Violent Optical Variations and Correlation between Optical and X-ray Variability During the 2015 Outbursts in V404 Cygni

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Abstract

We performed the optical photometry of the two outbursts in 2015–2016 in V404 Cyg, a black-hole X-ray transient and investigated the connection between our optical data and the X-ray data derived from *Swift*/XRT, *Swift*/BAT and *INTEGRAL* IBIS/ISGRI monitoring. Analyzing the simultaneous optical and X-ray data, we found large-amplitude optical variations with regular patterns (the period: 30 min–2.5 hours, the amplitude: about 2 mag) at low luminosity (even at one hundredth of the Eddington luminosity) in the June outburst for the first time in black-hole X-ray transients. Prior to the outburst, repetitive variations in these objects had been observed only at high luminosity (e.g., GRS 1915+105) and the existing theories were developing to explain these observations before the outburst. The correlation between the repetitive optical variations and the X-ray ones was good. With the time lag between them and the multi-wavelengths SED analysis, we demonstrated that the repetitive optical variability was mainly dominated by reprocessing of X-ray irradiation in the disk (Kimura et al. 2016). Also in the December outburst, the repetitive optical variations were detected in one term. In addition, we found that the X-ray emission delayed to the optical one by about 30–50 s. The time lag inconsistent with both disk reprocessing and synchrotron emission related to jet ejections. There is a possibility that many kinds of optical variations having different origins were observed during the two outbursts in 2015 in V404 Cyg.

Key words: accretion, accretion disc – black holes physics – binaries: general – X-ray: stars – stars: individual (V404 Cygni)

1. Introduction

V404 Cyg is one of transient black-hole (BH) low-mass X-ray binaries (LMXBs). LMXBs are composed of a black hole or a neutron star (the primary) and a low-mass star (the secondary) (Lewin et al. 1995). They are known to exhibit sporadic outbursts, which are caused by the thermal instability due to partial ionization of hydrogen (see e.g., chapter 5 Kato et al. (2008)). This system underwent outbursts in June and December in 2015 after the 26 years dormancy.

2. Observations

We performed the CCD photometry in the optical I_{C}, R_{C}, V and B bands and with the clear filters with telescopes having 20 cm–2 m diameters at 27 and 17 sites during the June and December outbursts, respectively. The observers measured magnitudes of V404 Cyg relative to local comparison stars whose magnitudes were measured by A. Henden from the AAVSO Variable Star Database[1] or taken from United States Naval Observatory (USNO) B1.0 catalogue or USNO A1.0 catalogue or the fourth U.S. Naval Observatory CCD Astrograph Catalog (UCAC4).

