A decelerating jet observed by the EVN and VLBA in the X-ray transient XTE J1752−223

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ABSTRACT
The recently discovered Galactic X-ray transient XTE J1752−223 entered its first known outburst in 2010, emitting from the X-ray to the radio regimes. Its general X-ray properties were consistent with those of a black hole candidate in various spectral states, when ejection of jet components is expected. To verify this, we carried out very long baseline interferometry (VLBI) observations. The measurements were carried out with the European VLBI Network (EVN) and the Very Long Baseline Array (VLBA) at four epochs in 2010 February. The images at the first three epochs show a moving jet component that is significantly decelerated by the last epoch, when a new jet component appears that is likely to be associated with the receding jet side. The overall picture is consistent with an initially mildly relativistic jet, interacting with the interstellar medium or with swept-up material along the jet. The brightening of the receding ejecta at the final epoch can be well explained by initial Doppler deboosting of the emission in the decelerating jet.

Key words: stars: individual: XTE J1752−223 – ISM: jets and outflows – radio continuum: stars – X-rays: binaries.

1 INTRODUCTION

It is clear from the literature of the past three decades that, for almost every black hole X-ray transient (XRT) observed at radio wavelengths, a radio counterpart has been discovered (Fender 2006). In a small number of sources, the ejecta have been resolved and monitored as they travel away from the central source. Thus, it has been possible on rare occasions to measure proper motions, sometimes at apparently superluminal velocities: e.g. GRS 1915+105 (Mirabel & Rodríguez 1994; Fender et al. 1999), GRO J1655−40 (Hjellming & Rupen 1995; Tingay et al. 1995), GX 339−4 (Corbel et al. 2010), and even detect the only known instances of a Galactic parsec-scale jet being decelerated in the interstellar medium (ISM): XTE J1550−564 (Corbel et al. 2002; Kaaret et al. 2003) and XTE J1748−288 (Hjellming et al. 1998; Miller-Jones et al. 2008). Jet deceleration has also been investigated in GRS 1915+105 although no conclusive evidence was found (Miller-Jones et al. 2007).

The XRT XTE J1752−223 was discovered by the Rossi X-ray Timing Explorer (RXTE) on 2009 October 23 (Markwardt et al. 2009) at the start of its first known X-ray outburst. It showed a long and gradual rise at X-ray energies, whilst remaining spectrally hard. The X-ray source later evolved, became softer (Brocksopp et al. 2010a; Homan 2010) and entered a spectral state commonly associated with jet ejection events (Fender et al. 2004, 2009). The outburst has been well monitored by the Monitor of All-sky X-ray Image (MAXI; Nakahira et al. 2010), RXTE (Shaposhnikov et al. 2010) and Swift (Curran et al. 2010) at X-ray energies. All these X-ray observations show that XTE J1752−223 is likely to be a black hole transient.

Following the activation of XTE J1752−223, we initiated the Australia Telescope Compact Array (ATCA) radio observations and discovered the radio counterpart with a flux density of $\sim 2$ mJy at 5.5 GHz (Brocksopp et al. 2009; 2010a). The later ATCA monitoring observations showed that the radio source entered a series of flares, peaking at 5–20 mJy (Brocksopp et al. in preparation), after the transition from X-ray hard to soft state. To detect the potential ejecta and study their evolution, we carried out a European very long baseline interferometry (VLBI) Network (EVN) experiment and three follow-up VLBA experiments at 5 GHz in 2010 February. In this Letter, we present the results of these VLBI observations.

2 RAPID EVN AND VLBA OBSERVATIONS

The performed VLBI experiments are summarized in Table 1. The low declination and potentially weak flux of XTE J1752−223 were
possible problems for VLBI observations. Therefore, to quickly resolve these concerns, we initiated an e-VLBI experiment with the western European telescopes (Szomoru 2008). The EVN experiment used 1024 Mbps data rate (16 channels, 16 MHz per channel, 2 bit sampling, dual polarization). The real-time correlation was done with the Earth orientation parameters (EOP) predicted from the EOP model of 1 d earlier. We applied 2-s integration time, and 16 frequency points per channel. The participating stations were Medicina, Yebes, Torun, Onsala and Westerbork. In the EVN experiment, we used the 2002 coordinate: RA = 17°52′15.005′′, Dec. = −22°20′32.782′′ (positional uncertainty: σ = 0.3′′), which was determined by the ATCA observations (Brocksopp et al. 2009; 2010a). To obtain fringe-fitting solutions and a reference point, we scheduled a nearby (0:8) phase-referencing source: PMN J1755−2232 (RA = 17°55′26.285′′, Dec. = −22°32′10.593′′, J2000), position error σ ∼ 15 mas). As these sources have low elevation (<30°) in Europe, we used a short cycle time: 160 s on the target and 80 s on the reference source. We also observed a strong and compact source (NRAO 530) as the fringe finder and bandwidth calibrator.

