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

S. Corbel[1]⋆ , E. Koerding[2] and P. Kaaret[1,3].

[1] *Université Paris 7 Denis Diderot and Service d'Astrophysique, UMR AIM, CEA Saclay, F-91191 Gif sur Yvette, France.*
[2] *School of Physics and Astronomy, University of Southampton, Highfield, Southampton, Hampshire, SO17 1BJ, UK.*
[3] *Department of Physics and Astronomy, University of Iowa, Iowa City, IA 52242 USA.*

19 June 2008

ABSTRACT

We report results of *Chandra* X-ray and 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 8.3×10^{32} (d/3.5 kpc)^2 erg s^{-1}. The X-ray spectrum fit with an absorbed power-law model yields a photon index of 2.17 ± 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 reanalyzed 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 (~ 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 disks – binaries: general – ISM: jets and outflows – radio continuum: stars – X-rays: stars – stars: individual (V404 Cyg).

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 disk. 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 et al. 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 et al. 2003, 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 display a softer X-ray spectrum compare to the standard hard state (Corbel et al. 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 prep.). 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

---
⋆ E-mail:corbel@discovery.saclay.cea.fr

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 galatic black holes has been extended to active galactic nuclei by including an additional correction for taking into account the mass of the black hole (Merloni et al. 2003; Falcke et al. 2004; Körding et al. 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-radio observations of V404 Cyg in quiescence and re-examine archival observations of V404 Cyg during the decay of its 1989 outburst (§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 (§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 (§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 analyzed by Hynes et al. (2004). However, Hynes et al. (2004) only reported on the short term X-ray variability and contemporaneous optical behavior. Because no spectral analysis of the 2003 observations has been published, we decided to re-analyze 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 the spectral analysis giving an exposure of 55.6 ks. A standard data analysis was performed using the *Chandra* Interactive Analysis of Observations (CIAO) software package – version 3.4.1.1 – with the most up to date calibration database – version 3.4.

A bright X-ray source is detected at the location of V404 Cyg. We extracted the energy spectrum of V404 Cyg using a circular source extraction region of 3″, providing a total of 1943 photons. We rebinned the spectrum to have at least 30 counts in each energy bin. As already noted by Hynes et al. (2004), the 2003 observation was performed when V404 Cyg had on average a factor 5 lower count rate compared to the 2000 *Chandra* observation reported by Kong et al. (2002). A background spectrum was extracted from an annulus with an inner radius of 4″ and an outer radius of 18″. However, given the brightness of V404 Cyg, this background is negligible.

2.2   VLA observation of V404 Cyg in quiescence

We have reduced archival VLA data (PI: Hynes, AH823) of V404 Cyg in quiescence. The VLA observation in A-configuration was conducted on the 29th July between UT 0:20 and 14:15, simultaneously with the Chandra observation. The total time on source was ~ 5 hours at 8.4 GHz and 4.4 hours at 4.8 GHz. The target was observed using phase-referencing to the secondary calibrator 20252+33430. 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 %. 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), strict simultaneity is important to precisely contrain the X-ray versus radio flux correlation.

2.3   The 1989 outburst of V404 Cyg : archival data

In late May 1989, *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 et al. (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 et al. 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.
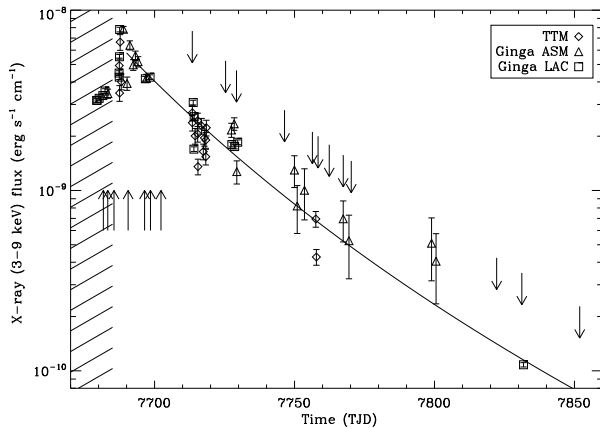
Figure 1. X-ray lightcurve in the 3–9 keV band constructed from archival data of *Ginga* (LAC and ASM) and *MIR/Kvant* (TTM). The line is a power-law fit to the decay of the outburst and has been used to estimate the X-ray flux during the radio observations. Arrows indicate the dates of the radio (VLA) observations of Han & Hjellming (1992). The radio data in the dashed area have not been used in our study.

