A transient relativistic radio jet from Cygnus X-1

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ABSTRACT
We report the first observation of a transient relativistic jet from the canonical black hole candidate, Cygnus X-1, obtained with the Multi-Element Radio-Linked Interferometer Network (MERLIN). The jet was observed in only one of six epochs of MERLIN imaging of the source during a phase of repeated X-ray spectral transitions in 2004 Jan–Feb, and this epoch corresponded to the softest 1.5–12 keV X-ray spectrum. With only a single epoch revealing the jet, we cannot formally constrain its velocity. Nevertheless, several lines of reasoning suggest that the jet was probably launched 0.5–4.0 d before this brightening, corresponding to projected velocities of $0.2c \lesssim v_{\text{app}} \lesssim 1.6c$, and an intrinsic velocity of $\gtrsim 0.3c$. We also report the occurrence of a major radio flare from Cyg X-1, reaching a flux density of $\sim 120$ mJy at 15 GHz, and yet not associated with any resolvable radio emission, despite a concerted effort with MERLIN.

We discuss the resolved jet in terms of the recently proposed ‘unified model’ for the disc–jet coupling in black hole X-ray binaries, and tentatively identify the ‘jet line’ for Cyg X-1. The source is consistent with the model in the sense that a steady jet appears to persist initially when the X-ray spectrum starts softening, and that once the spectral softening is complete the core radio emission is suppressed and transient ejecta/shock observed. However, there are some anomalies, and Cyg X-1 clearly does not behave like a normal black hole transient in progressing to the canonical soft/thermal state once the ejection event has happened.

Key words: accretion, accretion discs – black hole physics – ISM: jets and outflows – X-rays: binaries.

1 INTRODUCTION
Relativistic jets (e.g. Hughes 1991; Burgarella, Livio & O’Dea 1993; Livio 1999) are a common feature of accretion onto compact objects, most notably black holes, on all scales. They are important channels for the removal of gravitational potential and/or spin energy, as well as angular momentum, and yet the details of their formation remain largely unclear. Recent studies of stellar-mass ($3 M_\odot \lesssim M_{\text{BH}} \lesssim 15 M_\odot$) black holes in binary systems have led to some empirical understanding of the coupling between accretion ‘states’ and the jet formation process (Fender, Belloni & Gallo 2004 and references therein). Quantitative scalings between these low-mass black holes and the supermassive black holes in distant galaxies (e.g. Merloni, Heinz & di Matteo 2003; Falcke, Körding & Markoff 2004) have finally given firm grounding to the hope that by studying X-ray binaries we may further our understanding of active galactic nuclei.

Cygnus X-1 (HDE 226868, V1357 Cygni) comprises a supergiant secondary (spectral type O9.7 Iab) with mass between 20 and 33 $M_\odot$, together with a compact primary which is a strong black hole candidate with mass between 7 and 16 $M_\odot$ (e.g. Gies & Bolton 1986a). The system spends most of its time in a bright but hard X-ray state, with a bolometric X-ray luminosity around 2 per cent of Eddington (e.g. Di Salvo et al. 2001).

High angular resolution Very Long Baseline Array (VLBA) + phased Very Large Array (VLA) observations from 1998 Aug show a clearly resolved and persistent jet over three closely spaced epochs in the low/hard state (Stirling et al. 2001). This was the first direct imaging of steady radio jet from a source in the hard X-ray spectral state. More recently, Gallo et al. (2005) have discovered a large-scale ($\gtrsim 5$ arcmin) radio and optical lobe approximately orientated with the mas-scale jet. Assuming the lobe is the result of the prolonged action of the jet on the ambient medium, Gallo et al. (2005) were
Figure 1. Radio and X-ray monitoring of Cygnus X-1, from the RT and RXTE ASM. All data points are daily averages. The top panel shows the radio and X-ray fluxes, and the lower panel shows the ratio of counts in the (5–12)/(1.5–3) keV bands; higher values indicate ‘harder’ X-ray spectra. Clear periods of radio–X-ray correlations (hard X-ray state) and anticorrelations (softer X-ray state) are evident. The epochs of MERLIN observations are indicated by arrows at the top of the figure. Only the first MERLIN run, when the core radio source was very faint, revealed a jet.

able to demonstrate that the jet must be carrying a time-averaged power comparable to the present-day X-ray luminosity.

