Analysis of IR and X-ray Light Curves of Cyg X-3

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Abstract. We present detailed infrared light curves of Cyg X-3 in *JK* bands obtained with the 2.5m telescope of CMO SAI MSU. The mean light curves look remarkably similar to the mean normalized X-ray light curve. The shape of the latter suggests that additional wind structures may be present in the WR wind of Cyg X-3 – the bow shock and the so-called "clumpy trail". The similarity of *JK* light curves to the X-ray one and unusual *J-K* color variations suggest that the infrared flux of Cyg X-3 is created by two sources: the free-free emission of the WR wind and a spatially compact IR source located near the compact companion. We describe a model which should be used to quantitatively fit the data.

Keywords: binaries: close; stars: Wolf–Rayet; stars: individual:Cyg X-3; X-rays: binaries

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1 Introduction

Cyg X-3 is the only known binary in the Galaxy consisting of a WR star and a compact object (van Kerkwijk 1993). At the orbital period $\sim 4.8\,\mathrm{h}$, the binary is extremely close with the probable distance between the components about $4\,\mathrm{R}_\odot$. The orbital period is gradually increasing (Antokhin & Cherepashchuk 2019) due to loss of angular momentum through the WR wind. The system is a known X-ray source with frequent changes of the X-ray flux between several states. However, the underlying orbital X-ray variations are remarkably stable. The X-ray minimum corresponds to the compact object position behind the WR star and is due to the absorption of X-ray flux from the compact object by the WR wind. There are no reliable determinations of the mass function and orbital inclination of the system, thus the nature of the compact object (neutron star or a black hole) remains uncertain. Unfortunately, due to very high interstellar absorption, optical observations in the visual photometric bands are impossible.

Surprisingly, very little infrared (IR) photometric observations are present in the literature. In this paper, we present the detailed *JK* photometry of the system and compare the IR light curves with the X-ray one. This interesting comparison allows us to make some reasonable guesses about the structures presented in the WR wind and the sources of IR flux.

2 X-ray and IR Mean Normalized Light Curves

The most comprehensive X-ray photometry of Cyg X-3 to date has been obtained by the *Rossi X-ray Timing Explorer (RXTE)* and the *Monitor of All-sky X-ray Image (MAXI)*. These instruments provide almost continuous monitoring of Cyg X-3 X-ray flux in various bands for more than 25 years. The light curve in the energy range 2-10 KeV is shown in the left part of Fig. 1. To filter out the irregular aperiodic changes of the X-ray flux, we followed the same procedure as outlined by Zdziarski et al. (2012). It basically consists in dividing all individual fluxes by a moving average and in further averaging of the normalized fluxes in orbital phase bins. From Fig. 1 (left) it is evident that the shape of the X-ray light curve is remarkably stable on the time interval of more than 25 years.

We have also obtained 14 nights of IR observations at the 2.5m telescope of CMO SAI MSU in *JHK* bands. Like in the X-ray domain, the individual nightly IR light curves are highly variable and the mean flux level significantly changes from one night to another. Thus, to filter out the irregular variability, we applied a procedure similar to that used for the X-ray data. The difference is that after converting stellar magnitudes to fluxes, we divided the individual measurements of a given night by the average flux within that night. The detailed results will be presented in a subsequent paper, here we only show the mean and normalized *JK* light curves, see Fig. 1.

The shapes of the X-ray and IR light curves are remarkably similar.

3 Qualitative Model

The two characteristic features of the X-ray light curve are (i)the asymmetric primary minimum with faster ingress and slower egress parts, and (ii)the depression of the flux around orbital phase ~ 0.4. A possible explanation of the depression was suggested by Vilhu & Hannikainen (2013). These authors assumed that narrow relativistic jets in Cyg X-3 can trigger creation of dense clumps in the WR wind which would cause additional absorption of X-ray flux. After being created, the clumps would follow the normal wind flow gradually decreasing their density and hence absorption. As a result, a so-called “clumpy trail” would be formed. Numerical simulations performed by Vilhu & Hannikainen (2013) have

