Rapid Optical Variations Correlated with X-rays in the 2015 Second Outburst of V404 Cygni (GS 2023+338)

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ABSTRACT

We present optical multi-colour photometry of V404 Cyg during the outburst from December, 2015 to January, 2016 together with the simultaneous X-ray data. This outburst occurred less than 6 months after the previous outburst in June–July, 2015. These two outbursts in 2015 were of a slow rise and rapid decay-type and showed large-amplitude (∼2 mag) and short-term (∼10 min–3 hours) optical variations even at low luminosity (0.01–0.1 $L_{\text{Edd}}$). We found correlated optical and X-ray variations in two ∼1 hour time intervals and obtained a Bayesian estimate of an X-ray delay against the optical emission, which is ∼30–50 s, during those two intervals. In addition, the relationship between the optical and X-ray luminosity was $L_{\text{opt}} \propto L_X^{0.25-0.29}$ at that time. These features cannot be easily explained by the conventional picture of transient black-hole binaries, such as canonical disc reprocessing and synchrotron emission related to a jet. We suggest that the disc was truncated during those intervals and that the X-ray delays represent the required time for propagation of mass accretion flow to the inner optically-thin region with a speed comparable to the free-fall velocity.

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

Transient low-mass X-ray binaries (LMXBs) are composed of a central neutron star or black hole and a low-mass companion star with an accretion disc around the central object. They show sporadic outbursts lasting for dozens of days up to several years in mainly X-rays and other wave-lengths (Tanaka & Shibazaki 1996). The outbursts are considered to be caused by thermal-viscous instability over the accretion discs (see chapter 5 of Kato et al. 2008; Lasota 2001; Dubus et al. 2001). During their outbursts, reprocessing of X-ray irradiation in the outer cool discs has long been thought to dominate optical flux (Shakura & Sunyaev 1973).

On the other hand, some LMXBs show rapid optical variations having timescales between milliseconds and minutes in quiescence and the low/hard state (e.g., Hynes et al. 2004; Motch et al. 1982; Uemura et al. 2002). The origin of optical emission of these short-term variations is still unclear.

V404 Cyg is a member of these transient LMXBs. This system hosts a 9M⊙ black hole (Kharharia et al. 2010) and a 0.7M⊙ companion star of spectral type K0(±1) III-V (Shahbaz et al. 1994; Wagner et al. 1992; Casares et al. 1993; Hynes et al. 2009). It is located at a distance of 2.4 kpc (Miller-Jones et al. 2009). It was originally discovered as a nova in 1938 and its 1989 outburst was detected as an X-ray transient by the GINGA satellite (Makino 1989). At that time, the optical counterpart was subsequently identified with the 1938 nova (Wagner et al. 1989). During the 1989 outburst, short-term X-ray variability was observed (e.g., Życki et al. 1999). On June 15th in 2015, it underwent a short outburst after 26 years of quiescence (Barthelmy et al. 2015a) and showed large flares in radio (Mooley et al. 2015; Tetarenko et al. 2015), infrared (Tanaka et al. 2016), optical (Rodriguez et al. 2015; Martí et al. 2016; Kimura et al. 2016; Gandhi et al. 2016), X-ray (King et al. 2015; Natalucci et al. 2015; Negoro et al. 2015; Segreto et al. 2015; Walton et al. 2017; Radhika et al. 2016; Jourdain et al. 2017; Huppenkothen et al. 2017) and gamma-ray wavelengths (Roques & Jourdain 2016; Siegert et al. 2016; Jenke et al. 2016; Loh et al. 2016; Piano et al. 2017).

This system exhibited violent optical variations with regular patterns for some intervals during the 2015 June outburst, when most of the optical flux was likely to be produced by the reprocessing of X-ray irradiation in the outer disc (Kimura et al. 2016). A lack of optical and near-infrared polarisation was reported by Tanaka et al. (2016) in two periods during the outburst. There was, however, evidence of a strong contribution of synchrotron emission related to jet ejections in some other epochs (Rodriguez et al. 2015; Martí et al. 2016; Shahbaz et al. 2016; Lipunov et al. 2016; Bernardini et al. 2016). Gandhi et al. (2016) found second optical flaring events and proposed that not only X-ray reprocessing but also non-thermal emission contributed to them. Thus the origin of optical emission in the outburst is still under debate.

At 05:19:52 UT on December 23rd, 2015, the Swift Burst Alert Telescope (BAT) initially detected that the X-ray flux increased above the detection limit (Barthelmy et al. 2015b). Just after the BAT detection, MASTER-Amur began observing this object on December 23:385 UT in optical wavelengths (Lipunov et al. 2015). Muñoz-Darias et al. (2017) reported evidence of a strong wind with their optical spectroscopy and the multi-wavelength variability, which were very similar to those in the June outburst. In this paper, we report on our optical photometry of the December outburst in V404 Cyg and study their correlation with the simultaneous X-ray data of INTEGRAL Imager on Board the Integral Satellite (IBIS)/CdTe array (ISGRI) monitoring.

2 OBSERVATION AND ANALYSIS

2.1 Optical Observations

Time-resolved CCD photometry was carried out by the Variable Star Network (VSNET) collaboration team (Kato et al. 2004) at 17 sites (Table S1) in the 2015 December outburst in V404 Cyg. Table S2 shows the log of our photometric observations in the V, R_C and I_C bands and with a clear filter. The exposure times were 15–540 s. We also used the data downloaded from the American Association of Variable Star Observers (AAVSO) archive1. All of the observation times were converted to barycentric Julian date (BJD). The comparison stars are listed in Table S3. The constancy of the comparison stars was checked by nearby stars in the same images. The data reduction and the calibration of the comparison stars were performed by each observer. The magnitude of each comparison star was measured by A. Henden from the AAVSO Variable Star Database2. The tables are displayed in the supplements to this paper.

