

A weak compact jet in a soft state of Cygnus X-1

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ABSTRACT

We present evidence for the presence of a weak compact jet during a soft X-ray state of Cygnus X-1. Very-high-resolution radio observations were taken with the VLBA, EVN and MERLIN during a hard-to-soft spectral state change, showing the hard state jet to be suppressed by a factor of about 3–5 in radio flux and unresolved to direct imaging observations (i.e. $\lesssim 1$ mas at 4 cm). High time-resolution X-ray observations with the *RXTE*-PCA were also taken during the radio monitoring period, showing the source to make the transition from the hard state to a softer state (via an intermediate state), although the source may never have reached the canonical soft state. Using astrometric very long baseline interferometry (VLBI) analysis and removing proper motion, parallax and orbital motion signatures, the residual positions show a scatter of ~ 0.2 mas (at 4 cm) and ~ 3 mas (at 13 cm) along the position angle of the known jet axis; these residuals suggest that there is a weak unresolved outflow, with varying size or opacity, during intermediate and soft X-ray states. Furthermore, no evidence was found for extended knots or shocks forming within the jet during the state transition, suggesting that the change in outflow rate may not be sufficiently high to produce superluminal knots.

Key words: stars: individual: Cygnus X-1 – ISM: jets and outflows – X-rays: binaries.

1 INTRODUCTION

The outflow of highly collimated jets appears to be a universal aspect of accreting black holes (BH), from stellar-mass X-ray binaries (XRBs) to supermassive active galactic nuclei. Galactic XRBs are at the low end of this mass range, and due to their relative proximity and rapid changes in mass accretion rate (\dot{m}), their outburst cycles can be well observed over a few weeks. Therefore, understanding the disc–jet relationship in each of the characteristic accretion states

of an XRB is of critical importance in developing a universal (scale invariant) relationship holding over all BH masses.

BH XRBs broadly accrete in two states that are classified according to their X-ray spectra, although many intermediate states have also been identified. *Soft X-ray states* are seen only at high X-ray luminosities ($\gtrsim 1$ per cent L_{edd}) dominated by a thermal X-ray component, and are associated with weak radio emission. *Hard X-ray states* can show all luminosities for $1 \gtrsim L/L_{\text{edd}} \gtrsim 10^{-8}$ and are dominated by a power-law component extending to ~ 100 keV; this state is also associated with relatively strong, flat-spectrum radio emission. Compact jets are normally inferred from the flat spectrum, although only two BH XRBs have shown resolved jets [using very long baseline interferometry (VLBI) imaging] during hard states:

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Table 1. Details of the radio observations of Cygnus X-1 taken in 2010 July. Orbital phase is defined as the superior conjunction of the black hole (using the ephemeris in Brocksopp et al. 1999).

VLBI obs.	Epoch (MJD)	Orbital phase	Start (UT)	End (UT)	Array	λ (cm)	I_{total} (mJy)	Noise ($\mu\text{Jy beam}^{-1}$)	$\theta_{\text{maj}} \times \theta_{\text{min}}$ (mas)	PA ($^{\circ}$)
	55 380.1	0.840	02–19:38	03–09:28	MERLIN	6	5.5 ± 0.2	114	59.9×40.5	28
	55 381.0	0.001	03–16:30	04–09:28	MERLIN	6	5.3 ± 0.2	122	50.9×43.7	5
	55 382.0	0.179	04–16:31	05–09:28	MERLIN	6	10.4 ± 0.2	124	51.5×43.7	7
	55 383.1	0.376	05–17:30	06–09:20	MERLIN	6	6.5 ± 0.2	113	58×50	27
0	55 386.0	0.893	08–18:32	09–05:39	e-EVN	6	15.2 ± 0.1	116	13.8×9.6	–70
	55 387.3	0.126	09–20:39	10–09:28	MERLIN	4	6.7 ± 0.2	106	88×38	–25
	55 388.0	0.251	10–16:30	11–09:28	MERLIN	4	2.3 ± 0.3	148	136×82	–4
1	55 388.0	0.251	10–18:17	11–05:24	e-EVN	6	5.0 ± 0.1	97	13.6×7.8	–73
	55 388.8	0.394	11–16:31	11–21:23	MERLIN	4	2.4 ± 0.2	132	130×80.0	–20
2	55 389.4	0.501	12–08:45	12–11:15	VLBA	4	5.9 ± 0.2	155	2.2×0.8	–23
						13	5.3 ± 0.2	184	9.8×8.1	32
3	55 392.4	0.037	15–06:28	15–11:33	VLBA	4	3.8 ± 0.1	104	2.0×0.7	–16
						13	5.2 ± 0.2	157	15.0×8.0	–34
4	55 394.4	0.394	17–06:23	17–11:33	VLBA	4	3.1 ± 0.1	102	2.1×0.7	–18
						13	3.1 ± 0.2	172	15.1×7.9	–35
5	55 396.4	0.751	19–06:27	19–11:34	VLBA	4	1.4 ± 0.1	95	2.1×0.7	–20
						13	1.2 ± 0.2	159	15.4×8.0	–36
6	55 399.4	0.287	22–06:25	22–11:33	VLBA	4	2.7 ± 0.1	99	1.9×0.7	–16
						13	5.7 ± 0.2	206	20.0×7.3	45
	55 400.1	0.412	23–00:30	23–05:30	WSRT	6	3.2 ± 0.2	50	$16\,000 \times 6000$	–36

