Large-scale, Decelerating, Relativistic X-ray Jets from the Microquasar XTE J1550−564

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We have discovered at x-ray and radio wavelengths large-scale moving jets from the microquasar XTE J1550−564. Plasma ejected from near the black hole traveled at relativistic velocities for at least four years. We present direct evidence for gradual deceleration in a relativistic jet. The broadband spectrum of the jets is consistent with synchrotron emission from high energy (up to 10 TeV) particles accelerated in shock waves formed within the relativistic ejecta or by the interaction of the jets with the interstellar medium.
XTE J1550−564 offers a unique opportunity to study the dynamical evolution of relativistic jets on time scales inaccessible for active galactic nuclei jets, with implications for our understanding of relativistic jets from Galactic x-ray binaries and active galactic nuclei.

Collimated relativistic jets produced by active galactic nuclei (AGN) and by accretion-powered stellar compact objects in sources called microquasars (MQL) are commonly observed at radio wavelengths. Such jets are produced close to black holes (supermassive ones in AGN and stellar-mass ones in microquasars) and may help probe the dynamics of matter being accreted in intense gravitational fields. The unprecedented sub-arcsecond resolution of the Chandra x-ray observatory has recently allowed the detection of x-ray jets in many AGNs. Whereas the radio emission of AGN jets is thought to originate from synchrotron emission, the nature of the x-ray emission is still under debate, but synchrotron or inverse Compton radiation are likely involved (3). Jets produced by Galactic black holes, such as XTE J1550−564 should evolve much more rapidly than AGN jets and, therefore, could provide insights to the dynamical evolution of relativistic outflows and also to the processes of particle acceleration. Here, we present the first detection of large-scale, moving, relativistic jets ejected from a Galactic black hole binary.

The x-ray transient XTE J1550−564 (Galactic longitude and latitude \( l = 325.88^\circ, \ b = -1.83^\circ \)) was discovered by the All-Sky Monitor (ASM) aboard the Rossi X-ray Timing Explorer (RXTE) on 7 September 1998 (4). Shortly after its discovery, a strong and brief (about one day) x-ray flare was observed on 20 September 1998 (5,6) and radio jets with apparent superluminal velocities (> 2 c, where c is the speed of light) were observed starting on 24 September 1998 (7). Subsequent optical observations showed that the dynamical mass of the compact object is \( 10.5 \pm 1.0 \ M_\odot \), indicating that the compact object in XTE J1550−564 is a black hole, revealed the binary companion to be a low mass star, and led to a distance estimate of about 5.3 kpc (8).
Following the re-appearance of x-ray emission from XTE J1550−564 in early 2002 (9), we initiated a series of radio observations with the Australia Telescope Compact Array (ATCA). Observations on 16 January 2002 showed renewed activity at radio wavelengths from the XTE J1550−564 black hole binary (10). These observations also revealed a new radio source ~ 22 arc sec to the west of the black hole binary. ATCA observations performed on 29 January 2002 (Fig. 1), in an array configuration allowing higher spatial resolution imaging, showed that the western source had a possible extension pointed toward XTE J1550−564. The position angle of this radio source relative to XTE J1550−564 was –85.8° ± 1.0°, which is consistent with the position angle (–86.1° ± 0.8°, (11)) of the western component of the superluminal jet observed during the September 1998 radio flare with long baseline interferometry (7).

Prompted by the detection of the western source along the axis of the jet from XTE J1550−564, we searched archival data from Chandra taken in 2000 for x-ray sources located along the jet axis of XTE J1550−564. The field of view of XTE J1550−564 was imaged by Chandra on 9 June, 21 August and 11 September 2000. Examination of the 0.3–8 keV images (Fig. 2) revealed an x-ray source ~ 23 arc sec to the east of XTE J1550−564 at a position angle of 93.8° ± 0.9° from XTE J1550−564, lying along the axis of the eastern components of the radio superluminal jets (7) (at a position angle of 93.9° ± 0.8°; (11)). The angular separation between this eastern source and XTE J1550−564 increased from 21.3 ± 0.5 arc sec on June 9 to 23.4 ± 0.5 arc sec on September 11, implying that the eastern source moved with an average proper motion of 21.2 ± 7.2 mas day\(^{-1}\) between these two observations. This marks the first time that an X-ray jet proper motion measurement has been obtained for any accretion powered Galactic or extra-galactic source. Our radio observations (Fig. 1) performed with ATCA between April 2000 and February 2001 showed a weak, decaying, and moving radio source consistent with the position of the eastern x-ray source. It was not detected in February 2002 (Fig. 1) with a three sigma upper limit of 0.18 mJy at 3.5 cm.
With the discovery of the western radio source in early 2002, we obtained a 30 ks Chandra observation on 11 March 2002. In the resulting 0.3–8 keV image (Fig. 2), three sources were detected along the axis of the jet: the x-ray binary XTE J1550–564, an extended x-ray source at the position of the western radio source, and a faint source that is 29.0 ± 0.5 arc sec east of XTE J1550–564. This weak x-ray source was the eastern source that had smoothly decayed and moved by 5.7 ± 0.7 arc sec since September 2000. The eastern source was active during a period of at least two years (from April 2000 to March 2002).

