Revisiting the radio/X-ray flux correlation in the black hole V404 Cyg: from outburst to quiescence

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ABSTRACT
We report results of Chandra X-ray and Very Large Array (VLA) radio observations of the Galactic accreting black hole V404 Cyg (GS 2023+338) in its quiescent state. V404 Cyg is detected at its faintest level of radio and X-ray emission with a 0.5–10 keV unabsorbed luminosity of $8.3 \times 10^{32} (d/3.5 \text{ kpc})^2 \text{ erg s}^{-1}$. The X-ray spectrum fit with an absorbed power-law model yields a photon index of $2.17 \pm 0.13$. Contrary to previous findings, this clearly indicates that V404 Cyg undergoes – like most black holes in quiescence – a softening of its X-ray spectrum at very low luminosity compared to the standard hard state. The quiescent radio emission is consistent with the presence of self-absorbed compact jets. We have also re-analysed archival data from the decay of the 1989 outburst of V404 Cyg in order to quantify more precisely the correlation between radio and X-ray emission in the hard state of V404 Cyg. We show that this correlation extends over five decades in X-ray flux and holds down to the quiescent state of V404 Cyg. The index of this correlation ($\sim 0.5$) may suggest that synchrotron self-Compton emission is the dominant physical process at high energy in V404 Cyg. However, this index is also consistent with scale invariant jet models coupled to an inefficiently radiating accretion disc. We discuss the properties of the quiescent state of black holes and highlight the fact that some of their properties are different from the standard hard state.

Key words: accretion, accretion discs – binaries: general – stars: individual: V404 Cyg – ISM: jets and outflows – radio continuum: stars – X-rays: stars.

1 INTRODUCTION
Accreting black holes in X-ray binaries are known to undergo transitions between various ‘X-ray’ spectral states (see McClintock & Remillard 2006, for a review), mainly (but not only, see Homan et al. 2001) due to variation of the accretion rate within the accretion disc. The quiescent state is the lowest luminosity state and is a factor of $\sim 10^6$ or more fainter than the brightest outburst state. In addition, a hard state is usually observed in the initial and final phases of an outburst with typical luminosity in the range $10^{-3}–10^{-1}$ of the Eddington luminosity.

The quiescent and hard states share similar properties (e.g. Tomsick, Kalemcı & Kaaret 2004). Indeed, the quiescent state is often viewed as a lower luminosity version of the hard state. The compact jet observed in the hard state (Corbel et al. 2000) appears also in quiescence as inferred from the characteristics of the radio spectrum (Gallo et al. 2006). The strong correlation between radio and X-ray emissions in the hard state (Corbel et al. 2003) seems to be maintained down to quiescence (Corbel et al. 2003; Gallo, Fender & Pooley 2003; Gallo et al. 2006).

However, current X-ray satellites (especially Chandra and XMM–Newton) have revealed new details of the spectrum of quiescent black holes. It appears that a fraction of them displays a softer X-ray spectrum compared to the standard hard state (Corbel, Tomsick & Kaaret 2006). In addition, deviations to the standard radio/X-ray flux correlation have been observed in the black hole GX 339−4 at very low luminosity (Corbel et al., in preparation). These peculiarities might imply that the quiescent state has to be considered as distinct from the standard hard state.

The universal radio/X-ray flux correlation presented by Gallo et al. (2003) is dominated by two sources (GX 339−4 from Corbel et al. (2003) and V404 Cyg) plus additional points from other sources. A 0620−00 in quiescence is, remarkably, consistent with an extrapolation of the V404 Cyg and GX 339−4 correlations down to quiescence (Gallo et al. 2006), but the exact track of A 0620−00 in outburst is unknown as no radio observations of a hard state were conducted in that time. The correlation observed in the hard state of accreting galactic black holes has been extended to active Galactic nuclei by including an additional correction for taking into

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account the mass of the black hole (Merloni, Heinz & di Matteo 2003; Falcke, Kürdinger & Markoff 2004; Kürdinger, Falcke & Corbel 2006). This fundamental plane of black hole activity relies strongly on the correlation observed in V404 Cyg (Gallo et al. 2003) and GX 339−4 (Corbel et al. 2003). Thus, it is important to assess the reliability of the correlation for Galactic systems.

