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Optical and X-ray observations of the microquasar V404 Cyg during its June 2015 outburst.

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Abstract

We present a multiwavelength analysis of the simultaneous optical and X-ray light curves of the microquasar V404 Cyg during the June 2015 outburst. We have performed a comprehensive analysis of all the INTEGRAL/IBIS, JEM-X, and OMC observations during the brightest epoch of the outburst, along with complementary NuSTAR, AAVSO, and VSNET data, to examine the timing relationship between the simultaneous optical and X-ray light curves, in order to understand the emission mechanisms and physical locations. We identified all optical flares with simultaneous X-ray observations, and performed cross-correlation analysis to estimate the time delays between the optical and soft and hard X-ray emission. We have also compared the evolution of the optical and X-ray emission with the hardness-ratios. From this analysis, we identified several types of behaviour during the outburst, including simultaneous optical/X-ray flares, optical flares lagging the X-ray flares, and optical emission preceding the X-ray emission.

1 Introduction

V404 Cygni (hereafter V404 Cyg) is a transient low-mass X-ray binary (LMXB) consisting of a black hole (BH) that accretes mass from a low-mass optical companion. The distance to the system is 2.39±0.14 kpc (15). The orbital period is 6.47 d and the mass function is $f(M)$=6.08±0.04 $M_\odot$ (4). The inclination of the orbit is in the range 56–67° (17; 16; 10). The donor star is a K0 III–K2 IV (10; 7), and the mass of the black hole is M_{BH} = 9–12 $M_\odot$.

The X-ray counterpart GS 2023+338 was discovered in X-rays by the Ginga satellite during an X-ray outburst in May 1989 (13). On 15 June 2015 18:32 UTC (MJD 57188.772), after 26 years of quiescence, the Burst Alert Telescope (BAT, Barthelmy et al. 2) on board the *Swift* satellite (6) detected renewed X-ray activity from V404 Cyg (3). This outburst reached its peak on 26 June 2015 and then rapidly decayed, returning to quiescence in mid-August (18). The outburst was intensively observed by most of the available space telescopes and ground-based facilities worldwide.

In this work, we analyse all the available *INTEGRAL* data during the brightest period of the June 2015 outburst, that is, from 18 June 2015 to the fast decay of the optical and X-ray emission in 27 June 2015.

2 Observations

The INTErnational Gamma-Ray Astrophysics Laboratory (*INTEGRAL*, (21)) observed V404 Cyg in the period MJD 57191.5 to 57216. We analyse here the data obtained during the interval MJD 57191.75 to 57200.25, when intense flaring activity was detected from the system. We study the optical light curves in the V band provided by the Optical Monitoring Camera (OMC, (14)), and the X-ray light curves provided by the Joint European X-Ray Monitor (JEM-X, (12); 3–10 keV), and by the Imager on Board the *INTEGRAL* Satellite (IBIS, (19); 20–80 keV and 80–200 keV). We complemented our data with the X-ray light curves provided by the Nuclear Spectroscopic Telescope Array (*NuSTAR*, (8)) in the 3–10 and 10–79 keV band (see (20) for details on these observations), and with public optical observations provided by the American Association of Variable Star Observers (AAVSO, (9)) and with optical data from the Variable Star Network (VSNET) Collaboration (see (11) for a description of this dataset).

3 Data analysis

We have identified all the optical flares that have simultaneous X-ray observations in our data. These flares are flagged with identifying numbers in Fig. 1. For all of them, we performed a cross-correlation analysis with the X-ray light curves of the system in order to identify possible time lags between the optical and X-ray emission.

For this analysis, we used the discrete cross-correlation function (DCF, (5)), a method that avoids interpolating in the temporal domain when the temporal binning is not regular (this is the case for some of the optical observations in this work). In the results from the

