Evolution of relativistic jets from XTE J1550-564 and the environment of microquasars

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Abstract. Two relativistic X-ray jets have been detected with the Chandra X-ray observatory in the black hole X-ray transient XTE J1550-564. We report a full analysis of the evolution of the two jets with a gamma-ray burst external shock model. A plausible scenario suggests a cavity outside the central source and the jets first travelled with constant velocity and then are slowed down by the interactions between the jets and the interstellar medium (ISM). The best fitted radius of the cavity is $\sim$0.36 pc on the eastern side and $\sim$0.46 pc on the western side, and the densities also show asymmetry, of $\sim$0.015 cm$^{-3}$ on the east to $\sim$0.21 cm$^{-3}$ on the west. Large scale low density region is also found in another microquasar system, H 1743-322. These results are consistent with previous suggestions that the environment of microquasars should be rather vacuous, compared to the normal Galactic environment. A generic scenario for microquasar jets is proposed, classifying the observed jets into three main categories, with different jet morphologies (and sizes) corresponding to different scales of vacuous environments surrounding them.

Keywords: microquasars; jets; outflows; black hole accretion; XTE J1550-564; X-ray; ISM; GRB afterglow theory

PACS: 04.20.-q; 04.20.Cv; 04.20.Dw; 04.20.Gz; 04.20.Jb; 04.70.-s; 04.70.Bw; 95.30.Sf; 97.60.Lf

INTRODUCTION

Microquasars are well known miniatures of quasars, with a central black hole (BH), an accretion disk and two relativistic jets very similar to those found in the centers of active galaxies, only on much smaller scales (Mirabel & Radríguez 1999).

Since discovered in 1992, radio jets have been observed in several BH binary systems and some of them showed apparent superluminal features. In the two well known microquasars, GRS 1915+105 (Mirabel & Radríguez 1999) and GRO J1655-40 (Tingay et al.1995; Hjellming & Rupen 1995), relativistic jets with actual velocities greater than 0.9c were observed. In some other systems, small-size "compact jets", e.g. Cyg X-1 (Stirling et al. 2001), and large scale diffuse emission, e.g. SS433 (Dubner et al. 1998), were also detected.

XTE J1550-564 was discovered with RXTE in 1998 during its strong X-ray outburst on September 7 (Smith 1998). It is believed to be an X-ray binary system at a distance of $\sim$5.3 kpc, containing a black hole of 10.5$\pm$1.0 solar masses and a low mass companion star (Orosz et al. 2002). Soon after the discovery of the source, a jet ejection with an apparent velocity greater than 2c was reported (Hannikainen et al. 2001). In the period between 1998 and 2002, several other outbursts occurred but no similar radio and X-ray
FIGURE 1. The smoothed Chandra X-ray images of the eight observations of XTE J1550-564 and the two jets together. The green elliptical regions are source emission regions by wavdetect. Observation 4 shows the good alignment of the two jets and the central source.

flares were detected again in these outbursts (Tomsick et al. 2003).

With the help of the Chandra satellite, Corbel et al (2002) found two large scale X-ray jets lying to the east and the west of the central source, which were also in good alignment with the central source. The eastern jet has been detected first in 2000 at a projected distance of \( \sim 21 \) arcsec from the central black hole. Two years later, it could only be seen marginally in the X-ray image, while a western counterpart became visible at \( \sim 22 \) arcsec on the other side. The corresponding radio maps are consistent with the X-ray observations (Corbel et al. 2002).

There are altogether eight 2-dimentional imaging observations of XTE J1550-564 in Chandra archive during June 2000 and October 2003 (henceforth observations 1\~8). Here we report a full analysis of these X-ray data, together with the kinematic and spectral evolution fittings for all these observations.

**OBSERVATIONS OF XTE J1550-564**

The basic information of observations 1\~8 is listed in Table 1, including the observation ID, date, and the angular separation between the eastern and western jets and the central source. The positions are obtained by the Chandra Interactive Analysis of Observations (CIAO) routine wavdetect (Freeman et al. 2002). In observations 5 and 6, no X-ray source is detected by wavdetect at the position of the eastern jet. However, from the smoothed images (Fig.1), a weak source could be recognized in observation 6. We thus select the center of the strongest emission region as the position of the jet in that observation. We calculate the source centroid for the central source and the X-ray jet respectively and for all the five observations, the calculated position changed by less than 0.5\". Therefore, an upper limit of 0.5\" is set for the error of the jet distance.

