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Large scale jets in Microquasars

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Abstract. Relativistic jets are now believed to be a fairly ubiquitous property of accreting compact objects, and are intimately coupled with the accretion history. Associated with rapid changes in the accretion states of the binary systems, ejections of relativistic plasma can be observed at radio frequencies on timescale of weeks before becoming undetectable. However, recent observations point to long term effects of these ejecta on the interstellar medium with the formation of large scale relativistic jets around binary systems. In this paper, we review the observations of these large scale structures in microquasars, highlighting their contributions at high energies.

Key words. black hole physics – radio continuum: stars – ISM: jets and outflows

1. Introduction: relativistic ejections from X-ray binaries.

During periods of outburst activity in black hole (BH) binaries, strong radio flares are sometimes observed around the transition from the hard state to the soft state (more precisely from the intermediate state to the steep power law state; Corbel et al. 2004). This is usually interpreted as synchrotron emission from relativistic electrons ejected from the system with large bulk velocities. In a few cases, such jets have been directly resolved into one-sided (or two-sided) components moving away from the stationary core with apparent velocities greater than the speed of light. After ejection, the moving plasma condensations are observed in the radio band for a few weeks until their emission fadesbelow detection level due to adiabatic expansion. GRS 1915+105 (Mirabel & Rodríguez 1994) and GRO J1655−40 (Tingay et al. 1995; Hjellming & Rupen 1995) are the first two so-called superluminal sources.

Since 1994, the number of BHs displaying apparent superluminal motion has greatly increased. For example XTE J1550−564 (Hannikainen et al. 2001), XTE J1748−288 (Rupen et al. 1998), V4641 Sgr (Hjellming et al. 2000; Orosz et al. 2001) and GX 339-4 (Gallo et al. 2004; Hynes et al. 2004) exhibited such behaviours and it is reasonable to think that all BHs (and also some neutron stars) are likely to exhibit highly relativistic jets at some point in their lifetimes. In fact, in recent years, almost all active BHs have been associated with radio emission.

2. The historical large scale radio lobes: 1E 1740.7−2942 and GRS 1758−258.

Historically, the "morphological bridge" (and hence the name microquasar) between the Galactic stellar mass black holes and the supermassive black hole at the center of Active Galactic Nuclei has been brought to light in

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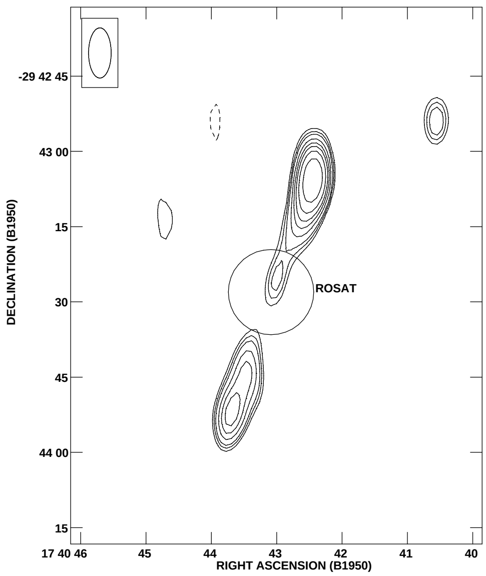

Fig. 1. Large scale radio jets (at 4.8 GHz) from 1E1740.7-2942 (Mirabel et al. 1992).

1992 with the discovery of large scale radio jets in two Galactic systems. Indeed, the BHs 1E 1740.7−2942 (Fig. 1 from Mirabel et al. 1992) and GRS 1758−258 (Martí et al. 2002) in the Galactic Bulge are located at the center of two large (about 3 light years) scale radio lobes, probably indicating the long term action of past relativistic ejections on the surroundinGX339−4 ISM.

3. Large scale decelerating X-ray jets in XTE J1550−564.

Recently, X-ray observations (Fig. 2) by Chandra have led to the discovery of extended (up to 30″) X-ray jet emission from the microquasar XTE J1550−564. In observations made between June 2000 and January 2003, two sources moving away from the XTE J1550−564 black hole are detected. The most likely scenario (Corbel et al. 2002) is that the eastern jet is the approaching jet and the western jet the receding jet, and that the jet material was ejected from the black hole during a major radio flare in September 1998 (Hannikainen et al. 2001). Both the radio and X-ray emission of the western jet appeared extended towards XTE J1550−564, and the morphologies associated with each wavelength matched well. The broadband spectra of the jets are consistent with synchrotron emission from high-energy (up to 10 TeV) particles accelerated in shocks formed by the interaction of the jets with the ISM (Corbel et al. 2002) (i.e. similar to the stationary non-thermal emission from the large scale lobes in SS 433 (Seward et al. 1980).