V404 Cyg has the longest orbital period of any black hole system detected in quiescence to date. Corbel et al. (2006) reported that long orbital period systems have quiescent spectra consistent with the hard state, contrary to short orbital period systems that have softer spectra. However, the long orbital period group was statically dominated by the spectrum of V404 Cyg and recent XMM–Newton observations of V404 Cyg show a soft quiescent spectrum (Bradley et al. 2007). Therefore, we used a new Chandra observation to reconsider the X-ray spectrum of V404 Cyg and the properties of black holes in quiescence.

In this paper, we describe the results of radio and X-ray observations of V404 Cyg in quiescence and re-examine archival observations of V404 Cyg during the decay of its 1989 outburst (Section 2). The observations in quiescence provide a detailed measurement of the X-ray spectrum of V404 Cyg as well as a radio detection at its faintest level of emission (Section 3). These first simultaneous radio and X-ray observations of V404 Cyg in quiescence led us to revisit the radio/X-ray flux correlation in V404 Cyg (Section 4). For that purpose, we reconsidered all X-ray observations of V404 Cyg during its 1989 outburst, allowing us to study this correlation in much finer detail. Our conclusions are summarized in Section 5.

2 OBSERVATIONS AND DATA ANALYSIS

2.1 Chandra observation of V404 Cyg in quiescence

V404 Cyg has been observed by Chandra on two occasions while it was in or close to quiescence. A first ∼10 ks observation performed in 2000 has been published by Kong et al. (2002), while the second one conducted in 2003 has been analysed by Hynes et al. (2004). However, Hynes et al. (2004) only reported on the short-term X-ray variability and contemporaneous optical behaviour. Because no spectral analysis of the 2003 observations has been published, we decided to re-analyse these data in light of the possible difference in X-ray photon indices between short and long orbital period black hole systems suggested in Corbel et al. (2006).

In 2003, V404 Cyg was observed by Chandra on July 28 and 29 for ∼60 ks with the Advanced CCD Imaging Spectrometer spectroscopic array (ACIS-S; Bautz et al. 1998). V404 Cyg was placed on the back-illuminated ACIS Chip S3 in 1/8 sub-array mode to reduce pileup. We constructed light curves from all valid events on the S3 chip to search for times of high background. We found no background flares and therefore use the whole Chandra observation for V404 Cyg in quiescence. The total time on source was ∼20 h at 8.4 GHz and 14.15 h at 4.8 GHz. The target was observed using phase-referencing to the secondary calibrator 20252+3343. The absolute flux calibration was established by observing the quasar 3C 286. We assume that the absolute flux calibration introduces a systematic uncertainty of ∼5 per cent. The data reduction was performed using standard AIPS procedures.

To our knowledge, these VLA observations are the only radio observations that have been conducted strictly simultaneously with X-ray observations while V404 Cyg was in a quiescent state. The quiescence observations reported in Gallo et al. (2003) were not simultaneous. As V404 Cyg is known to vary significantly in its quiescent state (Hynes et al. 2004; Bradley et al. 2007; Miller-Jones et al. 2008), strict simultaneity is important to precisely constrain the X-ray versus radio flux correlation.

2.3 The 1989 outburst of V404 Cyg: archival data

In late 1989 May, Ginga detected new activity from GS 2023+338 consistent with the location of the variable star V404 Cyg. Analysis of the X-ray outburst initially indicated that the source stayed in the hard state for the whole duration of its active period (Oosterbroek et al. 1997). According to Życki, Done & Smith (1999a), a very short excursion to a thermal state was observed early in the outburst. However, since a bright radio flare was detected by Han & Hjellming (1992) very early in the outburst and such bright ejection events are usually associated with state transitions (e.g. Corbel et al. 2004; Fender, Belloni & Gallo 2004), it seems very likely that V404 Cyg was in a different X-ray state in the early phase of the outburst and that the ejection event was associated with a state transition.

