The outburst of V404 Cygni in 2015

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Black hole binary systems are either permanent or transient X-ray sources. Transient sources are much more numerous and spend most of their time in a quiescent state. The outburst happens after some years or dozens of years and the object becomes one of the brightest X-ray sources in the sky. One of the most spectacular examples of transients is the microquasar V404 Cygni consisting of a black hole and a K-type star. Recent outburst of this object started on June 15th, 2015, after 31 years of quiescence. Contrary to the previous outburst, this time V404 Cygni was observed by dozens of satellites and on-ground facilities. This resulted in a substantial progress in our understanding of the physics of transient systems. In particular, the INTEGRAL satellite spent about a month observing the source in the X-ray and gamma-ray domains. A short review of the INTEGRAL results is presented here, with an emphasis on the broad band spectral study.

1 Introduction

The X-ray source GS 2023+338 detected by the Ginga satellite on 22 May 1989 was soon identified as Nova V404 Cygni, observed before in the optical band in years 1938 and 1956. The binary system of 9 solar masses black hole (BH) and late K-type star has the orbital period of 6.47 d. Compared to the other BH transients V404 Cygni is rather peculiar, with a highly variable lightcurve and a strong absorption of the X-ray spectra. In addition, a common q-shape track in the hardness-intensity diagram is not observed for this source, showing no soft state branch.

Recent source brightening was detected by the Swift satellite on 15 June 2015 (Barthelmy et al., 2015). Very extensive observational campaign started soon after the Swift alert, in all energy bands ranging from low-frequency radio up to high-energy gamma rays[1]. The major part of the outburst lasted about two weeks, however, an episodic activity of the source was observed up to Jan. 2016.

Within two years after the 2015 outburst the number of publications related to this event exceeded 200. Among them, there were reports about repetitive rapid optical variability (Kimura et al., 2016), dust scattering rings (Beardmore et al., 2016), very low-frequency quasi-periodic oscillations (Huppenkothen et al., 2017) and extreme jet ejections (Tetarenko et al., 2017).

The INTEGRAL satellite monitored V404 Cygni activity in 2015 for almost a month. Various results of this campaign were presented in numerous papers (e.g., Rodriguez et al., 2015; Sánchez-Fernández et al., 2017; Jourdain et al., 2017). Below we present a broad band spectral study of the source during the bright phase of the outburst, when the emission above 200 keV was detected many times by the PICsIT instrument onboard of the INTEGRAL mission.

[1]See the outburst data repository http://deneb.astro.warwick.ac.uk/phsaap/v404cyg/data/

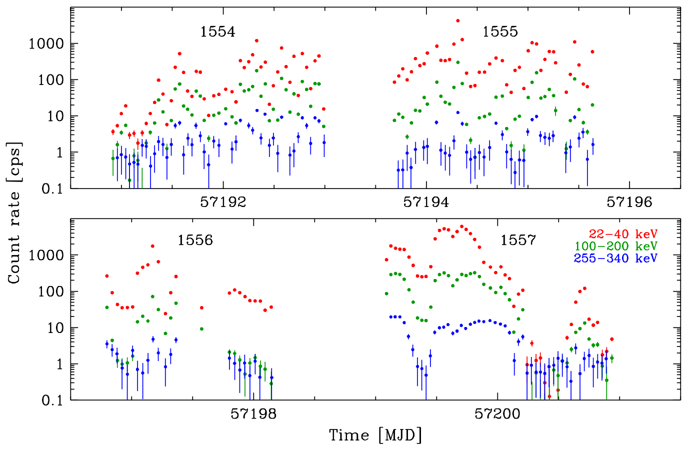

Fig. 1: INTEGRAL/IBIS lightcurves of V404 Cygni extracted for satellite revolutions 1554–1557. The 22–40 and 100–200 keV data were obtained with the ISGRI instrument, whereas the 255–340 keV data were taken using the PICsIT instrument.

2 Data reduction

The results presented in this report are based on data extracted from three INTEGRAL instruments. The pair of JEM-X detectors operate in the 3–35 keV band, whereas the IBIS detector upper (ISGRI) and lower (PICsIT) layers provide the data in the nominal 17–1000 keV and 170–8000 keV bands, respectively. For the extraction of the lightcurves and spectra from JEM-X and ISGRI data we used the standard OSA software (Courvoisier et al., 2003), version 10.2. Since the OSA package allows only for a limited PICsIT data analysis, a dedicated software based on a direct treatment of the Poisson density distributions and careful background modelling was used (Lubiński, 2009). The PICsIT data were of a prime interest in our broad band study. Since this instrument is background dominated, data are integrated onboard to reduce the telemetry, and the minimal temporal resolution is a single satellite pointing period, lasting usually 0.5–2.0 h. Thus, in our analysis we used data corresponding either to a single pointing or to a sum of many pointings.