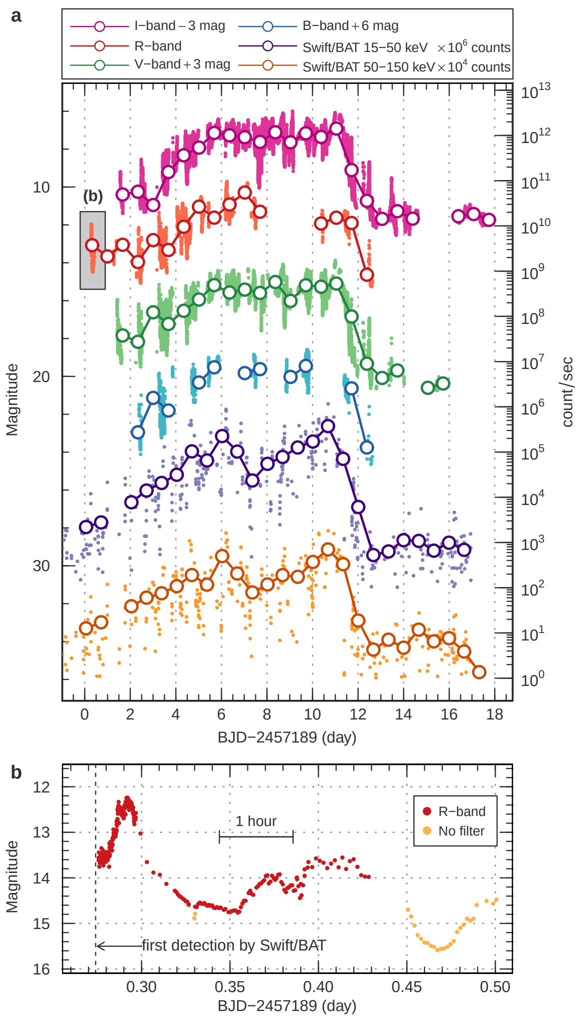

Fig. 1. Optical and X-ray light curves of V404 Cyg during an outburst in 2015 June–July. Panel a shows overall multi-colour light curves and Swift/BAT light curves. The plotted points are averaged for every 0.67 days. Panel b is an enlarged view of the shaded box in panel a (the first detection of short-term variations). On BJD 2,457,203, the mean magnitude dropped below V=17.0. Superimposed on this rapid fading, the amplitude of variations became progressively smaller and smaller. After BJD 2,457,205, the mean magnitude seemed to be constant, and the outburst virtually ended.

*1 <http://www.aavso.org/vsp>

3. Results

3.1. Overall Light Curves

The overall optical and X-ray light curves in the 2015 June and December outbursts are displayed in Figures 1 and 2, respectively. We found the whole trend of the optical light curves, a slow rise and rapid decay, resemble the X-ray ones in both two outbursts. The duration of these outbursts were a few weeks. The amplitude of the December outburst was smaller than that of the June outburst. The interval between the two outbursts was less than 6 months.

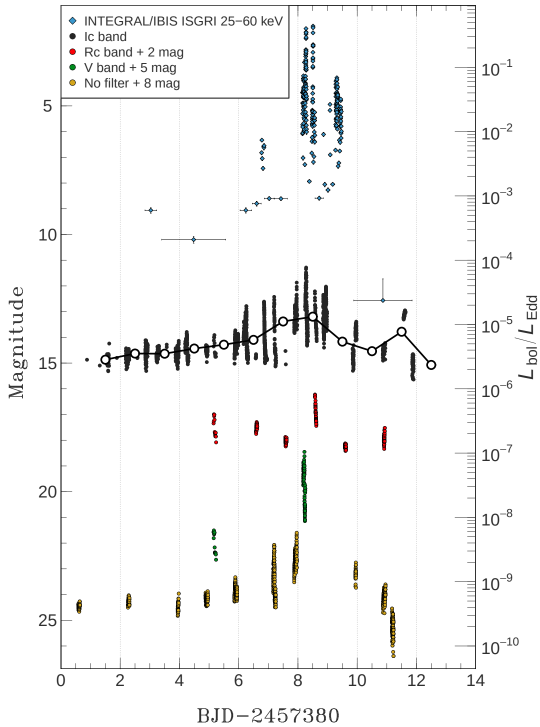

Fig. 2. Overall light curves in the I_C, R_C, V bands and with no filter and in the X-ray 25–60 keV energy band during the outburst of V404 Cyg from December, 2015 to January, 2016. The horizontal axis represents days from BJD 2457380. The plotted open circles are averaged magnitude for every 1 day. Here, L_{Edd} is equal to 1.35×10^{39} [erg/s].

3.2. Correlation between Optical and X-ray Variations

It is noteworthy that V404 Cyg exhibited violent optical variations with regular patterns throughout the June outburst. Some examples are shown in Figure 3. We classified them into two types. One is 'dip-type' oscillations which consist of repetitions of a gradual rise followed by a sudden dip of $\sim$2 mag amplitude, sometimes with accompanying spikes on timescales of $\sim$30 min to $\sim$2.5 hours. The other is 'heartbeat-type' oscillations which have rhythmic small spikes of $\sim$0.1 mag amplitude with short periods of $\sim$5 min. The dip-type oscillations arose not only at high luminosity near the