The most remarkable feature of this Chandra observation is the discovery of x-ray emission associated with the western radio source. Both the radio and x-ray emission of the western source appeared extended towards XTE J1550–564, and the morphology matched well between the two wavelengths. Most (70%) of the x-ray emission was concentrated in the leading peak which has a full width at half maximum (FWHM) of 1.2 arc sec. A trailing tail, pointed back towards XTE J1550–564, gave a full width at 10% of maximum intensity of 5 arc sec.

The alignment of the eastern and western sources with the axis of the jet observed on 24 September 1998 (7), as well as the proper motion of the eastern source, imply that both new sources are related to the jets of XTE J1550–564. In addition, both sources are likely connected with the apparently superluminal ejecta from the brief and intense flare of 20 September 1998 (7). Indeed, large scale ejections of relativistic plasma (from XTE J1550–564) have been observed and resolved only during this occasion; radio emission when detected at other epochs has been associated with the compact jet of the low-hard x-ray spectral state (12). Also, the RXTE/ASM has not detected any other x-ray flares similar to the large flare of 20 September 1998 in subsequent monitoring. The fact that the eastern source apparently moves faster (see below) than the western source is consistent with the interpretation in which the eastern source constitutes the jet that is pointing toward Earth (the approaching jet) and the western source the
receding jet.

With the positions of the eastern (and approaching) jet on 9 June 2000 and that of the western (and receding) jet on 16 January 2002, we find average proper motions of $32.9 \pm 0.7$ mas day$^{-1}$ and $18.3 \pm 0.7$ mas day$^{-1}$, respectively. At a distance of 5.3 kpc ($8$), this corresponds to average apparent velocities on the plane of the sky of $1.0 \, c$ and $0.6 \, c$ for the eastern and western jets, respectively. The proper motion of $21.2 \pm 7.2$ mas day$^{-1}$ measured by Chandra for the eastern jet between 9 June 2000 and 11 September 2000 is significantly smaller than its corresponding average proper motion, which indicates that the ejecta decelerated after the ejection. This is confirmed by the Chandra detection of the eastern jet in March 2002, implying an average proper motion of $10.4 \pm 0.9$ mas day$^{-1}$ between 11 September 2000 and 11 March 2002. The relativistic plasma was originally ejected at greater velocities, as the relative velocity was initially greater than $2 \, c$ (the initial proper motion was greater than 57 mas day$^{-1}$ for the approaching jet, ($7$)). These observations provide the first direct evidence for gradual deceleration of relativistic materials in a jet. Previous observations of other microquasars are consistent with purely ballistic motions (e.g. ($2,13$)) except for the system called XTE J1748\(-288$, where, after ballistic ejections, the jet was observed to stop suddenly, presumably following a collision with environmental material ($14, 15$).

The eastern and western jets have been detected up to angular separations from XTE J1550\(-564$ of 29 arc sec and 23 arc sec, respectively, which correspond to projected physical separations of 0.75 pc and 0.59 pc, respectively, for a distance of 5.3 kpc ($8$). These are large distances for moving relativistic ejecta (in GRS 1915\(+105$, the ejecta have been observed to travel up to projected distance of 0.08 pc and on a maximum time scale of four months, ($9$)). Persistent large scale (1-3 pc) jets have previously been observed only at radio wavelengths, e.g. 1E 1740.7\(-2942$ and GRS 1758\(-258$ ($16, 17$), but without indication of associated moving ejecta. Our observations reveal that the relativistic ejecta of a Galactic black hole have been
able to travel over parsec scale distances at relativistic velocities during several years. An important aspect of our discovery is that it provides the first direct evidence for a large-scale, moving x-ray jet from any black hole (Galactic or in AGN).

