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The radio spectrum of a quiescent stellar mass black hole

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ABSTRACT

Observations of V404 Cyg performed using the Westerbork Synthesis Radio Telescope at four frequencies, over the interval 1.4–8.4 GHz, have provided us with the first broad-band radio spectrum of a 'quiescent' stellar mass black hole. The measured mean flux density is of 0.35 mJy, with a spectral index $\alpha = +0.09 \pm 0.19$ (such that $S_\nu \propto \nu^\alpha$). Synchrotron emission from an inhomogeneous partially self-absorbed outflow of plasma accounts for the flat/inverted radio spectrum, in analogy with hard-state black hole X-ray binaries, indicating that a steady jet is being produced between a few 10^{-6} and a few per cent of the Eddington X-ray luminosity.

Key words: binaries: general – stars: individual: V404 Cyg – ISM: jets and outflows.

1 INTRODUCTION

While accreting gas at relatively low rates, black hole candidates in X-ray binary (BHXB) systems are able to power steady, collimated outflows of energy and material, oriented roughly perpendicular to the orbital plane. The jet interpretation of the radio emission from hard-state BHXBs came before the collimated structures were actually resolved using Very Long Based Interferometry (VLBI) techniques. In a seminal work, Blandford & Königl (1979) proposed a model to interpret the flat radio spectrum of extragalactic compact radio sources in terms of isothermal, conical outflows, or jets. A jet model for X-ray binaries was later developed by Hjellming & Johnston (1988), in order to explain both the steady radio emission with flat/inverted spectra observed in the hard state of BHXBs, and transient outbursts with optically thin synchrotron spectra. We refer the reader to McClintock & Remillard (2004) and Fender (2004) for comprehensive reviews on X-ray states and radio properties (respectively) of BHXBs. High-resolution maps of Cyg X-1 in the hard X-ray state have confirmed the jet interpretation of the flat radio–millimetre spectrum (Fender et al. 2001), imaging an extended, collimated structure on a milliarcsec scale (Stirling et al. 2001). Further indications for the existence of collimated outflows in the hard state of BHXBs come from the stability in the orientation of the electric vector in the radio polarization maps of GX 339–4 over a 2-yr period (Corbel et al. 2000). This constant position angle, being the same as the sky position angle of the large-scale, optically thin radio jet powered by GX 339–4 after its 2002 outburst (Gallo et al. 2004), clearly indicates a favoured ejection axis in the system. Finally, the optically thick milliarcsec-scale jet of the (somewhat peculiar) BH candidate GRS 1915+105 (Dhawan, Mirabel & Rodrí 2000) in the plateau state (Klein-Wolt et al. 2002) supports the association of hard X-ray states of BHXBs with steady, partially self-absorbed jets.

Having established this association, a natural question arises: what are the required conditions for a steady jet to exist? We wonder especially whether the jet survives in the very low-luminosity, *quiescent* X-ray state. While radio emission from BHXBs in the thermal dominant (or high–soft) state is suppressed by up to a factor of ∼50 with respect to the hard state (e.g. Fender et al. 1999; Corbel et al. 2001 and references therein), most likely corresponding to the physical disappearance of the jet, little is known concerning the radio behaviour of quiescent stellar mass BHs, mainly due to sensitivity limitations. Among the very few systems detected in the radio range is V404 Cygni, which we shall briefly introduce in the next Section.

1.1 V404 Cyg (=GS 2023+338)

The X-ray binary system V404 Cyg is thought to host a strong BH candidate, with a most probable mass of $\sim 12\,M_\odot$ (Shahbaz et al. 1994), and a low-mass K0IV companion star, with an orbital period of 6.5 d and orbital inclination to the line of sight of approximately 56° (Casares & Charles 1994; Shahbaz et al. 1994). Following the decay of the 1989 outburst that led to its discovery (Makino et al. 1989), the system entered a quiescent X-ray state, in which it has remained ever since. The relatively high quiescent X-ray luminosity of V404 Cyg [with an *average* value of approximately $6 \times 10^{33} \times (D/4\ \mathrm{kpc})^2$ erg s^{-1} in the range 0.3–7.0 keV; Garcia et al. 2001; Kong et al. 2002; Hynes et al. 2004] is possibly related to the long orbital period and surely indicates that the some accretion continues to take place at $L_X \simeq 4 \times 10^{-6}\,L_{\mathrm{Edd}}$, where L_{Edd} is the Eddington X-ray luminosity (for a 12-$M_\odot$ BH).

