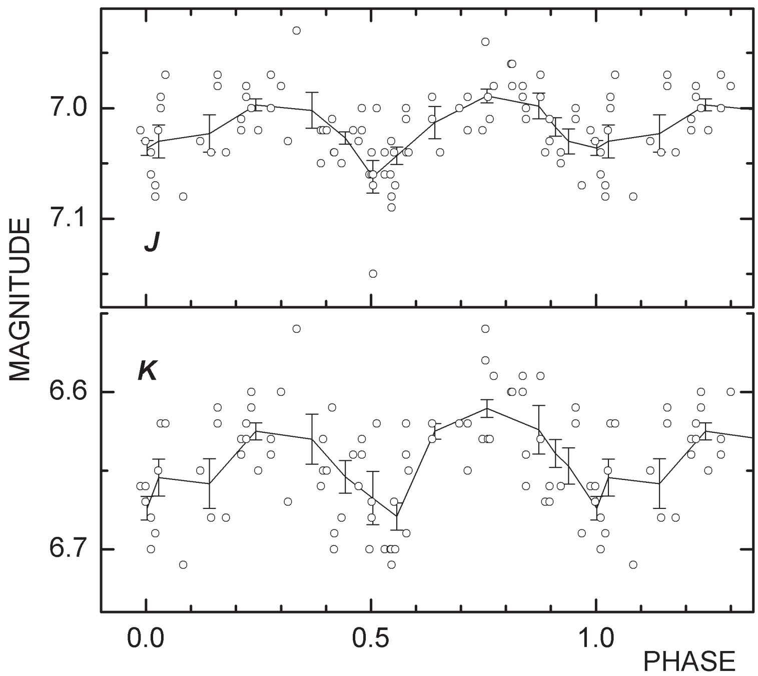

Figure 2. The 1995–2007 JK light curves of Cyg X-1 folded with the orbital periods. The broken lines are for averaged values.

In 1998–2004, an activity increase of the X-ray source was accompanied with a decrease of the binary's optical activity (Karitskaya et al. 2006). In the near-IR range, on the contrary, the activity of the X-ray source probably caused some increase both of the IR brightness and of the color temperature. It is clearly seen in Fig. 1, where the lines 1, 2, and 3 mark the approximate time intervals of the maximum (line 1) and minimum (line 2) in the optical brightness and in the X-ray source activity (line 3).

In other words, we can assume that there is a "long-term" component of the JK radiation with a variability time scale of about 11.5 years in the observed JK brightness variations of Cyg X-1 . The "long-term" component and the activity of the binary's X-ray component are probably interrelated.