2.2 X-ray Analysis

We extracted X-ray light curves with time bin sizes of 1 s and 5 s in the 25–60 keV energy band to use them for timing analyses (Sec. 3.2 and 3.3) from the archived data of the INTEGRAL IBIS/ISGRI monitoring set. We employed the latest version of the standard data analysis software Off line Scientific Analysis (OSA) v.10.23 for pipeline processing. The publicly available pointing observations between MJD 57387.65–57387.80 are composed of 4 science windows (SCWs). Each of the SCWs has a typical good time of ~3 ks in duration. An image in the 25–60 keV energy band was generated from IBIS-ISGRI data by using an input catalogue, gmrlrefcat_0009.fits. Background maps provided by the ISGRI team were used for background correction. We put gmrlrefcat_0009.fits [ISGRI_FLG2==5 & ISGRI_FLUX>100] (the default parameter) in the parameter “brSrcDOL” in the IBIS Graphical User Interface. The spectra and 1-s and 5-s binned light curves were extracted with the tool ii_light and a catalogue composed of the strong sources in the field of view (FOV); AX J1949.8+2534, Cygnus X–1, Cygnus X–3 and GINGA 2023+338 (V404 Cyg). We derived the X-ray light curves in flux scales using a conversion parameter of 1 [count s⁻¹] to be 5.632×10⁻¹¹ [ergs cm⁻² s⁻¹] with the HEASoft package assuming a Crab-like spectrum. Moreover, we obtained lists of photons in the

1 <http://www.aavso.org/data/download/>
2 <http://www.aavso.org/vsp>
3 <http://www.isdc.unige.ch/integral/analysis#Software>
We detected large-amplitude and short-term optical variations with amplitudes ranging from 0.4 to 2.5 mag on timescales of ~10 min–3 hours during the 2015 December outburst in V404 Cyg. The bolometric luminosity derived from the X-ray flux with the correction factor (see Sec. 2.2) was low. The overall optical light curves of the outburst in the I_C, R_C, V and no-filter bands, and the X-ray 25–60 keV light curves of INTEGRAL IBIS/ISGRI monitoring with time bin size of 64 s downloaded from the archive data (Kuulkers et al. 2016) are displayed in Figure 1. Here, we choose BJD 2457380 as the time reference and report the time from that day. Sudden dips in brightness were detected for several time intervals (during the day 4.18–4.31 for example). The variations with amplitudes of ≥2 mag were observed only when the nightly average magnitude was brighter than ~14.2 mag in the I_C band, in the middle term of the outburst. The maximum magnitude in the brightest interval during the December outburst (the day 8.24–8.34) was 11.3 mag in the I_C band and the maximum bolometric luminosity in that interval was 4.37×10^{−1}L_{Edd}. The average brightness gradually increased during the day 0–7.5, was constant during the day 7.5–8.8 and rapidly decreased during the day 8.8–11.3. A small rebrightening was observed soon after the rapid decay (see the I_C-band light curves in Figure 1).
Figure 1. Overall light curves in the optical $I_C$, $R_C$, $V$ bands and with no filter and in the X-ray 25–60 keV energy band of INTEGRAL IBIS/ISGRI monitoring during the 2015 December outburst in V404 Cyg. For clarity, the plotted magnitude for the unfiltered data is fainter by 2 mag than measured. The horizontal axis represents days from BJD 2457380. Here, $L_{\text{Edd}}$ is equal to $1.35 \times 10^{39}$ [erg/s]. For visibility, only data points having horizontal error bars less than 1 hour are plotted. The grey shadings represent the overlapped optical and X-ray observational periods.

9 The 5-s binned X-ray light curves were derived with the tool ii_light described in Sec. 2.2.

in the vertical axis (Pelt et al. 1994). The model also adopts heteroskedastic Gaussian measurement errors.

The DRW process is a stochastic process to describe a random walk with a tendency to move back towards a central location. This process is known to be appropriate for modelling accretion-type light variation such as the variability observed in active galactic nuclei (AGNs) because of its power-law type power spectral density (Kelly et al. 2009; Kozłowski et al. 2010; MacLeod et al. 2010). This process is also suitable for modelling another accretion-type...
light variation in a black-hole binary. This is because the power spectral densities (PSDs) of the X-ray light variations in V404 Cyg in the SCWs (162800020010, 162800030010, 16280040010 and 16280050010) including intervals (1) and (2) are well expressed by a power-law ($P \propto f^{-\Gamma}$) with an index $\Gamma$ of $1.6 \pm 0.1$, $1.5 \pm 0.1$, $1.6 \pm 0.1$ and $1.0 \pm 0.2$, respectively (see also Figure S1 in the supplements to this paper).10

Our data, however, do not completely meet the second model assumption (i.e., one of the latent light curves is a parallel-shifted version of the other). This is because our optical light curves have smaller amplitudes than the X-ray ones unlike gravitationally lensed light curves as originally applied in Tak et al. (2016a). Thus we scaled the X-ray light curve to the optical one using the results of the power law regression (see Sec. 3.2 and Table 1) to meet the assumption before implementing the Bayesian method; we treated the scale change in the X-ray light curve as originally applied in Tak et al. (2016a). Therefore, we employed powerspec software in the FTOOLS Xronos package from the lists of photons. The values of “dnu” and “rebin” parameters were 1 s and −1.8, respectively. The Nyquist frequency of these observations was 0.5 Hz.

We used an R package, timedelay, which we made available to the public at CRAN11, to implement the Bayesian model via a Markov chain Monte Carlo (MCMC) method; see Appendix A for details of the model, implementation, and model checking. Figure 5 exhibits the histogram of 300,000 posterior samples of the time lag between the optical and X-ray light curves for interval (1) on the left panel and that for interval (2) on the right panel. The estimation results are summarised in Table 2; the posterior median of the time delay for interval (1) was $-45.3_{-1.1}^{+0.3}$ s and that for interval (2) was $-33.1_{-0.2}^{+0.3}$ s, i.e., the X-ray variations were delayed to the optical variations by $45.3_{-1.1}^{+0.3}$ s for interval (1) and $33.1_{-0.2}^{+0.3}$ s for interval (2). The Gelman-Rubin convergence diagnostic statistics (Gelman & Rubin 1992) were 1.0004 and 1.0009 in intervals (1) and (2), respectively, close enough to unity. To check the consistency between different estimation methods, we compared our estimates with the results of a locally normalized discrete correlation function (LNDCF; Lehar et al. 1992). The LNDCF estimates averaged with time bin size equal to 25.92 s showed $-35.1_{-13}^{+13}$ s time lags in both intervals (1) and (2) (see also Figure S2 in the supplements to this paper). Both Bayesian and LNDCF methods result in consistent estimates, considering the large uncertainties of the LNDCF estimates.

10 We employed powerspec software in the FTOOLS Xronos package from the lists of photons. The values of “dnu” and “rebin” parameters were 1 s and −1.8, respectively. The Nyquist frequency of these observations was 0.5 Hz.

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

Table 2. Bayesian estimates of the time delays for interval (1) during the day 8.18–8.22 and interval (2) during the day 8.24–8.29. The 68% interval indicates the quantile-based interval and the 68% HPD interval represents the highest posterior density interval.

| Intervals | Median $^*$ | 68% Interval | 68% HPD Interval |
|-----------|-------------|--------------|-----------------|
| (1)       | $-45.4$ s   | $(-45.6, -45.1)$ s | $(-45.6, -45.0)$ s |
| (2)       | $-33.1$ s   | $(-33.3, -32.8)$ s | $(-33.4, -32.9)$ s |

$^*$ We report posterior medians because posterior means are not reliable indicators for the centre of a multi-modal distribution. The posterior mode and median of time delays are identical up to three decimal places for interval (1). For interval (2), the posterior mode is $-33.2$ s.