As reported by Hjellming et al. (2000), since (at least) early 1999 the system has been associated with a variable radio source with flux density ranging from 0.1 to 0.8 mJy on time-scales of days and it is known to vary at optical (Wagner et al. 1992; Casares et al.

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1993; Pavlenko et al. 1996; Hynes et al. 2002; Shahbaz et al. 2003; Zurita, Casares & Shahbaz 2003) and X-ray wavelengths (Wagner et al. 1994; Kong et al. 2002; Hynes et al. 2004, for a coordinated variability study) as well. Yet no *broad-band* radio spectrum of V404 Cyg in quiescence, nor of any other stellar mass BH below $10^{-5}\,L_{\rm Edd}$, is available in the literature to date (see Corbel et al. 2000, for a two-frequency radio spectrum of GX 339–4 at $\sim10^{-5}\,L_{\rm Edd}$). Given the quite large degree of uncertainty concerning the overall structure of the accretion flow in quiescence (e.g. Narayan, Mahadevan & Quataert 1998 for a review), it has even been speculated that the total power output of a quiescent BH could be dominated by a radiatively inefficient outflow (Fender, Gallo & Jonker 2003) rather than by the local dissipation of gravitational energy in the accretion flow. It is therefore of primary importance to establish the nature of radio emission from quiescent BHXBs. In this brief paper we show that the radio properties of V404 Cyg closely resemble those of a canonical hard-state BH, suggesting that there is no fundamental difference in terms of radio behaviour between the quiescent and the canonical hard X-ray state. A comprehensive study of the spectral energy distribution of V404 Cyg in quiescence, from radio to X-rays, will be presented elsewhere (Hynes et al., in preparation).

2 RADIO EMISSION FROM V404 CYG

2.1 WSRT observations

The Westerbork Synthesis Radio Telescope (WSRT) is an aperture synthesis interferometer that consists of a linear array of 14 dish-shaped antennas arranged on a 2.7 km east–west line. V404 Cyg was observed by the WSRT at two epochs: (i) on 2001 December 28, start time 05:28 UT (MJD 522 71.3), at 4.9 GHz (6 cm) and 8.4 GHz (3 cm), for 8 h at each frequency; observations were performed with the (old) digital continuum backend (DCB), using eight channels and four polarizations; (ii) on 2002 December 29, start time 06:29 UT (MJD 526 37.3), at 1.4 GHz (21 cm), 2.3 GHz (13 cm), 4.9 GHz (6 cm) and 8.4 GHz (3 cm) for a total of 24 h. Frequency switching between 8.4–2.3 and 4.9–1.3 GHz was operated every 30 min over the two 12-h runs, resulting in ∼5.5 h on the target and ∼0.5 h on the calibration sources (3C 286 and 3C 48) at each frequency. During this set of observations, the WSRT was equipped with the digital z = last backend (DZB) using eight intermediate-to-video conversion (IVC) subbands of 20-MHz bandwidth, 64 channels and four polarizations. Seven out of the eight subbands were employed to reconstruct the images, as the subband IVC-IF6 failed to detect any signal other than noise over the whole 24-h period. The telescope operated in its *max-short* configuration, which is particularly well suited for observations shorter than a full 12-h synthesis, and with a minimum baseline of 36 m (see http://www.astron.nl/wsrt/wsrtGuide/ for further details). The data reduction, consisting of editing, calibrating and Fourier transforming the (u, v)-data on the image plane, has been performed using the Multichannel Image Reconstruction Image Analysis and Display (MIRIAD) software (Sault & Killeen 1998). The 1.4- and 2.3-GHz data, containing several sources with flux density well above 100 mJy, were self-calibrated in phase.

2.2 Results: spectrum and variability

2.2.1 2001 December 28 (MJD 522 71.3)

An unresolved (beam size of $\sim5.8 \times 3.0$ arcsec^2 at 8.4 GHz) ∼0.50-mJy radio source is detected at both 4.9 and 8.4 GHz, at a position consistent with that of V404 Cyg [α(J2000) = 20$^{\rm h}$ 24$^{\rm m}$ 03$^{\rm s}$.78; δ(J2000) = +33° 52′ 03″.2; e.g. Downes et al. 2001]. Table 1 lists the measured flux densities with errors at each frequency; the corresponding spectral index (hereafter defined as $\alpha = \Delta \log S_\nu / \Delta \log \nu$, such that $S_\nu \propto \nu^\alpha$) is 0.04 ± 0.68; such a large error bar is mainly due to the high noise in the 8.4-GHz map (see Table 1). The signal-to-noise ratios are too low to measure linearly polarized flux from the source at the expected level of a few per cent, assuming a synchrotron origin for the radio emission (see Section 3).