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* (LAC and 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 et al. 1997 for more details). We assume an error of 10% 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 (Figure 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 HEASARC[1] assuming a shape for the X-ray spectrum typical of the hard state, specifically a power-law with photon index of 1.6, (McClintock & Remillard 2006) and a hydrogen column density of 8×10^{21} cm^{-2}. We note that extra absorption was observed during outburst (Oosterbroek et al. 1997; Życki et al. 1999a,b), but its effect is not significant in the 3-9 keV band used in this study. At this stage, we do not use X-ray fluxes in Crab units as the Crab spectrum is significantly different from a typical hard state spectrum Gallo et al. (2003).

By interpolating the X-ray decay light-curve (Figure 1), we were able to obtain reasonable estimates for the 3–9 keV flux at the times of the radio observations listed in Table 1 of Han & Hjellming (1992) (ten of these observations were quasi-simultaneous with an X-ray observations). In addition, when V404 Cyg was very faint (1989 November 1 and 1990 August 16), we reduced directly the *Ginga* LAC spectrum provided by HEASARC in order to obtain a very
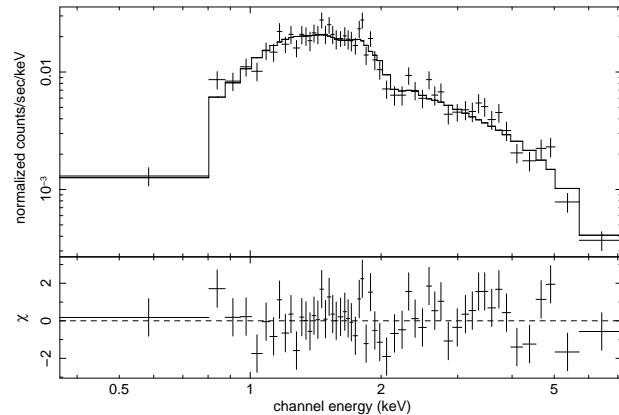
Figure 2. *Chandra* energy spectrum of V404 Cyg in 2003 from 0.3 to 8 keV fitted with a power-law modified by interstellar absorption. The residuals in the form of the contribution to the value of χ^2 for each energy bin are plotted in the bottom panel.

good estimate of the X-ray flux. In total, we have 20 pairs of measurements/estimates of the radio and X-ray flux of V404 Cyg during the decay of its 1989 outburst (compared to 10 measurements in Gallo et al. 2003). We do not use the quiescence point of Gallo et al. (2003) because the X-ray and radio observations were not conducted at the same time, but we use, instead, our quiescence measurements as describe in this paper. In addition, our procedure led to another important quasi-simultaneous measurement at an X-ray flux almost two decades brighter than quiescence (see the point labeled Ginga/VLA in Figure 4). These measurements should be more precise than those in the broader study of Gallo et al. (2003).

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. Tomsick 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 modeling of V404 Cyg with *XMM-Newton* can be found in Bradley et al. (2007).