The full set of X-ray and radio observations also provided the first direct evidence for gradual deceleration of relativistic material in a jet. More details on the X-ray jets of XTE J1550−564 can be found in Corbel et al. (2002), Tomsick et al. (2003) and Kaaret et al. (2003). These results indicate that emission due to relativistic plasma ejected in September 1998 has been detected for at least 5 years (S. Corbel, in prep.) as direct beamed X-ray emission, and demonstrate that Galactic BHs are able to accelerate particles up to very high energies.

4. A large scale fossil X-ray jet in 4U 1755−33

Very recently, Angelini & White (2003) reported the XMM-Newton detection of large scale (7′) persistent X-ray jets (Fig. 3) centered on the position of 4U 1755−33, a black hole candidate. Chandra observations (Park et al. 2004) confirm that the jetlike feature observed by XMM-Newton is truly diffuse and is not associated with knots like emission. 4U 1755−33 had been a bright, persistent source for at least twenty years until it became X-ray quiet in 1995. If the jet had a velocity close to c, then it would have taken about 13 years to expand to its currently observed length of $\approx$ 4 pc (for a distance of 4 kpc). The jet/ISM interaction in 4U 1755−33 might be similar to that seen in XTE J1550−564, provided the jets were being ejected quasi-continuously over its twenty years of X-ray activity.

The scale of the moving X-ray and radio lobes (0.5 to 0.8 pc) in XTE J1550−564 is intermediate in size between the moving "super-