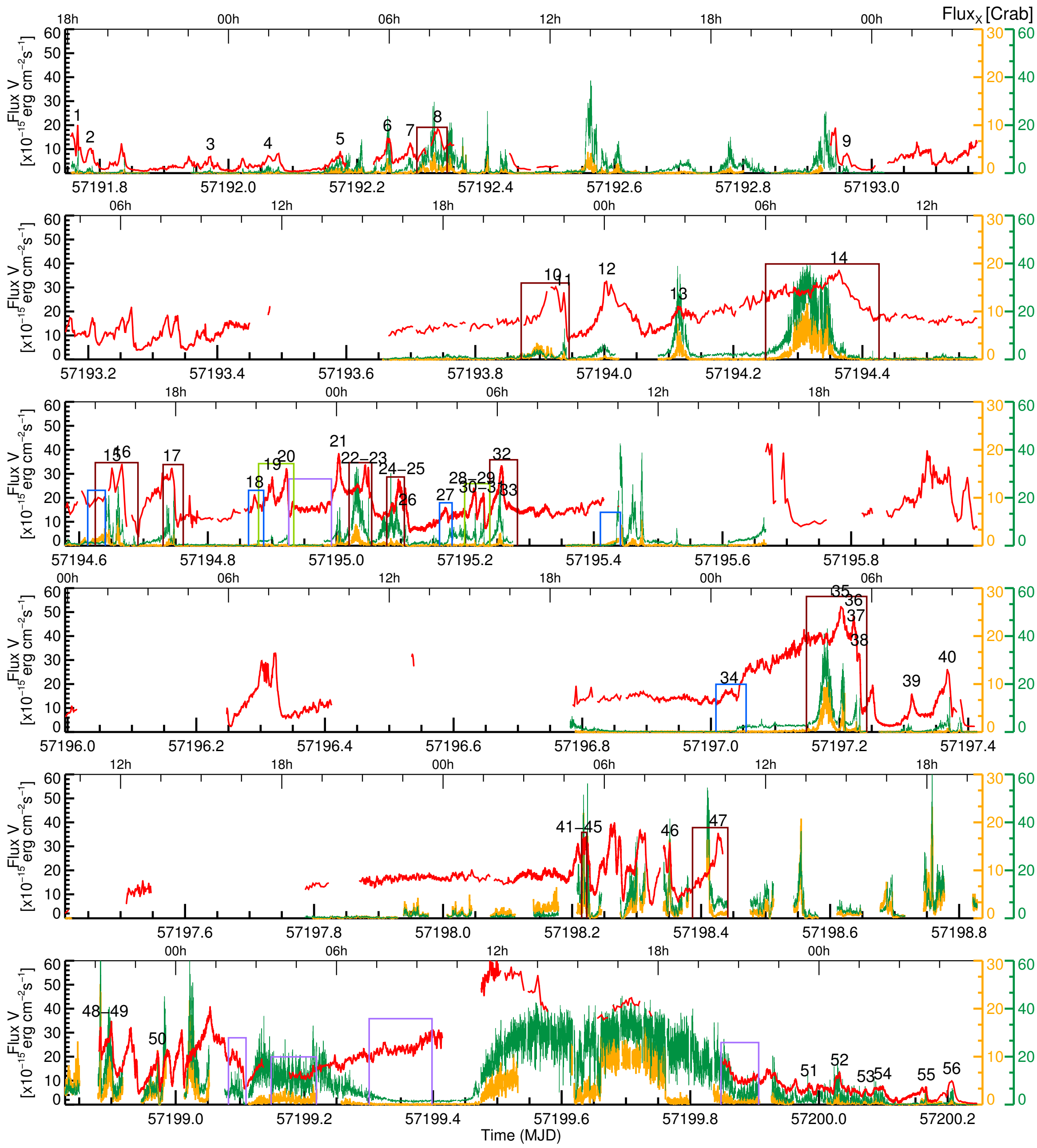

Figure 1: Optical and X-ray light curves of V404 Cyg during the June 2015 outburst from MJD 57191.75 to MJD 57200.25. The optical observations are plotted in red, the soft X-ray emission in the 3–10 keV band is plotted in orange, and the hard X-ray emission in the 20–80 keV band for *INTEGRAL*/IBIS and in the 10–79 keV band for the *NuSTAR* observations are plotted both in green. The numbers in black refer to the optical flare identifications. Brown and blue boxes mark flares with positive and negative lags, respectively. Light green boxes represent double symmetric optical flares with simultaneous X-ray emission. Purple boxes represent epochs where heartbeat-type oscillations are observed (see text).

DCF analysis, a positive lag means that the optical follows the X-rays, a negative lag means that the optical precedes the X-rays, and zero lag means that the optical and the X-rays are simultaneous. Some flares displaying the different observed behaviours are shown in Fig. 2. For each subplot, the optical and X-ray light curves (top), the hardness-ratios (middle), and the DCF (bottom) are shown.

4 Discussion

We studied the optical and X-ray light curves of V404 Cyg during the June 2015 outburst, and identified those flares observed in both energy ranges. We have used the DCF technique to search for time lags between the flare emission detected at both wavelengths.

For one third of the flares, we do not find any lags between the optical and X-ray flares (taking the uncertainties in the determination of the lags into account). In this case, we interpret that the optical and X-ray emission is coming from the same, or at least physically very close regions within the system, which can include emission from the inner hot flow and from the base of the jet.

In other cases, we measured short positive lags (<2 min). We have observed these lags in single flares and in intervals with flickering (heartbeat-type) oscillations. In this case, the optical lags could be due to reprocessing of the X-ray emission on the companion star, and/or the external parts of the accretion disc.

For other flares, we measured optical lags longer than 2 minutes, and the optical emission cannot be due to reprocessing inside the binary system. These long lags could be explained by irradiation of surrounding material around the system or by interaction of jet ejections blobs with this surrounding material or with other ejected blobs. We observed a large variety of measured lags, shape and brightness of the optical flares. It seems that in the case of long lags, different mechanisms should be taking place along the outburst, including interaction of ejections from the jet with the surrounding material or with previous ejected blobs, irradiation of distant surrounding material by the central source, or synchrotron emission from discrete ejections.