From Table 1 and Fig.1, we could see clearly that an X-ray emission source is detected to the east of the central source in the first four observations and another source is detected to the west in the last five observations. Calculations also show that these
| Num | ID   | Date       | Eastern Jet | Western jet | Photon Index | Flux (ergs cm$^{-2}$ s$^{-1}$) |
|-----|------|------------|-------------|-------------|--------------|-------------------------------|
| 1   | 679  | 2000 06 09 | 21.5±0.5    |             |              |                               |
| 2   | 1845 | 2000 08 21 | 22.8±0.5    |             |              |                               |
| 3   | 1846 | 2000 09 11 | 23.4±0.5    |             |              |                               |
| 4   | 3448 | 2002 03 11 | 28.6±0.5    | 22.6±0.5    | 1.75±0.11    | (1.9 ± 0.4) × 10$^{-13}$      |
| 5   | 3672 | 2002 06 19 | 23.2±0.5    | 23.4±0.5    | 1.71±0.15    | (1.6 ± 0.3) × 10$^{-13}$      |
| 6   | 3807 | 2002 09 24 | 29.2±0.5    | 23.4±0.5    | 1.94±0.17    | (8.6 ± 1.5) × 10$^{-14}$      |
| 7   | 4368 | 2003 01 28 | 23.7±0.5    | 23.4±0.5    | 1.81±0.22    | (5.5 ± 1.0) × 10$^{-14}$      |
| 8   | 5190 | 2003 10 23 | 24.5±0.5    | 1.97±0.20   | (3.1 ± 0.6) × 10$^{-14}$      |

two sources, when presented in a single combined image, are in good alignment with the central compact object with an inclination angle of 85.9°±0.3°. By calculating the average proper motion, an approximate estimate of deceleration could be seen for both jets.

ENERGY SPECTRUM AND FLUX

Since the emission from the eastern jet has been studied fully (Corbel et al. 2002; Tomsick et al. 2003), we mainly focus our spectral analysis on the western jet. The X-ray spectrum in 0.3-8 keV energy band is extracted for each observation of the western jet. We use a circular source region with a radius of 4″, an annular background region with an inner radius of 5″ and an outer radius of 15″, for each observation. Instrument response matrices (rmf) and weighted auxiliary response files (warf) are created using CIAO programs mkacisrmf and mkwarf, and then added to the spectra. We re-bin the spectra with 10 counts per bin and fit them in Xspec.

The results of spectra fitting with an absorbed power-law model are also shown in table 1. We use the Cash statistic since it is a better method when counts are low. The absorption column density is fixed to the Galactic value in the direction of XTE J1550-564 obtained by the radio observations ($N_H = 9 \times 10^{21} \text{cm}^{-2}$) (Dickey & Lockman 1990). Our results are quite consistent with previous works by Karret et al.(2003). The calculated absorbed energy flux in 0.3-8 keV band is comparable to the value of the eastern jet. The observed flux decayed rather quickly, from $\sim 1.9 \times 10^{-13} \text{erg cm}^{-2} \text{s}^{-1}$ in March 2002 to only one sixth of this value in October 2003 (see section 4.2).

JET MODEL

Kinematic Model

In the external shock model for afterglows of GRBs, the kinematic and radiation evolution could be understood as the interaction between the outburst ejecta and the surrounding ISM. Microquasar jet systems are also expected to encounter such interac-
tions. In this section, we describe our attempts after Wang et al. (2003) in constructing
the kinetic and radiation model based on these theories.