Table 1. The JK photometry of V1357 Cyg (Cyg X-1), 1995–2007

JD (2440000+)	J	$\sigma(J)$	K	$\sigma(K)$	JD (2440000+)	J	$\sigma(J)$	K	$\sigma(K)$
9885.521	7.091	0.005	6.673	0.012	11774.338	7.010	0.005	6.624	0.007
9885.528	7.083	0.006	6.667	0.007	11774.345	7.005	0.005	6.600	0.007
9905.538	7.034	0.008	6.609	0.010	11775.354	7.015	0.005	6.606	0.007
9969.287	7.072	0.018			11776.392	7.017	0.006	6.591	0.003
9969.295	7.059	0.014			11776.400	7.014	0.006	6.595	0.004
9969.300	7.062				11777.382	7.025	0.007	6.619	0.005
11063.339	6.972	0.011	6.549	0.010	11777.390	7.050	0.006	6.618	0.007
11063.346	6.991	0.012	6.549	0.009	11778.310	7.066	0.005	6.657	0.003
11065.339	6.995	0.014	6.566	0.011	11779.395	7.015	0.009	6.591	0.007
11065.346	7.002	0.012	6.561	0.012	11780.367	7.047	0.006	6.620	0.008
11066.347	7.007	0.018	6.574	0.009	11780.368	7.036	0.010	6.622	0.007
11066.355	7.012	0.017	6.574	0.010	11782.363	6.973	0.009	6.593	0.016
11067.264	6.995	0.015	6.577	0.011	11782.370	7.005	0.011	6.599	0.009
11067.270	6.997	0.014	6.597	0.012	11802.298	6.987	0.007	6.547	0.007
11067.277	7.009	0.013	6.603	0.009	11802.305	6.984	0.007	6.557	0.005
11068.356	6.975	0.015	6.549	0.017	11824.283	7.006	0.007	6.591	0.004
11068.363	6.981	0.011	6.551	0.015	11832.202	7.041	0.005	6.636	0.006
11069.374	7.011	0.017	6.584	0.014	11834.298	7.035	0.006	6.626	0.008
11069.380	6.997	0.015	6.572	0.008	11850.258	7.022	0.006	6.614	0.007
11069.387			6.576	0.012	11864.178	7.035	0.004	6.634	0.007
11072.316	7.005	0.008	6.589	0.014	11865.270	7.075	0.007	6.673	0.010
11072.323	7.017	0.008	6.595	0.012	11866.208	7.020	0.005	6.607	0.006
11383.403	6.989	0.006	6.584	0.006	11867.152	7.045	0.007	6.649	0.003
11383.410	7.000	0.008	6.584	0.014	11887.139	7.023	0.010	6.616	0.006
11383.417	6.989	0.006	6.578	0.013	12125.448	7.034	0.009	6.655	0.012
11384.466	6.980	0.009	6.580	0.008	12127.417	7.014	0.010	6.627	0.012
11384.474	6.986	0.010	6.589	0.006	12127.425	7.029	0.015	6.618	0.013
11385.422	7.020	0.009	6.589	0.029	12153.366	7.060	0.009	6.657	0.008
11385.430	7.019	0.018	6.612	0.013	12153.374	7.043	0.008	6.657	0.010
11387.445	6.941	0.007	6.524	0.012	12154.396	6.994	0.008	6.614	0.009
11387.452	6.943	0.009	6.536	0.013	12154.403	7.023	0.009	6.582	0.007
11393.362	6.960	0.013	6.558	0.012	12158.336	7.042	0.011	6.663	0.009
11393.370			6.564	0.011	12163.365	7.027	0.008	6.631	0.006
11420.377	6.993	0.004	6.584	0.017	12188.251	6.994	0.008	6.590	0.008
11420.384	7.008	0.005	6.592	0.012	12209.205	7.061	0.002	6.637	0.003
11421.372	6.978	0.007	6.563	0.010	12209.210	7.041	0.004	6.631	0.003
11421.380	6.962	0.008	6.560	0.010	12450.456	7.035	0.013	6.611	0.012
11451.304	6.977	0.008	6.579	0.007	12454.463	6.975	0.011	6.563	0.007
11451.310	6.966	0.012	6.573	0.007	12455.434	7.028	0.008	6.625	0.015
11452.290	6.928	0.008	6.525	0.005	12456.448	7.044	0.018		
11452.297	6.927	0.008	6.519	0.008	12458.444	7.045	0.008	6.644	0.018
11453.288	6.996	0.008	6.575	0.009	12458.450	7.061	0.010	6.661	0.010
11454.319	7.002	0.010	6.585	0.010	12514.377	7.032	0.010	6.623	0.011
11455.326	6.989	0.006	6.594	0.013	12514.385	7.031	0.011	6.627	0.010
11456.255	6.971	0.018	6.577	0.009	12867.288	7.085	0.007	6.648	0.009
11738.444	7.048	0.009	6.635	0.007	12867.297	7.074	0.007	6.652	0.005
11738.450	7.049	0.009	6.645	0.009	13962.376	7.045	0.006	6.651	0.008
11741.431	7.073	0.010	6.652	0.013	14023.319	7.023	0.009	6.604	0.008
11742.418	7.043	0.007	6.645	0.006	14337.372	7.057	0.008	6.655	0.004
11744.390	7.055	0.011	6.661	0.008					

The average J and K magnitudes and $J-K$ color indices of Cyg X-1 for some intervals of our observations (1995–2007, 1984–1994, and 1984–2007) are collected in Table 2. The standard errors (se) for average magnitudes, maximal and minimal magnitudes, and numbers of averaged values (N) are given. It follows from Table 2 that the source became brighter (its JK brightness increased) and hotter (its $J-K$ color index decreased) during 1995–2007, compared to 1984–1994.