3 Variability during outburst

In Fig. 1 we present the variability of V404 Cygni in the hard X-ray and soft γ-ray bands observed by INTEGRAL's ISGRI and PICsIT instruments during the bright period of the flare. These data were collected during the satellite revolutions 1554 – 1557 (2015-06-17 22:30 – 2015-06-27 21:53). During the first 6 days of the flare (MJD 57191.5–57197.5) the object has shown an erratic variability, with many flaring episodes. Then, up to MJD 57200.3 there appeared a smoother evolution of the overall source emission.

The source was detected above 200 keV only occassionally, except for the brightest period of revolution – 1557. In general, the count rates in the three bands shown in Fig. 1 are correlated, however, the correlation between the 22–40 keV band and

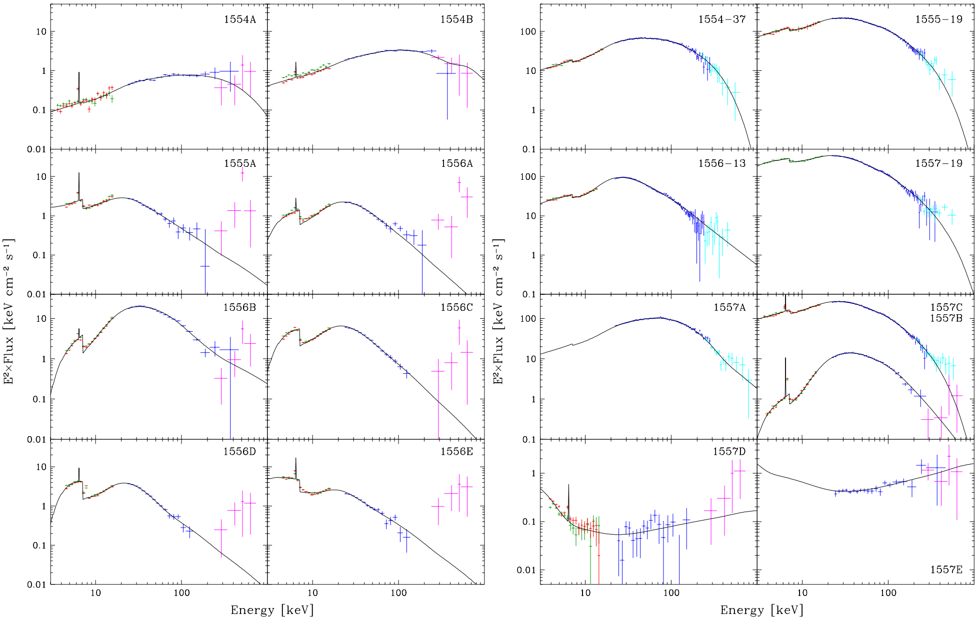

Fig. 2: Hybrid Comptonization EQPAIR model fitted to the JEM-X 1 (red), JEM-X 2 (green), ISGRI (blue) and PICsIT (magenta and cyan, see the text) spectra. Left: eight spectral sets of revolutions 1554, 1555 and 1556. Right: single pointing spectra of each revolution with the highest flux and five spectral sets of the revolution 1557.

two other bands weakens when the source reaches the highest brightness levels. The count rates in the 100–200 keV and 255–340 keV bands appear saturated at around 320 cps and 20 cps, respectively.

4 Spectral analysis

The INTEGRAL spectra were extracted for 4 pointings of the highest flux level during each revolution and for 13 longer periods, when there was a similar flux and spectral shape observed for individual pointings. The exposure time of these spectra is in a range between 3 and 46 ks. Details of the spectral set selection will be given in a forthcoming paper (Lubiński et al., 2018). The JEM-X spectra were not always available due to too large off-axis angle at which V404 Cygni was observed during several pointings. In case of PICsIT, we have verified the detection reliability through a study of the noise level induced by the background fluctuations, as described in Lubiński (2009). Only for six spectra presented with a cyan color in Fig. 2 we can claim a clear detection and these spectra were fitted together with the JEM-X and ISGRI spectra. For other cases we just plotted the PICsIT spectra (in magenta) against the model fitted to the spectra from other instruments.

The spectra were fitted with the two most advanced Comptonization models implemented in the XSPEC fitting code (Arnaud, 1996), namely COMPPS and EQPAIR. The first allows for a study of thermal plasma emission with several options

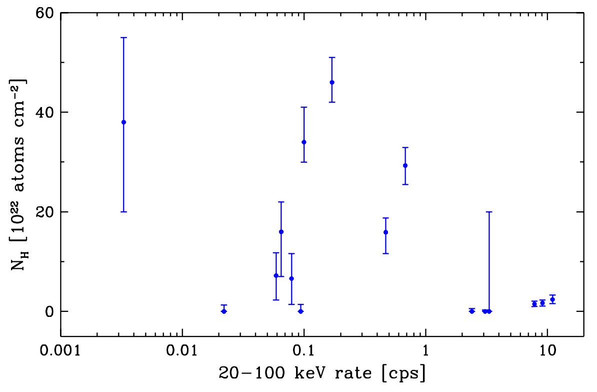

Fig. 3: Hydrogen column density of the local absorber fitted with the EQPAIR model of the primary continuum and plotted against the 20-100 keV count rate.

of the source geometry (Poutanen & Svensson, 1996), the second offers a possibility to model a hybrid thermal/non-thermal plasma emission[2]. Both models gave a good fit for a majority of the spectral sets, except for several cases, especially the spectra extracted for revolution 1556. These problematic cases will be tested with a more sophisticated spectral models in the future work.

