The radio spectrum of a quiescent stellar mass black hole

E. Gallo\textsuperscript{1}, R. P. Fender\textsuperscript{1⋆}, R. I. Hynes\textsuperscript{2†}

\textsuperscript{1}Astronomical Institute ‘Anton Pannekoek’, University of Amsterdam, and Center for High Energy Astrophysics, Kruislaan 403, 1098 SJ Amsterdam, The Netherlands
\textsuperscript{2}McDonald Observatory and Department of Astronomy, The University of Texas at Austin, 1 University Station C1400, Austin, Texas 78712, USA

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 with 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-mm spectrum (Fender et al. 2001), imaging an extended, collimated structure on milliarcsecond 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 two year 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 milliarcsecond scale jet of the (somewhat peculiar) BH candidate GRS 1915+105 (Dhawan, Mirabel & Rodríguez 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 up to a factor \textasciitilde50 with respect to the hard state (\textit{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 about the radio behaviour of quiescent stellar mass BHs, mainly due to sensitivity limitations. Among the very few systems detected in radio is V404 Cygni, which we shall briefly introduce in the next Section.

1.1 V404 Cyg (\textit{\textsuperscript{=}}GS 2023+338)

The X-ray binary system V404 Cyg is thought to host a strong BH candidate, with a most probable mass of \textasciitilde12 M\odot (Shahbaz et al. 1994), and a low mass KOIV companion star, with orbital period of 6.5 days, and orbital inclination to the line of sight is of about 56° (Casares & Charles 1994; Shahbaz 1994). Following the decay of the 1989 outburst that led to its discovery (Makino 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 about \textasciitilde6 \times 10\textsuperscript{34} \times (D/4 \text{kpc})\textsuperscript{2} erg sec\textsuperscript{−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

⋆ Present address: School of Physics and Astronomy, University of Southampton, Hampshire SO17 1BJ, United Kingdom
† Present address: Louisiana State University, Department of Physics and Astronomy, Baton Rouge, LA 70803-4001, USA
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take place at $L_X \approx 4 \times 10^{-6}L_{\text{Edd}}$, where $L_{\text{Edd}}$ 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. 1993; Pavlenko et al. 1996; Hynes et al. 2002; Shahbaz et al. 2003; Zurita et al. 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 broadband radio spectrum of V404 Cyg in quiescence, nor of any other stellar mass BH below $10^{-5}L_{\text{Edd}}$, is available in the literature to date (see Corbel et al. 2000 for a 2-frequency radio spectrum of GX 339-4 at $\sim 10^{-5}L_{\text{Edd}}$). Given the quite large degree of uncertainty about the overall structure of the accretion flow in quiescence (e.g. Narayan, Mahadevan & Quataert 1999 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 antennae 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 52271.3), at 4.9 GHz (6 cm) and 8.4 GHz (3 cm), for 8 hours at each frequency; observations were performed with the (old) DCB backend, using 8 channels and 4 polarizations; ii) on 2002 December 29, start time 06:29 UT (MJD 52637.3), 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 hours. Frequency switching between 8.4–2.3 GHz and 4.9–1.3 GHz was operated every 30 minutes over the two 12 hour runs, resulting in $\sim 5.5$ hour on the target and $\sim 0.5$ hour on the calibration sources (3C 286 and 3C 48) at each frequency. During this set of observations, the WSRT was equipped with the DZB backend using eight IVC sub-bands of 20 MHz bandwidth, 64 channels and 4 polarizations. Seven out of the eight sub-bands were employed to reconstruct the images, as the sub-band IVC-IF6 failed to detect any signal other than noise over the whole 24 hour period. The telescope operated in its max-short configuration, particularly well suited for observations shorter than a full 12 hour 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 with the MIRIAD (Multichannel Image Reconstruction Image Analysis and Display) 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.