GRS 1915+105 (Dhawan, Mirabel & Rodríguez 2000) and Cygnus X-1 (Stirling et al. 2001).

The exact disc–jet coupling for XRBs is therefore related to the particular accretion state. During hard states, the power-law component is attributed to thermal Comptonization by a hot plasma in an optically thin corona around the inner accretion disc, which acts as a ‘reservoir’ for the jet outflow (Thorne & Price 1975; Bisnovatyi-Kogan & Blinnikov 1976; Sunyaev & Trümper 1979). When the mass accretion rate increases, the disc temperature rises and the bolometric luminosity starts to become dominated by the thermal disc. It has been suggested that the hard-to-soft state transition is also associated with a rapid increase in the jet Lorentz factor, until the position of the source in the X-ray hardness–intensity diagram (HID) crosses the ‘jet-line’ (Fender, Belloni & Gallo 2004), when shocks may be formed within the jet, observed as discrete ejecta propagating away from the system (Vadawale et al. 2003). Once in the soft state, the outflowing material is thought to be quenched and no compact core jets have previously been detected (see observations by Tananbaum et al. 1972; Fender et al. 1999b, and theoretical work by Livio, Ogilvie & Pringle 1999; Meier 2001).

We present a detailed, high-resolution VLBI monitoring campaign of the XRB Cygnus X-1 over a hard-to-soft state transition. This system contains a black hole candidate with a mass of $14.8 \pm 1.0 M_{\odot}$ in a 5.6-d orbit with a supergiant star of mass $19.2 \pm 1.9 M_{\odot}$ (Kemp et al. 1987; Orosz et al. 2011). Mass transfer between the star and compact object occurs via a focused stellar wind from the supergiant. During the hard state, Stirling et al. (2001) showed that at 8.4 GHz, a ~ 15 mas jet was persistently present to the north-west (NW) of the core over the full binary orbit, with a position angle of $\sim 22^{\circ}$ west of north. More recent VLBI observations in 2009 confirmed that the compact jet was still present with the same orientation (Rushton et al. 2011). Fender et al. (2006) presented evidence that a weak transient knot was produced ~ 50 mas from the core of Cygnus X-1, after the X-ray state crossed a ‘jet-line’ during a hard-to-soft state transition in 2004. However, their

observations were limited by poor uv -coverage. Our aims were to verify the existence of these knots, determine whether the compact jet is completely quenched in the soft state and test the existence of the ‘jet-line’.

2 OBSERVATIONS AND RESULTS

Targeted radio and X-ray observations of Cygnus X-1 were triggered after a series of *Astronomer’s Telegram*¹ reports suggested a hard-to-soft state transition was starting in late 2010 June (e.g. Negoro et al. 2010; Rushton et al. 2010; Sabatini et al. 2010). Table 1 gives a summary of all long baseline radio observations and Fig. 1 shows the radio (AMI-LA, MERLIN, e-EVN, VLBA and WSRT) and X-ray (*RXTE*-ASM and *Swift*-BAT) light curves.