We successfully detected a radio source, consistent with an ejection from the black hole candidate (Brocksopp et al. 2010b) during the EVN experiment and then performed three follow-up VLBA experiments. We used the same phase-referencing source, cycle time and observing frequency. The recording data rate was 512 Mbps (16 channels, 8 MHz per channel, 2 bit sampling, dual polarization). There were eight VLBA telescopes available at the first epoch, nine at other two epochs. The data were averaged in each IF and then split into single-source files then transferred to XTE J1752−223 by linear interpolation. (5) The background large image is the VLBA image of 2010 February 26. The cross in each image marks the position of component A at the first epoch (RA = 17°55′26.0370′′, Dec. = −22°20′31′′9838′′, J2000). At the bottom of the large background image, there is another jet component marked as component B at an angular separation 488 mas from component A and at a position angle consistent with the moving direction of component A. The related map parameters are listed in Table 1.

Component A, surrounded with the beam pattern, is clearly seen with a peak brightness of 2.32 mJy beam−1 in the dirty map at the first epoch, when natural weighting is used. After removing component A with a circular Gaussian model, we notice that there may be at least one more jet component. One candidate is located at angular separation 18.7 mas, position angle −84°0; the other at angular separation 70.6 mas and position angle −36°3. Both candidates have a peak brightness ∼0.91 mJy beam−1 (∼4σ_{rms}) using natural weighting. In Fig. 1(a), the two candidates show the second positive contours. If either candidate is removed by circular Gaussian model fitting, the other also becomes faint. If we reduce the contribution of the long baselines, both become brighter and show a small peak (∼5 per cent) brightness difference. Due to the limited sensitivity and u − v coverage during the 1.2-h observations, neither components can be unambiguously identified as a true jet component. However, there is evidence for the extended emission for the source as the total restored flux density is much lower than that (∼16 mJy at 5.5 GHz) measured by the ATCA (Brocksopp et al. in preparation).

### Table 1. The summary of the image parameters of Fig. 1.

| Exp. | Date (dd/mm/yy) | Array | N_{ant} | T_{int} (h) | \(S_{peak}\) (mJy b−1) | \(\sigma_{rms}\) (mJy b−1) | \(b_{maj}\) (mas) | \(b_{min}\) (mas) | \(\phi_{pa}\) (°) |
|------|----------------|-------|---------|-------------|-----------------|------------------|----------------|----------------|-------------|
| RY001 | 11/02/10       | EVN   | 5       | 1.2         | 2.32            | 0.21             | 14.5            | 6.1            | −3          |
| BB290A | 18/02/10       | VLBA  | 6       | 3.0         | 0.77            | 0.072            | 10.0            | 10.0          | 0           |
| BB290B | 23/02/10       | VLBA  | 7       | 6.0         | 0.60            | 0.068            | 10.0            | 10.0          | 0           |
| BB290C | 26/02/10       | VLBA  | 7       | 6.0         | 0.37            | 0.057            | 10.0            | 10.0          | 0           |

The columns give (1) experiment code, (2) date, (3) array name, (4) total number of the used telescopes, (5) total observing time, (6) peak flux density, (7) off-source noise level and (8–10) sizes of the major and minor axes of restoring beam and its position angle.

### 4 VLBI DETECTION OF XTE J1752−223

The imaging results for the XRT XTE J1752−223 are shown in the left-hand panel of Fig. 1. The top small panels from the left-hand side to the right-hand side are the EVN images of 2010 February 11 and the VLBA images of 2010 February 18 and 26, respectively. The background large image is the VLBA image of 2010 February 26. The cross in each image marks the position of component A at the first epoch (RA = 17°55′26.0370′′, Dec. = −22°20′31′′9838′′, J2000). At the bottom of the large background image, there is another jet component marked as component B at an angular separation 488 mas from component A and at a position angle consistent with the moving direction of component A. The related map parameters are listed in Table 1.
Figure 1. The decelerating jet of the XRT XTE J1752−233. All the VLBI images are centred at the location of component A on 2010 February 11, indicated by a cross. Component B was not detected until 2010 February 26. The contours start from 3σ off-source noise level and increase by a factor of −1.4, −1, 1, 1.4, 2 and 2.8. The related map parameters are listed in Table 1. The right-hand panel plots the fitting results (Table 3) of the proper motion data (Table 2) of component A using the models with (solid curve) and without deceleration rate (dotted line). The reference time MJD 55238.4 corresponds to the first VLBI observations.