Fitting the *Chandra* spectrum (Figure 2) with the absorbed power-law resulted in a photon index Γ of 2.17 ± 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% 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 November 2005 ($\Gamma = 2.09 \pm 0.08$) as reported by Bradley et al. (2007). The unabsorbed 3-9 keV flux during
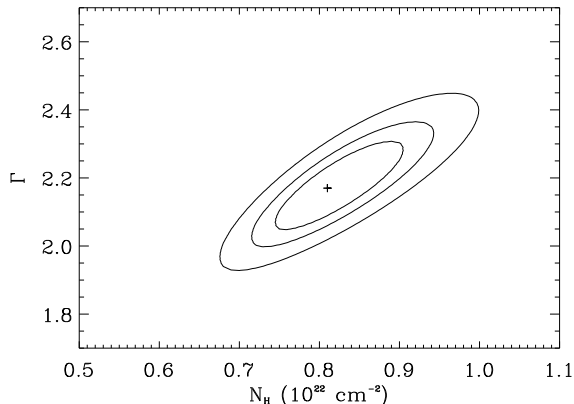
Figure 3. Error contours for the hydrogen column density (N_H) and the power-law index (Γ) derived from the *Chandra* spectrum of V404 Cyg. The cross marks the location of the best-fit value, and 68% ($\Delta\chi^2 = 2.30$), 90% ($\Delta\chi^2 = 4.61$) and 99% ($\Delta\chi^2 = 9.21$) confidence contours are shown.

the 2003 *Chandra* observation is $(1.79^{+0.13}_{-0.06}) \times 10^{-13}$ erg s^{-1} cm^{-2}. This corresponds to a 0.5–10 keV unabsorbed luminosity of 8.3×10^{32} (d/3.5 kpc)^2 erg s^{-1}. This is a factor 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 et al. 2001).

Figure 3 illustrates the 68%, 90%, and 99% error contours allowing two parameters (Γ 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 ± 0.07 with an hydrogen column density frozen to the optical measurement, and 1.81 ± 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 that the one deduced from optical observations. In addition, we found that the 2000 *Chandra* spectrum of Kong et al. (2002) was moderately affected by pile-up. We refitted their spectrum using the pile-up model in *Xspec* and found $\Gamma = 2.06^{+0.26}_{-0.29}$ with $N_H = 7.5^{+1.5}_{-0.8} \times 10^{21}$ 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 ± 38 μJy and 193 ± 22 μJy at 4.8 GHz and 8.4 GHz respectively, giving a spectral index of $\alpha = +0.29 \pm 0.46$ defined as $S_\nu \propto \nu^\alpha$ where S_ν is the flux density at frequency ν. This is the faintest level of radio emission ever reported from this source. In light of the significant X-ray variability during the *Chandra* observations (Hynes et al. 2004), we searched for radio variability by dividing the radio dataset in two parts, but we did not find any significant radio variabilty.

Despite a fainter level of emission, the radio spec-

trum of V404 Cyg (admittedly not very well constrained) is fully consistent with previous observations conducted with Westerbook (Gallo et al. 2005). A flat spectrum and stable radio emission are fully consistent with the presence of self-absorbed compact jets (Hjellming & Johnston 1988; Blandford & Konigl 1979) in the quiescent state of V404 Cyg (see also the discussion in Gallo et al. 2005). In addition, the Spitzer data of Gallo et al. (2007) would still be consistent with an extrapolation of our new radio spectrum up to infrared and therefore our results do not alter their conclusions.