SS 433 is the only other x-ray binary for which large scale (up to \( \sim 40 \) arc min, i.e. several tens of parsecs), non-thermal x-ray emission has been previously observed, probably associated with interactions of the jets with the interstellar medium (ISM) \([18, 19, 20, 21, 22]\). The helical pattern observed in the lobes, at radio wavelengths, indicates a connection between the lobes and the corkscrew pattern associated with plasma ejection close to (on arc sec scale) the core of the SS 433/W50 system \([23]\). However, relativistic motion at large scales has not been observed in SS 433. We note that thermal X-ray emission arising from moving relativistic ejecta, but only out to \( \sim 0.05 \) pc from the compact object, has been reported in SS 433 \([24, 25]\).

Our results demonstrate that the emission from relativistic ejecta of Galactic black holes can be observed at wavelengths extending up to x-rays. Future sensitive, high-resolution observations of other Galactic black hole jets in the infrared \([26]\), optical, and x-rays bands may reveal that broadband emission from relativistic ejecta of Galactic black holes is more common than previously thought and offer an exciting way to probe the physics of the jets. AGN jets, which were previously detected at radio and optical wavelengths, are now known, with the advent of the Chandra observatory, to often produce x-rays. Whereas the radio emission of AGN jets is thought to originate from synchrotron emission, the nature of the x-ray emission has not always been clearly identified. Although it is thought to be non-thermal, it is not always known whether synchrotron or inverse Compton radiation predominates for a particular object \([3, 27, 28, 29]\).

The nature of the physical mechanism producing the emission from the relativistic jets of XTE J1550–564 can be understood by looking at the broadband spectrum, e.g. for the western jet on 11 March 2002 (Fig. 3). The position and morphology of the radio and x-ray counterparts of the western jet are consistent with each other (Figs 1 and 2) and the spectral energy distribu-
tion is consistent with a single power law (of spectral index $-0.660 \pm 0.005$). These facts favor a scenario in which the broadband emission from the jets is synchrotron emission from high energy particles. Similar conclusions could be drawn for the eastern jet in 2000, because the overall radio flux was also consistent with an extrapolation of the x-ray spectrum with a spectral index of $-0.6$. Detection of x-ray synchrotron emission would imply a large Lorentz factor, of the order of $2 \times 10^7$ (corresponding to an energy of $\sim 10$ TeV), for the x-ray emitting electrons (under the equipartition assumption giving a magnetic field of $\sim 0.3$ mG).

Acceleration in a shock wave is the most likely origin for the very high energies required. Shock waves could be produced by internal instabilities (30) or by varying flow speeds within the jet, as proposed to occur in some models of gamma-ray bursts or AGNs (31, 32). If several relativistic plasmoids were ejected around 24 September 1998 (7) and their velocities were slightly different, then it would have taken several months (maybe years) for them to collide. Such a collision would have produced shock waves, particle acceleration, and the brightening of the jets.

A more plausible alternative is that the shock waves are produced when the jet material moving with bulk relativistic speed interacts with the ISM (i.e. an external shock). In fact, the gradual deceleration we observed for the eastern jet would be easily explained by such interactions. Inhomogeneities in the ISM could also be at the origin of the brightening of the eastern and western jet at different epochs. The origin of the western jet is less clear as no proper motion has been yet observed. Future observations will show whether or not the western jet is still moving and together with high spatial resolution observations and broadband spectra will be important in deciding between the models (internal or external shocks). Also, regular observation of the jets of XTE J1550$-$564 would map the propagation of the shocks and allow estimation of the energy dissipated in the jets while decelerating in the ISM. Therefore, XTE J1550$-$564 offers a unique opportunity to study the dynamical evolution of relativistic
jets on time scales inaccessible for AGN jets, and has implications not only for the study of jets from Galactic x-ray binaries, but also for our understanding of relativistic jets from AGNs.
References and Notes

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Figure 1: Uniform weighted maps of the field of view around the black hole candidate XTE J1550−564 on 1 June 2000 (top) and 29 January 2002 (bottom) showing the radio counterpart to the eastern and western jets (when detected). The stationary black hole binary XTE J1550−564 is at the center of the image, and has a radio spectrum typical of the self-absorbed compact jet (33, 34) that is observed during the x-ray low/hard spectral state (ref 12).

(A) (1 June 2000): Map at 4800 MHz (6 cm). The position of the eastern radio jet is $\alpha_{\text{J2000}} = 15h 51m 01s.30$ and $\delta_{\text{J2000}} = -56^\circ 28' 36.9''$ with a total uncertainty of 0.3 arc sec. The synthesized beam (in the lower right corner) is $5.5 \times 2.1$ arc sec with the major axis in position angle of $63.1^\circ$. The peak brightness in the image is 1.1 mJy per beam. Contours are plotted at $-3$, $3$, $4$, $5$, $6$, $9$ times the r.m.s. noise equal to 0.1 mJy per beam. The cross marks the position of the western jet, as measured on 29 January 2002.