4 DISCUSSION

4.1 Similarities between the Two Outbursts in 2015

Large-amplitude and short-term optical variations at low luminosity, which have good correlations with simultaneous X-ray variability, were observed during the two outbursts in 2015 in V404 Cyg (see also Kimura et al. 2016). This behaviour seems to be a common feature in every outburst of this system. Actually, violent optical variations with amplitudes of $\sim 1$ mag on timescales of days or minutes were observed also in the late stage of the 1989 outburst (Wagner et al. 1991). The amplitudes and timescales of these optical variations and the occasional sudden dips in brightness during the December outburst were similar to those during the June outburst.

The overall trend of our optical light curves (a slow rise and rapid decay) in the December outburst was also similar to that in the June/July outburst as Muñoz-Darias et al. (2017) already pointed out. This trend is different from the most common type of outburst in transient LMXBs (Chen et al. 1997). The slow rise could be the result of an inside-out outburst which is considered to arise more frequently than an outside-in outburst in these objects (Lasota 2001, for a review). This possibility has already been suggested during the June outburst by estimating the disc radius at which an optical precursor was ignited (Bernardini et al. 2016a).

Figure 2. Simultaneous optical and X-ray light curves during (1) the day 8.18–8.22 and (2) the day 8.246–8.292. Each of the intervals is $\sim 1$ hour long. The blue rhombuses, green squares and black circles represent the X-ray 25–60 keV, optical V-band and optical $I_C$-band light curves. The optical flares are broader than the X-ray ones.
Figure 3. Optical and X-ray correlations during interval (1) on the day 8.18–8.22 (the left panel) and interval (2) on the day 8.246–8.292 (the right panel). The filled squares and circles represent the optical V-band and Ic-band luminosity. The horizontal axes exhibit X-ray luminosity in the 25–60 keV energy band. The dashed lines represent the estimated power law regression formulae for the relations between the optical and X-ray luminosity. The values of the power law index ($b$) are also reported.

Figure 4. X-ray and optical data sets used for the time delay estimates in interval (1) during the day 8.18–8.22 and interval (2) during the day 8.246–8.292. The X-ray light curves are rescaled by using the results of power law regression described in Sec. 3.2. The rhombuses, squares and circles represent the X-ray light curves in the 25–60 keV energy band with time bin size of 5 s after scaling, the optical V-band light curves and the optical Ic-band light curves. For visibility, the X-ray magnitudes are offset by 7.7 for interval (1) and 4.7 for interval (2), respectively.

4.2 Differences in the Short-term Variability between the Two Outbursts in 2015

Although the morphology of violent and rapid optical variations during the June and December outbursts resemble each other, the nature of these variations during the December outburst seems to be different from those during the June outburst. This is because we found X-ray variations lagging optical ones by ~30–50 s for the two intervals during the December outburst (Sec. 3.3), which had not been detected during the June outburst. We consider whether two commonly known mechanisms of optical emission in X-ray binaries could explain the X-ray delays. They were expected to have been dominant at least some time intervals during the June outburst. The first one is the reprocessing of X-ray irradiation from the inner disc (e.g., van Paradijs & McClintock 1994) and the second one is cyclo-synchrotron emission from magnetic flares, which would be related to a jet (e.g., Merloni et al. 2000; Markoff et al. 2001). X-ray reprocessing will produce optical delays against X-rays on timescales of tens of seconds (e.g., Hynes et al. 1998). On the other hand, cyclo-synchrotron radiation will induce very short time lags within 1 s between optical and X-ray variations, which are not consistent with the lags caused by X-ray reprocessing (e.g., Kanbach et al. 2001). We, therefore, conclude that these processes would fail to explain the observed X-ray delays in the December outburst. Even if we observed the expanding jet ejecta, the expected time lag was a $\gtrsim$10 min optical delay (van der Laan 1966; Mirabel et al. 1998) as discussed also in the June outburst (Rodriguez et al. 2015; Martí et al. 2016). It is quite different from the X-ray delays that we estimated.

There are some other models including synchrotron radiation, which have been developed to explain recently detected anti-correlated cross-correlation function (CCF) signals with X-ray emission lagging optical one by a few seconds and narrower optical auto-correlation functions (ACFs) to X-ray ones in several LMXBs (e.g., Gandhi et al. 2008; Durant et al. 2008; Malzac et al. 2004; Veledina et al. 2011). The timescales of the X-ray delays detected in this study,

\[ b = 0.25 \pm 0.06 \]

\[ b = 0.29 \pm 0.04 \]
however, are inconsistent with the odd timing properties expected by these models as well as the smoother optical flares to the X-ray ones and the positive peaks at negative optical time lags in the DCFs (see also Figures 2 and S2).

There is some evidence to support that the effect of X-ray reprocessing and/or cyclo-synchrotron emission was weak. First, the estimated relation between the optical and X-ray luminosity in Sec. 3.2 was $L_{\text{opt}} \propto L_X^{0.25-0.29}$ and this value disagrees with both that expected by standard disc reprocessing ($L_{\text{opt}} \propto L_X^{0.5}$, van Paradijs & McClintock 1994) and that predicted by jet ejections plus X-ray irradiation ($L_{\text{opt}} \propto L_X^{0.5-0.7}$, Russell et al. 2006). Second, the optical/X-ray flux ratios in the December outburst (~0.05 in the V band and ~0.01 in the Ic band) were smaller by a factor of 2–5 than those in the June outburst when X-ray reprocessing considerably dominated the optical flux. This would indicate that the effect of reprocessing was weaker in the December outburst than that in the June outburst. We suggest the reason is that the outer disc would be depleted due to ionisation during the June outburst and/or the strong outflow discussed in Muñoz-Darias et al. (2016). On the other hand, in the June outburst, the outer disc is thought to have been optically thick (Kimura et al. 2016).

### 4.3 Time Delay Caused by Propagation of Mass Accretion Flow in the Inner Disc

We propose an interpretation that short-term variations of the mass-accretion rate in the outer disc (whose origin is still unknown) propagate to the inner disc via optical fluctuations which will thereby prompt X-ray fluctuations. This then replaces the mechanisms discussed in the previous subsection as a possible origin of the delays. If the standard thin disc extends close to the central black hole, it will take longer for the observed delays to propagate in an accretion flow from the optical emission region to the X-ray emission region. This is because the speed of a propagating heating wave is proportional to the speed of sound ($c_a$) in the standard disc (i.e., $v_t \sim \alpha c_a$; Meyer 1984). Here, $\alpha$ represents the viscous parameter. Thus we consider the condition that the disc is composed of an optically-thin flow as an advection-dominated accretion flow (ADAF) and a truncated geometrically-thin standard disc. This picture was considered during the 2002 outburst in V4641 Sgr, another black-hole transient LMXB, when a 7-min delay of the X-ray variations against the optical ones was detected at the fading stage (Uemura et al. 2004).