4 DISCUSSION

4.1 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 hours) 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 pile-up 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 et al. 2005). However as outlined in recent studies (e.g. Gallo et al. 2006), ADAF solutions have several difficulties in self-consistently modeling 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 November 1989 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 2.5×10^{-10} erg s^{-1} cm^{-2} equivalent to a luminosity of $\sim 3 \times 10^{-4}$ L_{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} to 10^{-5} L_{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. Tomsick et al. 2004). The quiescent state may be related to new accretion disk properties or other characteristics of the outflow, e.g. 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 reanalyzed 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 allow 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 et al. 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 figure 4, we plot the radio flux density F_{Rad} 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 $F_{rad} = k\,F_X^b$ 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 $k = 4.6\pm0.3$ 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 parametrise 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 $\log F_{rad} = (0.66 \pm 0.04) \log F_X^b$). 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
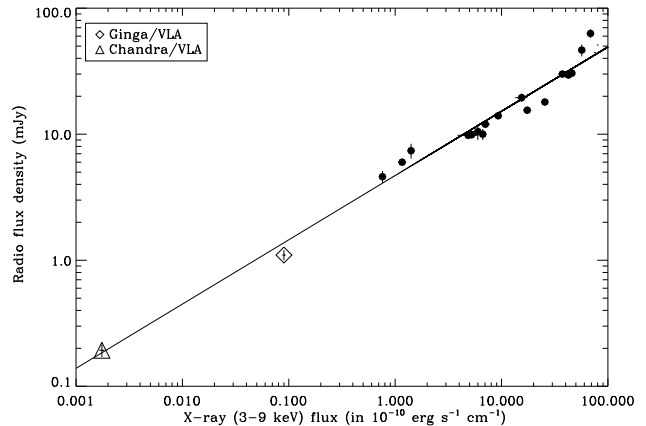

Figure 4. Radio flux density F_{Rad} at 8.4 GHz versus the unabsorbed 3-9 KeV flux F_X for V404 Cyg for the decay of the 1989 outburst and the recent *Chandra/VLA* observations in quiescence. The straight line is a fit to these data-points with a function of the form $F_{Rad} \propto F_X^b$, with $b = 0.51 \pm 0.06$. The two points with the lowest fluxes were not included in the fit, but they agree perfectly with the correlation observed in the decay of 1989 outburst.

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 behavior observed from GX 339−4 (Corbel et al. in prep), 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 prep.). 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 Figure 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 (c.f. section 2.3) or possibly to variation in the absorbing column density as observed by *Ginga* (Oosterbroek et al. 1997; Życki 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 ± 0.2 measured by Gallo et al. (2003) using only data from

V404 Cyg). Our larger sample allow 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^{-6} L_{Edd} , 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 et al. (2005). If the X-ray emission is SSC, then it depends more strongly on the jet power ($\sim Q_{jet}^{\frac{11}{4}}$) than if it is synchrotron emission ($\sim Q_{jet}^{\frac{7}{4}}$) (e.g., Falcke & Biermann 1995). Thus, the correlation between radio luminosity (which depends on the jet power as ($\sim Q_{jet}^{\frac{17}{12}}$)) and X-ray luminosity from SSC is flatter and gives $b \approx \frac{17}{12}/\frac{11}{4} \approx$ 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 prep). This could potentially indicate that we are witnessing an interplay between various emission processes (synchrotron, SSC, external Comptonisation) 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 an 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 reevaluate the correlation between radio and X-ray emission. The main conclusions of our work can be summarized as follows:

• 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.

• 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.

• 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 synchrotron self-Compton emission. 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 Comptonisation) with different mechanisms favoured under conditions that still need to be understood.

REFERENCES

Bautz M. W., Pivovaroff M., Baganoff F., Isobe T., Jones S. E., Kissel S. E., Lamarr B., Manning H. L., Prigozhin G. Y., Ricker G. R., Nousek J. A., Grant C. E., Nishikida K., Scholze F., Thornagel R., Ulm G., 1998, in Hoover R. B., Walker A. B., eds, Proc. SPIE Vol. 3444, p. 210-224, X-Ray Optics, Instruments, and Missions, Richard B. Hoover; Arthur B. Walker; Eds. Vol. 3444 of Presented at the Society of Photo-Optical Instrumentation Engineers (SPIE) Conference, X-ray CCD calibration for the AXAF CCD Imaging Spectrometer. pp 210–224

Blandford R. D., Konigl A., 1979, ApJ, 232, 34

Bradley C. K., Hynes R. I., Kong A. K. H., Haswell C. A., Casares J., Gallo E., 2007, ArXiv e-prints, 706