Table 1. WSRT observations of V404 Cyg.

Date	ν (GHz)	S_ν (mJy)	S/N ratio
2001-12-28	4.9	0.49 ± 0.04	12.2
(MJD 522 71.3)	8.4	0.50 ± 0.20	2.5
2002-12-29	1.4	0.34 ± 0.08	4.2
(MJD 526 37.3)	2.4	0.33 ± 0.07	4.7
	4.9	0.38 ± 0.05	7.6
	8.4	0.36 ± 0.15	2.4

2.2.2 2002 December 29 (MJD 526 37.3)

V404 Cyg is detected at four frequencies with a mean flux density of 0.35 mJy; flux densities at each frequency are listed in Table 1. The fitted four-frequency spectral index is $\alpha = 0.09 \pm 0.19$. Radio contours as measured at 4.9 GHz are plotted in Fig. 1, while Fig. 2 shows the radio spectra of V404 Cyg at two epochs.

Since returning to quiescence, V404 Cyg is known to vary on time-scales of days, or even shorter, both in the radio and in the X-ray ranges; such variability is actually detected in our 2002 WSRT observations. The low flux of V404 Cyg makes it practically impossible to subtract from the (u, v)-data all the other radio sources in the field and generate a reliable light curve of the target. We thus divided each of the two ∼11-h data sets on-source into time intervals of ∼5.5 h (of which only ∼2.75 h is on-source per frequency, due to the frequency switching) and made maps of each time interval.

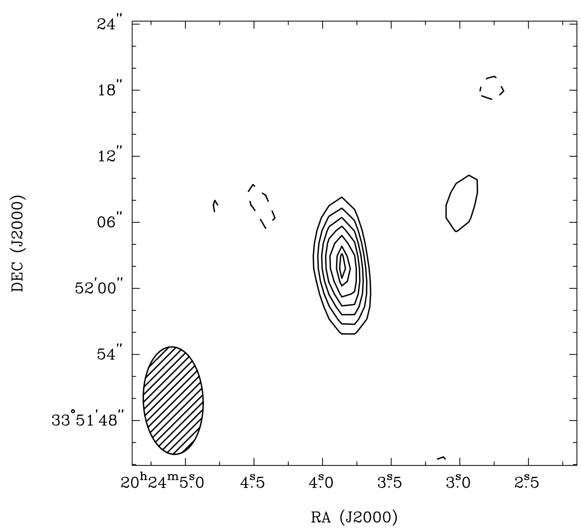

Figure 1. Naturally weighted contour map of V404 Cyg as observed by Westerbork at 4.9 GHz on 2002 December 29 (MJD 526 37.3); contour levels are at −3, 3, 4, 5, 6, 7, 8 times the rms noise level of 0.05 mJy; the synthesized beam is shown in the bottom left-hand corner.

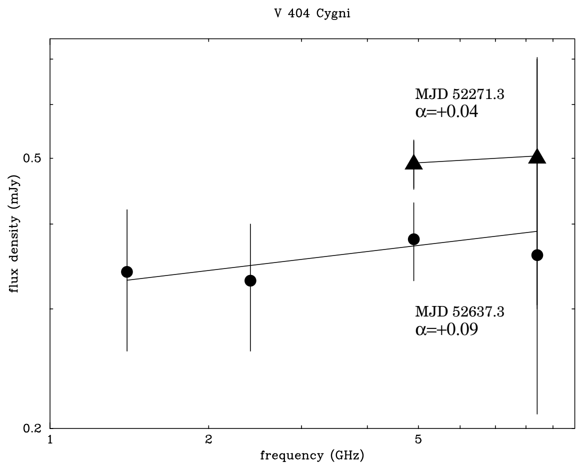

Figure 2. The radio spectrum of V404 Cyg as measured by the WSRT on 2001 December 28 (MJD 522 71.3) and 2002 December 29 (MJD 526 37.3); flux densities are listed in Table 1.