Figure 1. Naturally weighted contour map of V404 Cyg as observed by Westerbork at 4.9 GHz on 2002 December 29 (MJD 52637.3); contour levels are at $\sim -3,4,5,6,7,8$ times the rms noise level of 0.05 mJy; the synthesized beam is shown on the bottom left corner.

| date          | $\nu$ (GHz) | $S_\nu$ (mJy) | $S/N$ |
|---------------|-------------|---------------|-------|
| 2001-12-28    | 4.9         | 0.49 $\pm$ 0.04 | 12.2  |
| (MJD 52271.3) |             |               |       |
| 2002-12-29    | 1.4         | 0.34 $\pm$ 0.08 | 4.2   |
| (MJD 52637.3) | 2.4         | 0.33 $\pm$ 0.07 | 4.7   |
|               | 4.9         | 0.38 $\pm$ 0.05 | 7.6   |
|               | 8.4         | 0.36 $\pm$ 0.15 | 2.4   |

2.2 Results: spectrum and variability

2.2.1 2001 December 28 (MJD 52271.3)

An unresolved (beam size of $\sim 5.8 \times 3.0$ arcsec$^2$ at 8.4 GHz) $\sim 0.50$ mJy radio source is detected at both 4.9 and 8.4 GHz, at the position consistent with that of V404 Cyg ($\alpha$(J2000) = 20:24:03.78; $\delta$(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 of 0.04$\pm$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/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).

2.2.2 2002 December 29 (MJD 52637.3)

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 Figure 1, while Figure 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 radio and in X-rays;
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-hour data sets on-source in time intervals of ~5.5 hours (of which only ~2.75 hours on source per frequency, due to the frequency switching) and made maps of each time interval. Significant variability (checked against other bright sources in the field) is detected at 4.9 GHz: the flux density varied from 0.27\pm0.07 mJy in the first half of the observation, to 0.47\pm0.07 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 thorough discussions in e.g. Hjellming & Han (1995), Mirabel & Rodríguez (1999) and Fender (2001; 2004). Here we shall 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 Baseline Array (VLBA) observations of Cyg X-1 (Stirling et al. 2001) and GR S 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\times1.0 mas\(^2\) at 8.4 GHz (Mirabel et al. 2001) may challenge the jet interpretation (Fender et al. 2001). However, apart from GR S 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 \(L_{\text{Edd}}\) (Di Salvo et al. 2001), while XTE J1118+408 was observed at roughly one order of magnitude lower level (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 ten times smaller than that of Cyg X-1 (which is \(2\times6\) mas\(^2\) at 9 GHz, at about the same distance), and thus still point-like in the VLBA maps presented by Mirabel et al. (2001).

Garcia et al. (2003) have pointed out that long period (\(\gtrsim 1\) day) BHXBs undergoing outbursts tend to be associated with spatially resolved optically thin radio emissions, while short period systems would be associated with unresolved, and hence physically smaller, radio jets. 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 hour orbital period, the shortest known for a BHXB. It is worth mentioning that, by analogy, a long period system, like 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 broadband (1.4–8.4 GHz) radio spectrum of a stellar mass BH candidate below 10\(^{-5}\)\(L_{\text{Edd}}\). 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 ionised plasma. The donor in V404 Cyg is a KOIV star with most probable mass of 0.7 \(M_{\odot}\) and temperature around 4300 K (Casares & Charles 1994; Shahbaz et al. 1994), simply too cool to produce any observable free-free radio emission (see Wright & Barlow 1975). Alternatively, the accretion flow onto 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 to be lost to a wind. Under the rough assumption that models developed for ionised stellar winds (e.g. Wright & Barlow 1975, Reynolds 1986; see Dhawan et al. 2000 for an application to the steady jet of GR S 1915+105) might provide an order of magnitude estimate of the mass loss rate even for such "advection-driven" winds, still the required mass loss rate in order to sustain the observed radio emission for a fully ionised hydrogen plasma is close the Eddington accretion rate for a 12 \(M_{\odot}\) BH (assuming a 10 per cent efficiency in converting mass into light). Lower ionisation parameters would further increase the needed 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 can not 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
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) | R⊙ | mas |
|-------------|----------------|-----------|-----|-----|
| T_b < 10^{12} K | 1.4 | $\gtrsim 5 \times 10^{11}$ | $\gtrsim 7$ | $\gtrsim 0.01$ |
| L < c $\Delta t$ | 4.9 | $\lesssim 6 \times 10^{14}$ | $\lesssim 8530$ | $\lesssim 10$ |

4 SUMMARY

WSRT observations of V404 Cyg performed on 2002 December 29 (MJD 52637.3) at four frequencies over the interval 1.4–8.4 GHz have provided us with the first broadband radio spectrum of a quiescent (with average $L_X$ of a few $10^{-6}L_{Edd}$) 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 one year 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 mass loss rates far too high 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-hour time-scale variability detected at 4.9 GHz, we can 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 X-rays; e.g. Kong et al. 2002), will hopefully provide an answer about the ubiquity of compact jets from stellar mass black holes with a hard spectrum.

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