Brocksopp C., Bandyopadhyay R. M., Fender R. P., 2004, New Astronomy, 9, 249

Campana S., Parmar A. N., Stella L., 2001, A&A, 372, 241

Chen W., Shrader C. R., Livio M., 1997, ApJ, 491, 312

Corbel S., Fender R. P., Tomsick J. A., Tzioumis A. K., Tingay S., 2004, ApJ, 617, 1272

Corbel S., Fender R. P., Tzioumis A. K., Nowak M., McIntyre V., Durouchoux P., Sood R., 2000, A&A, 359, 251

Corbel S., Nowak M. A., Fender R. P., Tzioumis A. K., Markoff S., 2003, A&A, 400, 1007

Corbel S., Tomsick J. A., Kaaret P., 2006, ApJ, 636, 971

Falcke H., Biermann P. L., 1995, A&A, 293, 665

Falcke H., Körding E., Markoff S., 2004, A&A, 414, 895

Fender R. P., Belloni T. M., Gallo E., 2004, MNRAS, 355, 1105

Gallo E., Fender R. P., Hynes R. I., 2005, MNRAS, 356, 1017

Gallo E., Fender R. P., Miller-Jones J. C. A., Merloni A., Jonker P. G., Heinz S., Maccarone T. J., van der Klis M., 2006, MNRAS, 370, 1351

Gallo E., Fender R. P., Pooley G. G., 2003, MNRAS, 344, 60

Gallo E., Migliari S., Markoff S., Tomsick J. A., Bailyn C. D., Berta S., Fender R., Miller-Jones J. C. A., 2007, ApJ, 670, 600

Han X., Hjellming R. M., 1992, ApJ, 400, 304

Hjellming R. M., Johnston K. J., 1988, ApJ, 328, 600

Homan J., Wijnands R., van der Klis M., Belloni T., van Paradijs J., Klein-Wolt M., Fender R., Méndez M., 2001, ApJS, 132, 377

Hynes R. I., Charles P. A., Garcia M. R., Robinson E. L., Casares J., Haswell C. A., Kong A. K. H., Rupen M., Fender R. P., Wagner R. M., Gallo E., Eves B. A. C., Shahbaz T., Zurita C., 2004, ApJ, 611, L125

Kalemci E., Tomsick J. A., Rothschild R. E., Pottschmidt K., Corbel S., Kaaret P., 2006, ApJ, 639, 340

Kong A. K. H., McClintock J. E., Garcia M. R., Murray S. S., Barret D., 2002, ApJ, 570, 277

Körding E., Falcke H., Corbel S., 2006, A&A, 456, 439

Markoff S., Nowak M., Corbel S., Fender R., Falcke H., 2003, A&A, 397, 645

Markoff S., Nowak M. A., Wilms J., 2005, ApJ, 635, 1203

McClintock J. E., Narayan R., Garcia M. R., Orosz J. A., Remillard R. A., Murray S. S., 2003, ApJ, 593, 435

McClintock J. E., Remillard R. A., 2006, Black hole binaries. Compact stellar X-ray sources, pp 157–213

Merloni A., Heinz S., di Matteo T., 2003, MNRAS, 345, 1057

Oosterbroek T., van der Klis M., van Paradijs J., Vaughan B., Rutledge R., Lewin W. H. G., Tanaka Y., Nagase F., Dotani T., Mitsuda K., Miyamoto S., 1997, A&A, 321, 776

Tomsick J. A., Corbel S., Fender R., Miller J. M., Orosz J. A., Rupen M. P., Tzioumis T., Wijnands R., Kaaret P., 2003, ApJ, 597, L133

Tomsick J. A., Kalemci E., Kaaret P., 2004, ApJ, 601, 439

Yuan F., Cui W., 2005, ApJ, 629, 408

Yuan F., Cui W., Narayan R., 2005, ApJ, 620, 905

Życki P. T., Done C., Smith D. A., 1999a, MNRAS, 309, 561

Życki P. T., Done C., Smith D. A., 1999b, MNRAS, 305, 231