A complete analysis of all the flares identified during these observations, and a more detailed discussion can be found in (1).

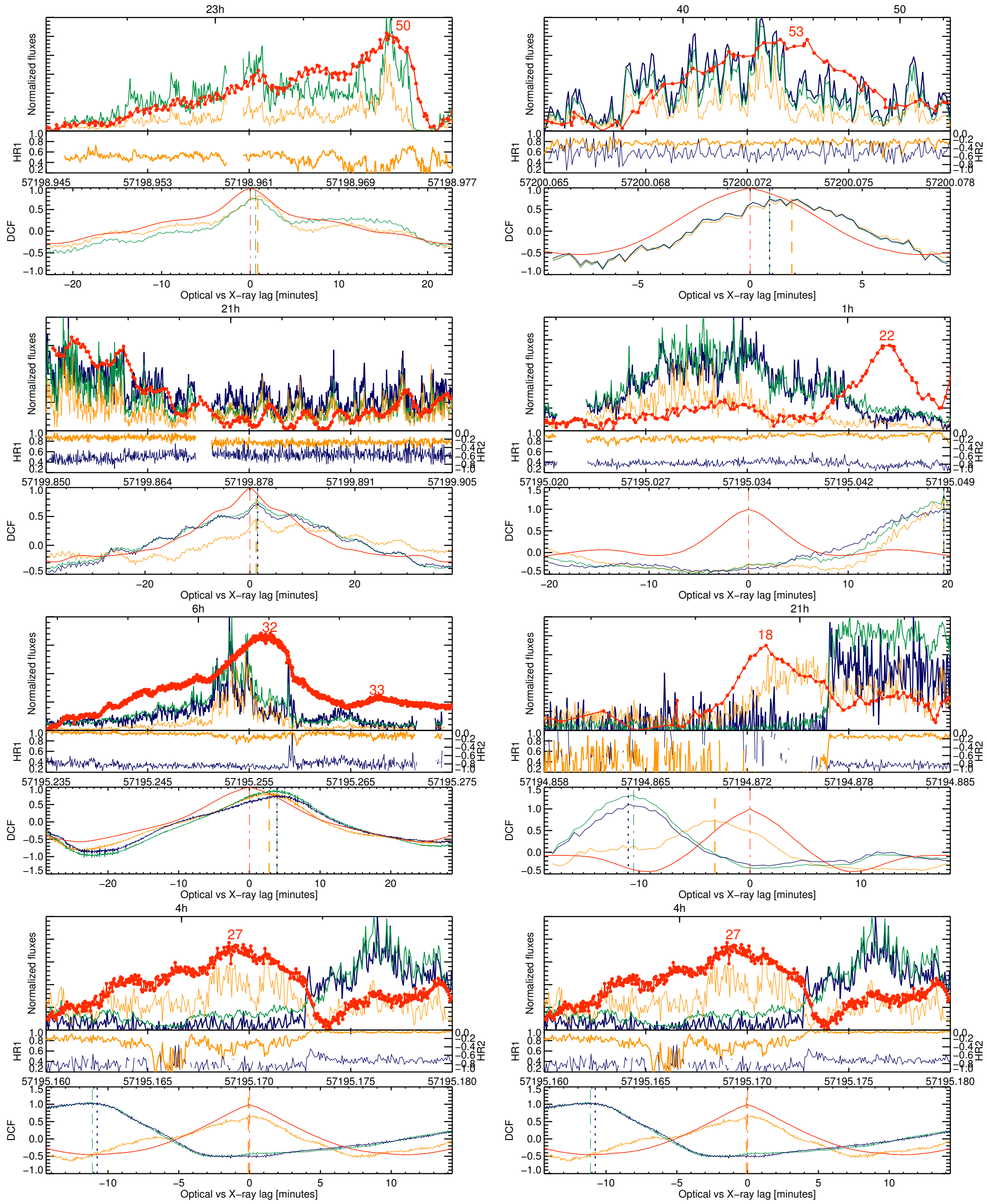

Figure 2: Zoomed-in optical and X-ray light curves where optical/X-ray flares lags display different behaviours: zero lags (top), short positive lags (second row), long positive lags (third row), negative lags (bottom). Optical observations are shown in red, soft X-ray (3-10keV) in orange, hard X-ray (20-80keV for ISGRI, or 10-79keV for *NuSTAR*) in green, and very hard X-ray (80-200keV) in dark blue. For each subplot, HR1 (the ratio between the soft and the hard X-ray bands) is plotted in orange; and HR2 (the ratio between the hard and very hard bands) is plotted in dark blue. The DCFs (optical autocorrelation function is shown in red, optical/soft X-ray DCF in orange, optical/hard X-ray DCF in green, and optical/very hard X-ray in dark blue) are shown below the light curves.

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