In the follow-up VLBA observations, the higher resolution and sensitivity are achieved by more telescopes and longer observing time. To image the extended source, we used natural weighting again. Because of the resolved structure and the decaying peak flux density, the source is only seen clearly in the dirty map with the synthesized beam (16.2 × 3.9 mas at position angle −15°.6) at the first VLBA epoch. However, the large-scale beam pattern around the faint source could also be easily identified at the later two epochs. If we taper the long baselines, use the short baselines only or increase the image pixel size, the source becomes significantly brighter in the dirty map at the later two epochs. None of the suspected ejecta candidates in the EVN image is further seen after 7 d in the later VLBA images. Because the diffuse emission cannot be well restored by clean components, Gaussian models were used in making all the VLBI images of Fig. 1. Due to the limited signal-to-noise ratio (S/N) (6–12), circular rather than elliptical Gaussian model fitting was adopted to reduce the number of free parameters.

Table 2 lists the best-fitting parameters of the circular Gaussian model. To show the motion of component A, we take the position of component A measured at the first epoch as the reference origin. The random position error was estimated by \( \sqrt{b_{\text{maj}}b_{\text{min}}} \), where \( b_{\text{maj}} \) and \( b_{\text{min}} \) are the size of the major and minor axes of the used restoring beam, and \( \text{S/N} = \frac{S_{\text{peak}}}{\sigma_{\text{rms}}} \) listed in column 7 of Table 2. Note that the rather large systematic position error from the reference source will not affect our proper motion measurements. The fitted size has the same random error as the position for each component. Since the measured sizes (≥8 mas) are much larger than that (4.2 mas) of the reference source, they should be very close to the true size of the ejecta. At the second epoch, we notice that component A shows an elongated structure in the east–west direction and the eastern side is brighter than the western side. This brightness distribution caused a slightly different position angle of the component, compared to what is measured at later epochs. The VLBI flux density errors are usually ∼5 per cent.

5 GRADUAL JET DECELERATION

The angular separation of component A versus time is shown in the right-hand panel of Fig. 1. We take the position and the time of component A measured at the first epoch as the reference origin. We fit these data points to the following proper motion model:

\[
r = r_0 + \mu_0 t - 0.5\dot{\mu} t^2,
\]

where \( r \) is the angular separation, \( t \) is the observing time, \( r_0 \) and \( \mu_0 \) are the angular separation and the proper motion at \( t = 0 \) and \( \dot{\mu} \) is the apparent deceleration rate. The dotted straight line and the solid curve represent the uniform proper motion model (\( \dot{\mu} = 0 \)) and the proper motion model with the deceleration rate (\( \dot{\mu} \neq 0 \)).

Table 2. The circular Gaussian model fitting results of the detected jet components in the XRT XTE J1752−233.

| Comp. | MJD (d) | Separation (mas) | Position Angle (°) | Size (mas) | Flux (mJy) | S/N |
|-------|---------|------------------|--------------------|------------|------------|-----|
| A     | 55238.4 | 0 ± 0.4          | 0                  | 7.9        | 4.35       | 11.0|
| A     | 55245.6 | 57.4 ± 0.5       | −41.18 ± 0.90      | 13.8       | 2.20       | 10.7|
| A     | 55250.6 | 85.5 ± 0.6       | −50.14 ± 0.63      | 19.0       | 2.32       | 8.8 |
| A     | 55253.6 | 100.6 ± 0.8      | −49.23 ± 0.70      | 13.9       | 1.05       | 6.1 |
| B     | 55253.6 | 387.9 ± 0.8      | 128.08 ± 0.18      | 11.9       | 0.86       | 6.4 |

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respectively. The best-fitting parameters are listed in Table 3. The model of $\mu = 0$ gives an average proper motion of $\bar{\mu} = \mu_0 = 6.90 \pm 0.05$ mas d$^{-1}$ with the reduced $\chi^2 = 118.4$. The degree of freedom (DoF) is listed in the last column. The model of $\mu \neq 0$ gives $\mu_0 = 9.15 \pm 0.15$ mas d$^{-1}$ at MJD 55238.4 and a deceleration rate of $\dot{\mu} = 0.34 \pm 0.02$ mas d$^{-2}$ with the reduced $\chi^2 = 3.9$. With the deceleration rate, component A has a proper motion of 4.0 mas d$^{-1}$ at the last epoch. It is clear that the deceleration rate should be included in the proper motion model.