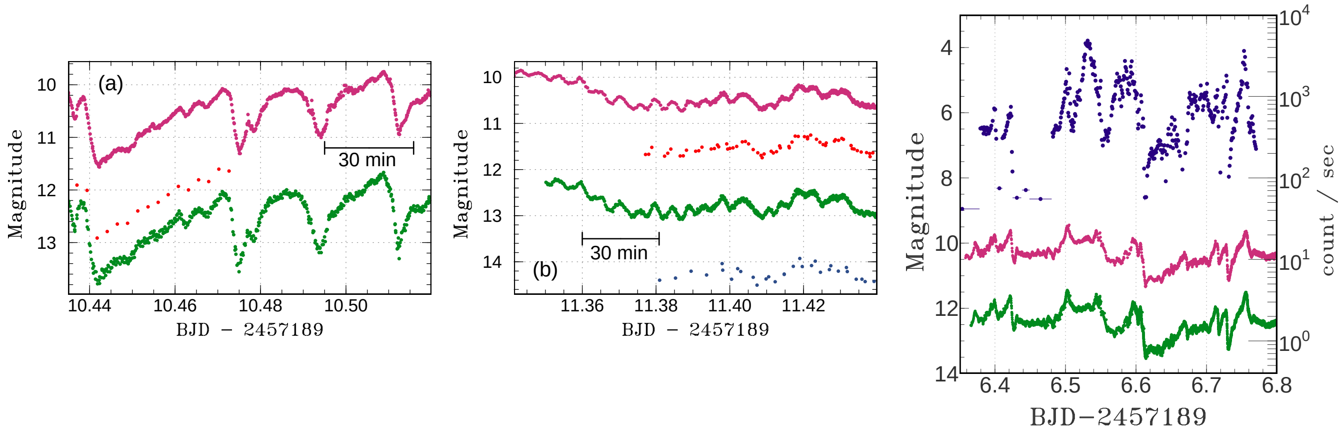

Fig. 3. Repetitive optical variations during (a) BJD 2457199.435–2457199.52 and (b) BJD 2457200.34–2457200.44 in the 2015 June/July outburst and the correlation between repetitive optical and X-ray variations (the right panel). (a) an example of dip-type oscillations. (b): an example of heartbeat-type oscillations. The blue, green, red, pink and navy dots represent the light curves in the B, V, R_{C}, I_{C} bands and in the *INTEGRAL* 25–60 keV X-ray energy band.

Eddington luminosity (L_{Edd}) but especially at low luminosity ($\sim 0.01 L_{\mathrm{Edd}}$) in the outburst. The bolometric luminosity was estimated from the *Swift*/BAT survey data in the 15–50 keV energy band and *INTEGRAL* IBIS/ISGRI monitoring data in the 25–60 keV energy band. This kind of oscillations were also seen for one interval in the December outburst.

Moreover, the same kind of variations were observed in optical and X-ray wavelengths when the dip-type oscillations were observed (see the right panel of Figure 3). The time delay of optical variations to X-ray ones were estimated to be about 1 min by CCFs. In addition, the estimated disk radius was $\sim 2.0 \times 10^{12}$ [cm] with the multi-wavelengths SED analyses. Additionally, it was demonstrated the synchrotron emission was not able to explain the high optical flux.

Except for the repetitive variations, stochastic variations were detected. We identified the two intervals in which the random optical and X-ray variability were correlated. As a result of Spearman's rank tests, the correlations were proved to be statistically significant. We estimated time delays between our optical light curves and the *INTEGRAL* IBIS/ISGRI X-ray light curves with time bin size of 5 s in the 25–60 keV energy band for the two terms (1) BJD 2457388.18–2457388.22 and (2) BJD 2457388.246–2457388.292 using a Bayesian method that was originally proposed to estimate time delays between gravitationally lensed stochastic light curves (Tak et al. 2016). The 5-s binned X-ray light curves were derived with the tool `ii_light`. This method assumes that the irregularly sampled light curves are generated by a latent continuous-time damped random walk (DRW) process (Kelly et al. 2009) and that one of the latent light curves is a shifted version of the other by the time lag in the horizontal axis and by the magnitude offset in the vertical axis (Pelt et al. 1994). The model also adopts heteroskedastic Gaussian measurement errors. We used

Table 1. Bayesian estimates of the time delays for term (1) BJD 2457388.18–2457388.22 and (2) BJD 2457388.246–2457388.292. (We report posterior medians because posterior means are not reliable indicators for the center of a multi-modal distribution. The posterior mode of time delays and median are identical up to three decimal places for term (1). For term (2), the posterior mode is −33.2 s.) The 68% interval indicates the quantile-based interval and the 68% HPD interval represents the highest posterior density interval.