Significant variability (checked against other bright sources in the field) is detected at 4.9 GHz: the flux density varied from 0.27 ± 0.07 mJy in the first half of the observation and to 0.47 ± 0.07 in the second half.

3 DISCUSSION

As mentioned in the introduction, synchrotron radiation from a relativistic outflow accounts for the observed flat radio spectra of *hard*-state BHXBs; we refer the interested reader to more thorough discussions in, for example, Hjellming & Han (1995), Mirabel & Rodríguez (1999) and Fender (2001, 2004). Here we note that the *collimated* nature of these outflows is more debated, as it requires direct imaging to be proven. Even though confirmations come from Very Long Based Array (VLBA) observations of Cyg X-1 (Stirling et al. 2001) and GRS 1915+105 (Dhawan et al. 2000; Fuchs et al. 2003) in hard states, failure to image a collimated structure in the hard state of XTE J1118+480 down to a synthesized beam of 0.6 × 1.0 mas^2 at 8.4 GHz (Mirabel et al. 2001) may challenge the jet interpretation (Fender et al. 2001). However, apart from GRS 1915+105, which is persistently close to the Eddington rate (see Fender & Belloni 2004 for a review), Cyg X-1 in the hard state displays a 0.1–200 keV luminosity of 2 per cent $L_{\rm Edd}$ (Di Salvo et al. 2001), while XTE J1118+408 was observed at a level of roughly one order of magnitude lower (e.g. Esin et al. 2001). If the jet size scaled as the radiated power, we would expect the jet of XTE J1118+408 to be roughly 10 times smaller than that of Cyg X-1 (which is 2 × 6 mas^2 at 9 GHz, at approximately the same distance), and thus still be point-like in the VLBA maps presented by Mirabel et al. (2001).

Garcia et al. (2003) have pointed out that long-period ($\gtrsim$1 d) BHXBs undergoing outbursts tend to be associated with spatially resolved optically thin radio ejections, while short-period systems would be associated with unresolved, and hence physically smaller, radio ejections. If a common production mechanism is at work in optically thick and optically thin BHXB jets (Fender, Belloni & Gallo 2004), the above arguments should apply to steady optically thick jets as well, providing an alternative explanation to the unresolved radio emission of XTE J1118+480, with its 4-h orbital period, the shortest known for a BHXB. It is worth mentioning that, by analogy, a long-period system, such as V404 Cyg, might be expected to have a relatively larger optically thick jet.

3.1 A synchrotron emitting outflow in the quiescent state of V404 Cyg

3.1.1 Emission mechanism

The WSRT observations of V404 Cyg performed on 2002 December 29 provide us with the first broad-band (1.4–8.4 GHz) radio spectrum of a stellar mass BH candidate below $10^{-5}\,L_{\rm Edd}$. As we do not have direct evidence (no linear polarization measurement, no especially high brightness temperature, see below) for the synchrotron origin of the radio emission from V404 Cyg in quiescence, we must first briefly explore different mechanisms, such as free–free emission from an ionized plasma. The donor in V404 Cyg is a K0IV star with a most probable mass of 0.7 $M_{\odot}$ and a temperature of around 4300 K (Casares & Charles 1994; Shahbaz et al. 1994), which is simply too cool to produce any observable free–free radio emission (see Wright & Barlow 1975). Alternatively, the accretion flow on to the compact object may provide the needed mass-loss rates and temperatures in order to produce a flat/inverted free–free radio spectrum. In (line- and radiation-driven) disc wind models, global properties such as the total mass-loss rate and wind terminal velocity depend mainly on the system luminosity (see, e.g., Proga & Kallman 2002; Proga, Stone & Drew 1998 and references therein); very high accretion rates are required in order to sustain significant mass-loss rates and hence observable wind emission, ruling out a disc wind origin for the observed radio flux from V404 Cyg. However, that mass loss via winds in sub-Eddington, radiatively inefficient accretion flows (ADAFs) may be both dynamically crucial and quite substantial, has been pointed out by Blandford & Begelman (1999). Quataert & Narayan (1999) calculated the spectra of such advection-dominated inflows taking into account wind losses, and found that the observations of three quiescent black holes, including V404 Cyg, are actually consistent with at least 90 per cent of the mass originating at large radii being lost to a wind. Under the rough assumption that models developed for ionized stellar winds (e.g. Wright & Barlow 1975; Reynolds 1986; see Dhawan et al. 2000 for an application to the steady jet of GRS 1915+105) might provide an order of magnitude estimate of the mass-loss rate even for such 'advection-driven' winds, the required mass-loss rate in order to sustain the observed radio emission for a *fully ionized* hydrogen plasma is still close to the Eddington accretion rate for a 12-$M_{\odot}$ BH (assuming 10 per cent efficiency in converting mass into light). Lower ionization parameters would further increase the required mass loss, bringing it to super-Eddington rates. Even taking into account geometrical effects, such as wind collimation and/or clumpiness, the required mass-loss rates cannot be more than three orders of magnitude below the spherical homogeneous wind, i.e. still far too high for a $\lesssim 10^{-5}$ Eddington BH to produce any observable radio emission. As free–free emission does not appear to be a viable alternative, we are led to the conclusion that the radio spectrum of V404 Cyg in quiescence is likely to be synchrotron in origin. This conclusion is supported by polarization measurements during the second phase (following a bright optically thin event) of the 1989 radio outburst of V404 Cyg, when a slow-decay, optically thick component had developed (Han & Hjellming 1992). At this time, after 1989 June 1–3, V404 Cyg displayed the same flat/inverted spectrum of the present 2002 WSRT observations, but was at a few mJy level, still high enough to allow the detection of a linearly polarized flux, which confirmed the synchrotron nature of the emission. In addition, the roughly constant and similar polarization angles measured at that time, indicated that the averaged magnetic field orientation changed very little, if at all. As V404 Cyg entered a quiescent regime following the decay of that outburst (it reached the typical quiescent flux densities approximately 1 yr after the outburst peak), it seems reasonable to assume that the present ~0.5-mJy radio emission with a flat/inverted spectrum is of the same nature as the few mJy flat/inverted spectrum component detected in 1989, and therefore is synchrotron in origin.