We are primarily interested in precisely locating V404 Cyg in quiescence on the radio/X-ray correlation using the simultaneous X-ray and radio fluxes reported below. We therefore decided to see if we could improve the original work of Gallo et al. (2003) on the correlation in V404 Cyg. For this purpose, we used the original X-ray data from the 1989 outburst as measured by Ginga [Large Area Counter (LAC) and All Sky Monitor (ASM)], as well as by Mir/Kvant (HEXE and TTM). These data were available in form of flux light curves (in erg s^{-1} cm^{-2}) in different energy bands (see Chen, Shrade & Livio 1997, for more details). We assume an error of 10 per cent for the Mir/Kvant fluxes as no errors are quoted for these light curves. We considered only the portion of the light curves during the decay when V404 Cyg is clearly in a standard hard state with a typical inverted radio spectrum as reported by Han & Hjellming (1992), specifically, we use only data after 1989 June 8.

We first constructed light curves (Fig. 1) in the standard X-ray band (3–9 keV) used for these correlation studies by converting the original flux data in the 3–9 keV band using WebPimms from High Energy Astrophysics Science Archive Research Centre (HEASARC)1 assuming a shape for the X-ray spectrum typical of

1 http://heasarc.nasa.gov/Tools/w3pimms.html
3 RESULTS

3.1 The X-ray spectrum of V404 Cyg in quiescence

Even though, V404 Cyg is the brightest quiescent black hole (e.g. Tomsson et al. 2003), the Chandra spectrum is adequately well fitted with a simple phenomenological model consisting of a power law modified by interstellar absorption. This model is adequate for our purpose, as we aim primarily to compare the power-law photon index of V404 Cyg with the values catalogued in Corbel et al. (2006) for a sample of quiescent black holes (see also Kong et al. 2002).

More detailed spectral modelling of V404 Cyg with XMM–Newton can be found in Bradley et al. (2007). Fitting the Chandra spectrum (Fig. 2) with the absorbed power law resulted in a photon index $\Gamma = 2.17 \pm 0.13$ and a hydrogen column density $N_H$ of $(8.1 \pm 0.1) \times 10^{21}$ cm$^{-2}$ and gave an adequate fit with $\chi^2 = 62.3$ for 53 degrees of freedom. The quoted uncertainties are at the 90 per cent confidence level for one parameter. The hydrogen column density deduced from this Chandra observations is slightly greater than the one deduced from optical measurement, but this is not unusual as already mentioned by Kong et al. (2002). These results are fully consistent with the spectral parameters measured for the XMM–Newton observation conducted in 2005 November $(\Gamma = 2.09 \pm 0.08)$ as reported by Bradley et al. (2007). The unabsorbed 3–9 keV flux during the 2003 Chandra observation is $(1.79 \pm 0.06) \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$. This corresponds to a 0.5–10 keV unabsorbed luminosity of $8.3 \times 10^{32}$ (d$\leq5$ kpc)$^2$ erg s$^{-1}$. This is a factor of 5 fainter than in the previous Chandra observation conducted in 2000 (Kong et al. 2002), consistent with the flux in 2005 reported by Bradley et al. (2007), and slightly fainter than in the BeppoSAX observations (Campana, Parmar & Stella 2001).

Fig. 3 illustrates the 68 per cent, 90 per cent and 99 per cent error contours allowing two parameters ($\Gamma$ and $N_H$) to vary, and indicates that these parameters are well constrained by our observations. The Chandra and the XMM–Newton observations therefore confirm that the X-ray spectrum of V404 Cyg is softer in quiescence than in outburst, contrary to what was originally reported by Kong et al. (2002) from the 2000 Chandra observations (they obtained a photon index of 1.55 $\pm$ 0.07 with a hydrogen column density frozen to the optical measurement, and 1.81 $\pm$ 0.14 with $N_H$ free to vary). The new Chandra and XMM–Newton data are both consistent in term of $N_H$ estimations and favour a value higher than the one deduced from optical observations. In addition, we found that the 2000 Chandra spectrum of Kong et al. (2002) was widely affected by pileup. We refitted their spectrum using the pileup model in Xspec and found $\Gamma = 2.06_{-0.36}^{+0.32}$ with $N_H = 7.5_{-0.8}^{+0.5} \times 10^{21}$ cm$^{-2}$, values that are now fully consistent with the new Chandra and XMM–Newton spectra.