Terms	Median	68% Interval	68% HPD Interval
(1)	−45.4 s	(−46.5 s, −45.1 s)	(−45.6 s, −45.0 s)
(2)	−33.1 s	(−33.3 s, −32.8 s)	(−33.4 s, −32.9 s)

an R package, `timedelay`, which is publicly available at CRAN[2], to implement the Bayesian model via a Markov chain Monte Carlo (MCMC) method. Before the estimations, we examined the correlations between the optical and X-ray luminosity with power law regressions and scaled the X-ray light curves using the estimated coefficients of the regressions to meet the assumption in Tak et al. (2016). The estimation results are summarized in Table 1. We obtained the $\sim$30–50 s X-ray delay to the optical emission. The Gelman-Rubin convergence diagnostic statistics (Gelman & Rubin 1994) were 1.0004 and 1.0009 in terms (1) and (2), respectively, close enough to unity.

4. Discussion

4.1. Origin of Optical Variations with Regular Patterns

The repetitive variations, especially the dip-type oscillations, are observed in both June and December outbursts in 2015. First, the X-ray spectral analyses of the simultaneous X-ray data in the June outburst indicate that there

*2 <https://cran.r-project.org/package=timedelay>

was no tendency for increased absorption when the X-ray flux decreased, suggesting that these dips do not originate from absorption (see Sec. 3 of Methods in Kimura et al. (2016)). In some epochs, we found evidence for heavy obscuration as found in the *GINGA* data during the 1989 outburst (Życki et al. 1999); however this is not related to dip-type variations. We can thus infer that the short-term fluctuations directly reflect variations in radiation from the accretion disc or its associated structures. Second, detailed analyses of the typical simultaneous broad-band SED analyses in the June outburst show that the majority of the optical flux is most likely produced by reprocessing of X-ray irradiation in the disc. Third, we detected the $\sim$1 min delay of optical lights to the X-ray ones is consistent to the estimetd disc size. Thus, we conclude that the optical flux was mainly originated from the X-ray reprocessing at the outer accretion disk when the dip-type oscillations were observed in V404 Cyg.

In GRS 1915+105, it has been proposed that the observed X-ray repetitive variability (Belloni et al. 2000) is caused by limit-cycle oscillations in the inner accretion disc due to the Lightman-Eardley viscous instability (see e.g., Janiuk & Czerny (2011)), which can explain a slow rise in brightness (mass accumulation) followed by a sudden drop (accretion to the black hole). Such models assume that the black hole is accreting mass nearly at the Eddington rate. The theory is not adopted to the repetitive optical variations at low luminosity in V404 Cyg. We, therefore, suggest that an unknown instability is related to the variability. We propose that they are caused by disc properties which are inherent in black-hole binaries with long orbital periods.

4.2. Origin of Short X-ray Delays

To explain the X-ray delay of $\sim$30–50 s detected in the December outburst to the optical emission, we consider the condition that the disc was composed of an advection dominated accretion flow (ADAF) and a thin disc. We assume that the thin standard disc was extended to the transition radius $R_{\rm tr}$ and that there was the ADAF in the inside of the radius. In the ADAF, the matter moves to the central object with the free-fall time scale (Narayan & Yi 1994). The speed in which the matter falls approximately follows the equation, $v_{\rm f} \sim \alpha v_{\rm ff}$. Here, $v_{\rm ff}$ and α represent the free fall speed and the viscous parameter. If we consider that the optical flare was triggered at the thin disc and that the hot region accreted to the central black hole with the free-fall time scale, the optical emission source can be located at the radius larger than 6.5×10^8 [cm] and the value of $R_{\rm tr}$ was estimated to be $\sim$6.5–8.5$\times 10^8$ [cm] for $\alpha = 0.1$. This value corresponds to $\sim 300 r_{\rm S}$. Here, $r_{\rm S}$ ($= 2GM/c^2$) represents the Schwarzschild radius for a $9M_\odot$ black hole. When the bolometric luminosity and the coefficient of radiation efficiency (η) are $\sim 0.1 L_{\rm Edd}$ and $\sim$0.1, respectively, the temperature at the radius is estimated to be about 10^4 [K] which is consistent to the temperature in optical emission region in a standard disc. The spectral state in this picture is expected to be hard and the low/hard spectral state during 8.15–10.32 days (Motta et al. 2016) supports this picture. In addition, the estimated value of $R_{\rm tr}$ is as much as the value of the inner disc radius estimated with the SED analyses in the June outburst (see Sec. 8 of Methods in Kimura et al. (2016)). Moreover, the smaller amplitude of the optical variations than that of the X-ray ones can be explained by the presence of the optical continuum emission at the outer disc.

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