Part 3. Microquasars

Jets at all Scales
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Microquasars: an observational review.

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Abstract. In the past decade, several considerable achievements have been reached in the field of Galactic microquasars, especially in light of the extreme variability of their relativistic jets. These jets are now known to exist in at least three different flavours: the self absorbed compact jets in the hard state, the transient and discrete ejection events associated with the state transitions, and the emission associated with the interaction of the jets on the interstellar medium. Although their phenomenology is now starting to be rather well established, their emission and contribution to the total energy budget of microquasars is still the subject of active debate. One way to probe the origin of their emission at various wavelengths is to use the broadband correlations that may exist between different energy domains. Initiated in the radio and X-ray ranges, these broadband flux correlations now include optical and infrared observations of black hole candidates and also neutron star systems. In this review, I also outline the current observational status of the emission of relativistic jets at high energy.

Keywords. accretion, accretion disks – black hole physics – binaries: general – ISM: jets and outflows – radio continuum: stars – X-rays: stars.

1. Introduction

1.1. *Historical notes*

Eighteen years ago, microquasars were "discovered" based on the detection of large scale symmetric radio jets around the X-ray source 1E 1740.7−2942, located closed to the Galactic Center (Mirabel *et al.* 1992). The comparison with Active Galactic Nuclei (AGNs) was even more straightforward, after the detection of superluminal motions in the black hole accreting binary GRS 1915+105 (Mirabel & Rodriguez 1994), immediately followed by GRO J1655−40 (Tingay *et al.* 1995; Hjellming & Rupen 1995). These discoveries stimulated significant interest as microquasars represented ideal systems to study the inflow – outflow coupling in accreting systems on very short timescales (much faster than in AGNs), more compatible with human lifespans. As an additional comment, it is important to stress that microquasars are not only associated with black hole systems, as the most ultra-relativistic jets in our Galaxy are from the neutron star binary Cir X−1 (Fender *et al.* 2004a). Furthermore, jets from microquasars come in different forms or flavours (self absorbed compact jets, discrete ejection events and large scale lobes or hot spots), even if they are very rarely spatially resolved by the observations. This implies that almost all X-ray binaries (at least the ones with low magnetic fields) could potentially be considered as a microquasars if they were observed at the right time of their lifetime and with enough sensitivity to detect the emission of their jets. With the limited space available in this review, I will highlight only a few important results. More details could be found in the recent book review "The Jet Paradigm" (Belloni 2010 and references therein).

1.2. *Black holes spectral states*

Stellar mass black holes in accreting binary systems are known to undergo transitions between different spectral states, which are often defined by their X-ray spectral and timing behaviour (see McClintock & Remillard 2006 for a review), i.e. by the properties of the inner accretion flow. However, outflows in general (under their various forms), are now also crucial for the characterisation of these different spectral states. The two major spectral states can be defined as follows: 1) the hard state is generally characterised by a weak or absence (however see Tomsick *et al.* 2009) of thermal contribution from the accretion disk and the presence of powerful self-absorbed compact jets, and 2) the soft state is mostly dominated by thermal emission from the standard accretion disk and the absence of relativistic jets. In addition, the intermediate states are associated with many changes in the inflow - outflow coupling, including for example, the major and minor radio flares associated with relativistic jets (see Fender 2006) or the major changes in timing properties (e.g. Belloni 2010), usually ascribed to highest accretion rate in the inner part of the accretion disk. The Hardness-Intensity Diagram (HID) represents the evolution of the X-ray intensity versus the X-ray hardness, and is a convenient illustration for the evolution of the outburst of black hole transients (and also for neutron star or accreting white dwarf, see Körding *et al.* 2008) along the course of a typical outburst.

2. On the influence of compact jets in the hard state

2.1. *Powerful compact jets*

In addition to the more "spectacular superluminal" ejections from these systems (aka "à la GRS 1915+105"), new kind of jets have been introduced in these recent years that might have a significant impact on the spectral energy distribution of black holes (especially in the hard state). Indeed, the hard states are usually associated with weak (at the mJy level) unresolved radio sources, that are variable on daily to weekly timescales (Corbel *et al.* 2000; Fender 2001). The radio spectra are usually flat or slightly inverted (i.e. with a positive spectral index, α, and a definition of the radio flux density, S_ν, as $S_\nu \propto \nu^\alpha$). This is characteristic of the presence of conical self-absorbed compact jets, similar to that considered for flat spectrum AGNs (Blandford & Konigl 1979). These small-scale (a few tens of astronomical units) jets have been spatially resolved in only two cases: e.g. Cyg X−1 (Stirling *et al.* 2001) and GRS 1915+105 (Dhawan *et al.* 2000; Fuchs *et al.* 2003), but their presence is inferred in many other systems, including neutron star binaries (Migliari & Fender 2006).