We adopt the model of a collimated conical beam with a half opening angle \( \theta_j \)
expanding into the ambient medium with the number density \( n \). The initial kinetic
energy and Lorentz factor of the outflow material are \( E_0 \) and \( \Gamma_0 \), respectively. Shocks
should arise as the outflow moves on and heat the ISM, and its kinetic energy will turn
into the internal energy of the medium gradually. Neglect the radiation loss, the energy
conservation function writes (Huang, Dai, & Lu 1999):

\[
(\Gamma - 1)M_0c^2 + \sigma(\Gamma_{\text{sh}}^2 - 1)m_{\text{sw}}c^2 = E_0
\]  

(1)

The first term on the left of the equation represents the kinematic energy of the
ejecta, where \( \Gamma \) is the Lorentz factor and \( M_0 \) is the mass of the original ejecta. The
second term represent the internal energy of the swept-up ISM, where \( \Gamma_{\text{sh}} \) and \( m_{\text{sw}} \)
are the corresponding Lorentz Factor and mass of the shocked ISM respectively, and
\( m_{\text{sw}} = \left(\frac{4}{3}\right)\pi R^3 m_p n \left(\frac{\theta_j^2}{4}\right) \).

Coefficient \( \sigma \) differs from 6/17 to 0.73 for ultrarelativistic and nonrelativistic jets.
We adopt the approximation of \( \sigma \sim 0.7 \) after Wang et al.(2003). Equation (1) and the
relativistic kinematic equations

\[
\frac{dR}{dt}_a = \frac{\beta(\Gamma)c}{1 - \beta(\Gamma)\cos \theta}, \frac{dR}{dt}_r = \frac{\beta(\Gamma)c}{1 + \beta(\Gamma)\cos \theta}
\]  

(2)

can be solved and give the relation between the projected angular separation \( \mu \) and time
\( t \). In equation (2), the subscript \( a \) and \( r \) represent the approaching and receding jets in
a pair of relativistic jets respectively. \( R \) is the distance between the jet and the source,
which can be transformed into the proper motion separation by \( \mu = R \sin \theta / 5.3 \text{ kpc} \), and
\( \theta \) is the jet inclination angle to the line of sight. We can get the \( \mu - t \) curve numerically
with the above equations. To be consistent with the work done to the eastern jet, we
choose the same initial conditions that \( \Gamma_0 = 3, E_0 = 3.6 \times 10^{44} \text{ erg}, \) and \( \theta_j = 1.5 \). Then
the parameters needed to be fit are \( n \) and \( \theta_j \).

In the case of the eastern jet, the number density of the ISM was assumed as a constant
in the whole region outside the central source. This assumption does not work well in
the case of its western counterpart. The western jet decelerated quite fast, requiring a
local dense environment, but if the ISM is dense everywhere, the jet will be unable to
travel that far from the central BH. As a result, we consider a model that the ISM density
varies as the distance changes. For simplicity, we test the ideal case that the jet travelled
first through a “cavity" with a constant velocity and then through a dense region and was
decelerated there. A new parameter \( r \), the outer radius of the cavity, is introduced and
the ISM number density is set to be a constant \( n \) outside this region and zero inside. The
fittings improved a lot but not well constrained because of the limited number of the data
points. A combination of Lightcurve fitting is required to help the determination.
Radiation Model

In the standard GRB scenario, the afterglow emission is produced by the synchrotron radiation or inverse Compton emission of the accelerated electrons in the shock front of the jets (Wang et al. 2003 and references there). Wang et al.(2003) found that the reverse shock emission, originating from the electrons of the jet when a shock moves back through the ejecta, decay rather fast and describe the data of the eastern jet quite well. We thus take this model in our work as well.

Assuming the distribution of the electrons obeys a power-law form, \( n \gamma_e d \gamma_e = K \gamma_e^{-p} d \gamma_e \), for \( \gamma_e < \gamma_e < \gamma_a \), the volume emissivity at frequency \( \nu' \) in the comoving frame is given by

\[
j_{\nu'} = \frac{\sqrt{3} q^3}{2 m c^2} \left( \frac{4 \pi m_c \nu'}{3 q} \right)^{(1-p)} \left( \frac{B_{\perp}}{B_{\pm}} \right)^{\frac{p+1}{2}} K F_1 (\nu', \nu_a', \nu_a),
\]

where \( F_1 (\nu, \nu_a', \nu_a) = \int_{\nu_a'}^{\nu_a} F(x) x^{(p-3)/2} dx \), with \( F(x) = x x_0^{5/3} K_{5/3}(t) \) and \( K_{5/3}(t) \) is the Bessel function. The physical quantities in these equations include \( q \) and \( m_\gamma \), the charge and mass of the electron, \( B_{\perp} \), the magnetic field strength perpendicular to the electron velocity, and \( \nu_a' \) and \( \nu_a' \), the characteristic frequencies for electrons with \( \gamma_e \) and \( \gamma_a \).