3.2 Radio emission from V404 Cyg in quiescence

A radio source is detected at the location of V404 Cyg with flux densities of $164 \pm 38$ $\mu$Jy and $193 \pm 22$ $\mu$Jy at 4.8 and 8.4 GHz,
be consistent with an extrapolation of our new radio spectrum up to infrared and therefore our results do not alter their conclusions.

\section{Discussion}

\subsection{Softening of Black Holes X-ray Spectra in Quiescence}

By analyzing the X-ray spectra of black holes in quiescence, Corbel et al. (2006) found that a significant fraction of those black holes had an X-ray spectrum that was significantly softer in the quiescent state with respect to the brighter standard hard state. They also noticed that the three black holes with the highest orbital periods had spectra consistent with the hard state, whereas the short orbital period ($< 60$ h) systems were all consistent with a soft spectrum. However, the difference between the two groups was statically dominated by the 2000 Chandra spectrum of V404 Cyg.

As described above, the 2003 Chandra and 2005 XMM–Newton spectra of V404 Cyg clearly indicate that V404 Cyg also undergoes a softening in quiescence. These results differ from the conclusion of Corbel et al. (2006). That conclusion was based on the assumption that the 2000 Chandra spectrum of V404 Cyg (Kong et al. 2002) represented the quiescent state of V404 Cyg (which we have now shown in Section 3.1 is also consistent with the new measurements if pileup is taken into account). In light of our new results, we find that there is no statistically significant difference in the quiescent X-ray spectra of black holes with long or short orbital period. On the contrary, the new spectrum of V404 Cyg generalizes the finding of Corbel et al. (2006) that all black holes in quiescence have a softer X-ray spectrum than the standard hard state.

As discussed in Corbel et al. (2006), there are several different possible physical reasons for this softening. The softening could be related to an advection dominated accretion flow (ADAF) (McClintock et al. 2003) or a jet located above an ADAF (Yuan, Cui & Narayan 2005). However, as outlined in recent studies (e.g. Gallo et al. 2006), ADAF solutions have several difficulties in self-consistently modelling the powerful outflows that may be present in quiescence.

Interestingly, now that the softening of V404 Cyg is clearly brought to light, inspecting the original Ginga/LAC data revealed that such softening was already on beginning a few months after the peak of the 1989 outburst. Indeed, after a peak around 1989 May 30, the Ginga spectrum in 1989 November was much softer than in the other observations conducted during the decay (as indicated by table 2 in Życki et al. 1999b). The transition to the soft quiescent state therefore occurred around a 0.5–10 keV unabsorbed flux of $2.5 \times 10^{-10}$ erg s$^{-1}$ cm$^{-2}$ equivalent to a luminosity of $\sim 3 \times 10^{-4} L_{\text{Edd}}$ for a distance of 3.5 kpc (according to Życki et al. 1999b). In addition, it is worth noting that other black holes have also shown indication of softening at these intermediate luminosities (see section 4.3 in Corbel et al. 2006, and references therein).

Black hole systems at luminosity below $10^{-4} \ldots 10^{-5} L_{\text{Edd}}$ may, therefore, enter a quiescent state with different properties (at least a softer X-ray spectrum) than the hard state. This is contrary the standard view that the quiescent state is an extension of the hard state, which has arisen due to the continuous evolution of some of the X-ray properties (e.g. timing) at low luminosity (e.g. Tompkins et al. 2004). The quiescent state may be related to new accretion disc properties or other characteristics of the outflow, for example inefficient particle acceleration. Further observations of black holes during the decay of their outbursts would (as in Kalemci et al. 2006) be important to constrain the properties of the quiescent state.
4.2 Revisiting the radio/X-ray flux correlation in V404 Cyg