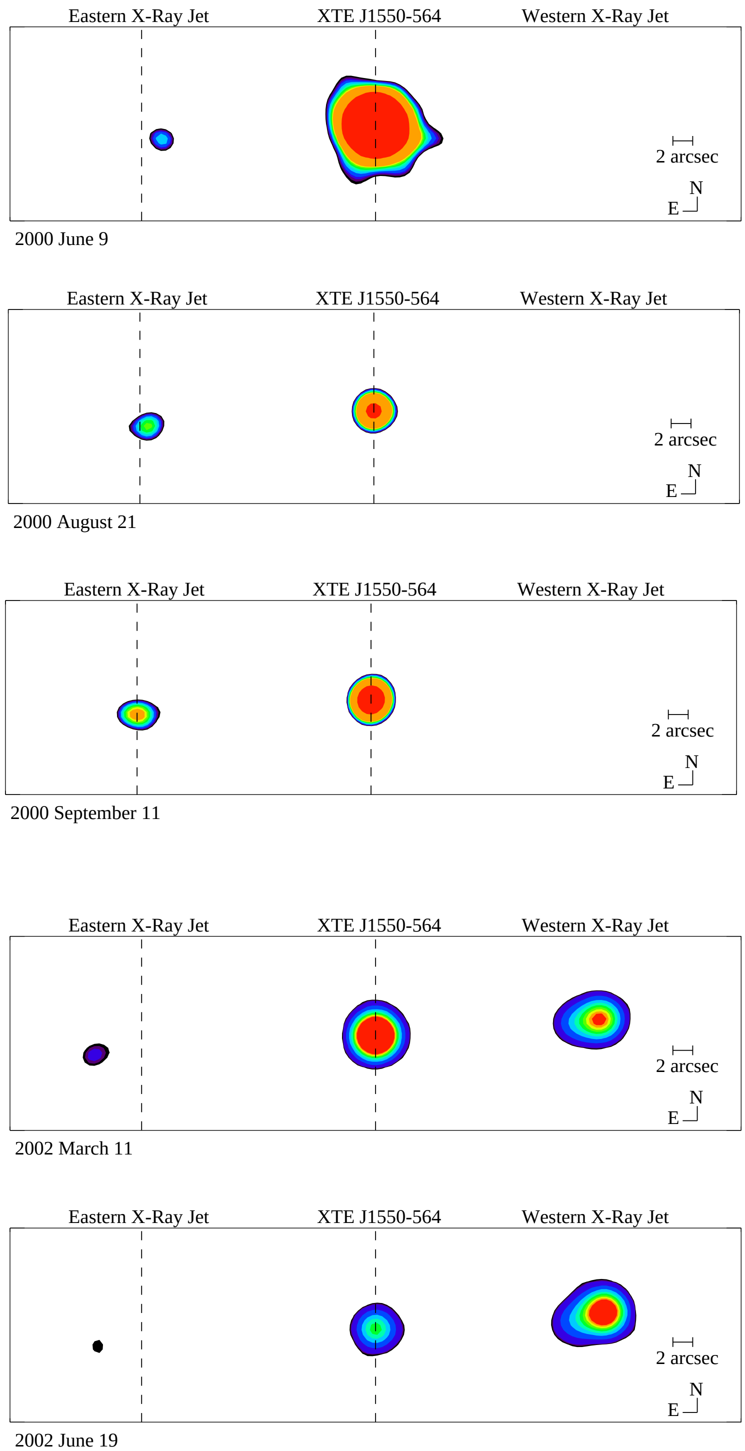

Fig. 2. Five *Chandra* 0.3-8 keV images showing the evolution of the eastern and western X-ray jets from XTE J1550–564, between June 2000 and June 2002. The observations are ordered chronologically from top to bottom, and each image is labeled with the observation date. The dashed lines mark the positions of XTE J1550-564 and the eastern X-ray jet on 11 September 2000. Adapted from Corbel et al. 2002; Kaaret et al. 2003; Tomsick et al. 2003.

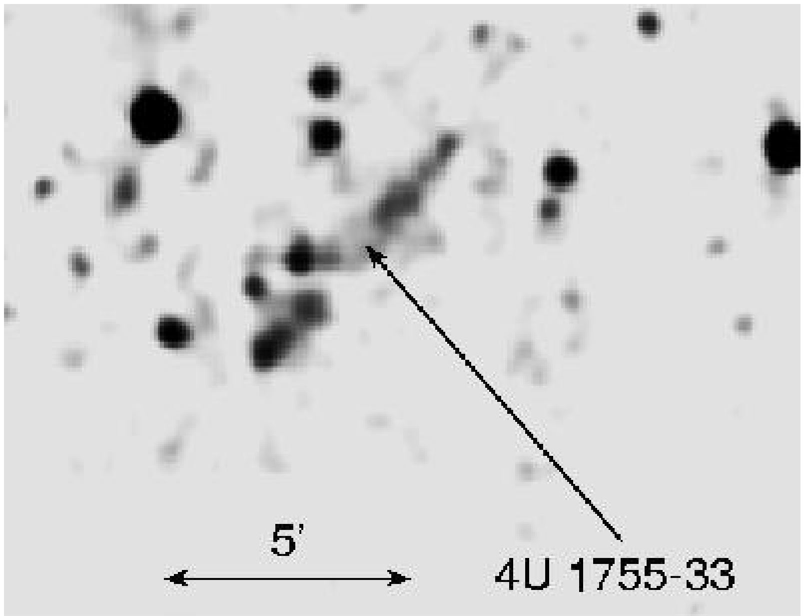

Fig. 3. *XMM-Newton* image of 4U 1755−33 (Angellini & White (2003). The arrow indicates the position of 4U 1755−33. Figure adapted by P. Kaaret (Kaaret et al. 2003b).

luminal" ejections very close (< 0.1 pc) to the compact object (like in e.g. GRS 1915+105) and the stationary lobes (1-4 pc) such as in 1E 1740.7−2942 or in 4U 1755−33. This suggests a morphological evolution: The large scale stationary lobes would be the results of the long term action of past relativistic ejections on the local ISM.

5. Further large scales jets in microquasars

5.1. GX 339−4

GX 339−4 is one of the best-studied black hole binaries, and has been the key source for unraveling the association of X-ray states and the formation of jets in accreting black holes (Fender et al. 1999; Corbel et al. 2000, 2003; Gallo et al. 2004). Following more than two years in quiescence, the source re-brightened in early 2002 to its brightest level in a decade. In May 2002, while brightening in X-rays, GX 339−4 produced an intense and rapid radio flare, further observations with ATCA have tracked the formation of a well-collimated one-sided jet (Figure 5) extending to about 12 arcsec, implying an apparent velocity greater than 0.9c given the 4 kpc distance estimate favored at the time of those observations (Gallo et al. 2004), but more recent work has placed a lower limit on the distance to GX 339-4 of 6 kpc, making this jet superluminal (Hynes et

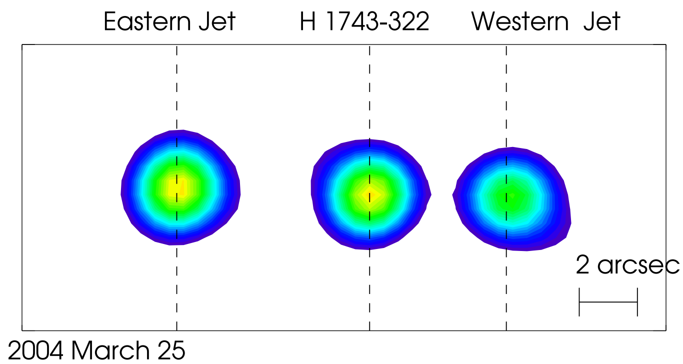

Fig. 4. *Chandra* 0.3-8 keV image of H 1743−322 in 2004 (Corbel et al. 2004). The black hole (at the center) as well as the two jets are detected.

al. 2004). This jet is consistent with shocks waves formed within the jet itself (as several radio flares were observed) and/or by the action of an underlying highly relativistic outflow on the ISM. The luminosity of the jets decreased much more rapidly than in the case of XTE J1550−564, by being undetectable at radio frequencies in less than a year (Gallo et al. 2004). No X-ray emission has been reported from its large scale jets.