(B) (29 January 2002): Map at 8640 MHz (3.5 cm). The position of the western radio jet is $\alpha_{\text{J2000}} = 15h 50m 55s.94$ and $\delta_{\text{J2000}} = -56^\circ 28' 33.5''$ with a total uncertainty of 0.3 arc sec. The synthesized beam is $2.4 \times 1.3$ arc sec with the major axis in position angle of $-54.6^\circ$. The peak brightness in the image is 1.79 mJy per beam. Contours are plotted at $-3$, $3$, $4$, $5$, $6$, $9$, $15$, $20$, $30$ times the r.m.s. noise equal to 0.05 mJy per beam. The cross marks the position of the eastern jet, as measured on 11 March 2002 during the Chandra observation.
Figure 2: *Chandra* 0.3–8 keV images (using the Advanced CCD Imaging Spectroscopy array ACIS-S), which show the black hole binary XTE J1550–564 (center), the approaching eastern x-ray jet (left) and the receding western x-ray jet (right). The observations are ordered chronologically from top to bottom, and each image is labeled with the observation date. These filled contour plots have been produced by convolving the original Chandra image with a 2-dimensional Gaussian with a width of 2 pixels in both directions. In 2000 (A), there are 11 contours between the lowest contour of $1.33 \times 10^{-3} \text{ count s}^{-1} \text{ pixel}^{-1}$ and the highest contour of $8.16 \times 10^{-3} \text{ count s}^{-1} \text{ pixel}^{-1}$. The same contour levels are used in all three 2000 images, but it should be noted that the flux levels for 9 June 2000 are not directly comparable to those for the other two observations because a grating was inserted for the June 9 observation. For the 2002 image (B), there are 11 contours between $0.33 \times 10^{-3} \text{ count s}^{-1} \text{ pixel}^{-1}$ and $8.16 \times 10^{-3} \text{ count s}^{-1} \text{ pixel}^{-1}$. The dashed lines mark the positions of XTE J1550-564 and the eastern x-ray jet on September 11 when the sources were separated by $23''$.4. The proper motion of the x-ray jet is $21.2 \pm 7.2 \text{ mas day}^{-1}$ between 9 June 2000 and 11 September 2000 and averages $10.4 \pm 0.9 \text{ mas day}^{-1}$ between 11 September 2000 and 11 March 2002, indicating deceleration of the jet. Assuming a power-law spectral shape with a photon index of 1.7 and interstellar absorption of $N_\text{H} = 9 \times 10^{21} \text{ cm}^{-2}$, a count rate of $1.33 \times 10^{-3} \text{ count s}^{-1}$ corresponds...
Figure 3: The spectral energy distribution of the western jet around 2002 March 11. The radio points near $10^{10}$ Hz are ACTA measurements from March 6. The radio flux density were 5.7 ± 0.3, 3.60 ± 0.08 and 2.55 ± 0.07 mJy at 2496, 4800, 8640 MHz respectively, giving a spectral index of −0.63 ± 0.05 in the radio range. The x-ray measurement near $5 \times 10^{17}$ Hz is the Chandra measurement from March 11. X-ray spectral fitting of the Chandra data for the western source assuming a powerlaw form with interstellar absorption fixed to the total Galactic HI column density ($N_H = 9.0 \times 10^{21}$ cm$^{-2}$) gives a spectral index of −0.70 ± 0.15 (90% confidence level). The spectrum may be somewhat steeper if there is additional absorption near the source. The unabsorbed 0.3–8 keV flux is $3.8 \times 10^{-13}$ ergs cm$^{-2}$ s$^{-1}$ (i.e. 18 nJy at 2.2 keV). The optical upper limits (99% confidence level) in between are derived from deep observations carried out with the 8.2 metre Unit 3 telescope at the European Southern Observatory, Paranal. The source was observed with the FORS1 instrument in the Bessel $V$ and $R$ filters on March 10, with limiting magnitudes for point sources of 25.2 and 25.5 mag., respectively, and on March 18 with FORS1 and the Bessel $I$ filter, with a limiting magnitude for point sources of 25.5 mag. We assumed an optical extinction of $A_V = 4.75$ mag. The broadband spectral energy distribution is consistent with a single powerlaw of spectral index −0.660 ± 0.005.