V404 Cyg was the second Galactic black hole for which a strong correlation between radio and X-ray emission was observed (Gallo et al. 2003). As outlined in Section 2.3, we have re-analysed some of the data from its 1989 outburst, allowing us to obtain a more precise estimate of the X-ray flux during the decay of the outburst, as well as almost double the number of pairs of near simultaneous radio/ X-ray fluxes. With the 2003 Chandra/VLA observations and the 2000 Ginga/VLA observations, we are able to provide two precise and simultaneous fluxes while V404 Cyg was in quiescence. This allows us to revisit the correlation found by Gallo et al. (2003) in much finer detail than before.

For that purpose, we only consider the radio observations after TJD 7685 (1989 June 8) as a secondary X-ray and optical re-flare was observed during the decay (see light curves in Brocksopp, Bandopadhyay & Fender 2004). This ensures that we are considering observations that are in the hard state, as confirmed by the flat or inverted radio spectrum after this date that is a characteristic of the self-absorbed compact jets (Blandford & Konigl 1979). In Fig. 4, we plot the radio flux density $F_{\text{рад}}$ at 8.4 GHz versus the unabsorbed 3–9 keV flux $F_X$, indicating (as originally observed for V404 Cyg by Gallo et al. 2003) that a strong correlation between these two frequency domains is present.

We fit the correlation with a power law of the form $F_{\text{rad}} = k F_X^b$ in log space, taking the uncertainties in both the measured radio and X-ray flux into account. A fit to all the data with the measured uncertainties yields $k = 4.6 \pm 0.3$ and $b = 0.51 \pm 0.02$, with a merit function of 102 for 17 degrees of freedom. Thus, there are some deviations from the power-law fit exceeding the uncertainties. We can parametrize these deviations by adding some isotropic excess scatter to the data. To obtain a good fit, we have to introduce 0.068 dex scatter. With the excess scatter, we find for the fit parameters $k = 4.6 \pm 0.4$ and $b = 0.51 \pm 0.03$ [in log space, we obtain log $F_{\text{rad}} = (0.66 \pm 0.04) \log F_X^b$]. If we fit the data without the last two points near quiescence we find the same fit values albeit with larger uncertainties: $k = 4.7 \pm 0.6$ and $b = 0.51 \pm 0.06$. The quiescent measurements are consistent within the uncertainties with the extrapolation of this fit to the luminous data. A fit using the radio fluxes at 4.8 GHz from Han & Hjellming (1992) instead of 8.4 GHz does not change the overall index, as one obtain $k = 4.0 \pm 0.4$ and $b = 0.53 \pm 0.04$.

To test if significant spectral evolution of the source is responsible for the low correlation index (0.51 compared to 0.7), we also fit the correlation using 1.2 to 37.2 keV X-ray fluxes. Here, the scatter is slightly larger (0.14 dex excess scatter) but we find similar fit values as before $k = 1.94^{+0.93}_{-0.63}$ and $b = 0.52 \pm 0.10$. The larger uncertainties mainly arise due to the lower sample size for which 1.2 to 37.2 keV fluxes are available (only 8 measurements). We therefore do not see an evolution of the correlation index in the 1.2 to 37.2 keV energy range.

The correlation observed during the decay of the 1989 outburst therefore holds down to deep in the quiescent state. Contrary to the behaviour observed from GX 339–4 [Corbel et al. (in preparation)], there is no deviation to the correlation for V404 Cyg in quiescence, at least when comparing to the track measured from the 1989 outburst [several tracks are observed in GX 339–4; Corbel et al. (in preparation)]. This constitutes the best example (almost five decades in X-ray flux) – to date – for a non-linear correlation between radio and X-ray fluxes in the hard state of a black hole candidate. We note that even if the dispersion of the data-points along the fit in Fig. 4 is much smaller than in Gallo et al. (2003), there is still some fluctuation (quantified with the isotropic excess) along the fitted line (in log space). This residual deviation may possibly be related to our procedure of estimating the X-ray fluxes of V404 Cyg (cf. Section 2.3) or possibly to variation in the absorbing column density as observed by Ginga (Oosterbroek et al. 1997; Zycki et al. 1999a, b). The latter is more likely as some fluctuations were also observed at radio frequencies (Han & Hjellming 1992).