The spectra of these compact jets are believed to be almost continuous from radio up to the near infrared/optical frequencies, in which a cut-off has been detected in black holes (e.g. Corbel & Fender 2002) and neutron stars (e.g. Migliari *et al.* 2010). With emission up to infrared, the compact jets are extremely powerful, implying that a significant fraction (at least 10%) of the accretion power could be released in these jets (Fender 2001; Corbel & Fender 2002). As a final note, the compact jets, believed to be ubiquitous in the hard state (however, see discussions on outliers in section 3.2), are quenched once the X-ray sources reach the soft X-ray state (Fender *et al.* 1999; Corbel *et al.* 2000).

2.2. *On the nature of the hard X-ray emission in the hard state*

The hard state of weakly accreting black holes has been the focus of many recent studies due to the presence of several emission processes that are very difficult to disentangle in this regime. Indeed, in this accretion state, the geometry is likely dominated by three main and different sites: the standard optically thick and geometrically thin accretion disk (Shakura & Sunyaev 1973), the self-absorbed compact jets (Fender 2001), and an optically thin corona of hot electrons (Sunyaev & Titarchuk 1980) that may or may not be the basis of the compact jets (e.g. Markoff *et al.* 2005). Emission from the companion star is usually negligible in low mass X-ray binaries. With the development of large campaigns of multi-wavelength observations, several attempts have been conducted to model the spectral energy distribution (SED) of black holes in their regimes of faint X-ray emission (e.g. McClintock *et al.* 2001; Markoff *et al.* 2003; Yuan *et al.* 2005). It turns out that optically thick synchrotron emission from the compact jets dominates the radio to near-infrared range (Corbel & Fender 2002; Buxton & Bailyn 2004; Homan *et al.* 2005; Russell *et al.* 2006; Coriat *et al.* 2009). When the accretion disk is detectable in the hard state, it is usually in optical and soft X-ray with the notable exception of XTE J1118+480 that was observed even in ultraviolet (McClintock *et al.* 2001). In hard X-rays, inverse Compton emission on the ambient photon field is the main emission process, with an active debate on whether it is thermal or non-thermal comptonisation, or synchrotron self-Compton (see for a review McClintock & Remillard 2006). Optically thin synchrotron emission from the compact jet may eventually play a role at high energy (Markoff *et al.* 2001; Homan *et al.* 2005; Russell *et al.* 2010). An alternative to the direct synchrotron case is the possibility of inverse comptonization (external or synchrotron self-Compton) in the base of the jets (e.g. Markoff *et al.* 2005; Migliari *et al.* 2007).

3. Broadband correlations in the hard state

3.1. *Radio / X-ray and Infrared / X-ray flux correlations*

Another way to probe the emission properties of these black hole systems is to search for peculiar correlations between various wavelengths. The tight non-linear correlation (with an index of ~ 0.7) between radio and X-ray emission in GX 339−4 (Corbel *et al.* 2000, 2003) demonstrated a strong coupling between the compact jets and the X-ray emitting media. This correlation could possibly indicate that X-rays in GX 339−4 originate from optically thin synchrotron emission from the compact jet (Corbel *et al.* 2003; Markoff *et al.* 2003) or from a radiatively inefficient accretion flow (Merloni *et al.* 2003; Heinz 2004, but see also Körding *et al.* 2006). Gallo *et al.* (2003) extended this correlation study to a larger sample of black holes and proposed a universal correlation (still with an index of ~ 0.7) between the radio and X-ray luminosity. The correlation observed in the hard state seems to be maintained down to quiescence (Corbel *et al.* 2003; Gallo *et al.* 2003, 2006). By taking into account the mass of the black holes, this correlation was extended to active galactic nuclei and led to the definition of the fundamental plan of black hole activity and possibly to universal scaling laws relating physics of accreting black holes on very different mass scales (Merloni *et al.* 2003; Falcke *et al.* 2004; Körding *et al.* 2006).