2.1 Radio monitoring

Initial high-resolution radio monitoring was carried out with MERLIN at 6 and 4 cm (between 2010 July 2 and 10) followed by VLBI observations with the EVN (at 6 cm) on 2010 July 8 and 10 in e-VLBI mode (a.k.a. e-EVN); participating e-EVN telescopes were Jodrell Bank MkII, Knockin, Cambridge, Westerbork, Effelsberg, Torun, Yebes, Medicina, Onsala 25-m and Shanghai. Data were transferred from each antenna to the correlator using high-speed dedicated network links, sustaining connection rates of up to 1024 Mbps per antenna, yielding maximum bandwidths of 128 MHz per polarization, with dual polarization. Follow-up VLBA observations were scheduled in the dual 4/13 cm mode, using the long wavelength to probe larger spatial scales. A total of five VLBA epochs were taken, on 2010 July 12, 15, 17, 19 and 22 using all 10 antennas, with a recording rate of 512 Mbps (divided equally between 4 and 13 cm),

¹ Available from www.astronomerstelegram.org

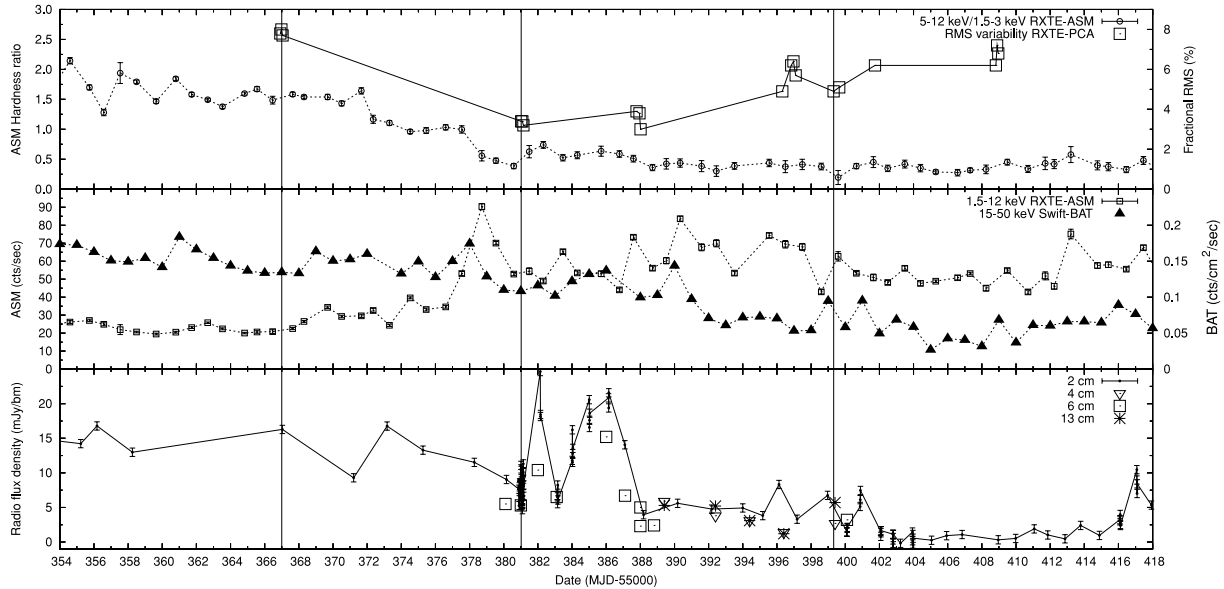


Figure 1. X-ray and radio light curves of Cygnus X-1 over a hard-to-soft state transition during 2010 June/July. From top to bottom: the fractional rms variability of the X-ray emission monitored with the *RXTE*-PCA and the 5–12 keV/1.5–3 keV hardness ratio from the *RXTE*-ASM; total X-ray intensity between 1.5–12 keV and 15–50 keV with the *RXTE*-ASM and *Swift*-BAT respectively; AMI-LA radio flux density at 2 cm, including the epochs and radio flux densities measured by the e-EVN, MERLIN, VLBA and WSRT (at 4, 6 or 13 cm). The solid vertical lines mark the *RXTE*-PCA power spectra shown in Fig. 4.