Table 2. The mean JK magnitudes and $J-K$ color index for several intervals of observations of Cyg X-1 (1984–2007)

Parameter	Mean	se	Max	Min	N
		1995–2007			
J	7.021	0.004	6.93	7.15	110
K	6.606	0.004	6.52	6.68	107
$J-K$	0.412	0.001	0.37	0.44	105
		1984–1994			
J	7.046	0.005	6.91	7.22	83
K	6.612	0.005	6.44	6.70	73
$J-K$	0.433	0.004	0.35	0.59	70
		1984–2007			
J	7.032	0.003	6.91	7.22	193
K	6.608	0.003	6.44	6.70	180
$J-K$	0.420	0.002	0.35	0.59	175

Variations of JK Magnitudes and $J-K$ Color of Cyg X-1 in the Course of Orbital Motion

Figure 2 displays variations of the J and K brightness of Cyg X-1 versus the orbital phase, from observations of 1995–2007. The broken lines are for averaged values (the error bars are standard errors). Averaging was performed for a phase bin width about 0.07. Phases were calculated with the elements (Brocksopp et al. 1999):

$$\mathrm{MinI} = 2441163.529 + 5\overset{\mathrm{d}}{.}599829 \cdot \mathrm{E}.$$

The long-term component in the JK brightness variations (Fig. 1) was treated as a trend in JK magnitudes for observations of 1995–2007. Improved relations of the J and K magnitudes and $J-K$ color on the orbital phase were derived after removing the trend. Figure 3 exhibits the final orbital J and K light curves. The calculated relations are plotted as dashed curves, they correspond to minimal errors. The vertical bars are standard errors, which are se(J) $\leq$ 0.006, se(K) $\leq$ 0.007. The orbital JK light curves plotted in Fig. 3 as solid curves are from Nadzhip et al. (1996).

The averaged JK magnitudes and $J-K$ color indices for different orbital phases (near minima and quadratures in 1995–2007), without and with correction for the long-term variation component of the JK radiation, are presented in Table 3 (a, b). In the Table, m are observed magnitudes; se, standard errors; φ, average phases; N, numbers of averaged data points.

Table 3. The mean JK magnitudes and $J-K$ color indices near orbital minima and quadratures of Cyg X-1 (1995–2007)

a. No correction for long-term variations of the JK brightness

	$\varphi = 0.05 \pm 0.05$ $N = 16$		$\varphi = 0.25 \pm 0.05$ $N = 11$		$\varphi = 0.50 \pm 0.05$ $N = 16$		$\varphi = 0.75 \pm 0.05$ $N = 13$	
	m	se	m	se	m	se	m	se
J	7.029	0.009	7.008	0.009	7.044	0.007	6.987	0.008
K	6.614	0.008	6.594	0.009	6.637	0.007	6.574	0.009
$J-K$	0.413	0.003	0.415	0.006	0.407	0.004	0.415	0.005

b. After correction for long-term variations of the JK brightness

	$\varphi = 0.05 \pm 0.05$ $N = 16$		$\varphi = 0.25 \pm 0.05$ $N = 11$		$\varphi = 0.50 \pm 0.05$ $N = 16$		$\varphi = 0.75 \pm 0.05$ $N = 13$	
	m	se	m	se	m	se	m	se
J	7.088	0.005	7.071	0.006	7.107	0.006	6.987	0.008
K	6.653	0.004	6.641	0.007	6.682	0.007	7.055	0.007
$J-K$	0.439	0.003	0.436	0.005	0.429	0.004	7.055	0.007

It follows from the data of Table 3, Figs. 2 and 3 that the J and K orbital brightness variations are almost sinusoidal. The orbital JK light curves have appreciable asymmetry in quadratures. For example, the J magnitude of Cyg X-1 near the phase 0.75 is brighter approximately by $0^{\rm m}\!.012$ than near the phase 0.25. The secondary minimum (the X-ray source in front) is deeper compared to the primary minimum (the optical component in front). The brightness difference is at least $0^{\rm m}\!.02$ at 2.2 microns (the K band). The source probably becomes hotter (a minimum of the $J-K$ color index) at a secondary minimum. After the correction for the trend, the $J-K$ color index becomes larger (the source becomes cooler) at all orbital phases.