It is important to note that the universal radio/X-ray correlation presented by Gallo *et al.* (2003) is dominated by two sources (GX 339−4 and V404 Cyg) with few measurements from additional sources that are often close to transition to softer states. The fundamental plane relies on the correlation for the Galactic black holes, so it is important to review its validity. Corbel *et al.* (2008) revisited the correlation for V404 Cyg and confirmed the tight correlation from outburst down to quiescence with an index of ~ 0.6 that is more consistent with X-rays emanating from synchrotron self-compton emission at the base of the compact jets or from an inefficient accretion disk. New data from GX 339−4 also confirm the stability of the correlation (also with an index of ~ 0.6) over several different outbursts, though several peculiarities were also observed (Corbel *et al.* 2010, to be submitted).

Following these results, a similarly tight correlation was also found between X-ray and optical/near-infrared in a sample of black hole candidates and also in GX 339−4 over different outbursts (Homan *et al.* 2005; Russell *et al.* 2006; Coriat *et al.* 2009). In GX 339−4, Coriat *et al.* (2009) found tight OIR/X-ray correlations over four decades with

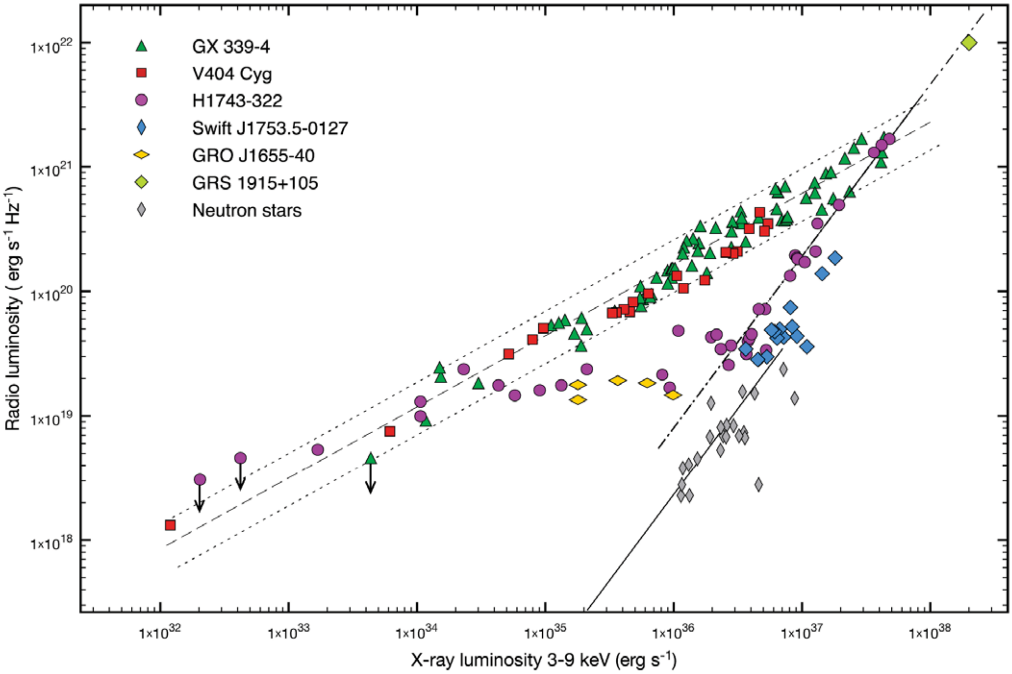

Figure 1. Radio 8.5 GHz luminosity against X-ray 3-9 keV luminosity from the hard state of H 1743−322 with a few other black hole candidates, as well as the hard state neutron stars sample of Migliari & Fender (2006). The dashed line is the fit to the high luminosity data of H 1743−322 and the neutron stars. Figure extracted from Coriat *et al.* submitted.

the presence of a break in the IR/X-ray correlation in the hard state. This correlation is the same for all four studied outbursts and could be interpreted in a consistent way by considering a synchrotron self-Compton origin of the X-rays in which the break frequency varies between the optically thick and thin regime of the jet spectrum. If correct, this interpretation would be consistent with the results based on the characterization of the SEDs (see section 2.2).

