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Broad-band spectral properties of V404 Cygni during its 2015 outburst

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Summary. — We investigated the spectral properties of the black hole X-ray transient V404 Cyg during its 2015 outburst, by performing the time-resolved spectroscopy on data from the *Swift* satellite. We confirmed previous results which evidenced the presence of high and variable absorption local to the source, and thanks to sensitivity to the hard X-rays provided by BAT, we showed that a significant fraction of the radiation from the accretion flow is reprocessed by the local absorber.

1. – Introduction

V404 Cyg is a transient black hole X-ray binary [1] system hosting a stellar mass black hole located at a distance of ~ 2.4 kpc [2]. Similarly to most transient systems, V404 Cyg spends most of the time in a quiescent state characterised by a low X-ray luminosity ($10^{34–35}$erg/s), and occasionally enters relatively short (weeks to months) outburst phases, during which the X-ray luminosity increases by several orders of magnitudes (up to $10^{38–39}$erg/s).

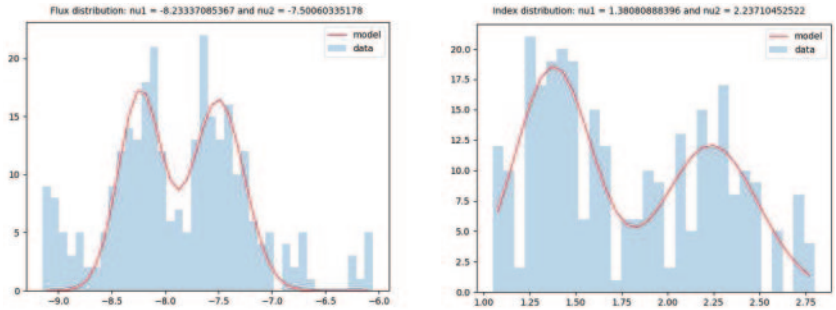
V404 Cygni was discovered on May 21, 1989, by the GINGA satellite, which observed a new bright transient X-ray source in the Cygnus region, and found it to be coincident with the position of V404 Cyg, an optical nova identified in 1938 [3]. Subsequently, the source returned to the quiescent state, and remained silent until 15 June 2015, when Swift/BAT triggered on a bright hard X-ray flare coming from a bright new transient that was soon associated with V404 Cyg. During the 2015 outburst, the system was monitored almost continuously by a vast number of space-bound and ground-based facilities covering the entire electromagnetic spectrum, which allowed an in-depth study of the properties of this system to be performed.

V404 Cyg exhibits characteristics that make it different from the typical BH X-ray transient. The bright outburst emission observed during its outbursts —possibly due to near-Eddington accretion— is severely affected by heavy absorption local to the source, which makes it difficult to unambiguously recover the source's intrinsic spectrum. The high accretion rate on the central black hole is also thought to be responsible for the formation of intense outflows, which include optically thick winds, that form and are launched from a radiation-pressure dominated inflated accretion disc [4]. As a result, the emission from the source was extremely variable, on times scales of a few hours down to seconds or less, partly because of accretion driven variability, and partly because of strong variations in the Compton-thick absorber. This caused a large fraction of the radiation to be either scattered away from our line of sight, or to be lost to absorption.

2. – Analysis and results

Motta *et al.* [4] thoroughly studied V404 Cygni in the 0.3–10 keV energy band using data from the Neil Gehrels Swift observatory (*Swift*). These authors analysed the data from the most active phase of the 2015 outburst of the source performing time resolved spectroscopy. They discovered that many of the peculiar characteristics of the source can be explained if the accretion flow takes the form of a slim disc, which forms when the accretion rate approaches and exceeds the Eddington accretion rate. At that point, the radiative cooling time scale to radiate the energy dissipated locally in the disc becomes longer than the accretion time scale, and radiation is trapped inside the accretion flow. This causes the disc to heat up and inflate, becoming a *slim disc*, which can launch a cold, clumpy outflow via which large amount of material leave the accretion flow, and form a curtain that partially shields the emission from the central part of the accretion flow.

Motta *et al.* [4] used only *Swift*/XRT data, covering the soft X-rays (0.6–10 keV). Such data, due to the limited energy coverage, did not allow completely clarifying the impact of the radiation reprocessing induced by the local absorber, which affects the soft and the hard X-rays in different ways. While in the soft X-rays a fraction of the emission is lost to absorption, the hard X-rays show the effect of the up-scattering of photons, which originate an extra component in the spectrum, often referred to as reflection (although sometimes improperly, as the term reflection refers to re-processing of material with infinite optical depth). The work presented here builds on the results obtained by Motta *et al.* [4], and focuses on the spectral analysis of V404 Cyg. The main aim of this work is to determine what physical processes dominate the evolution of the spectrum and, in particular, what is the role of reprocessing in the spectra, especially at high energies (> 10 keV). We employed data collected by two instruments on-board the *Swift* satellite, XRT and BAT, in order to cover a large energy range, *i.e.*, up to 150 keV. The results are based on a selection of the XRT spectra already presented in Motta *et al.* [5], and simultaneous BAT spectra. The BAT spectra were extracted from the BAT survey data retrieved from the HEASARC public archive by using the BatImager code developed by [6], which is dedicated to the processing of coded mask instrument data. In total we have studied 107 BAT spectra and 191 XRT spectra. Since the exposure of the XRT spectra is variable (from a few seconds to a few minutes), while the exposure of the BAT spectra is always approximately 5 minutes, we could associate more than one XRT spectrum to each BAT spectrum.