Assuming the reverse shock heats the ejecta at time \( t_0 \) at the radius \( R_0 \), the physical quantities in the adiabatically expanding ejecta with radius \( R \) will evolve as \( \gamma_e = \gamma_e (t_0) R_0 / R, \gamma_a = \gamma_a (t_0) R_0 / R \) and \( K = K (t_0) (R / R_0)^{-2+p}, B_{\perp} = B_{\perp} (t_0) (R / R_0)^{-2} \), where the initial values of these quantities are free parameters to be fitted in the calculation.

With these assumptions, we can then calculate the predicted flux evolution of the jets. The comoving frequency \( \nu' \) relates to our observer frequency \( \nu \) by \( \nu = D \nu' \), where \( D \) is the Doppler factor and we have \( D_1 = 1 / \Gamma (1 - \beta \cos \theta) \) and \( D_2 = 1 / \Gamma (1 + \beta \cos \theta) \) for the approaching and receding jets respectively. Considering the geometry of the emission region, the observed X-ray flux in 0.3-8 keV band could be estimated by

\[
F(0.3-8 \text{ keV}) = \int_{\nu_0}^{\nu_b} \frac{\nu^2}{4} \left[ \frac{\Delta R}{d} \right] \Delta R D^3 \nu' d\nu',
\]

where \( \Delta R \) is the width of the shock region and is assumed to be \( \Delta R = R / 10 \) in the calculation.

To reduce the number of free parameters, we set \( \gamma_a = 100 \) in our calculation because the results are quite insensitive to this value. We choose the time that the reverse shock takes place according to our kinematic model in section 3.1. Then we fit the data to find out the initial values of \( K \) and \( B_{\perp} \).

Next step, we combine the kinematic and radiation fitting together. We know that the energy and the number density of the gas in the pre-shock and post-shock regions are connected by the jump conditions \( n' = \tilde{\xi} \Gamma n \) and \( \epsilon' = \eta \Gamma n m' c^2 \), where \( \tilde{\xi} \Gamma \) and \( \eta \Gamma \) are coefficients related to the jet velocity. Therefore if we assume the shocked electrons and the magnetic field acquire constant fractions \( (\epsilon_e, \epsilon_e) \) of the total shock energy, we have \( \gamma_e' = \epsilon_e (p-2) m_e (\Gamma-1) / (p-1) m_e, K = (p-1) n' \gamma_e^{p-1}, \) and \( B_{\perp} = \sqrt{8 \pi \epsilon_e \rho} \).

If we further assume that the \( \epsilon_e \) of the eastern and the western jets is the same, we may infer that \( K \propto \epsilon_e' \propto n \) for the two jets. As a result, we search for the combination...
of parameters that could satisfy the kinematic and radiation fitting, as well as the relationship $K_e/K_w \sim n_e/n_w$.

A set of parameters has finally been found (Please refer to the left panel in Fig.2). The boundary of the cavity lies at $r \sim 14$ arcsec to the east and $\sim 18$ arcsec to the west of the central source. The corresponding number density of the ISM outside this boundary is $\sim 0.00675$ cm$^{-3}$ and $\sim 0.21$ cm$^{-3}$, respectively. These values are both lower than the canonical ISM value of $\sim 1$ cm$^{-3}$, although the value in the western region is much higher than in the eastern region. The electron energy fraction relationship is satisfied as $K_e/K_w \sim n_e/n_w \sim 0.03$. But the other relation concerning the magnetic field strength could not be satisfied simultaneously by these parameters. Although the cavity radius and the number density are allowed to vary significantly, the best fitted magnetic field strength remains quite stable($\sim 0.4$-0.6 mG). One possible interpretation for this is that the equipartition parameter varies as the physical conditions of the jet varies; an alternative explanation may involve the in situ generation (or amplification) of the magnetic field.

