Radio and X-ray observations of jet ejection in Cygnus X-2

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ABSTRACT
The ejection of a relativistic jet has been observed in the luminous Galactic low-mass X-ray binary Cygnus X-2. Using high-resolution radio observations, a directly resolved ejection event has been discovered while the source was on the horizontal branch of the Z-track. Contemporaneous radio and X-ray observations were made with the European VLBI Network at 6 cm and the Swift X-ray observatory in the 0.3–10 keV band. This has been difficult to achieve because of the previous inability to predict jet formation. Two sets of ~10 h observations were spaced 12 h apart, the jet apparently switching on during Day 1. The radio results show an unresolved core evolving into an extended jet. A preliminary value of jet velocity v/c of 0.33 ± 0.12 was obtained, consistent with previous determinations in Galactic sources. Simultaneous radio and X-ray lightcurves are presented and the X-ray hardness ratio shows the source to be on the horizontal branch where jets are expected. The observations support our proposal that jet formation can in future be predicted based on X-ray intensity increases beyond a critical value.

Key words: acceleration of particles – accretion: accretion discs – stars: neutron – X-rays: binaries – X-rays: individual: Cygnus X-2.

1 INTRODUCTION
Cygnus X-2 is a bright Galactic low-mass X-ray binary belonging to the Z-track group of sources having X-ray luminosities at or above the Eddington limit (Schulz, Hasinger & Trümper 1989; Hasinger & van der Klis 1989). These sources display three tracks in hardness-intensity: the horizontal branch (HB), normal (NB) and flaring branch (FB) showing that major physical changes which have not been understood take place within the sources. Radio jets have been observed from these sources, notably in Sco X-1 (Fomalont, Geldzahler & Bradshaw 2001) but predominantly when the source is on the horizontal branch (Penninx 1989). There is also strong interest in the disc–jet connection (e.g. Migliari, Miller-Jones & Russell 2011).

Based on an emission model for low-mass X-ray binaries embodying the extended nature of the accretion disc corona (Church & Bałucińska-Church 2004), we have proposed a detailed and novel physical explanation of the Z-track sources (Church et al. 2012). On the normal and horizontal branch, there is a strong increase of neutron star temperature and so of radiation pressure which disrupts the inner disc, launching the jets. Based on this improved understanding it becomes important to obtain simultaneous radio and X-ray observations which allow detailed investigation of changes at the inner accretion disc at the time of jet launching and subsequent to this launch. The present observations then provide an adequate strategy to observe these events. It is moreover important to investigate differences between neutron star and black hole systems as the latter do not have a stellar surface.

We observed Cygnus X-2 during two 10 h periods separated by 12 h in 2013 February 2013, in both radio and X-rays. The observing strategy was designed to maximize the likelihood of observing Z-track motion, and to capture the location of the source on the horizontal branch.

2 THE RADIO OBSERVATIONS AND RESULTS
Radio observations of Cygnus X-2 were made at a wavelength of 6 cm with the European VLBI Network (EVN) on 2013 February 22nd and 23rd, using the electronic VLBI technique (e-VLBI, see e.g. Rushton et al. 2007) where real-time data are transferred from the telescopes to the correlator at JIVE (the Joint Institute for VLBI
in Europe), the Netherlands, on national and international academic communication networks. The data rate from each telescope was 1024 Mbps, and the link from Jodrell Bank used a Bandwidth-on-Demand connection from London to JIVE across the Janet, GÉANT and SURFnet Networks. This was the first time such a link has been used for e-VLBI observations and was set up as part of the NEXPeres project. The EVN telescopes used were the Effelsberg (Germany) 100 m, Jodrell Bank (UK) 76 m, Medicina (Italy) 32 m, Noto (Sicily) 32 m, Omsla (Sweden) 25 m, Toruń (Poland) 32 m, Yebes (Spain) 40 m, Westerbork (the Netherlands) tied array of 12 × 25 m telescopes and Shanghai (China) 25 m. The frequency band used was 4926.49 to 5054.49 MHz in 8 × 16 MHz sub-bands in both hands of circular polarization. Two-bit sampling was used at the Nyquist rate giving a total data rate of 1024 Mbps. Medicina and Shanghai both used one-bit sampling at 512 Mbps and therefore had the same frequency coverage. The upper 16 MHz sub-band was dropped at Noto due to link bandwidth limitations, giving a data rate for that telescope of 896 Mbps. Initial observations were made each day on BL Lac as a ‘fringe finder’ in order to find clock offsets, followed by a 5 min cycle of 2 min on the phase reference source J 2134+4050 and 3 min on the Cyg X-2 target. Alternate observations of the reference source were dropped by the Jodrell Bank Lovell 76 m telescope giving a 10 min cycle period, due to slewing limitations. The observations on Cyg X-2 ran from 09:37 to 16:55 UT on February 22nd and 09:22 to 17:28 UT on February 23rd, except for Shanghai where observation terminated at 10:00 and 10:05 UT, respectively, due to the source setting.