A further argument for the *jet* interpretation of this synchrotron emission is the fact that the radio and X-ray fluxes of V404 Cyg over the decline of its 1989 outburst *and* at its current quiescent X-ray and radio luminosities, display the same non-linear correlation found to hold for the whole hard state of BHXBs (Corbel et al. 2003; Gallo, Fender & Pooley 2003) and later extended to super-massive nuclei in active nuclei as well (Merloni, Heinz & Di Matteo 2003; Falcke, Körding & Markoff 2004), where there is little doubt concerning the jet origin of the radio emission.

3.1.2 *Angular size*

The maximum brightness temperature for a galactic incoherent synchrotron source is a (weak) function of the measured spectral index, the upper frequency $\nu_{\rm up}$ of the synchrotron spectrum and the Doppler boosting factor D (e.g. Hughes & Miller 1991). For $\alpha = 0.1$ and $\nu_{\rm up} = 8.4$ GHz, as in the case presented here, $T_{\rm b} \lesssim 10^{12} \times D^{1.2}$ K at 1.4 GHz. With an orbital inclination of 56°, the Doppler boosting factor is likely to vary in the range $D = 1$ –1.1, calculated for bulk Lorentz factors of between 1 and 1.7. Assuming a distance to V404 Cyg of 4 kpc (Jonker & Nelemans 2004 and references therein), we can thus derive a minimum linear size for the (1.4-GHz) emitting region of $\sim 5 \times 10^{11}$ cm, or $\sim 7\,{\rm R}_\odot$. This corresponds to approximately one-fifth of the system orbital separation (Shahbaz et al. 1994). For comparison, the highest *measured* brightness temperature in a Galactic binary system is of a few 10^{11} K at 5 GHz, during a flaring event in Cyg X-3 (Ogley et al. 2001).