2 OBSERVATIONS

2.1 Ryle Telescope and RXTE ASM monitoring

The Ryle Telescope (RT) is used from time to time for monitoring variable sources, including Cygnus X-1, at 15 GHz. The basic parameters of the RT and its monitoring program are described in Pooley & Fender (1997). The approximately daily monitoring of Cygnus X-1 with the RT is complemented by data from the Rossi X-ray Timing Explorer (RXTE) all sky monitor (ASM). In addition to tracking the evolution of the total X-ray flux of the source, the RXTE ASM data also allow us to measure hardness ratios, indicative of the X-ray ‘state’ of the source (e.g. Fender et al. 2004; Belloni 2005; Homan & Belloni 2005; McClintock & Remillard 2006).

Daily-averaged data from the RT and RXTE ASM, centred on the period of our Multi-Element Radio-Linked Interferometer Network (MERLIN) observations (see below) are presented in Fig. 1; see also Figs 3–6.

2.2 MERLIN

MERLIN was initially triggered to observe Cyg X-1 by a change in the X-ray behaviour of Cyg X-1 to a generally brighter and more variable state, commencing around 2003 December (see Fig. 1). This trigger resulted in observations at epochs M1 and M2 (see Table 1). A major radio flare detected by the RT on 2004 Feb 20 resulted in a second MERLIN trigger and observations at epochs M3-6. We observed while the array was undergoing engineering work and so the specific telescopes observing changed between epochs. Altogether we obtained varying amounts of data over eight separate days. All of the MERLIN observations were taken at 4.994 GHz and with 16-MHz bandwidth in each of the LL, RR, LR and RL polarization products.

The epochs of the MERLIN observations are marked on Fig. 1. From 2004 Feb 20 to Feb 22, Cambridge was involved sporadically (about 50, 10 and 30 per cent, respectively, of each days’ observing time) and Knockin had a warm receiver cryostat throughout, it was removed from the array at 2004 Feb 23, 10:00. While available Knockin was included, although noisy, to improve the (uv) plane coverage.
Figure 3. Radio and X-ray monitoring around the time of the MERLIN observations. The top panel presents the RT 15-GHz flux densities and the total (2–12 keV) X-ray count rate from the RXTE ASM. Arrows indicate the times of the MERLIN observations; only the first observation (epoch M1, see text) detected an extended jet. The dotted triangle in the upper panel indicates the time of the large radio flare plotted in Fig. 4, which corresponded to a large increase in the X-ray flux. The lower panel indicates the hardness ratio from the ASM (5–12/1.5–3 keV), and the vertical lines indicate our best estimate of the range of launch times for the jet which brightened during epoch M1.

Figure 4. A close up of the radio flare observed at 15 GHz with the RT on 2005 Feb 20, with 32-s sampling. This is the highest radio flux density recorded from the source with the RT to date. MERLIN epochs M3-6 were performed between 1 and 5 d after this event, and yet none of them resolved a discrete ejection event, unlike epoch M1.

The data reduction was done in the standard way for continuum mapping, outlined in the MERLIN user guide. We used 3C 286 as a flux density and polarization position-angle calibrator, OQ 208 or 0552+398 as a point source calibrator. The approximately 400-mJy source 1951+355, which is unresolved to MERLIN at this frequency, was used as a phase reference and to calibrate the d terms. The useful bandwidth was 14 MHz after editing the end channels.