The data were correlated with the EVN Software Correlator at JIVE (SFXC) using eight sub-bands with four polarizations, i.e. including cross hands, with 32 frequency channels per band and 2 s integration. The correlated data were then processed using the automatic pipeline (Reynolds, Paragi & Garrett 2002) which now uses ParselTongue (Kettenis & Sipior 2012) scripts to run AIPS programs. The data were initially calibrated using antenna noise temperature and gain tables and then fringe fitted, to allow frequency-dependent slopes across each band and fringe rates to be corrected. The data from the pipeline were edited to remove obvious errors and the phase reference source imaged by self-calibration, and the solutions found for this source used to correct the phases of the target source. The reference source was unresolved and strong enough to give good solutions and initial imaging was done using the DIFMAP program in the Cal-Tech VLBI package (Shepherd, Pearson & Taylor 1994).

The positions and flux densities of the components are given in Table 1. The 2005 position found by the Multi-Element Radio-Linked Interferometer Network (MERLIN) is also shown in the table. The proper motion from 2005 May to 2013 February is therefore $-3.0 \pm 0.68 \text{mas yr}^{-1}$ in right ascension and $-0.64 \pm 0.68 \text{mas yr}^{-1}$ in declination. Absolute position errors are estimated as 0.45 mas on the 22nd and 0.50 mas on the 23rd, with relative errors between the two days of 0.3 mas in both coordinates. The position error in the MERLIN measurement was 5.3 mas in each coordinate.

The change in structure suggests that a radio jet with a bright head (the SE component) has been ejected, while emission from the core had weakened by the second day. The head component moved by 6 mas in position angle 141°. A distance for Cygnus X-2 was published of 7.2 ± 1.1 kpc (Orosz & Kuulkers 1999). From peak X-ray burst fluxes a distance of 11.6 ± 0.13 was found by Smale (1998) and 11 ± 2 kpc by Galloway et al. (2008) for an H-fraction $X = 0.7$. However, not all bursts exhibited the radius expansion required for distance determination. We adopt a distance of 9 kpc which gives an apparent ejection velocity of 0.33 c, taking about 24 h between the measurements.

The signal-to-noise ratio and aperture plane coverage on the first day were sufficient to allow model fitting of a circular Gaussian component to the image for short (0.5–1 h) sections of data.

### Table 1. VLBI positions of components (J2000); the observation of 2005, May 21 shown for comparison was made using MERLIN.

| Epoch       | Cmpt | Flux     | RA     | Dec.   |
|-------------|------|----------|--------|--------|
|             |      | (mJy)    | (h m s)| (" ''')|
| 2013 Feb 22 | Single | 0.59      | 21 44 41.152497 | 38 19 17.06210 |
| 2013 Feb 23 | NW   | 0.38      | 21 44 41.152594 | 38 19 17.06168 |
|             | SE   | 0.55      | 21 44 41.152898 | 38 19 17.05822 |
| 2005 May 21 | Single | 1.7       | 21 44 41.154453 | 38 19 17.06712 |

Data were then transferred to AIPS for more detailed calibration, followed by transfer to DIFMAP for further imaging and model fitting. Unfortunately, snow storms on February 23rd resulted in data from Effelsberg and Medicina being lost. The resultant images are shown in Fig. 1 left and right for the two days, the second image having higher noise levels as expected. To our surprise and pleasure the second day shows a double structure suggesting an outburst producing an ejected jet.

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![Figure 1. European VLBI Network observations at 5 GHz: (left) 2013 Feb 22; (right) Feb 23 centred on RA 21h 44m 41;52.497 and Dec. +38°19′17″02.10. The contours scale linearly with a step of 89.6 μJy; the peak flux density rms for the epoch 1 and epoch 2 maps are 523/20 and 583/30 μJy beam−1, respectively. The cross is marked at the peak of the Day 1 map showing the core peak to have moved on Day 2. Some evidence for a counter jet may be seen.](https://academic.oup.com/mnrasl/article-abstract/435/1/L48/1095967)


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3 THE SWIFT OBSERVATIONS AND RESULTS

Cygnus X-2 was observed using the Swift satellite on 2013 February 22nd and 23rd, as a target of opportunity that allowed simultaneous X-ray and radio observations. There were 7~1600 s observations spread over 10 h on the first day, beginning at 7:32 UT, then a gap of 12 h followed by a second similar period of 7 short observations. The X-ray telescope (XRT) observations were made in Windowed Timing mode because of the brightness of the source. In this mode, the central 200 pixel columns are used while each set of 10 pixel rows are binned together. The CCDs are then read out with rapid clocking and the two-dimensional structure is lost, the image appearing as a strip of 200 columns only a few units wide. On Day 1, in observations 2, 3 and 4 the source was not located optimally, but off the end of the strip, as a result of operational constraints. In these cases, a substantial number of counts were lost but correction could be made using the point spread function.