giving a total bandwidth for each frequency band of 32 MHz per polarization, with dual polarization. All VLBI observations were phase referenced to the calibrator J1953+3537, separated by a distance of 1:1 from the target (1:0 in RA and 0:4 in Dec.). In the last four VLBA observations a geodetic VLBI calibrator block was inserted, in order to improve the astrometric accuracy and image quality of the target source without using self-calibration (see AIPS Memo 110 for more details). Also, we substituted J1957+3338 for every ~ 7 th scan on the target source for a positional check. The VLBA data were correlated using the National Radio Astronomy Observatory (NRAO) implementation of the DiFX software correlator (Deller et al. 2011). All data were reduced using the standard AIPS VLBI algorithms (e.g. VLBAUTIL), using the standard EVN pipeline for initial processing of the e-EVN data. Finally, a single lower resolution observation was taken with the WSRT on 2010 July 23.

All high-resolution radio observations of Cygnus X-1 were found to be unresolved down to the beam size of the respective arrays, showing that the compact core jet was quenched to less than a few milliarcseconds in size. Also, despite clear evidence of a typical X-ray spectral state change (Section 2.2), no evidence for discrete ejecta was found immediately after the transition. Although the source was unresolved, we fitted the position of the centroid of the emission at each epoch and subtracted the estimated contributions of proper motion, parallax and orbital motion (Reid et al. 2011). The residual positions are shown in Fig. 2; estimates of the systematics are $\sim 38 \mu\text{arcsec}$ in RA and $\sim 47 \mu\text{arcsec}$ in Dec. (Pradel, Charlot & Lestrade 2006), which was confirmed by scaling the measured scatter in the check source positions ($39 \mu\text{arcsec}$ in RA and $55 \mu\text{arcsec}$ in Dec. at 4 cm) by the relative distances of the target and check source to the phase reference calibrator. Also note that an error was reported in the AIPS Earth Orientation Parameter (EOP) affecting all VLBI astrometric experiments between 2009 September 21 and 2011 August 4; however, after re-analysing the data with the corrected EOPs we found a positional shift of only $18 \pm 35 \mu\text{arcsec}$ at X-band (i.e. within the error).

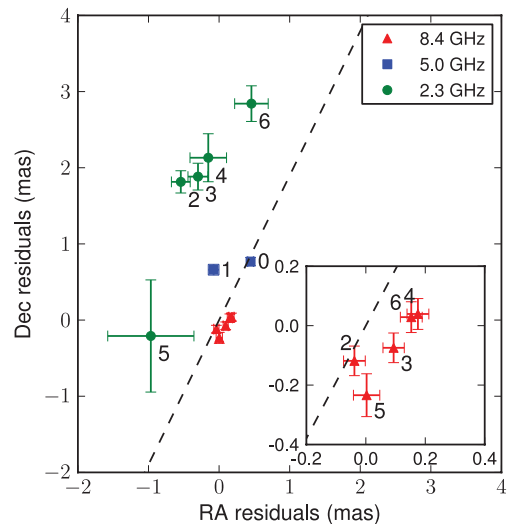


Figure 2. Residual astrometric VLBI positions of Cygnus X-1 in 2010 July, after removing the proper motion, parallax and orbital motion signatures. Note that the longer wavelength positions are systematically offset due to a frequency dependence of the fitted position of the phase reference calibrator. Epochs 0–2 had no geodetic calibration block, possibly causing a slight offset. The inset shows a zoom-in of the 4-cm positions. Numbers indicate the ordering of the 2010 VLBI epochs listed in Table 1. Dashed black line indicates the known jet axis.

At both 4 and 13 cm, the residuals are scattered along an axis which is aligned with the known position angle of the hard state jet (note that epochs 0–2 did not have a geodetic calibration block, possibly causing a slight offset). The positional shift between different frequencies is an artefact caused by a frequency- and resolution-dependent shift in the fitted centroid position of the phase reference calibrator, as a jet structure is seen to the south of the core at 4 cm in J1953+3537 (with a PA of -172° east of north) that is unresolved

at 13 cm. This shifts the measured centroid at 13 cm along the calibrator jet axis, away from the X-band core, from which the assumed source position was taken. The alignment of our astrometric residuals with the known jet axis in Cygnus X-1 is consistent with the existence of an unresolved compact jet during our observations, with slightly varying size or optical depth (τ).