We assume that the thin standard disc extended to the transition radius ($R_t$) and that there was the ADAF on the inside of the radius (e.g., Hameury et al. 1997). In the ADAF, the matter moves to the central object with a speed comparable to the free-fall velocity ($v_{ff}$) ($v_t \sim \alpha v_{ff}$; Narayan & Yi 1995). If the optical fluctuations, which were triggered at a region close to the truncation radius, propagated to the central black hole via the accretion of mass flow on the free-fall timescale in the ADAF, the transition radius is estimated to be $2.5 \times 4.0 \times 10^8$ [cm] by using the above approximation for $\alpha \approx 0.1$ (Sano et al. 1998; Machida & Matsumoto 2003) and our estimates of X-ray delays. The estimated value of $R_t$ corresponds to $\sim 100-150 r_s$. Here, $r_s = (2GM/c^2)$ represents the Schwarzschild radius for a $9M_\odot$ black hole. The estimated value is close to that of the inner disc radius derived through the SED analyses in the June outburst (see Sec. 8 of Methods in Kimura et al. 2016). The region at the radius is, however, too hot to emit thermal optical photons predominantly; hence the picture may be problematic. It is likely that the optical emission was non-thermal as discussed in e.g., Uemura et al. (2002). In addition, the smaller amplitude of the optical variations can be explained by the presence of the optical continuum emission from the outer disc.

**Figure 5.** Posterior distributions of the time delays of the optical variations against the X-ray ones for interval (1) on the day 8.18-8.22 (the left panel) and interval (2) on the day 8.246-8.292 (the right panel). The solid line indicates the posterior median of the time lag and the dashed lines represent the 68% quantile-based interval. The time lag estimate shown in each figure is the posterior median with 68% quantile-based interval. There are invisibly small modes near $-30.5$ s and $-25.8$ s in the posterior distribution for interval (1) and near $-48.1$ s in that for interval (2), but we displayed only major modes.
4.4 Testing Possibilities of the Origin of X-ray Delays

An optically-thin flow like an ADAF inside a truncated standard disc has been widely proposed as a possible scenario for the low/hard state in black-hole X-ray binaries, although the interpretation remains under discussion (Remillard & McClintock 2006; Done et al. 2007; Belloni et al. 2011, for a review). The average value of the bolometric luminosity during intervals (1) and (2), 0.03–0.1L_Edd, is consistent with the low/hard state (Done & Gierliński 2003; Dunn et al. 2010), the existing theory (Yuan et al. 2007) and the 3D magnetohydrodynamics (MHD) simulations (Micha et al. 2006; Oda et al. 2007). The spectral state was also reported to be the low/hard state during the day 8.15–10.32 (Motta et al. 2016); however, a detailed spectral analysis would be useful to test our interpretation since the peculiar X-ray spectral behaviour similar to that of an obscured AGN was found for some time intervals during the June outburst by Sanchez-Fernandez et al. (2017) and Motta et al. (2017). They suggested, on the basis of the spectral behaviour, that optically thick outflowing material would obscure substantial X-rays from the central part of V404 Cyg and that the intrinsic luminosity was close to the Eddington luminosity. This situation implies the existence of a slim disc; however, it would be difficult for short-term variability and time delays to coexist in this circumstance. Additionally, a slim disc itself would be difficult to maintain during the December outburst since the averaged X-ray flux during this outburst was much smaller than that during the June outburst.

5 CONCLUSIONS

We report on the photometric observations in the outburst of V404 Cyg from December, 2015 to January, 2016. Our main findings are summarised below.

(i) The 2015 December outburst in V404 Cyg was very similar to the 2015 June–July outburst in the following two aspects. One is that violent and rapid optical variability with amplitudes of ~2 mag on timescales of ~10 min–3 hours was observed at low luminosity. It is likely that this kind of variation is commonly seen in the outbursts including the 1989 one in this object. The other is that the trend of the overall light curves was a slow rise and rapid decay.

(ii) We detected an X-ray delay of ~30–50 s against the optical emission in the two intervals during the December outburst, when the large-amplitude stochastic optical variations were observed at the low average luminosity, ~0.03–0.1L_Edd. In addition, the relation between the optical and X-ray luminosity for these two intervals was L_{X} \propto L_{opt}^{0.25–0.29}. We suggest that the X-ray delay can be due to propagation of mass accretion flow in an inner optically-thin hot flow like an ADAF with a speed comparable to the free-fall velocity.

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Sporadic mass accretion is unlikely to occur due to the high accretion rate in a slim disc. A variable absorber to cause the observed variability in the June outburst was suggested by Sanchez-Fernandez et al. (2017) and Motta et al. (2017) instead, but this condition would not produce time lags between optical and X-ray emission.
## APPENDIX A: DETAILS OF THE BAYESIAN MODEL, IMPLEMENTATION, AND MODEL CHECKING

We use a Bayesian model (Tak et al. 2016a) to estimate the time lag between optical and X-ray light curves. The notation \( x = (x_1, \ldots, x_n) \) indicates the observed magnitudes of the X-ray light curve whose reported standard deviations of the measurement errors are \( \delta_j = (\delta_1, \ldots, \delta_n) \) at \( n \) observation times \( t_k = (t_1, \ldots, t_n) \). Similarly, the observed magnitudes of the optical light curve are \( y = (y_1, \ldots, y_m) \) with reported standard deviations of the measurement errors \( \eta_j = (\eta_1, \ldots, \eta_m) \) at \( m \) observation times \( t_j = (t_1, \ldots, t_m) \). The number of observations for the X-ray light curve \( n \) can be different from that for the optical light curve \( m \), and observation times of the X-ray light curve \( t_k \) can be different from those of the optical light curve \( t_j \). The model assumes that the observed magnitudes are generated from Gaussian distributions centred at the latency magnitudes with standard deviations of the measurement errors, i.e.,

\[
x_i \mid X(t_k) \sim N(X(t_k), \delta_i^2)
\]

for \( i = 1, 2, \ldots, n \),

\[
y_j \mid Y(t_j) \sim N(Y(t_j), \eta_j^2)
\]

for \( j = 1, 2, \ldots, m \),

where \( X(t_k) \) and \( Y(t_j) \) are the latent magnitudes of the X-ray and optical light curves at times \( t_k \) and \( t_j \), respectively. A curve-shifted model (Pelt et al. 1994) assumes that the latent optical light curve is a shifted version of the latent X-ray light curve, i.e.,

\[
Y(t_j) = X(t_j - \Delta) + \beta_0,
\]

where \( \Delta \) is the time delay in days and \( \beta_0 \) is the magnitude offset between the latent optical and X-ray light curves. Using (A3), we re-express (A2) as, for \( j = 1, 2, \ldots, m \),

\[
y_j \mid X(t_j - \Delta), \Delta, \beta_0 \sim N\left(X(t_j - \Delta) + \beta_0, \eta_j^2\right).
\]  