The raw data were assembled into an events file using XRTPIPELINE. Standard screening was applied. Xselect was then used to extract a lightcurve from a source region consisting of an annulus of inner and outer radii 4 pixel (0.16 arcmin) and 25 pixel (1 arcmin). The central part of the source region was not used because of the unacceptable degree of pulse pile-up in that region. Lightcurves were obtained in a total band of 0.3–10 keV and also sub-bands of this including 2.5–4.5 keV and 4.5–10.0 keV to allow construction of a hardness ratio. Background was obtained from a region outside the source annulus. XRTLCORR was used to correct the lightcurves taking into account vignetting, the point spread function allowing for the different position angles in different sub-observations. This was done for all observations including the three observations not optimally directed; however, because of the larger corrections made, the systematic errors in these cases were higher.

The total background-subtracted lightcurve in the band 0.3–10 keV of the whole two days of observation is shown in Fig. 2 (upper panel), together with the radio 5 GHz data. Day 1 data are shown in black; sub-observations 2, 3 and 4 are shown in green and can be seen with larger errors corresponding to the observations not optimally directed. Day 2 observations are shown in red. The X-ray luminosity in the band 1–30 keV was typical for the source, varying between 1.3 and 1.7 × 10^{38} erg s^{-1} during Day 2. During the second half of the observations, an X-ray burst was seen at the time marked on the figure lasting a few seconds (and so not seen at 64 s binning). X-ray bursts are unusual in Z-track sources which have luminosities more than 10 times higher than those of X-ray burst sources. Type 1 bursts have been seen in Cyg X-2 over a number of years (Kahn & Grindlay 1984; Smale 1998; Galloway et al. 2008).

A hardness ratio was formed from the ratio of the counts in the band 4.5–10.0 keV to that in the band 2.5–4.5 keV and is shown in Fig. 3 as a function of the intensity in the band 0.3–10 keV. The approximate inferred positions of the normal and flaring branch are indicated by dashed lines. It can be seen that there is no change in hardness ratio while the intensity changes by a factor of 2, showing the source to be on the horizontal branch. The factor of 2 is typical and implies that the Hard Apex between horizontal branch and normal branch will be approximately as indicated by the intersection of the dashed line with the data. We have re-analysed previous RXTE data on Cygnus X-2 using the same energy bands as in this work. The hardness-intensity plot may have a slightly different shape from that in RXTE but the horizontal branch remains horizontal and there is no possibility of confusion with the normal branch or flaring branch. It is clear that the source is on the horizontal branch. This is supported by spectral fitting, a detailed account of which will be published separately elsewhere.

Figure 2. Upper panel: X-ray intensity in Swift in the band 0.3–10.0 keV; lower panel: 5 GHz radio fluxes.

Table 2. Results of model fitting to second day’s data.

| Date, time | Component | Flux (mJy) | Separation (mas) |
|-----------|-----------|------------|-----------------|
| Feb 23 11.11 | Core | 0.36 | | |
| Feb 23 15.14 | Core | 0.43 | 5.016 |
| Feb 23 15.14 | SE | 0.44 | 5.256 |

(flux densities shown in Fig. 2). The data did not allow accurate determination of velocity but the position in right ascension suggests that the component moved to the east by the end of the run.

The velocity may be further determined as follows. The loss of the two telescopes on the second day meant that model fitting to short sections of data was unreliable; however, splitting the data into two halves showed that the double structure was present in both sections. If we examine the radio 5 GHz lightcurve (Fig. 2, lower panel), a small radio flare seemed to occur at around 11:40 UT on Day 1. Table 2 shows the time of the mid-points of the two sections of data on Day 2, the flux densities and separation of components in the two halves. If we take the mean time for the first section of data on the second day as a time at which the double structure was clearly established and the time of the weak flare as the ejection time then the apparent velocity is v/c = 0.33 ± 0.12 for a distance of 9 kpc.

The core component has decreased in flux density slightly while the ejected (SE) component decreases in flux in the second half of Day 2. There is evidence that the source is still expanding, though at a rate lower than since the previous day (1.4 mas d^{-1}). However, the results show that the source has expanded by 11:00 UT on February 23rd, 23.3 h after the weak flare on February 22nd.