In general we found that the V404 Cygni emission during various phases of the outburst is sometimes dominated by a purely thermal plasma emission and sometimes a hybrid plasma is needed to explain a power-law tail seen in the spectra. Our analysis points towards both variable primary emission and variable Compton reflection plus variable absorption of that emission. In Fig. 3 we present the fitted column density results against the 20–100 keV count rate. There is no clear correlation between the source brightness and absorption, in contradiction to the previous findings stating that the variable absorber is a primary variability driver (e.g., Życki et al., 1999; Motta et al., 2017).

5 Positron annihilation line

An origin of the positrons forming a strong positron-electron annihilation line observed in the Galactic bulge and disc spectra is not well understood (Prantzos et al., 2011). Microquasars, with highly energetic phenomena observed in the γ-ray energy band, are candidates for an efficient positron production. A detection of the annihilation line in the spectra of several BH systems was claimed in 1990-ties but the evidences were not strong (Prantzos et al., 2011). After the 2015 ouburst of V404 Cygni the annihilation feature was reported to be detected in the spectra of the INTEGRAL's SPI detector of revolutions 1554, 1555 and 1557 (Siegert et al., 2016). An alternative analysis of the SPI data raised some concerns about this detection (Roques et al., 2015).

Our analysis of the PICsIT spectra offers an independent check of the annihilation feature presence because SPI and PICsIT operate in a similar energy band and are characterized by a quite similar sensitivity (Lubiński et al., 2016). Fig. 4 presents

[2] Paolo Coppi, http://www.astro.yale.edu/coppi/eqpair/eqpap4.ps.

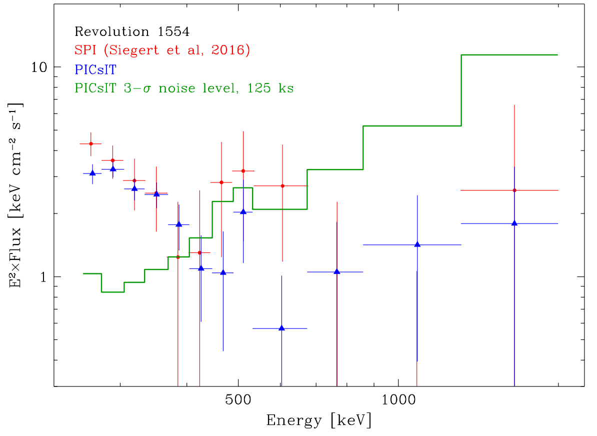

Fig. 4: Gamma-ray spectra above 250 keV extracted for V404 Cygni observation during INTEGRAL's revolution 1554. The $3-\sigma$ detection limit for PICsIT was obtained from a study of the background fluctuations during revolutions 1550–1553.

the Siegert et al. (2016) SPI spectrum of V404 Cygni taken during revolution 1554 plotted against corresponding spectrum extracted from the PICsIT data. Whereas the overall spectral shapes are similar below ≈ 430 keV, there is no broad feature seen in the PICsIT spectrum around 500 keV. For comparison we show a 3-σ noise level extracted for observations from revolutions 1550–1553, i.e. just before the outburst when an empty γ-ray field was observed by INTEGRAL. As can be seen, a signal with an amplitude as high as that of the SPI detector should be marginally detected with the PICsIT detector. Similar null result for the annihilation feature was found in the PICsIT spectra of revolutions 1555 and 1557.

6 Conclusions

Outburst of V404 Cygni in 2015 was the brightest outburst of any black hole binary system since 1989. Thanks to the high flux emission a multiwavelength observation campaign brought a welthiness of exciting results. Among them observations with the INTEGRAL satellite were quite fruitful due to its broad band coverage and a presence of several detectors.

Our analysis was focused on the spectral properties of the broad-band INTEGRAL's data, including the PICsIT instrument. Thanks to the detection of the source up to ≈ 600 keV, it was possible to constrain the parameters of the hot plasma model. Our main finding is that during the most intense phase of the outburst, there are interchanging periods of purely thermal and hybrid plasma emission. Analysis of the PICsIT spectra do not reveal a presence of the positron-electron annihilation feature.

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