(a) *Flux distribution* (b) *Photon index distribution*

Fig. 1. – In panel (a) the flux data obtained using the model with the additional reflection component are shown. Panel (b) represents the trend of the photon index data of the same model. The red line represents the Gaussian curves that best approximate the histogram. The values shown above correspond to the mean value of the two Gaussians.

We fitted the energy spectra with two different models: i) a partially-covered([1]) absorbed power law with the addition of a narrow Gaussian line at ~ 6.4 keV (the same model used by [5]); ii) a partially-covered absorbed power law with a narrow Gaussian line, and a spectral component accounting for the reprocessed emission.

We first verified that the results of the best fit to the XRT+BAT spectra are consistent with what found by Motta *et al.* [4], and confirmed that the model that these authors used was adequate, and remains generally valid even considering data at high energies. In both works it can be observed that both the density and the *clumpiness* of the absorber (*i.e.*, what is modelled with partial-covering) is highly variable. In particular, we confirmed that only those spectra requiring high column densities also require partial covering. None of the spectra that show the effects of a low-density absorber requires partial covering. Overall this means that the absorber tends to be homogeneous when its density is very low, and clumpy when the density is large.

Owing to the addition of the BAT spectra, in our work we recovered a different distribution in flux with respect to Motta *et al.* [4], using both the models described above. The flux distribution (reported in fig. 1) shows two peaks (instead of one as in [5]) and an additional smaller peak at low fluxes, possibly corresponding to those spectra affected by the strongest absorption.

It is interesting to compare the photon index obtained using the two models. We observe that in the photon index distribution there is a low-photon index tail in the distribution from the first model, which is likely due to the presence of reflection in some low-flux spectra, which - if not accounted for - forces the photon index to take lower values. The addition of the reflection to the model results in an increase of photon index, especially in the case of the spectra at lowest fluxes, where the contribution of reflection is the highest. Also using the second model led to a distribution characterised by two peaks.

([1]) A partial covering factor associated with the absorption component models the non-uniformity of the absorber local to the source. When it equals 1, the material is homogeneous, and the incident spectrum, in this case a power law, is fully absorbed. For any value lower than 1, the material is covering only a given fraction of the illuminating source, thus only part of the incident spectrum is absorbed, while the rest remains unchanged. The combined spectrum has a very characteristic shape.

The fact that our results are consistent with those obtained by Motta *et al.* [4], confirms the validity of the results obtained with XRT alone. However, our results show that the addition of the BAT spectra broke the spectral degeneracy that arises due to the limited energy band of XRT, and evidenced that a reflection component is necessary to describe at least a fraction of the spectra.

3. – Discussion and conclusions

The results obtained using our first model (*i.e.*, partially covered absorbed power law) model confirmed the results by Motta *et al.* [4]. Our results show that in some spectra, the addition of a reprocessed component is necessary and provides a better description of the spectrum. In order to determine whether reflection is a necessary component of the model, we performed an F-test, which allowed us to determine that 57% of the joint broad-band spectra considered required a reprocessed component in their best fit. The introduction of the BAT spectra at high energies allows the energy spectrum to be properly described, so that the spectral degeneracy that might exist due to the similar effects of the presence of absorption and reflection in the spectra can be broken, and the contribution of each component can be adequately accounted for.

Most of the properties that characterise V404 Cyg are unusual in Galactic binaries, but are sometimes observed in the super-massive BHs powering active galaxies, the so called Active Galactic Nuclei (AGN). Hence, understanding the physics of the emissions of this source could help better understand the processes at play in AGN, where the physics is thought to follow the same basic principles as in stellar mass BHs, but happens on much longer time scales owing to the much larger BH masses involved. The advantage of studying Galactic X-ray binaries (as opposed to the AGN) is that they are nearby, and —being less massive— evolve on much shorter time scales (weeks to less than seconds, rather than tens of years) than AGN.

The results we obtained open new prospects to better understand the emission of V404 Cyg. A natural next step to our analysis will be to employ a more complex spectral model that considers the reprocessing phenomenon as such, and enabling the geometry of the absorbing material to be described more accurately. An example could be the use of the BORUS model (see refs. [7] and [8] for more details), developed by Balokovic in 2018 in order to describe the physical phenomena that take place near AGN, which can also be used in the case of V404 Cyg. Such analysis will be presented in a forthcoming paper.

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