(A4)

We assume that the latent light curve follows a continuous-time damped random walk (DRW) process (Kelly et al. 2009) whose stochastic differential equation is defined as

\[
dx(t) = -\frac{1}{\tau}(X(t) - \mu)dt + \sigma dB(t),
\]

where \( \mu \) and \( \sigma \) denote the overall mean and short-term variation of the DRW process on the magnitude scale, respectively, \( \tau \) is a timescale of the process in days, and \( B(t) \) is a standard Brownian motion. The solution of this stochastic differential equation leads to the Gaussian distributions of the latent magnitudes as follows. We use the notation \( t^\Delta = (t_1^\Delta, \ldots, t_n^\Delta) \) to denote the sorted vector of \( n + m \) observation times among the \( n \) observation times \( t_k \) and the \( m \) time-delay-shifted observation times \( t_j - \Delta \). Then,

\[
X(t^\Delta_i) \sim N\left(\mu, \frac{\tau \sigma^2}{2}\right),
\]

and for \( j = 2, 3, \ldots, n + m \),

\[
X(t^\Delta_j) \mid X(t^\Delta_{j-1}) \sim N\left(\mu + a_j (X(t^\Delta_{j-1}) - \mu), \frac{\tau \sigma^2}{2}(1 - a_j^2)\right),
\]

(A5)

where \( a_j = \exp(-(t^\Delta_j - t^\Delta_{j-1})/\tau) \) and we suppress conditioning on \( \Delta, \mu, \sigma, \) and \( \tau \) in (A5).

Our independent and jointly prior distributions

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### Table S1. List of Instruments used for the photometry of the 2015 December outburst in V404 Cyg.

| CODE* | Telescope (& CCD) | Observatory (or Observer) | Site |
|-------|-------------------|----------------------------|------|
| COO   | T07° 43cm+STL-1100M | AstroCamp Observatory | Nerpio, Spain |
|       | T21° 43cm+FLI-L6303E | iTelescope.Net Mayhill | New Mexico, USA |
|       | T11° 60cm+FLI ProLine PL11002M | iTelescope.Net Mayhill | New Mexico, USA |
| CRI   | 35cm K-380+Apogee E47 | Crimean astrophysical observatory | Crimea |
| deM   | 29cm SC+QSI-516ws | Observatorio Astronomico del CIECEM | Huelva, Spain |
| DPV   | 28cmSC+MII G2-1600 | Astronomical Obs. on Kolonoka Saddle | Slovakia |
|       | 35cmSC+MII G2-1600 | Astronomical Obs. on Kolonoka Saddle | Slovakia |
|       | VNT 1m+FLI PL1001E | Astronomical Obs. on Kolonoka Saddle | Slovakia |
| GFB   | CDK 50cm+Apogee U6 | William Goff | California, USA |
| Ioh   | 30cmSC+ST-9XE CCD | Hiroshi Itoh | Tokyo, Japan |
| Kai   | 28cm SC+STTXXME | Kiyoshi Kasi | Switzerland |
| Kis   | 25cm SC+Alta F47 | Seiichiro Kiyota | Kamagaya, Japan |
| Ku2   | 40cm SC+Alta U6 | Kyoto U. Team | Kyoto, Japan |
| Mdy   | 35cm SC+ST10XME | Yutaka Maeda | Nagasaki, Japan |
| OKU   | 51cm+Andor DW936N-BV | OKU Astronomical Observatory | Osaka, Japan |
| Sac   | 20cmL+ST-7XME | Atsushi Miyashita | Tokyo, Japan |
| SWI   | C14 35cmSC+ST10XME | William L. Stein | New Mexico, USA |
| Trt   | 25cm ALC1CD5.2 (3HV6) | Tamás Tordai | Budapest, Hungary |
| PXR   | FTM 2mA+2E2 42-40 | LCOGT² | Hawaii, USA |
|       | 35cmSC+SVH-9 CCD | Roger D. Pickard | UK |

*Observer’s code: COO (Lewis M. Cook), CRI (Crimean Observatory), deM (Enrique de Miguel), DPV (Pavel A. Dubovsky), GFB (William Goff), Ioh (Hiroshi Itoh), Kai (Kiyoshi Kasi), Kis (Seiichiro Kiyota), Ku2 (Kyoto Univ. team), Mdy (Yutaka Maeda), OKU (Osaka Kyoku Univ. team), Sac (Atsushi Miyashita), SWI (William L. Stein), Trt (Tamás Tordai), PXR (Roger D. Pickard).

¹telescope.net.

²Las Cumbres Observatory Global Telescope Network.
Table S2. Log of observations of the outburst of V404 Cyg from December, 2015 to January, 2016.