Jet deceleration was also found in XTE J1550–564 using Chandra observations (Corbel et al. 2002; Kaaret et al. 2003) and XTE J1748–288 with VLA observations (Hjellming et al. 1998; Miller-Jones et al. 2008). Compared with them, the observed deceleration in XTE J1752–223 is free from the blending of multiple jet components caused by the low resolution (Hjellming & Rupen 1995). If there is a sequence of ejecta which decreased sequentially more rapidly in flux density with increasing distance from the core, the cluster of components may show a decreasing proper motion. In our case, these VLBI observations have a resolution of $< 10$ mas and can well identify single ballistic ejecta with a time resolution of less than 1 d, assuming an initial proper motion 10 mas d$^{-1}$. Therefore, the deceleration in XTE J1752–223 is the second known case of gradual jet deceleration, although on a much smaller scale ($\sim 100$ mas) than the first case of XTE J1550–564. As for the previous two sources, the jet deceleration in XTE J1752–223 is most likely due to interaction with the external dense ISM or the residual slowly moving ejecta from the previous ejection along the jet path.

### 6 COMPONENT B: THE RECEIVING EJECTA?

We interpret component A as an approaching jet component since the model of $\mu = 0$ gives an average proper motion of $\bar{\mu} = \mu_0 = 6.90 \pm 0.05$ mas d$^{-1}$ with the reduced $\chi^2 = 118.4$. The degree of freedom (DoF) is listed in the last column. The model of $\mu \neq 0$ gives $\mu_0 = 9.15 \pm 0.15$ mas d$^{-1}$ at MJD 55238.4 and a deceleration rate of $\dot{\mu} = 0.34 \pm 0.02$ mas d$^{-2}$ with the reduced $\chi^2 = 3.9$. With the deceleration rate, component A has a proper motion of 4.0 mas d$^{-1}$ at the last epoch. It is clear that the deceleration rate should be included in the proper motion model.

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### Table 3. Best-fitting parameters using the proper motion models with and without the deceleration rate.

| Model | $r_0$ (mas) | $\mu_0$ (mas d$^{-1}$) | $\dot{\mu}$ (mas d$^{-2}$) | $\chi^2$/DoF | DoF |
|-------|-------------|------------------------|---------------------------|--------------|-----|
| $\mu = 0$ | 0.06 ± 0.41 | 9.15 ± 0.15 | 0.34 ± 0.02 | 3.9 | 1 |
| $\mu \neq 0$ | 2.16 ± 0.39 | 6.90 ± 0.05 | 0 | 118.4 | 2 |

Figure 2. Evolution of the size of component A. The solid straight line shows the fitting result of the first three data points.

The receding jet component was ejected on the receding jet side at the same time as component A.

According to the expansion speed, component A was ejected 8.7 d earlier, i.e. at MJD 55229.7 (2010 February 2), which is represented by the x-intercept in Fig. 2. As component A may have significantly larger expansion speed and strong Doppler boosting effect if it is unhindered at this earlier stage, the inferred birth date may be the earliest possible birth date. Although such extrapolation is not guaranteed, the inferred date is at the beginning of the initial rising stage of the associated radio flare in the ATCA radio light curve (Brocksopp et al. in preparation). The average separation speed of the pair of components is $\bar{\mu}_{app} + \bar{\mu}_{rec} \geq 20.4$ mas d$^{-1}$ if they were indeed ejected on the inferred birth date. Since $\bar{\mu}_{rec} \geq \bar{\mu}_{app}$, there is $\bar{\mu}_{app} \geq 10.2$ mas d$^{-1}$, which is significantly higher than the average proper motion (6.9 mas d$^{-1}$) measured during our observations. Thus, component A had already been significantly decelerated before our VLBI observations.

If the jet expansion is linear and symmetric on both sides, the ratio of the approaching and receding component sizes is (e.g. Miller-Jones et al. 2004)

$$\frac{R_{app}(t_{app})}{R_{rec}(t_{rec})} = \frac{t_{app}}{t_{rec}} = 1 + \frac{\bar{\mu}_{app}(t_{app}) \cos \theta}{1 - \bar{\mu}_{rec}(t_{rec}) \cos \theta},$$

