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Correlated optical, X-ray, and γ-ray flaring activity seen with INTEGRAL during the 2015 outburst of V404 Cygni*

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ABSTRACT

After 25 years of quiescence, the microquasar V404 Cyg entered a new period of activity in June 2015. This X-ray source is known to undergo extremely bright and variable outbursts seen at all wavelengths. It is therefore an object of prime interest to understand the accretion-ejection connections. These can, however, only be probed through simultaneous observations at several wavelengths. We made use of the INTEGRAL instruments to obtain long, almost uninterrupted observations from 2015 June 20, 15:50 UTC to June 25, 4:05 UTC, from the optical V band up to the soft γ-rays. V404 Cyg was extremely variable in all bands, with the detection of 18 flares with fluxes exceeding 6 Crab (20–40 keV) within three days. The flare recurrence can be as short as ~20 min from peak to peak. A model-independent analysis shows that the >6 Crab flares have a hard spectrum. A simple 10–400 keV spectral analysis of the off-flare and flare periods shows that the variation in intensity is likely to be only due to variations of a cut-off power-law component. The optical flares seem to be at least of two different types: one occurring in simultaneity with the X-ray flares, the other showing a delay greater than 10 min. The former could be associated with X-ray reprocessing by either an accretion disk or the companion star. We suggest that the latter are associated with plasma ejections that have also been seen in radio.

Key words. accretion, accretion disks – X-rays: binaries – radio continuum: stars – stars: black holes – stars: individual: V404 Cygni

1. Introduction

V404 Cyg (hereafter V404) is a low-mass X-ray binary (LMXB) consisting of a black hole (BH) with mass estimates ranging from ~9 to 15 $M_\odot$, and a 0.7–1.3 $M_\odot$ K3 III companion (Casares & Charles 1994; Shabbaz et al. 1994; Khargharia et al. 2010), located at a parallax distance 2.39 ± 0.14 kpc (Miller-Jones et al. 2009). The inclination of the binary’s rotational axis is 67° ± 3° (Shahbaz et al. 1994; Khargharia et al. 2010), the orbital period 6.5 d (Casares et al. 1992). This transient underwent three periods of outbursts during the twentieth century (Richter 1989), the last, in May 1989, leading to its discovery as an X-ray transient by the Ginga satellite (as GS 2023+338, Makino et al. 1989). V404 showed bright X-ray flares on short time-scales (e.g. Makino et al. 1989; Terada et al. 1994), which makes it an excellent source to study the connections between the accretion and ejection phenomena, which are the probable origin of this behaviour. V404 is one of the closest stellar mass BHs, making it a rare case where quiescence can be studied in detail. Variable remnant activity, attributed to a compact jet, was detected from radio to hard X-rays (e.g. Hynes et al. 2004; Xie et al. 2014). V404 is one of the few sources that defines the radio/X-ray correlation over a wide range of luminosities, down into quiescence (Corbel et al. 2008). The good knowledge of the quiescent state makes understanding new outburst observations paramount as they allow the mechanisms responsible for the increased activity to be probed.

On 2015 June 15 (MJD 57 188), V404 went into outburst again. It was first detected by Swift (BAT and XRT) (Barthelmy et al. 2015) and then with MAXI and INTEGRAL (Negoro et al. 2015; Kuulkers et al. 2015). These early alerts triggered follow-up observations at all wavelengths. Preliminary results all report the detection of the source, variations of specific spectral features, and an extreme flaring activity at all wavelengths.

* Table 1 and Fig. 4 are available in electronic form at http://www.aanda.org
As source intensity and hardness vary strongly on short time-scales, we extracted luminosity/hardness dependent JEM-X, ISGRI, and SPI spectra over specific time intervals of clean data. The spectra from the same time intervals were jointly fitted within XSPEC v12.8.2. Since the instruments’ responses are possibly different for the high intensities observed, only phenomenological spectral fits are presented, and the fit results should be viewed with some caution.

The INTEGRAL/Optical Monitoring Camera (OMC) fluxes and magnitudes were derived from a photometric aperture of 3 × 3 pixels (1 pix. = 17.504′′), slightly circularized, that is, removing one quarter pixel from each corner (standard output from OSA). The photometric aperture was centred on the source coordinates (default centroid algorithm) and did not include any significant contribution from other objects. We removed measurements with a severe problem flag, and, to restrict the noise, only measurements of 50 and 200 s duration were considered.