Thus, it is possible to conclude that in 1995–2007 and 1984–1994 the orbital-phase relations for the J and K magnitudes were similar and can be explained by the model of ellipsoidal variability of an optical star during its orbital motion. It is possible to use the parameters of the binary system derived earlier (Nadzhip et al. 1996) for the observations of 1995–2007.

The mean amplitude of the J and K ellipsoidal variations was $\Delta m \sim 0^{\rm m}\!.038 - 0^{\rm m}\!.042$ (Table 3). In such a case, the ratio of average radius of the supergiant in quadratures and in minima is $R(\mathrm{O9.7,\ Max})/R(\mathrm{O9.7,\ Min}) \approx (10^{0.4\Delta m})^{0.5} \approx 1.02$ if the temperature of the optical component does not change during the orbital motion.

If the minimum of the $J-K$ color index near the orbital phase 0.5 (Table 3 and Fig. 2) is real, then the color temperature of the optical component at this phase is larger approximately by 1000 K than at the phase 0.75. As a result, the radius ratio $R(\mathrm{O9.7,\ 0.75})/R(\mathrm{O9.7}, 0.5)$ will be 1.05.

The 294-day Period

The analysis of data from the Vela and Ariel satellites (1969–1979) permitted to find a period about 300 days in the X-ray flux from Cyg X-1 (Priedhorsky et al. 1983). Kemp et al. (1983, 1987) found and carefully studied variations of the system's optical radiation with the period of 294 days. The changes of the J and K brightness of Cyg X-1 with the period $P = 294^{\rm d}.12$ and epoch JD(Min) = 2442955.9 (Kemp et al. 1987) are presented in Fig. 4. The solid and dashed curves are approximations by fourth-order polynomials, with their confidence intervals. Thus, a 294-day period with the amplitude $\sim 0^{\rm m}.03$ is probably present in the K filter (Fig. 4). The K-band minimum is at the phase 0.3, it is displaced approximately by 90 days with respect of the orbital elements from Kemp et al. (1987).

We see that the JK variations of the X-ray binary Cyg X-1 in 1995–2007 consisted of at least three components:

– the long-term J and K variations on a time scale ~ 11.5 years;
– the orbital J and K variations;
– the variations of the J and K magnitudes with a 294-day period.

The JK Brightness of Cyg X-1 Near the Primary Orbital Minimum (the Optical Star in Front)

An estimate of the interstellar extinction. We assume that only the optical component of Cyg X-1, the O9.7Ia supergiant HD 226868, contributes to the radiation in the J and K filters near the primary minimum.

The $J{-}K$ color index for a normal O9.7 supergiant is $-0^{\rm m}.116$ (Koornneef, 1983). The observed index (without a correction for the trend) near the primary minimum (Table 3a, $\varphi = 0.05$) is $J{-}K = 0^{\rm m}.413 \pm 0^{\rm m}.003$, i.e. the color excess is $\Delta(J{-}K) = 0^{\rm m}.529 \pm 0^{\rm m}.003$. Hence, the interstellar extinction for Cyg X-1 corresponds to $E(B{-}V) = (0^{\rm m}.529 \pm 0^{\rm m}.003)/0.54 = 0^{\rm m}.979 \pm 0^{\rm m}.006$, $A_V = 3^{\rm m}.04 \pm 0^{\rm m}.02$ for the normal law of the interstellar extinction (Koornneef, 1983). If the parameter A_V/d for Cyg X-1 is 1.3 kpc^{-1} (Margon et al. 1973), the distance to the star is $d = 2.34 \pm 0.04$ kpc.