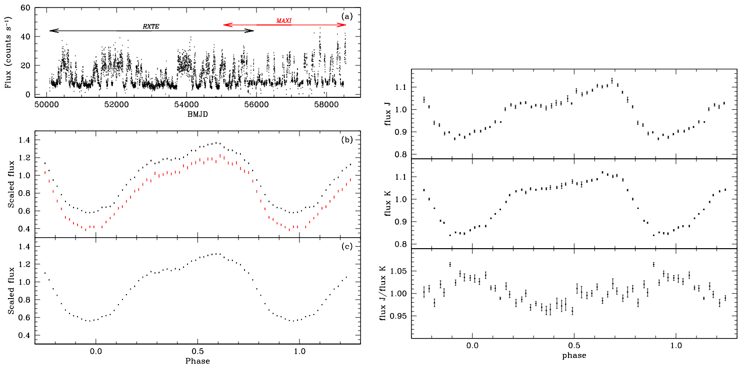

Fig. 1. Left: *RXTE* and *MAXI* observations of Cyg X-3 in the energy band $2 - 10$ KeV. (a)Flux variations as function of Modified Julian date, with *RXTE*- and *MAXI*- covered intervals shown by the arrows. (b) Mean normalized *RXTE* and *MAXI* light curves folded with the orbital period. The *MAXI* light curve is shifted down by 0.1 for clarity. (c) The mean folded normalized *RXTE*+*MAXI* light curve. Right: Mean normalized *JK* light curves folded with the orbital period. The bottom panel shows the color changes, the scale in this panel is increased by two times to better emphasis the observed color variations.

shown that at reasonable jet orientation and other WR wind parameters this mechanism may explain the flux depression around the orbital phase 0.4.

We are unaware of any published works which would try to explain the asymmetry of the primary minimum of the Cyg X-3 X-ray light curve. However, such asymmetry is not unusual in some WR X-ray binaries (Qiu et al. 2019). It can be explained by a bow shock in front of the compact object moving along its orbit in the dense WR wind (see Fig. 11 of the cited paper). The location of the bow shock is such that it will cause additional absorption at the orbital phases $\sim 0 - 0.3$ thus resulting in the slow egress.

In the IR domain, van Kerkwijk (1993) suggested that the only source of the continuum IR flux of Cyg X-3 is the free-free emission of the WR wind consisting of two regions – the hot one illuminated by the X-ray flux of the compact object, and the relatively cool one in the shadow of the WR star. Rotation of this two-component wind in course of orbital revolution should result in IR flux variations, the minimal flux occurring at the orbital phase 0. However, considering our newly obtained *JK* light curves, there are two problems with this model. First, in the van Kerkwijk (1993) model the IR light curve should be symmetric relative to the phase 0, the maximal flux is expected at the phase 0.5, which is not the case. The similarity of the IR and X-ray light curves suggests that apart from free-free emission of the WR wind, another IR source located near the compact object is present. Then this IR source undergoes absorption by the bow shock and the "clumpy trail" like its X-ray sibling, resulting in the similarity of the light curves in both domains. Second, in the van Kerkwijk (1993) model, the system should be redder at the phase 0 than at the phase 0.5, the reason is that at the phase 0 the cool (and hence redder) part of the WR wind is maximally exposed to the observer. Our *JK* light curves show the opposite. The observed color changes are easy to understand if indeed a spatially compact IR source exists in the system located near the compact object. As free-free absorption strongly increases with wavelength, this source will look blue when it is behind the WR star (at the orbital phase 0.5) and red when it is in front. Appropriate mixing of the two IR source fluxes may explain the observed color variations.

These qualitative considerations lead us to the following possible model of the X-ray and IR flux variability of the system: (i)the WR wind consists of the hot and cool (shadowed) parts; (ii)two additional structures are the bow shock in front of the compact object and the "clumpy trail"; (iii)the X-ray emission from the compact source is absorbed by the hot part of the WR wind, by the bow shock and by the "clumpy trail"; (iv)the IR flux is the sum of the free-free emission of the cool/hot parts of the WR wind and the emission of a spatially compact IR source located near the compact object.

The results of X-ray and IR light curves modeling with the proposed model will be published in a subsequent paper.

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