3. Model-independent description of the flaring

Multi-wavelength LCs of V404 from the V band up to γ-rays are highly structured with several large flares separated by calmer periods seen in all bands (Fig. 1, and see also Fig. 4 for a plot with all energy ranges). In the following, count rates (CR) are given in the ISGRI 20–40 keV range. When the source CR increased above ~150–200 cts/s, an intense X-ray flare systematically followed. In the following, we thus set 1 Crab1 as the typical limit between the off-flare and flaring intervals. We identified 18 main events, that is, peaks that reached at least 6 Crab (labelled with Roman numerals2 in Fig. 1, their main characteristics are given in Table 1), with 11 exceeding 20 Crab during our observations. Flares IV, XI, and XIII are the brightest we observed, reaching 43 Crab. The flares occurred isolated (e.g. III, IV, VI) as well as in groups with peak-to-peak intervals as short as 22 min (Va, Vb) The flares lasted 0.4–2.4 h, except for peaks IV and XIII. The former shows a rather broad profile and has multiple peaks. This event lasted 4.8 h in total and is the longest flare of our observation. The latter reached about 40 Crab. The peak itself lasted about 1.5 h, but was preceded by a ~3 h long, 3 Crab plateau seen only above 13 keV. It was followed by flares XIV and XV, which show decreasing peak values.

1 The ISGRI 20–40 keV CR of the Crab is 165 cts s−1 (Γ = 17.504′′). The dashed horizontal line corresponds to 1 Crab (20–40 keV).

2 V and XII contain two distinct events that are hardly distinguishable in Fig. 1. They appear under the same label in Fig. 1 (to keep it clear), and are named with a/b sub-labels in the text and Table 1.
The latter case we also only retained the hard intervals (SR corresponds to intervals around flares I). The ccf of Fig. 2a) shows a high level of emission with sporadic flares with a maximum 20–40 keV dynamical range of 940 (flare XI). During its flares, V404 became the brightest X-ray object in the sky. In the hard off-flare state the spectral analysis shows two spectral components: a cut-off power law typically attributed to thermal Comptonization and an extra power law at energies beyond 100 keV. Hard tails have now been seen in a large number of systems (e.g. GRS 1915+105, Swift J1753.5−0127, GX 339−4, or Cyg X–1, Rodriguez et al. 2008b, 2015b; Tomsick et al. 2015; Joint et al. 2007), and their origin is still highly debated, although a compact jet origin is favoured in the case of Cyg X–1 (e.g. Russell & Shahbaz 2014; Rodriguez et al. 2015b). It is interesting that the flaring activity seems primarily due only to spectral variations of the cut-off power law. We estimate an integrated luminosity \( \sim 2 \times 10^{31} \) erg s\(^{-1}\), or about 20% \( L_{\text{Edd}}\) for a 9 Ms\(_{\odot}\) BH.

### 6. Discussion

Over the four days covered by our INTEGRAL ToO, V404 showed a high level of emission with sporadic flares with a maximum 20–40 keV dynamical range of 940 (flare XVI). During its flares, V404 became the brightest X-ray object in the sky. In the hard off-flare state the spectral analysis shows two spectral components: a cut-off power law typically attributed to thermal Comptonization and an extra power law at energies beyond 100 keV. Hard tails have now been seen in a large number of systems (e.g. GRS 1915+105, Swift J1753.5−0127, GX 339−4, or Cyg X–1, Rodriguez et al. 2008b, 2015b; Tomsick et al. 2015; Joint et al. 2007), and their origin is still highly debated, although a compact jet origin is favoured in the case of Cyg X–1 (e.g. Russell & Shahbaz 2014; Rodriguez et al. 2015b). It is interesting that the flaring activity seems primarily due only to spectral variations of the cut-off power law. We estimate an integrated luminosity \( \sim 2 \times 10^{31} \) erg s\(^{-1}\), or about 20% \( L_{\text{Edd}}\) for a 9 Ms\(_{\odot}\) BH.
between the BH and the companion: using the system parameters from Sect. 1 and a 9 $M_\odot$ BH, we estimate $\sim 2.2 \times 10^{52}$ cm or $\sim 75$ light seconds. Hence, when no delay between the optical and the X-rays is observed (e.g. flare I in Fig. 2a), the mechanism producing the optical emission could be related to X-ray reprocessing, either by an accretion disk or by the companion. The maximum delays expected would be around 60 s (outer disk), and $\lesssim 150$ s (companion located at superior conjunction).