Cygnus X-1 has been continuously monitored at lower angular resolution by the AMI-LA at 2 cm (also shown in Fig. 1). A clear dip or quenching of the radio emission was observed in correlation with the X-ray spectral state change. During the VLBI observations, AMI-LA also detected radio emission, which suggested the source to have a flat or slightly inverted spectrum. However, at a later stage in the evolution of the soft state (between 2011 February 8 and 2011 April 9), the 2-cm flux became even weaker and the AMI-LA did not detect Cygnus X-1 (the formal mean flux density was $-6 \pm 80 \mu\text{Jy}$).

2.2 X-ray monitoring

In order to analyse the precise X-ray state of Cygnus X-1, targeted fast timing X-ray observations were triggered during the high-resolution radio monitoring, as well as using the *RXTE*-ASM and *Swift*-BAT monitoring instruments. A total of 19 pointed *RXTE*-PCA observations were carried out between 2010 June 19 and 2010 July 31, corresponding to about 68.5 ks of net exposure. All the observations were performed in the binned data mode (B_2MS_8B_0_35_Q), with 1.95 ms bin size in the ~ 2.1 –14.8 keV energy band. Data analysis was carried out using custom IDL software. Using the entire energy band, we extracted the power spectra normalized to units of fractional squared root-mean-square (rms) and the fractional rms variability of the whole data set. An HID of Cygnus X-1 from the *RXTE*-ASM over the period 1996–2011 is also shown in Fig. 3. The 1.5–12 keV X-ray intensity (binned into 1-d averages) is plotted against a hardness ratio (HR = 5–12 keV/1.5–3 keV). Most of the *RXTE*-ASM observations over the 15-year period were taken in the hard state, while the VLBI observations presented here were taken during a transi-

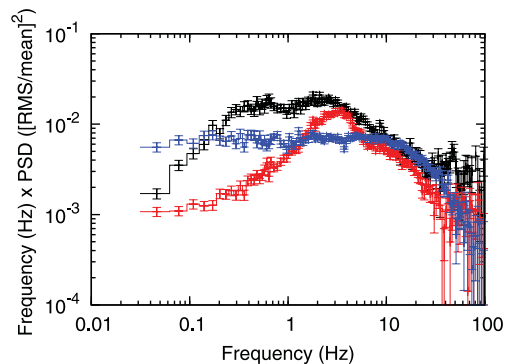


Figure 4. Power spectrum evolution of Cygnus X-1 over an X-ray state change. The source evolves from an intermediate state (black) to a soft state (red) and finally a very soft state (blue) on 2010 June 19, July 3 and July 22 (marked on Fig. 1).

tion between the intermediate and soft states (as marked by crosses in Fig. 3). It has been proposed by Fender et al. (2006) that the ‘jet-line’ is approximately at HR ~ 0.4 ; hence, our observations sampled this period well.

The pointed *RXTE*-PCA observations showed a drop in the rms variability during the state change (as shown at the top of Fig. 1). The fractional rms started at ~ 8 per cent on 2010 June 20 before the high-resolution radio monitoring began, and the power spectra (PDS) showed band-limited noise between 0.3–10 Hz (shown in black in Fig. 4), which suggests the source was in an intermediate state (Shaposhnikov & Titarchuk 2006). The rms then dropped to $\lesssim 4$ per cent on 2010 July 4, in between the X-ray and radio flares, and entered a soft state with a somewhat narrower noise component peaking at ~ 3 Hz (shown in red in Fig. 4). Finally, the source entered a very soft state by 2010 July 22 (shown in blue in Fig. 4) with the PDS showing the characteristic broken power-law noise and the rms remaining < 5 per cent when the VLBI observations detected an unresolved compact jet. Therefore, we are confident that Cygnus X-1 entered a soft state during the VLBI observations.