where $t_{app}$ and $t_{rec}$ are the intrinsic times at which light leaves the approaching and receding jet components, respectively, and arrive at the telescope at the same observing time; $\bar{\mu}$ is the average jet speed in units of light speed $c$ and $\theta$ is the inclination angle of the jet axis. By a linear extrapolation, the approaching jet component has a size of 21.3 mas at the fourth epoch. If there is no deceleration, $\beta(t_{app}) = \beta(t_{rec}) = \beta$, we can give $\beta \cos \theta = 0.3c$, which requires $\beta \geq 0.3c$ and $\theta \leq 73^\circ$. Note that the size of the receding jet component detected for the first time is not likely to be affected by the over-resolution since it is much younger than the approaching jet component ($t_{rec} \sim 0.5t_{app}$). Given the jet deceleration and $t_{rec} \leq t_{app}$ at the same telescope time, then $\beta(t_{rec}) \geq 0.3c$ and $\beta(t_{app}) \leq 0.3c$. Therefore, we can take 0.3c as the lower limit of the jet birth speed in the case of the jet deceleration.

The ratio of the flux density measured at $R_{app} = R_{rec}(t_{app} = t_{rec},$ free from its intrinsic luminosity evolution effect) for a pair of discrete jet components (Mirabel & Rodríguez 1999):

$$\frac{S_{app}}{S_{rec}} = \left( \frac{1 + \beta \cos \theta}{1 - \beta \cos \theta} \right)^{3 - \alpha}.$$

The receding jet component had a size of $R_{rec} = 11.9$ mas at the last epoch. The corresponding observing time for the approaching jet component is at MJD 55242.9 (between the first two epochs). At $t_{app} = t_{rec}$, the radio core is inferred to be at the centre: angular separation $\sim 174$ mas and position angle $\sim 130^\circ$. The radio core was not detected during any of the VLBI epochs but, since all four observations took place during the X-ray soft state, this is to be
expected, according to the unified model of Fender et al. (2004, 2009). The radio position confirms that its optical counterpart is Swift-UVOT source A (Curran et al. 2010). If we take the flux density at the first epoch as the upper limit of \(S_{\text{app}}\), then \(\delta_{\text{rec}} \leq 5\) and \(\beta \cos \theta \leq 0.2c < \beta(0, t_{\text{rec}}) \cos \theta\), in agreement with the jet deceleration scenario on both sides. The observed flux density from the receding jet is deboosted by a factor: \(\delta_{\text{rec}}^{-\cos \theta}\), where \(\delta_{\text{rec}} = (1 - \beta^2)^{0.5}(1 + \beta \cos \theta)^{-1}\). Because of the jet deceleration, the receding ejecta is less beamed away from our line of sight, and thus it looks relatively brighter. Note that the non-detection of the receding jet component at the first epoch may also be because it stayed at an earlier stage \((t_{\text{rec}} \sim 0.5\delta_{\text{rec}} \text{ if } \beta \cos \theta = 0.3)\) and its flux density was still much lower than the peak flux density of the radio flare. The caveat in the above argument is that component B might have not followed the same luminosity evolution model as component A. It is also possible that the brightening of the receding ejecta was due to sudden jet–cloud interaction, as in the case of XTE J1748–228 (Hjellming et al. 1998; Miller-Jones et al. 2008).

7 CONCLUSIONS

In this Letter, we present the results of the first VLBI observations of the new Galactic black hole candidate XTE J1752–223 during its first known outburst. With EVN and VLBA observations at four epochs in 2010 February, we imaged its radio counterpart at 5 GHz. We detect an ejected component at the first three epochs and find that its proper motion shows significant deviation from the uniform proper motion model and requires a deceleration rate of 0.34 ± 0.02 mas d\(^{-1}\). In the jet deceleration scenario, it has proper motion decelerating from 9.2 mas d\(^{-1}\) at the first epoch to 4.0 mas d\(^{-1}\) at the last epoch. It also shows slow but detectable variation of its transverse size indicating that its expansion is also significantly confined. This is the first time that a Galactic jet is found to be gradually decelerating on the 100 mas scale. The discovery provides strong evidence for the existence of significant interaction around the jet at an early stage of its evolution. In addition to the approaching jet component, we detect another jet feature at the last epoch, which is most likely associated with the receding ejecta. We infer that the jet deceleration should start at a time much earlier than our VLBI observations using the birth date (around 2010 February 2) from the ATCA radio light curve. Furthermore, we interpret the detection of the receding ejecta as a result of the reduced Doppler deboosting effect caused by the jet deceleration on the receding side and give a lower limit of 0.3c for the jet birth speed assuming symmetric jet motion. It has been reported by Shaposhnikov et al. (2010) that the distance, estimated by the spectral-timing correlation scaling technique, is around 3.5 kpc. Thus, the proper motion observed at the first epoch would correspond to an apparent jet speed of \(~0.2c\), in agreement with our results (but note that the technique is very model dependent).

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