| Start^1 | End^1 | Mag^2 | Error^3 | N^4 | Obs^5 | Band^6 | exp[s]^7 |
|---------|-------|-------|---------|-----|-------|--------|----------|
| 80.5857 | 80.6428 | 16.471 | 0.010 | 67 | GFB | CV | 60 |
| 81.5472 | 81.5759 | 14.871 | 0.029 | 17 | Kis | IC | 60 |
| 81.5840 | 81.6288 | 14.908 | 0.055 | 19 | COO | IC | 120 |
| 82.1913 | 82.3047 | 14.762 | 0.016 | 97 | Kai | IC | 30 |
| 82.2616 | 82.3117 | 16.270 | 0.015 | 58 | deM | CV | 60 |
| 82.5703 | 82.5799 | 14.720 | 0.038 | 5 | FJQ | IC | 60 |
| 82.8506 | 82.8902 | 14.677 | 0.033 | 72 | Sac | IC | 90 |
| 82.8654 | 82.9298 | 14.469 | 0.016 | 76 | Ioh | IC | 60 |
| 83.2243 | 83.3247 | 14.641 | 0.017 | 96 | Kai | IC | 30 |
| 83.8717 | 83.9765 | 14.666 | 0.018 | 113 | Ioh | IC | 60 |
| 83.9423 | 83.9762 | 2.092 | 0.023 | 54 | KU2 | CV | 30 |
| 84.1944 | 84.3028 | 14.438 | 0.029 | 121 | Kai | IC | 30 |
| 84.8485 | 84.9610 | 1.778 | 0.008 | 194 | KU2 | CV | 30 |
| 84.8949 | 84.9487 | 14.536 | 0.016 | 58 | Ioh | IC | 60 |
| 85.1498 | 85.2349 | 17.141 | 0.101 | 14 | CRI | V | 540 |
| 85.1520 | 85.2370 | 15.580 | 0.091 | 14 | CRI | RC | 540 |
| 85.1541 | 85.2327 | 14.455 | 0.082 | 13 | CRI | IC | 540 |
| 85.8562 | 85.9476 | 14.474 | 0.031 | 225 | KU2 | CV | 30 |
| 85.8590 | 85.8949 | 14.469 | 0.036 | 46 | Kis | IC | 60 |
| 85.8742 | 85.9006 | 14.204 | 0.029 | 45 | Sac | IC | 90 |
| 85.8807 | 85.9853 | 14.177 | 0.027 | 61 | Ioh | IC | 60 |
| 85.8896 | 85.9168 | 14.440 | 0.026 | 25 | OKU | IC | 90 |
| 86.1662 | 86.2920 | 13.832 | 0.032 | 170 | DPV | IC | 60 |
| 86.2803 | 86.3182 | 14.721 | 0.017 | 44 | deM | IC | 60 |
| 86.5761 | 86.5853 | 14.761 | 0.022 | 8 | FJQ | IC | 60 |
| 86.5864 | 86.6248 | 15.484 | 0.017 | 48 | GFB | RC | 60 |
| 86.8507 | 86.8892 | 14.088 | 0.064 | 87 | Kis | IC | 60 |
| 86.8620 | 86.9545 | 14.479 | 0.032 | 155 | OKU | IC | 90 |
| 87.1656 | 87.2502 | 15.685 | 0.042 | 165 | Trt | CV | 30 |
| 87.1920 | 87.2546 | 13.993 | 0.084 | 52 | Kai | IC | 30 |
| 87.5755 | 87.6155 | 16.053 | 0.013 | 50 | GFB | RC | 60 |
| 87.8738 | 87.9768 | 13.161 | 0.027 | 141 | Ioh | IC | 60 |
| 87.8743 | 87.9645 | 0.332 | 0.023 | 206 | KU2 | CV | 30 |
| 88.1771 | 88.2466 | 14.972 | 0.075 | 97 | Trt | V | 30 |
| 88.2804 | 88.3206 | 13.840 | 0.058 | 44 | PXR | IC | 60 |
| 88.5759 | 88.6195 | 14.942 | 0.045 | 50 | GFB | RC | 60 |
| 88.8485 | 88.8857 | 13.585 | 0.055 | 70 | Kis | IC | 60 |
| 88.8652 | 88.9784 | 13.321 | 0.024 | 229 | Ioh | IC | 60 |
| 89.5859 | 89.6227 | 16.246 | 0.011 | 46 | GFB | RC | 60 |
| 89.8472 | 89.8826 | 14.856 | 0.032 | 46 | Kis | IC | 60 |
| 89.9381 | 89.9754 | 13.794 | 0.020 | 79 | Ioh | IC | 60 |
| 89.9390 | 89.9591 | 0.822 | 0.031 | 42 | KU2 | CV | 30 |
| 90.8639 | 90.9495 | 14.549 | 0.020 | 60 | Ioh | IC | 60 |
| 90.8702 | 90.9571 | 1.711 | 0.022 | 115 | KU2 | CV | 30 |
| 90.8989 | 90.9337 | 15.957 | 0.026 | 45 | Mdy | RC | 30 |
| 91.1727 | 91.2256 | 17.334 | 0.049 | 75 | Trt | CV | 60 |
| 91.5676 | 91.6260 | 12.413 | 0.079 | 154 | SWI | IC | 15 |
| 91.8560 | 91.9038 | 15.126 | 0.044 | 40 | Sac | IC | 90 |
| 94.9056 | 94.9321 | 2.204 | 0.031 | 22 | KU2 | CV | 30 |
| 95.2544 | 95.2997 | 14.948 | 0.019 | 24 | PXR | IC | 60 |
| 97.8620 | 97.8926 | 14.909 | 0.028 | 28 | Ioh | IC | 60 |

^1BJD – 2457300.0.

^2Mean magnitude.

^3½ of mean magnitude.

^4Number of observations.

^5See the annotation in Table S1 and FJQ (Foster James).

^6Filter. “IC”, “RC”, “V” and “CV” mean IC, RC, V and no (clear) filter.

MNRS 000, 1-13 (2016)
Table S3. Comparison stars in the photometric campaign of the 2015 December outburst in V404 Cyg.

| Observer | Comparison star | RA (J2000) | Dec (J2000) |
|----------|-----------------|------------|-------------|
| COO      | AUID 000-BCL-455| 20:23:53.43| +33:52:24.6 |
| CRI      | USNO1238-0435621| 20:24:07.16| +33:50:51.8 |
| deM      | AUID 000-BCL-468| 20:24:08.89| +33:54:38.6 |
| DPV      | UCAC4 620-101865| 20:24:07.18| +33:50:51.7 |
| GFB      | AUID 000-BCL-475| 20:24:26.08| +33:49:51.4 |
| Ioh, Kai | AUID 000-BCL-460| 20:23:56.47| +33:48:16.9 |
| Mdy, Kis, Sac | AUID 000-BCL-467| 20:24:07.24| +33:50:52.2 |
| KU2      | USNO1200.15285418| 20:24:18.72| +33:53:13.9 |
| OKU, Sac | AUID 000-BCL-476| 20:24:28.31| +33:51:13.5 |
| SWI      | AUID 000-BCL-471| 20:24:59.41| +33:57:56.6 |
| Trt      | AUID 000-BCL-472| 20:24:18.66| +33:53:12.6 |
| PXR      | AUID 000-BCL-458| 20:23:55.26| +33:51:14.8 |

*see the annotation in Table S1.