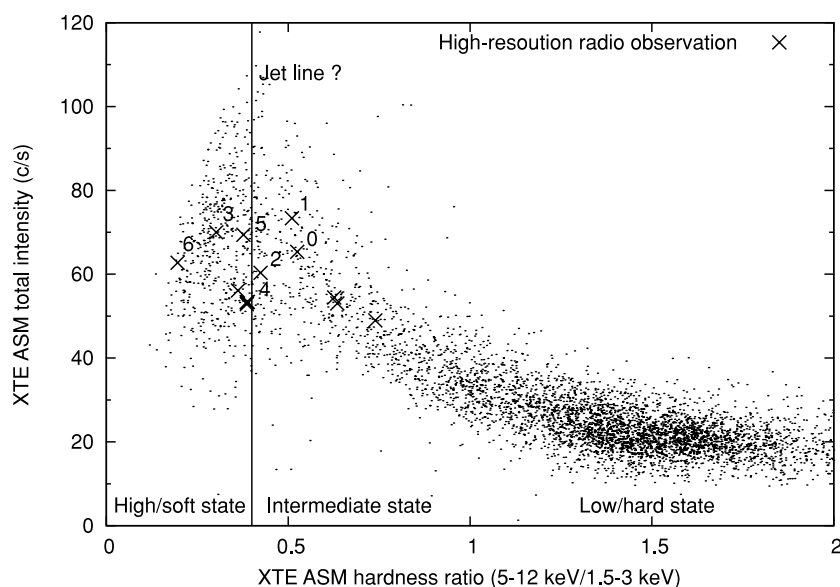


Figure 3. The HID of Cygnus X-1 from *RXTE*-ASM observations from 1996 to 2011. The 5–12 keV/1.5–3 keV ‘hardness ratio’ is compared with the total 1.5–12 keV X-ray intensity (cts s^{-1}) binned into 1-d averages. Crosses mark the closest *RXTE*-ASM epoch to each observation taken with either MERLIN, e-EVN, VLBA or WSRT (with the VLBI epochs numbered), showing that the proposed ‘jet-line’ was crossed during the high-resolution radio monitoring.

3 EVIDENCE FOR A COMPACT JET IN A SOFT STATE

The astrometric residual positions, scattered up and down the jet axis with time in Fig. 2, are indicative of a compact jet that is slightly smaller than the beam size. The variations in position are likely due to changes in the optical depth (τ) of a partially synchrotron self-absorbed steady jet (Blandford & Königl 1979). We interpret this as variations in the jet power, electron density or magnetic field causing the opacity to vary and the $\tau = 1$ surface to move up and down with time. The larger positional scatter at the longer wavelength also supports the self-absorbed compact jet interpretation, as one expects the apparent size of the outflow to be larger at lower frequencies, since the $\tau = 1$ surface is further out. The positions do not evolve linearly with time, and do not correlate with either radio flux density or spectral index. This suggests a quasi-continuous outflow with variable optical depth rather than a single moving component.

In the hard state, the radio flux is known to be modulated by ~ 15 – 20 per cent on the 5.6-d orbital period (Pooley, Fender & Brocksopp 1999; Lachowicz et al. 2006). It has also been suggested that the radio modulation is due to orbital changes in the line-of-sight free–free absorption of the stellar wind from the massive companion star (Brocksopp, Fender & Pooley 2002; Szostek & Zdziarski 2007). During the soft state, VLBI observations presented here have shown the jet flux at 4 cm is contained within ~ 0.7 au which is approximately an order of magnitude smaller than in the hard state at the same wavelength (Rushton 2009). Therefore, the soft state quenching of the radio flux could be partly due to an increased absorption by the wind as the emission originates closer to the black hole and companion star. While the sampling in time is too sparse and the signal-to-noise ratio is too low to rule out conclusively that a similar periodicity exists in the soft state, no clear orbital modulation was found during the VLBI results presented in this paper. Therefore, any variations are likely to be a combination of optical depth changes in both the jet and stellar wind.