Amplitude and phase self-calibration was performed on the phase reference source (shifting it to the phase centre) and interpolated to the target, Cygnus X-1. Observations taken on Cygnus X-1 and 1951+355 were flagged at elevations beneath 15° as phase and amplitude calibration transfer is generally poorer at low elevations. The imaging was performed using IMAGR within Astronomical Image Processing System (AIPS) (Diamond 1995). A preliminary image showed that our coordinates used in the correlation for either the phase reference or target source were slightly in error (∼30 mas north-east of the actual source position for Cygnus X-1) and the phase centre was shifted with UVFIX within AIPS to the target position. As the proper motion of Cygnus X-1 on time-scales of months is very small compared to our resolution this shift was applied to all of the epochs. From these observations our best coordinates for Cygnus X-1 are (J2000) RA 19h58m21.23s±0.02s Dec +21°01′04″±0.02″; the peak core flux densities listed in Table 1 were all measured within 4 mas of this position.

All of the images were restored with a 50-mas circular beam. Table 1 summarizes the results from each image. All epochs apart from epoch M1, were found to be point sources (limits on the flux from jets are given in Table 1). No linear polarization was detected. As the proper motion of Cygnus X-1 on time-scales of months is very small compared to our resolution this shift was applied to all of the epochs. From these observations our best coordinates for Cygnus X-1 are (J2000) RA 19h58m21.23s±0.02s Dec +21°01′04″±0.02″; the peak core flux densities listed in Table 1 were all measured within 4 mas of this position.

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far the weakest core emission. The source is resolved towards the
north-west with an apparent bright component, possibly superposed
on a smooth underlying jet. Applying the AIPS task IMFIT, we find
two approximately beam-sized Gaussian components of integrated
intensities 1.6 mJy (core) and 0.7 mJy (jet); see Table 1. The position
angle between the centres of these Gaussians is $-25^\circ \pm 3^\circ$. The
angular separation between core and jet is $70 \pm 5$ mas (corresponding
to 0.82 $\pm$ 0.06 light days at a distance of 2 kpc).

For comparison, epoch M6 is our image with the highest dynamic
range after the 120-mJy flare of 2004 Feb 20. We have used an
identical beam size and contouring scheme as used for epoch M1.

There is no trace of extension in any position angle. To stress the
point, had the extended ‘jet’ observed at epoch M1 been present in
any of the other epochs, it would have been detected – its detection
at epoch M1 is not just a consequence of the weaker core at this
time.

In an attempt to pin down the time of appearance of the extended
radio emission, we have broken epoch M1, which was a $\sim 23$-h
run from start to finish, into different segments. A significant gap
in the observations, between 2004 Jan 15, 21:00 and Jan 16, 03:00
separates the data into two segments, albeit of different length (6 and
15 h, respectively). The jet was only detected in the second of the
two blocks of data. However, since MERLIN does not have enough
baselines to operate as a ‘snapshot’ type of instrument (unlike the
VLA), the $uv$ coverage of the two blocks would have been very
different. We therefore tested whether the jet appearing in the second
half of the data would have been detected by the $uv$ coverage of the
first half. The clean components from the jet in the image of the
second half were selected using the AIPS task CCEDT and added back
in to the $uv$ data of the first half using the task UVSUB. Imaging this
modified $uv$ data set, it was not possible to unambiguously detect
the jet above the noise. A parallel approach was used in MIRIAD
modified states to ‘softer’ states at relatively high ($\sim$1 per cent Eddington)
luminosities. In the accretion flow this seems to be associated with
shocks which we identify as discrete components in radio maps of
X-ray transients (see also Kaiser, Sunyaev & Spruit 2000).

The behaviour of Cyg X-1 appears to follow a consistent pattern,
although with some anomalies. Fig. 3 presents a close-up of the
data around the time of the one resolved event, 2004 Jan 15/16.
Precisely around the time of the MERLIN observation the radio
flux dropped to very low levels, towards the end of a period of X-ray
spectral softening. The radio flux stayed at these very low ($<2$ mJy
at 5 GHz and undetectable at 15 GHz) levels for 12–18 h and then
recovered rapidly restored to previous levels 6–12 h before the X-
ray spectrum returned to a hard state. Unfortunately the RXTE ASM
sampling was rather sparse around this time and this hampers our
precise interpretation of the sequence of events.