Figure S1. PSDs of the X-ray light curves in the SCWs including interval (1) during the day 8.18–8.22 and interval (2) during the day 8.246–8.292. The horizontal and vertical axes represent frequency and power in logarithmic scales. For visibility, the powers in 162800020010, 162800030010, 162800040010 and 162800050010 are offset vertically by the value of $10^{-3}$, $10^{-2}$, $10^{-1}$, and $10^{0}$, respectively. The errors of PSDs represent $\pm 1\sigma$.

on the model parameters, i.e., $\Delta$, $\beta_0$, $\mu$, $\sigma^2$, and $\tau$, are

\[ \Delta \sim \text{Uniform}(w_1, w_2) \]
\[ \beta_0 \sim \mathcal{N}(0, 10^5) \]
\[ \mu \sim \text{Uniform}(-30, 30) \]
\[ \sigma^2 \sim \text{inverse Gamma}(1, 1) \]
\[ \tau^2 \sim \text{inverse Gamma}(1, 2 \times 10^{-7}) \]

where we fix the range of the Uniform distribution of $\Delta$ at $(-0.04, 0.04)$ for interval (1) and at $(-0.046, 0.046)$ for interval (2) to prevent spurious modes of the time delay on the margins of its space and to consider the longer observation period of interval (2). We choose the shape and scale parameters of the inverse Gamma distributions of $\tau$ and $\sigma^2$ in a way to constrain $\Delta$, considering shorter timescale of the observed data than gravitationally lensed light curves. Further details of the motivation for the choice of prior distributions are given in Sections 2.5 of Tak et al. (2016a).

Our full posterior density, $\pi(X(t^2), \Delta, \beta_0, \mu, \sigma^2, \tau \mid x, y)$, is proportional to the multiplication of the probability density functions, whose distributions are specified in (A1), (A4), (A5), and (A6). We use a Metropolis-Hastings within Gibbs sampler (Tierney 1994) to sample the full posterior distribution of the model parameters; see Section 3 of Tak et al.
(2016a) for details of this sampler. To improve the convergence of the MCMC for \( \Delta \) in the presence of multimodality, we adopt a repelling-attracting Metropolis algorithm (Tak et al. 2016b).

Before implementing the Bayesian method, we first checked the multi-modal behavior of \( \Delta \) by quickly mapping a wide range of \( \Delta \) between \(-86.40 \) s and \( 86.40 \) s using the profile likelihood function of \( \Delta \) defined as

\[
L_{\text{prof}}(\Delta) = \max_{\beta_0, \mu, \sigma^2, \tau} L(\Delta, \beta_0, \mu, \sigma^2, \tau).
\]

This profile likelihood is proven to be a simple approximation to its marginal posterior distribution; see Section 4 of Tak et al. (2016a). We confirmed that the highest mode is near \(-45 \) s and three weak modes are near \(-50 \) s and \(-30 \) s, and \(-25 \) s; the relative heights (the ratio of the profile likelihoods) of the modes near \(-50 \) s, \(-30 \) s, and \(-25 \) s compared to the mode near \(-45 \) s are \( 5.7 \times 10^{-3}, \) \( 5.1 \times 10^{-8} \) and \( 6.5 \times 10^{-9} \), respectively. In interval (2), the dominant mode is at around \(-33 \) s and an invisibly small mode is near \(-48 \) s; the relative height of the mode near \(-48 \) s compared to that of the mode near \(-33 \) s is \( 2.7 \times 10^{-7} \).

We initialize three Markov chains near the dominating mode for each time interval, running for 150,000 iterations; we discard the first 50,000 as burn-in iterations. The proposal scale of the Metropolis step for the time delay is \( \Delta \) is set to produce the largest acceptance rate while making the Markov chains jump frequently between the modes identified by the profile likelihood. The average acceptance rate of the time lag is 0.216 for interval (1) and 0.186 for interval (2).

We visually checked our estimates, shifting the optical light curves by the posterior medians of \( \Delta \) and \( \beta_0 \) in Figure A1; the fitted model matches the fluctuations of the two light curves well. We also conducted a model checking by plotting the posterior sample of the latent curve in grey; the grey areas encompass most of the observed light curves, which shows how well the fitted model predicts the observed data. A sensitivity analysis, though not shown here, exhibits that our inferential results in Table 2 are robust to changing the scale parameters in the inverse Gamma distributions of \( \sigma^2 \) and \( \tau \).

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### Table A1. Initial values of the parameters for each of three Markov chains used in the function bayesian of the R package timedelay for interval (1) during the day 8.18-8.22 and interval (2) during the day 8.246-8.292.

| Names of parameters | (1) | (2) |
|---------------------|-----|-----|
| theta.ini (\( \mu, \sigma, \tau \)) | (5.30, 100, 0.01) | (5.72, 100, 0.01) |
| delta.ini | (5.30, 10, 0.1) | (5.72, 10, 0.1) |
| delta.proposal.scale | 0.00005 | 0.00005 |
| tau.proposal.scale | 1 | 1 |
| tau.prior.shape | 1 | 1 |
| tau.prior.scale | \(2/10^7\) | \(2/10^7\) |
| sigma.prior.shape | 1 | 1 |
| sigma.prior.scale | 1 | 1 |
| adaptive.delta | FALSE | FALSE |
| multimodality | TRUE | TRUE |

- Initial values of the DRW parameters. Unit of magnitudes in \( \mu \) and \( \sigma \). Unit of days in \( \tau \).
- Initial value of the delay time for MCMC used in three Markov chains. Unit of days.
- Range of uniform prior distribution of the time delay \( \Delta \). Unit of days.
- Proposal scale of the Metropolis step for the time delay \( \Delta \). Unit of days.
- Proposal scale of the Metropolis-Hastings step for log(\( \tau \)). Units of \( \tau \) are days.
- Shape parameter of Inverse-Gamma hyper-prior distribution for \( \tau \).
- Scale parameter of Inverse-Gamma hyper-prior distribution for \( \tau \).
- Shape parameter of Inverse-Gamma hyper-prior distribution for \( \sigma^2 \).
- Scale parameter of Inverse-Gamma hyper-prior distribution for \( \sigma^2 \).
- We do not use the adaptive MCMC for the time delay \( \Delta \) in the presence of multi-modality because the adaptation may occur at a local mode.
- We use a repelling-attracting Metropolis algorithm to sample the time delay \( \Delta \).
- The order of a polynomial regression model. We do not consider the effect of microlensing in the case of V404 Cyg.
**Figure A1.** The X-ray light curves are denoted by orange squares, the optical light curves are denoted by blue circles, and the posterior samples of latent light curves at intervals of 300 iterations are denoted by grey circles in interval (1) on the day 8.18–8.22 (the left panel) and interval (2) on the day 8.246–8.292 (the right panel). Each optical light curve is shifted by the posterior mode of the time lag in the horizontal axis and by that of the magnitude offset in the vertical axis. The fitted model makes a good match of the fluctuations of the two light curves. The grey areas are encompassing most of the light curves, meaning that the fitted model describes the observed data well.
ERRATUM: Rapid Optical Variations Correlated with X-rays in the 2015 Second Outburst of V404 Cygni (GS 2023+338)