Because of limits on the signal propagation speed, the 5.5-h time-scale variability detected at 4.9 GHz gives an upper limit to the linear size L of the variable region: $L < 5.9 \times 10^{14}$ cm, or approximately 8530 ${\rm R}_\odot$. At a distance of 4 kpc, this translates into an angular extent $\theta \lesssim 10$ mas at 4.9 GHz (see Table 2). Within the framework of standard conical jet models (Blandford & Königl 1979; Hjellming & Johnston 1988; Falcke & Biermann 1996), flux variability could be induced by, for example, the propagation of shocks within the compact outflow. These shocks will not be visible until they reach the point along the outflow where it becomes optically thin at the observing frequency. The actual morphology of the radio source will depend on the ratio between the thickness Δr of the region where the variability occurs (the lower the observing frequency, the higher the thickness will be) and its distance R from the core. If $R \gg \Delta r$, we would expect a double radio source with flux ratios depending on Doppler boosting, while if $R \simeq \Delta r$, then we would expect to observe a continuous elongated structure. The ratio $\Delta r/R$ is unknown in the case of V404 Cyg and could only be determined by measuring *delays* between different frequencies. For comparison, the average flux rise time in the oscillations of the flat spectrum radio component in GRS 1915+105 is of approximately a few minutes, while the infrared–radio delays are typically of 15 min, indicating that the variable radio source should not be too distant from the core (Mirabel et al. 1998; Fender et al. 2002 and references therein). Combined with the extended core morphology of both Cyg X-1 (Stirling et al. 2001) and the core of GRS 1915+105 (Dhawan et al. 2000; Fuchs et al. 2003), this suggests that $R \simeq \Delta r$ in these two sources, but it is not clear how the outflow properties might scale with the luminosity.

Table 2. Constraints on the size L of the radio emission region in V404 Cyg; a distance of 4 kpc is adopted (Jonker & Nelemans 2004).

Requirement	Frequency (GHz)	Size (cm)	Size (${\rm R}_\odot$)	Size (mas)
$T_{\rm b} < 10^{12}$ K	1.4	$\gtrsim 5 \times 10^{11}$	$\gtrsim 7$	$\gtrsim 0.01$
$L < c\,\Delta t$	4.9	$\lesssim 6 \times 10^{14}$	$\lesssim 8530$	$\lesssim 10$

Han & Hjellming (1992), based on the same arguments, were able to constrain the linear size of the optically *thin* ejection associated with the fast-decay phase in the radio light curve of the 1989 outburst: from the 5-min time-scale variability measured on 1989 June 1, and from brightness temperature limits, they derived $\theta \simeq 0.2$ mas. Fluctuations on time-scales of tens of minutes were later measured during the slow-decay phase, when an optically thick component had developed, and interpreted as possible hot shocks propagating downstream is an underlying compact jet. By analogy, this would also appear to be a reasonable explanation for the 5-h time-scale variability detected in our WSRT observations.

4 SUMMARY

WSRT observations of V404 Cyg performed on 2002 December 29 (MJD 526 37.3) at four frequencies over the interval 1.4–8.4 GHz have provided us with the first broad-band radio spectrum of a quiescent (with an average $L_{\rm X}$ of a few $10^{-6}\,L_{\rm Edd}$) stellar mass BHXB. We measured a mean flux density of 0.35 mJy, and a flat/inverted spectral index $\alpha = 0.09 \pm 0.19$. WSRT observations performed 1 yr earlier, at 4.9 and 8.4 GHz, resulted in a mean flux density of 0.5 mJy, confirming the relatively stable level of radio emission from V404 Cyg on a year time-scale; even though the spectral index was not well constrained at that time, the measured value was consistent with the later one.

Synchrotron emission from an inhomogeneous, optically thick relativistic outflow of plasma seems to be the most likely explanation for the flat radio spectrum, in analogy with hard-state BHXBs (Fender 2001). Optically thin free–free emission as an alternative explanation is ruled out on the basis that far too high mass-loss rates would be required, either from the companion star or from the inflow of plasma to the accretor. The collimated nature of this outflow remains to be proven; based on brightness temperature arguments and the 5.5-h time-scale variability detected at 4.9 GHz, we conclude that the angular extent of the radio source is constrained between 0.01 at 1.4 GHz and 10 mas at 4.9 GHz (at a distance of 4 kpc; Jonker & Nelemans 2004). In the context of standard self-absorbed jet models, the flux variability may be due to shocks or clouds propagating in an inhomogeneous jet.

If our interpretation is correct, a compact steady jet is being produced by BHXBs between a few 10^{-6} and $\sim 10^{-2}$ times the Eddington luminosity, supporting the notion of quiescence as a low-luminosity level of the standard hard state. However, as V404 Cyg is the most luminous quiescent BHXB known to date, the existence of a steady jet in this system does not automatically extend to the whole quiescent state of stellar mass BHs. Sensitive radio observations of the nearby, truly quiescent system A0620–00 (three orders of magnitude less luminous than V404 Cyg in the X-ray range; e.g. Kong et al. 2002), will hopefully provide an answer concerning the ubiquity of compact jets from stellar mass black holes with a hard spectrum.

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