Fig. 3 also shows that the radio flare of 2004 Feb 20 (Fig. 4)
occurring around the time of a large step-like increase of the inte-
grated X-ray flux, while the source was in a ‘hard intermediate’
state (Fender et al. 2004; Homan & Belloni 2005). Fig. 5 (see also
Fig. 6) sheds more light on this in the form of a hardness–intensity
diagram (HID) for Cyg X-1. There is a clear peak in the luminosity
distribution of the source, corresponding to a hardness ratio HR2
(counts in 5–12 keV band/(counts in 1.5–3 keV band)) around 0.3–
0.4. In the canonical hard state $1.0 \lesssim HR2 \lesssim 1.5$ is more typical. It is interesting to note that epoch M1 – the only epoch at which a jet
was imaged – is the only epoch to the left of (softer than) the peak.

All of the other MERLIN epochs correspond to ‘hard intermediate’targets which we identify as discrete components in radio maps of

All of the other MERLIN epochs correspond to ‘hard intermediate’
states (HIMS; Belloni 2005) with $0.5 \lesssim HR2 \lesssim 1.0$. We therefore
tentatively associate HR2 $\sim 0.4$ with the ‘jet line’ (Fender et al.
2004) for Cyg X-1. This is consistent with the picture of Fender
et al. (2004) and Corbel et al. (2004) in which the steady jet (core
emission) persists during softening from the canonical hard state,
until some critical point (represented spectrally by the ‘jet line’) is
reached. Also marked in Fig. 5 are the state of Cyg X-1 at epochs
when a steady, compact ($\leq 20$ mas) jet was imaged with the VLBA
(Stirling et al. 2001; R. Spencer, private communication); these are
all in the canonical low/hard state.

Fig. 6 shows the evolution of daily-averaged counts for Cyg X-1
in the HID for the 4 d preceding and 2 d following the imaging of the
jet on 2004 Jan 15/16. Based on this more detailed analysis, we find
that the jet line is likely to lie close to HR$\sim 0.3$; this is indicated on
the figure. We note that Cyg X-1 exhibits X-ray temporal and spectral
variations on much shorter time-scales than those utilized here from
the RXTE ASM, and we may be missing key events by using daily
averages. It is also clear that Cyg X-1 does not behave like a ‘typical’transient once it has crossed the jet line, in progressing towards the
canonical soft/thermal state, but instead returns to the hard IS state
within 2 d. The only other source to exhibit such behaviour is GRS
1915+105, although it is likely that repeatedly radio-bright objects
such as Cygnus X-3 may behave similarly.

It is also interesting to speculate about the nature of the core
emission at epoch M1. It has been well established for some years
now (e.g. Fender et al. 1999) that the radio emission from black hole
X-ray binaries is suppressed in soft X-ray states compared to hard
states. An unambiguous detection of core (i.e. currently generated
flow) radio emission from a source in a steady soft state has not yet
been reported. If the ‘core’ radio emission we detect at epoch M1 is
indeed the suppressed level, then the quenching in Cyg X-1 is only
a factor of $\sim 10$, compared to $\geq 30$ and $\geq 50$ in the black hole X-ray
binaries GX 339-4 and XTE J1550-564, respectively (Fender et al.
1999; Corbel et al. 2001). However, there is no way of knowing
if this weak core is completely or only partially quenched given,
again, the known rapid variability of Cyg X-1. What we observe
as the core could in fact be emission from a receding jet which


Table 1. Summary of the MERLIN observations of Cygnus X-1.