Our measured power law index of $b = 0.5$ is significantly lower than the usual value of $b \sim 0.7$ (Corbel et al. 2003; Gallo et al. 2003) but it is consistent with the value of $0.7 \pm 0.2$ measured by Gallo et al. (2003) using only data from V404 Cyg. Our larger sample allows us to obtain a more precise estimation of this correlation index, and give us an opportunity to look in finer detail into the physical meaning of the correlation. For example, this index is still consistent with scale invariant jet models coupled to an inefficiently radiating accretion disc (Merloni et al. 2003).

Additionally, Yuan & Cui (2005) adapted an ADAF+jet model, originally developed for the hard state of XTE J1118+480, to black holes in quiescence. Assuming no change in jets physics from the hard state to quiescence, Yuan & Cui (2005) would have expected a change in the correlation index from $b = 0.7$ to $\sim 1.23$ below an X-ray luminosity of $10^{38} L_{\odot}$, which is slightly above the quiescent luminosity of V404 Cyg. We do not observe this behaviour, which either implies that the ADAF+jet model of Yuan & Cui (2005) is not applicable to the quiescent state or that jet physics change significantly in quiescence (a possibility discussed in Section 4.1).

In case that the X-ray emission originates from the jet, the low correlation index may indicate that the X-ray emission is created by synchrotron self-Compton emission (SSC) as also suggested by Markoff, Nowak & Wilms (2005). If the X-ray emission is SSC, then it depends more strongly on the jet power ($\sim Q_{\text{jet}}^{1/4}$) than if it is synchrotron emission ($\sim Q_{\text{jet}}^{1/2}$) (e.g. Falcke & Biermann 1995). Thus, the correlation between radio luminosity [which depends on the jet power as ($\sim Q_{\text{jet}}^{1/2}$)] and X-ray luminosity from SSC is flatter and gives $b \approx (17/12)/(11/4) \approx 0.51$, a value fully consistent with our derived index. If the SSC interpretation is correct, then this is different from the 1997–99 tracks of GX 339–4 which was consistent with $b = 0.7$ and a pure synchrotron origin (Corbel et al. 2003; Markoff et al. 2003). However, a lower correlation index was also noticed for GX 339–4 at intermediate luminosity in the recent outbursts [Corbel et al. (in preparation)]. This could potentially indicate that we are witnessing an interplay between various emission processes (synchrotron, SSC, external Comptonization) at high energy, for reasons that still need to be understood. In any case, a broadband fit to the spectral energy distribution of A 0620–00, using the jet model of Markoff et al. (2005), is consistent with a SSC origin for the hard X-ray emission in this quiescent black hole. It would be worthwhile to check for the presence of an SSC component in the broadband fit of V404 Cyg, as implied by our correlation study.

5 CONCLUSIONS

We publish the results of a Chandra and VLA observation of V404 Cyg in quiescence and we re-evaluate the correlation between radio and X-ray emission. The main conclusions of our work can be summarized as follows:

(i) The Chandra and VLA observations have allowed a detection of V404 Cyg at its faintest level of emission yet observed. The characteristics of the radio emission remain consistent with the presence of self-absorbed compact jets in the quiescent state.
(ii) The Chandra observation of V404 Cyg confirms the softening of its X-ray spectrum in quiescence. This implies that all black holes in quiescence have a softer X-ray spectrum in quiescence than in the standard hard state.

(iii) We revisit and improve the correlation between radio and X-ray emission in V404 Cyg and found an index of the correlation that may suggest that the X-ray emission in the hard state of V404 Cyg is due to SSC. Compared to other sources, this would imply that the X-ray emission in black holes could be the results of interplay of various emission mechanisms (synchrotron, SSC or external Comptonization) with different mechanisms favoured under conditions that still need to be understood.

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