The discovery of a compact jet in the soft state of a BH XRB has important implications for a universal model of accreting black holes. Regardless of whether the X-ray spectrum is dominated by a power-law component or soft thermal emission, a compact jet can remain a fundamental aspect of the accretion, even in a soft state (although the jet may not always be detectable). Across the state transition there is a complex anti-correlation between the soft X-rays and the radio jet, although a deterministic relationship does not always exist; there is a delay between changes in the inflow and outflow, as the soft X-ray flare clearly peaks ~ 3 d before the radio. However, once the source had entered the soft state for a few days, the radio jet was clearly quenched by a factor of ~ 3 – 5 and a few months later reduced by a factor of >7 . It should however be noted that the soft state of Cygnus X-1 might not be representative of XRBs in general, as the X-ray rms remains above ~ 4 per cent and may not get to the very low variability seen in the completely radio quenched states discussed by Fender, Homan & Belloni (2009).

Clear comparisons can be made with the BH candidate XRB GX 339–4, which also shows a quenching of the radio emission when the source transits into the soft state. Furthermore, the anti-correlation between the radio and X-ray flux in the soft state with GX 339–4 is even more pronounced. Whilst the radio flux density became undetectable with ATCA (<0.1 mJy) and >25 – 40 times weaker than in the corresponding hard state, the X-ray emission increased by a factor of ~ 10 (Fender et al. 1999a; Corbel et al. 2000). Similarly, the BH candidate XRBs H 1743–322 (Coriat et al. 2011)

and 4U1957+11 (Russell et al. 2011) have an even larger radio quenching of at least two orders of magnitude in their respective soft states. Therefore, if these sources still have a soft-state outflow, they are extremely weak.

4 ABSENCE OF BRIGHT DISCRETE EJECTA

The absence of bright, discrete ejections during the transition from the hard to soft state was unexpected. While a (delayed) radio flare was observed shortly after the X-ray state transition, the absence of resolved jet knots suggests either (i) no shocks formed within the compact jet, implying no sudden change in bulk Lorentz factor, or (ii) if a knot was produced, it expanded rapidly with a large opening angle and faded very quickly; however, the latter argument is unlikely as the surrounding jet medium is filled with material from the stellar wind that would interact with the knot (N.B. the knot seen by Fender et al. 2006 is possibly an imaging artefact).

These observations therefore demonstrate that not all black hole candidates necessarily produce strong discrete ejecta during a state transition; it was also reported by Paragi et al. (2010) that the black hole candidate MAXI J1659–152 did not exhibit any strong discrete ejecta during the early phases of a state change. The reasons for this are unclear. It has been suggested that Cygnus X-1 has a non-spinning black hole (Remillard & McClintock 2006; Miller et al. 2009), which may correspond to an outflow with a much lower velocity than a Kerr black hole (although recently it has been suggested by Gou et al. 2011 that the spin was drastically underestimated). Alternatively, knots could be related to a rapid change in accretion rate (\dot{m}), which is not seen in this wind-accreting system with a circular orbit.

Finally, the stellar wind itself could be important in suppressing the ‘jet-line’/formation of knots after a spectral state change. Strong recollimation shocks are thought to occur when the jet interacts with the wind causing disruption even for jet powers of several times 10^{36} erg s $^{-1}$ (Perucho, Bosch-Ramon & Khangulyan 2010). The other BH XRBs discussed in Section 3 all contain low-mass companions that may only emit an isotropic (disc) wind during the soft state. Therefore, while the quenching of radio emission during the soft state could still be partly due to free–free absorption, high-mass XRBs may always have too dense a surrounding environment to produce knots, unless the jet power is sufficiently high, as may be the case in Cygnus X-3, where discrete ejecta are frequently resolved during radio flares (Molnar, Reid & Grindlay 1988; Schalinski et al. 1995; Mioduszewski et al. 2001).

5 CONCLUSIONS

High-resolution VLBI observations have shown the first evidence of a compact jet-like outflow in a soft state of a BH XRB and no evidence of superluminal motion was detected after a state transition. We have removed all known astrometric signatures and orbital parameters to show that an unresolved compact jet is present, oriented along the same position angle as the larger jet seen in the hard state. Furthermore, we performed a detailed analysis of the X-ray timing properties and hardness ratio over the same time period to confirm the source had entered one of its known soft states; however, we note that during the VLBI observations presented here, Cygnus X-1 may not have entered the canonical soft state (seen in other BH XRBs) that may completely switch off the outflow.

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