Optical lags $\gtrsim 10$ min could be related to variable jet properties, either as their intrinsic synchrotron emission, or from their interaction with the surrounding medium. Radio and millimeter (mm) flaring activity ascribed to discrete ejections has been reported during this outburst (e.g. Sivakoff et al. 2015; Mooley et al. 2015; Tetarenko et al. 2015b). Delays between event (a $< \text{GRO J1655}$ X-rays and longer wavelengths are expected in the case of adiabatically expanding ejecta (van der Laan 1966; Mirabel et al. 2015; Tetarenko et al. 2015b). Delays between event (a $< \text{GRO J1655}$ states (Fig. 1), indicating that a different mechanism is responsible for the X-ray flaring (similar results were obtained from the 1989 outburst, e.g. Życki et al. 1999). This work was supported by NASA through the Smithsonian Astrophysical Observatory (SAO) contract SV-73016 for the Chandra X-Ray Center and Science Instruments. R.D. and X.L.Z. acknowledge support through the Deutsche Forschungsgemeinschaft under DFG project number PR 509/10-1 in the context of the Priority Program 1573 Physics of the Interstellar Medium. The high-energy flares could be due to the shock of the relativistic jets with the dense ambient medium. Then optically thin synchrotron emission would be expected at X-ray energies, while our analysis favours thermal Comptonization. More simultaneous multi-wavelength observations will help distinguish these different possibilities.

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References
Barthelmy, S. D., D’Ai, A., D’Avanzo, P., et al. 2015, GRB Coordinates Network, 17929, 1
Casares, J., & Charles, P. A. 1994, in The Evolution of X-ray Binaries, eds. S. Holt, & C. S. Day, AIP Conf. Ser., 308, 107
Casares, J., Charles, P. A., & Naylor, T. 1992, Nature, 355, 614
Corbel, S., Koerding, E., & Kaastra, P. 2008, MNRAS, 389, 1697
Domínguez, A., Alfonso-Garzon, J., Mas-Hesse, J. M., Rodríguez, J., & Bel, M. C. 2015, Atel, 7717, 1
Fender, R. 2006, in Compact stellar X-ray sources (Cambridge, UK: Cambridge University Press), 381
Fender, R. P., & Pooley, G. G. 1998, MNRAS, 300, 573
Ferrigno, C., Fotopoulou, S., Domínguez, A., et al. 2015, Atel, 7662, 1
Greiner, J., Morgan, E. H., & Remillard, R. A. 1996, ApJ, 473, L107
Hjellming, R. M., & Raper, M. P. 1995, Nature, 375, 464
Hynes, R. I., Charles, P. A., Garcia, M. R., et al. 2004, ApJ, 611, L125
Joinet, A., Jourdain, E., Malzac, J., et al. 2007, ApJ, 657, 400
Khargharia, J., Froning, C. S., & Robinson, E. L. 2010, ApJ, 716, 1105
Kuiukers, E., Motta, S., Kajava, J., et al. 2015, Atel, 7647, 1
Maccarone, T. J. 2000, MNRAS, 336, 1371
Makino, F., Wagner, R. M., Starrfield, S., et al. 1989, IAU Circ., 4786, 1
Miller-Jones, J. C. A., Jonker, P. G., Dhawan, V., et al. 2009, ApJ, 706, L230
Mirabel, I. F., Dhawan, V., Chatterjee, P., et al. 1999, Atel, 7661, 1
Motta, S., Beardmore, A., Oates, S., et al. 2015, Atel, 7666, 1
Munoz-Darias, T., Sanchez, D. M., Casares, J., et al. 2015, Atel, 7659, 1
Negoro, H., Matsumitsu, T., Mihara, T., et al. 2015, Atel, 7646, 1
Remillard, R. A., & McClintock, J. E. 2006, ARA&A, 44, 49
Richter, G. A. 1989, IBVS, 3362, 1
Rodriguez, J., Hannikainen, D. C., Shaw, S. E., et al. 2008a, ApJ, 675, 1436
Rodriguez, J., Shaw, S. E., Hannikainen, D. C., et al. 2008b, ApJ, 675, 1449
Rodriguez, J., Ferrigno, C., Cadelo Bel, M., et al. 2015a, Atel, 7702, 1
Rodriguez, J., Grinberg, V., Grinberg, V., et al. 2008a, Atel, 7607, 17
Russell, D. M., & Shahbaz, T. 2014, MNRAS, 438, 2083
Shahbaz, T., Ringwald, F. A., Bunn, J. C., et al. 1994, MNRAS, 271, L10
Sivakoff, G. R., Tetarenko, A., & Miller-Jones, J. C. 2015, Atel, 7671, 1
Strong, A. W., Diehl, R., Hallinan, H., et al. 2008, A&A, 444, 495
Terada, K., Miotello, S., Kitamoto, S., & Egoushi, W. 1994, PASJ, 46, 677
Terada, K., Miotello, S., Kitamoto, S., & Egoushi, W. 1994, PASJ, 46, 677
Tetarenko, A., Sivakoff, G. R., Gurwell, M. A., et al. 2015a, Atel, 7661, 1
Tetarenko, A., Sivakoff, G. R., Young, K., Wouterloot, J. G. A., & Miller-Jones, J. C. 2015b, Atel, 7708, 1
Tomsick, J. A., Rahou, F., Kalemkhan, M., et al. 2015, ApJ, 808, 85
Tsubono, K., Aoki, T., Asama, K., et al. 2015, Atel, 7701, 1
van der Laan, H. 1966, Nature, 211, 1131
Winkler, C., Courvoisier, J. T.-L., Di Cocco, G., et al. 2003, A&A, 411, L1
Xie, F.-G., Yang, Q.-X., & Ma, R. 2014, MNRAS, 442, L110
Życki, P. T., Done, C., & Smith, D. A. 1999, MNRAS, 300, 561