5.2. H 1743−322

In March 2003, INTEGRAL detected new activity from IGR J17464−3213 that was later found to correspond to the X-ray transient H 1743−322, originally discovered with Ariel 5 in August 1977. After its reactivation in 2003, a radio counterpart was found with the VLA and a bright radio flare (likely associated with a massive ejection event) was observed on 2003 April 8 (Rupen, Mioduszewski & Dhawan 2003). Similarly to XTE J1550−564, this ejection event was observed later to interact with the ISM with the formation of large scale lobes at radio AND X-ray frequencies (see Figure 4). For further details, see Corbel et al. (2005).

5.3. Other black hole systems

5.3.1. GRS 1915+105

GRS 1915+105 is the first Galactic black hole system displaying relativistic jets with apparent superluminal motion on arcsec scales (Mirabel & Rodríguez 1994). A tentative association with two apparently symmetric IRAS sources (located 17 arcmin from the jet's core) has been proposed by Chaty et al. (2001). Kaiser et al. (2004) also suggest that these two IRAS sources may represent the impact site of the jets of GRS 1915+105 with the ISM.

5.3.2. XTE J1748−288

After ballistic ejections in XTE J1748−288 during its 1998 outburst, the jet was observed to stop (and brighten) over the course of a few weeks, presumably following a collision with environmental material (Kotani et al. 2000).

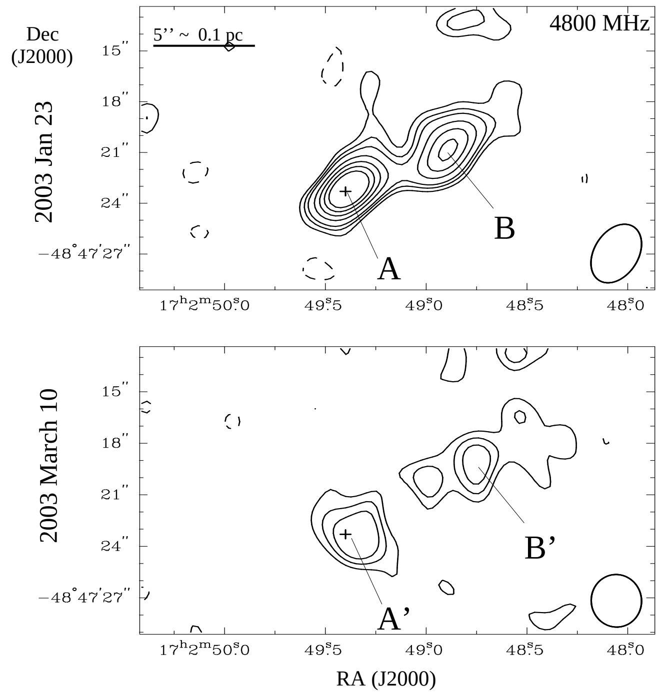

Fig. 5. Large scale transient radio jets in GX 339−4 (Gallo et al. 2004).

5.3.3. Cir X−1 and Sco X−1

Some neutron star systems are also associated with highly relativistic outflows: Sco X-1 (Fomalont et al. 2001) and Cir X−1 (Fender et al. 2004). In those cases, the knots moving with mildly relativistic bulk velocity (from 0.01 to 0.5 c) are energized by an unseen beam of particles that could be ultra-relativistic with bulk Lorentz factor > 10 for Cir X−1 (Fender et al. 2004) and > 3 for Sco X-1 (Fomalont et al. 2001). In these cases, the observed synchrotron emission could be powered locally during the interaction of the unseen beam with the interstellar medium (ISM) or by moving shocks within the flow itself.

5.3.4. XTE J1650−500

Corbel et al. (2004) report the detection in 2002 of radio emission from XTE J1650−500 in a Thermal Dominant state. This is contrary to what would have been expected in this state, which has always been associated with quenched radio emission (e.g. Fender et al. 1999; Corbel et al. 2000). It is possible that the observed radio emission is the result of the interaction of material previously ejected from the system with the ISM. If this is the case, then these interactions would have occured very close to the BH and therefore can not be considered a large scale jet as in e.g. XTE J1550−564.

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