There is some evidence for a counter jet in the radio image (Fig. 1 right). However, the peak of the emission to the NW of the source is only at about the 3σ level, and the feature could arise from noise or artefacts. The peak brightness of the clearly seen SE jet on Day 2 was found to be ~6 times the peak brightness at the position of the counter jet. From this ratio, some constraints may be placed on the jet velocity as discussed in Section 4.

The X-ray telescope (XRT) observations were made in Windowed Timing mode because of the brightness of the source. The systematic errors in these cases were higher.
The possible ejection could be one sided, have unequal velocities for the approaching and receding jet or more likely have intrinsic differences in radio flux between the two sides – perhaps due to significant absorption. High-resolution observations at two or more radio frequencies would be needed on future ejecta to investigate this possibility.

In the case of Sco X-1, there have been extensive investigations of the jets by Fomalont and co-workers (e.g. Fomalont et al. 2001) and there appear to be distinct similarities as might be expected as Sco X-1 is also a Z-track source although more luminous, having a luminosity typically three times higher than Cyg X-2. Sco X-1 exhibits a radio core, and north-east and south-west jets with measured average velocities of 0.45c. We suspect however, that formation of the relativistic jet is due to heating of the neutron star and the corresponding increased radiation pressure rather than other mechanisms such as disc instability. As the inner accretion disc in the Z-track sources is a thick disc, inflated to a height of the order of 50 km by the disc’s radiation pressure, collimation of the jet is possible at the conical opening in the hot inner disc, the radiation pressure having components both vertical and horizontal, the latter having a collimating effect.

3.1 Radio and X-ray correlations

On the first day, Cyg X-2 is already located on the horizontal branch as shown by the hardness ratio. During the observations it moves on this branch, increasing in intensity during the second sub-observation, moving towards the hard apex of the Z-track. After 2 h the radio flare appears. It seems likely that the radio flare corresponds to jet launching. As expected from this, the integrated radio image for Day 1 does not show a jet.

On Day 2, there is a substantial drop in X-ray intensity. If the radio data are not integrated as two halves but left as seven sub-observations, the first three points indicate a decrease in radio flux, but should be treated with some caution because of the loss of data from Effelsberg and Medicina. However, these data represent the first observation of the moment of jet launch in both radio and X-ray.

4 DISCUSSION

We have observed the formation of relativistic jets in Cyg X-2 in radio and X-rays and can probably locate the time of jet detachment from the neutron star system at the radio flare observed on Day 1. Based on this assumption, we find a preliminary value of the jet velocity v/c of 0.33 ± 0.12. This is based on assuming jet formation at the EVN flare and position of the head at the mid-point of the first radio measurement on Day 2. There is an uncertainty in the angle moved of 0.4 in 6 mas. We use the maximum possible range of distance values implied by uncertainties in the quoted values (Section 2) giving the above quoted uncertainty in v/c of 38 per cent.

The possible weak detection of a counter jet allows us to place constraints on the jet for particular assumptions. The ratio of the brightness of the approaching jet S_a to that of the receding jet S_b when Doppler boosting takes place is given by

\[ \frac{S_a}{S_b} = \left( \frac{1 + \beta \cos \theta}{1 - \beta \cos \theta} \right)^{k - \alpha}, \]

where \( \beta \) is v/c, \( \theta \) is the inclination angle, \( \alpha \) is the spectral index and \( k \) is a factor related to the geometry of the ejecta. We assume \( \alpha = 0 \) and \( k = 3 \) appropriate to ejection of discrete condensations. Using the measured ratio of ~6 and assuming an inclination of 62.5 (from the UVB lightcurves, Orosz & Kuulkers 1999) gives an intrinsic velocity for the jet of ~0.6 c and an apparent velocity of the approaching jet of ~0.8 c, higher than that observed.
a low intensity to above a critical value. Since the demise of RXTE, MAXI can be used in the same way. In the present observation, the jet was formed when the source had crossed the critical intensity giving strong support to our ability to predict jets.

5 CONCLUSIONS

We have captured jet formation in Cygnus X-2 in radio and X-rays for the first time. The Swift observations confirm that the source is on the horizontal branch of the Z-track.

The observations were found to take place at a period of increased X-ray intensity as monitored by Monitor of the All-sky X-ray Image (MAXI) supporting our findings from a study with the ASM and MAXI that a minimum critical intensity is needed for jet formation. We believe that we can now predict jet formation and it should be possible to trigger observations to observe jet formation in more detail, without the major uncertainty previously attached to observations at arbitrary epochs.

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