The color excess after correction for the trend is $\Delta(J{-}K) = 0^{\rm m}.554 \pm 0^{\rm m}.003$ and the interstellar extinction is $E(B{-}V) = (0^{\rm m}.554 \pm 0^{\rm m}.003)/0.54 = 1^{\rm m}.025 \pm 0^{\rm m}.006$, $A_V = 3^{\rm m}.18 \pm 0^{\rm m}.02$, and $d = 2.44 \pm 0.04$ kpc.

Thus, our estimate of $E(B{-}V) = 1^{\rm m}.025 \pm 0^{\rm m}.006$ after correction for the trend is close to that from UBV photometry (Karitskaya et al. 2006).

Parameters of the optical source from JK observations of 1995–2007. The radius of the source visible near the primary orbital minimum can be estimated from the equation:

$$R_* = d \cdot (F(J_0(0.0)/B(J,\ T_{ef}))^{0.5},$$

where $F(J_0(0.0))$ is the flux calculated for the J magnitude of Cyg X-1 near the primary orbital minimum (Table 3b), corrected for the interstellar extinction; $B(J, T_{ef})$ is the flux at 1.25 microns (J) for a black body of the temperature T_{ef}; d is the distance to Cyg X-1. The effective temperature of the O9.7 supergiant was assumed to be $T_{ef} \approx 29000$ K (Vacca et al. 1996). The calibration from Koornneef (1978) was used for transformation of magnitudes to fluxes. As a result, we find $R_* \approx 14.7 \cdot 10^{11}$ cm $\approx 21 R_\odot$ and $L_* \approx 1.1 \cdot 10^{39}$ erg/s $\approx 2.8 \cdot 10^5\ L_\odot$.

The color index $J{-}K = -0^{\rm m}.116 \pm 0^{\rm m}.003$ near the primary orbital minimum (after correction for interstellar extinction) corresponds to the source's color temperature $T_c = 21500 \pm 500$ K. The radius of such a source will be 25 $R_\odot$.

The long-term component. The difference between the $J{-}K$ color indices not corrected and corrected for the trend (Table 3a,b) corresponds to a variation range of color temperatures of (22000–26000) K near the primary orbital minimum. Such changes of the color temperature should lead, for example, to a change of the J brightness by more than $0^{\rm m}.2$, the radius of the source being constant. The observed changes (Table 3) do not exceed $0^{\mathrm{m}}.05$–$0^{\mathrm{m}}07$. In this case, a temperature increase of the supergiant by (4000–5000) K, for the observed increase of the J-band brightness by approximately $0^{\mathrm{m}}.05$, should be accompanied with a decrease of its radius approximately by 5–6% and an increase of its luminosity by a factor of 1.5–2. Thus, the long-term variation component in the J and K radiation from Cyg X-1 can be explained with changes of temperature, radius, and brightness of the hot supergiant on a time scale about 11.5 years.

4 CONCLUSIONS

The JK variations of the X-ray binary Cyg X-1 in 1995–2007 consist of at least three components:

– The J and K brightness variations due to the orbital motion. The orbital changes of the J and K brightness are almost sinusoidal. The orbital JK light curves possess appreciable asymmetry in quadratures. For example, the J magnitude of Cyg X-1 near the phase 0.75 is approximately by $0^{\mathrm{m}}012$ brighter than near the phase 0.25. The secondary minimum (the X-ray source in front) is deeper, compared to the primary minimum (the optical component in front). The brightness difference is at least $0^{\mathrm{m}}02$ at 2.2 μm (the K band). The source probably becomes hotter (a minimum of the $J-K$ color index) at the secondary minimum. The color index $J-K$ becomes larger at all orbital phases, i.e. the source becomes cooler, after correction for the trend.

– The long-term J and K brightness variations, on a time scale about 11.5 years.

– The J and K brightness variations with a 294-day period. The amplitude is $\sim 0^{\mathrm{m}}03$ in the K filter. The minimum of the K brightness is at the phase 0.3, it is shifted by approximately 90 days with respect of the orbital elements from Kemp et al. (1987).

The two last conclusions need verification, and thus it is necessary to continue near-IR photometry of Cyg X-1.

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