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

In the published paper (Kimura et al. 2017), the observation times of X-ray light curves were measured at the satellite and their system of times was Terrestrial Time (TT), while those of optical light curves were measured at the Earth and their system of times was Coordinated Universal Time (UTC). We have converted the times of these light curves to the common time system BJD (TT) with the tool barycent in OSA, and made time-delay analyses. In addition, we have reduced the X-ray data again by using the updated version of the tool ii_shadow_build from the one in OSA v10.2. In calculating the background normalization in the imaging step, the affected pixels by the bright sources V404 Cyg, Cyg X-1, and Cyg X-3 were taken into account by adding their names in the parameter ‘brSrcDOL’ in the IBIS Graphical User Interface. As a result of the time delay estimations with the new data, we found that the optical variations are delayed against the X-ray ones by $22.5^{+0.4}_{-0.1}$ s for time interval (1) and by $34.8^{+0.2}_{-0.2}$ s for time interval (2), although Kimura et al. (2017) described that $\sim$30–50 s X-ray delays were detected. The correct tables and figures on the time delay estimations, which are presented in Tables 2, A1 and Figures 4, 5, A1, replace the original ones. Ad-
tionally, the LNDCF estimates averaged with a time bin size equal to 34.56 s, which are displayed in Figure S2 and replace the original ones, are consistent with the Bayesian results as described in Kimura et al. (2017).

Under the assumption that photons move at the light speed from the inner region to the outer region of the disc, the estimated distance between the vicinity of the black hole to the optical emission region from the \( \sim 30 \)–s optical delay is \( \sim 10^{12} \) cm, which is only about a few times smaller than the disc size in the 2015 June–July outburst (Kimura et al. 2016). The optical delays are, therefore, naturally explained by X-ray reprocessing, and then the optical variations would reflect the X-ray activity, though Kimura et al. (2017) concluded that the time delays are caused by propagating mass accretion flow in the inner disc. As Kimura et al. (2017) described, the optical flux ratios against the X-ray flux were smaller than those in the June–July outburst, and the relation between the optical and X-ray luminosity did not follow the relation of the canonical X-ray reprocessing \( L_{\text{opt}} \propto L_{\text{X}}^{1/2} \). They, however, do not deny the existence of X-ray reprocessing, since the degree of X-ray reprocessing vary with the energy spectral shape, the radial distribution of the disc temperature, the X-ray albedo, the optical depth of the disc, and the disc structure. For example, Coriat et al. (2009) showed that the relation \( L_{\text{opt}} \propto L_{\text{X}}^{1/4} \) is derived from the assumption that the optical frequency lies in the Rayleigh-Jeans tail of the energy spectra and this relation seems to agree with our results. In addition, the possibly low surface density discussed in Sec. 4.2 in Kimura et al. (2017) also seems to be relevant to the small optical flux.

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Table 2. Bayesian estimates of the time delays for interval (1) during the day 8.18–8.22 and interval (2) during the day 8.24–8.292. The 68% interval indicates the quantile-based interval and the 68% HPD interval represents the highest posterior density interval.

| Intervals | Median | 68% Interval | 68% HPD Interval |
|-----------|--------|--------------|------------------|
| (1)       | 22.5 s | (22.4 s, 22.9 s) | (22.3 s, 22.8 s) |
| (2)       | 34.8 s | (34.6 s, 35.0 s) | (34.6 s, 35.0 s) |

*We report posterior medians because posterior means are not reliable indicators for the centre of a multi-modal distribution. The posterior mode and median of time delays are identical up to three decimal places.

Table A1. Initial values of the parameters for each of three Markov chains used in the function bayesian of the R package timedelay for interval (1) during the day 8.18–8.22 and interval (2) during the day 8.24–8.292. The explanation of each parameter is the same as that in Table A1.

| Names of parameters | (1) | (2) |
|---------------------|-----|-----|
| theta.ini \((\mu, \sigma, \tau)\)* | (5.23, 100, 0.01) | (6.54, 100, 0.01) |
| delta.ini | (5.23, 10, 1, 1) | (6.54, 1, 1) |
| delta.uniform.range | (−0.04, 0.04) | (−0.046, 0.046) |
| delta.proposal.scale | 0.0001 | 0.0001 |
| tau.proposal.scale | 1 | 1 |
| tau.prior.shape | 1 | 1 |
| tau.prior.scale | 2/107 | 2/107 |
| sigma.prior.shape | 1 | 1 |
| sigma.prior.scale | 1 | 1 |
| adaptive.delta | FALSE | FALSE |
| multimodality | TRUE | TRUE |
| micro | 0 | 0 |

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**Figure 4.** X-ray and optical data sets used for the time delay estimates in interval (1) during the day 8.18-8.22 and interval (2) during the day 8.24-8.29. The X-ray light curves are rescaled and the displayed amplitudes are 0.215 and 0.293 times smaller than the actual ones for interval (1) and (2), respectively. The scaling factors were derived from the power-law regressions between the X-ray and optical luminosity. The rhombuses, squares and circles represent the X-ray light curves in the 25–60 keV energy band with time bin size of 5 s after scaling, the optical V-band light curves and the optical I_c-band light curves. For visibility, the X-ray magnitudes are offset by 8.5 for interval (1) and 4.7 for interval (2), respectively.

**Figure 5.** Posterior distributions of the time delays of the optical variations against the X-ray ones for interval (1) on the day 8.18-8.22 (the left panel) and interval (2) on the day 8.24-8.292 (the right panel). The solid line indicates the posterior median of the time lag and the dashed lines represent the 68% quantile-based interval. The time lag estimate shown in each figure is the posterior median with 68% quantile-based interval. There are invisibly small modes near 37.5 s and 42.5 s in the posterior distribution for interval (1) and near 20.0 s and 31.8 s in that for interval (2), but we displayed only major modes.
Figure A1. The X-ray light curves are denoted by orange squares, the optical light curves are denoted by blue circles and the posterior samples of latent light curves at intervals of 300 iterations are denoted by grey circles in interval (1) on the day 8.18–8.22 (left-hand panel) and interval (2) on the day 8.246–8.292 (right-hand panel). Each optical light curve is shifted by the posterior mode of the time lag in the horizontal axis and by that of the magnitude offset in the vertical axis. The fitted model makes a good match of the fluctuations of the two light curves. The grey areas are encompassing most of the light curves, meaning that the fitted model describes the observed data well.

Figure S2. Estimated LNDCFs in interval (1) during the day 8.18–8.22 (black lines) and interval (2) during the day 8.246–8.292 (blue lines). The minus and plus signs in the horizontal axis indicate that X-ray emission is delayed to optical emission and that optical emission is delayed to X-ray emission. We can see correlated positive peaks at the $34.6^{+17}_{-17}$ s optical lags in the DCFs as for both two intervals.