**CONCLUSION AND DISCUSSIONS**

External shock model shows that a large scale cavity exists outside XTE J1550-564. This model has also been applied to another X-ray transient H 1743-322. Chandra X-ray and ATCA radio observations of this source from 2003 November to 2004 June revealed the presence of large-scale ($\sim 0.3$ pc) jets with velocity $v/c \sim 0.8$ (Rupen et al. 2004; Corbel et al. 2005). Deceleration is also confirmed in this system. The external shock model describes the data of this source consistently. A cavity of size $\sim 0.12$ pc is likely to exist, but not very clear in this case. Even if there is no vacuum cavity, the ISM density is found to be extremely low($\sim 3 \times 10^{-4}$ cm$^{-4}$), compared to the canonical Galactic value.

These studies led us to the suggestion that in microquasars the interactions between the ejecta and the environmental gas play major roles in the jet evolution and the low density of the environment is a necessary requirement for the jet to develop to a long distance.

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When putting together all the analyses of microquasar jets, we found that microquasar jets can be classified into roughly three groups: small scale moving jets, large scale moving jets and large scale jet relics. For the first type, the “small jets”, only radio emissions are detected. The jets are always relatively close to the central source and dissipate very quickly, including GRS 1915+105 (Rodríguez & Mirabel 1999; Miller-Jones et al. 2007), GRO J1655-40 (Hjellming & Rupen 1995), and Cyg X-3 (Marti et al. 2001). The typical spatial scale is $0.05 \sim 0.05$ pc and the time scale is several tenths of days. No obvious deceleration is observed before the jets become too faint. For the second type, the “large jets”, both X-ray and radio detections are obtained, at a place far from the central source several years after the outburst. Examples are XTE J1550-564, H1743-322, and GX 339-4 (Gallo et al. 2004). The typical jet travelling distance for this type is $0.2 \sim 0.5$ pc from the central engine and deceleration is clearly observed. The last type, the “large relics”, is a kind of diffuse structures observed in radio, optical and X-ray band, often ring or nebula shaped that are not moving at all. In this class, some well studied sources, Cygnus X-1 (Gallo et al.2005), SS433 (Dubner el al.1998), Circinus X-1 (Stewart et al. 1993) and GR1758-258 (Rodríguez et al. 1992) are included. The typical scale for this kind is $1 \sim 30$ pc, an order of magnitude larger than the second type. The estimated lifetime often exceeds one million years, indicating that they are related to previous outbursts.

From these properties, it is reasonable to further suggest a consistent picture involving all the sources together. We make a conjecture that large scale cavities, exist in all microquasar systems. The “small jets” observed right after the ejection are just travelling through these cavities. Since there are few or none interactions between the jets and the surrounding gas in this region, the jets travel without obvious deceleration. The emission mechanism is synchrotron radiation by particles accelerated in the initial outburst. The emissions of jets decay very quickly and are not detectable after several tenths of days. In some cases (e.g. XTE J1550-564), the cavity has a dense (compared to the cavity) boundary at some radius and the interactions between the jets and the boundary gas heat the particles again and thus make the jets detectable again. Those are the “large jets”. The emission mechanism then is synchrotron radiation by the re-heated particles in the external shocks. Then, after these interactions, the jets lost most of their kinetic energy into the ISM gradually, causing the latter to expand to large scale structures, the “large relics”, in a comparatively long time (several millions of years).

The creation of the cavities is not clear at this stage. Possible mechanism may involve supernova explosion, companion star winds or disk winds. Since some of the sources most likely never had supernovae before and the winds from the companion stars are not strong enough, the accretion disk winds may be the most plausible possibility. However, these assumptions all require further observations to justify.

Microquasars are powerful probes of both the central engine and their surrounding environment. More studies of the jets behaviors may give us information on the ISM gas properties, as well as the ejecta components. It will provide insights of the jet formation process and offer another approach into black hole physics and accretion flow dynamics.
ACKNOWLEDGMENTS

We thank Dr. Yuan Liu, Shichao Tang and Weike Xiao for useful discussions and Xiangyu Wang for providing the model codes. SNZ is grateful to Prof. Sandip Chakrabarti for his great effort in organizing this conference, and to the great hospitality of S.N. Bose National Centre for Basic Sciences, Kolkata, India. SNZ acknowledges partial funding support by the Yangtze Endowment from the Ministry of Education at Tsinghua University, Directional Research Project of the Chinese Academy of Sciences under project No. KJCX2-YW-T03 and by the National Natural Science Foundation of China under project no. 10521001, 10733010 and 10725313.

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