| Epoch | Date (2004) | Core peak (mJy beam$^{-1}$) | Jet peak (mJy beam$^{-1}$) |
|-------|-------------|-----------------------------|---------------------------|
| M1    | Jan 15/16   | 1.2 $\pm$ 0.07              | 1.2 $\pm$ 0.07            |
| M2    | Jan 26      | 11.8 $\pm$ 0.17             | <0.51                     |
| M3    | Feb 21      | 9.9 $\pm$ 0.20              | <0.60                     |
| M4    | Feb 22      | 6.9 $\pm$ 0.28              | <0.84                     |
| M5    | Feb 23      | 7.8 $\pm$ 0.30              | <0.90                     |
| M6    | Feb 25      | 13.6 $\pm$ 0.13             | <0.39                     |
in many cases will have a very small proper motion (much less than that of the approaching jet). In this scenario the jet emission would have to have some flux evolution including a local peak; for a symmetric monotonically decaying event the receding jet cannot appear brighter than the approaching.

3.2 Jet launch and velocity

As discussed above, it is very difficult to pin down the moment at which point the matter/energy associated with the resolved jet was launched. In the model of Fender et al. (2004), the launch moment would correspond to the end of a phase of X-ray spectral softening and would be immediately followed by a quenching/suppression of the core radio emission. However, given the limited quality of data from the RXTE ASM, even for a very bright source such as Cyg X-1, we can only say that 0 \lesssim \Delta t \lesssim 15, where \Delta t was the time since launch in days. The resulting associated proper motion and velocity would be \mu = 70/\Delta t \, \text{mas} \, \text{d}^{-1} \text{ and } v_{\text{app}} = 0.8c/\Delta t.\text{ The more detailed inspection of the HID structures outlined above suggests – no more – that the jet was launched at most around } \Delta t \approx 4 \text{ d before epoch M1. This interpretation is supported circumstantially by the very rapid decay of the large flare event on 2005 Feb 20 (Fig. 4). Furthermore, we estimate that proper motions larger than } \sim 100 \, \text{mas} \, \text{d}^{-1} \text{ would probably have caused smearing in the M1 image which was not observed.}

For 0.5 \lesssim \Delta t \lesssim 4 \text{ d, } 140 \lesssim \mu \lesssim 17.5 \, \text{mas} \, \text{d}^{-1}, \frac{1.6c}{\Delta t} \lesssim v_{\text{app}} \lesssim 0.2c.\text{ The Cyg X-1 system has been extensively modelled based on optical and X-ray data, from which a general consensus has emerged that the orbital inclination angle of the system is } \sim 30^\circ \text{ (e.g. Gies & Bolton 1986b). If the jet shares the same inclination angle (and this is by no means certain; Maccarone 2002), then the true velocity of the jet would be } \gtrsim 0.3c \text{ (given the accumulation of uncertainties, we cannot place an upper limit on the Lorentz factor of the jet – see Fender 2003; Miller-Jones, Fender & Nakar 2006 for further discussion).}

4 CONCLUSIONS

We report the first observation of a transient, extended (70 mas) radio jet from the classical black hole binary Cyg X-1. The jet was observed in only one of six MERLIN observations performed while the system was undergoing frequent X-ray state changes. The one epoch in which the jet was imaged was that with the softest 1.5–12 keV spectrum; at that moment the core radio emission was detectable but a factor \sim 10 weaker than normal. Estimates of the launch epoch of the jet indicate it probably has a bulk velocity \v \gtrsim 0.3c, with essentially no formal upper limit.

At the other five epochs the source X-ray spectrum was harder, although still not in the canonical hard state, and displayed more powerful core emission and no extended jet. Three of these observations were made within days of the brightest radio flare observed from Cyg X-1 (\sim 120 mJy at 15 GHz), and yet no extended radio emission was detected. It is not clear if this may be related to the jet expanding into a rarefied bubble (Gallo et al. 2005), or if for some reason the flare was, unusually, not associated with a jet. Throughout the interpretation of the X-ray:radio behaviour, we have to bear in mind that Cyg X-1 varies on much shorter time-scales than the RXTE ASM sampling, and we may have missed some key event. Nevertheless, the overall pattern of behaviour seems to be broadly consistent with the ‘unified’ model for black hole X-ray binary jets put forward by Fender et al. (2004) although there are some clear anomalies.

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