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Table 1. List of the >6 Crab flares and their main properties.

| Name | Start* (MJD) | Peak time (MJD) | Stop* (MJD) | CR_{3-13 keV} (cts/s) | CR_{20-40 keV} (cts/s) | Properties* |
|------|--------------|-----------------|-------------|----------------------|----------------------|-------------|
| I    | 57 193.9217  | 57 193.9356     | 57 193.9402 | 184                  | 1215                 | Multiple    |
| II   | 57 193.9703  | 57 193.9981     | 57 194.0827 | 181                  | 1234                 | Multiple    |
| III  | 57 194.0827  | 57 194.1152     | 57 194.1428 | 1055                 | 3209                 | Complex     |
| IV   | 57 194.2232  | 57 194.3107     | 57 194.3938 | 2010                 | 7040                 | Isolated/Complex |
| Va   | 57 194.6273  | 57 194.6399     | 57 194.6521 | 473                  | 3328                 | Multiple/Complex, preceded by plateau |
| Vb   | 57 194.6521  | 57 194.6579     | 57 194.6708 | 852                  | 3999                 | Multiple/Complex |
| VI   | 57 194.6960  | 57 194.7346     | 57 194.7473 | 129                  | 1974                 | Isolated/Complex |
| VII  | 57 194.9788  | 57 194.9996     | 57 195.0089 | 459                  | 2200                 | Multiple/Complex |
| VIII | 57 195.0089  | 57 195.0293     | 57 195.0501 | 865                  | 4950                 | Multiple/Complex |
| IX   | 57 195.0582  | 57 195.0826     | 57 195.1095 | 320                  | 2386                 | Multiple/Complex |
| X    | 57 195.2318  | 57 195.2503     | 57 195.2712 | 577                  | 3472                 | Multiple, preceded by succession of ~6 Crab peaks |
| XI   | 57 195.4294  | 57 195.4388     | 57 195.4450 | 857                  | 7036                 | Multiple    |
| XIIa | 57 195.4450  | 57 195.4573     | 57 195.4665 | 401                  | 3525                 | Multiple/Complex |
| XIIb | 57 195.4665  | 57 195.4723     | 57 195.4841 | 1231                 | 6299                 | Multiple, followed by plateau |
| XIII | 57 197.1373  | 57 197.1785     | 57 197.1924 | 2076                 | 7081                 | Multiple, preceded by plateau |
| XIV  | 57 197.1924  | 57 197.2020     | 57 197.2067 | 1240                 | 4368                 | Multiple    |
| XV   | 57 197.2124  | 57 197.2228     | 57 197.2310 | 210                  | 1793                 | Multiple/Complex |
| XVI  | 57 197.3450  | 57 197.3647     | 57 197.3705 | 151                  | 1036                 | Isolated    |

Notes. MJD 57 193 is 2015 June 20. (a) Start (resp. stop) time of a flare is defined as the time 20–40 keV CR reaches 165 cts/s (1 Crab) during the increase (resp. decrease), or by the minimum reached before (resp. after) the increase (decrease) for multiple flares. The uncertainty on the times is ±6 × 10^{-4} d. (b) Count rates at the peaks. (c) “Multiple” stands for series of well-defined flares occurring in rapid repetition. “Complex” stands for flares showing various peaks. “Plateau” indicates a >1 Crab plateau. (d) These peaks appear as single peaks in Fig. 1. They are in fact true multiples. (e) The 3–13 keV peak time occurred about 200 s before the 20–40 keV one, indicating a potential hard lag. (f) Data gap at the end of the flare. The stop time is the last point before the gap. (g) The 3–13 keV peak time occurred about 200 s after the 20–40 keV one, indicating a potential soft lag.

Fig. 4. INTEGRAL LCs of V404 over our ∼4-day-long observations. All spectral domains considered for the LC extraction are shown here. The dashed line in the 20–40 keV panel represents the approximate level of $L_{\text{Edd}}$ we estimated. MJD 57 193 is 2015 June 20.