3.2. *On the nature of outliers*

However, in recent years, significant efforts have been achieved to observe most new black holes transients in outburst at radio frequencies. This led to the discovery of several sources lying significantly below and outside the scatter of the original radio/X-ray correlation (e.g. XTE J1650−500 Corbel *et al.* (2004); IGR J17497−2821 Rodriguez *et al.* (2007), Swift J1753.5−0127 Cadolle Bel *et al.* (2007); Soleri *et al.* (2010)). Until recently, It remained unclear how these outliers were related to typical black holes such as GX 339−4 or V404 Cyg. With a global study of H 1743−322 and other sources, Coriat *et al.* (2010, submitted) also found a very tight correlation for H 1743−322 in the bright hard state, but with a different slope of 1.38 ± 0.03 (compared to 0.6 for the standard correlation). At lower luminosity (below 5×10^{-3} $L_{\rm Edd}$), H 1743−322 returned to the standard correlation (as defined by GX 339−4 and V404 Cyg). Coriat *et al.* (2010, submitted) proposed that the outliers could imply the presence of a radiatively efficient flow in the hard state at high accretion rate. In addition, below a critical accretion rate, the flow would have to become radiatively inefficient in order to account for the transition at lower luminosity. Alternatively, this could also imply a non linear coupling between

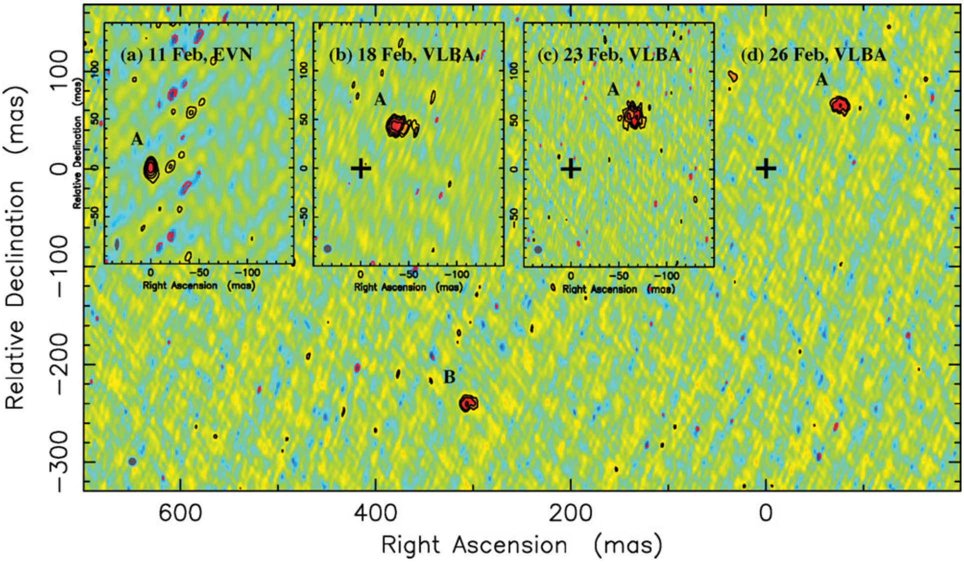

Figure 2. The decelerating jet of the X-ray transient XTE J1752−223. All the VLBI images are centered at the location of component A on 2010 February 11, indicated by a cross. Component B was not detected until 2010 February 26. See Yang *et al.* (2010) for more details (Figure extracted from this paper).

accretion power and jet power. Whatever the physical origin, the reason for finding these two groups of sources in the hard state at high accretion rate remains to be understood.

4. A unified model of disk jet coupling

The unified picture, which emerges from our current understanding, indicates that during the transition from the hard to soft states, a major radio flare may eventually be detected (if observed!) (Fender *et al.* 2004b; Corbel *et al.* 2004; Fender *et al.* 2009). This flare 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 imaged into one-sided (or two-sided) components moving away from the stationary core (e.g. Mirabel & Rodriguez 1994).

Broadly speaking, the jets on different scales (compact or discrete ejections) are rarely spatially resolved because of the lack of observations with sufficient resolution. The recent improvement of very long baseline interferometry should allow much better sampling, with faster reaction time, of the time evolution of relativistic jets. Recently, *RXTE* discovered the new transient XTE J1752−223, whose properties are very typical of black hole candidates. Yang *et al.* (2010) conducted in 2010 a series of very long baseline interferometry observations using the European VLBI Network (EVN) and the Very Long Baseline Array (VLBA). A moving jet component with significant deceleration is detected, as well as a likely receding jet in the last observation. 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.

The origin of the major radio flare can eventually be understood as a result of a variation of the Lorentz factor of the ejected material as the accretion disk reaches its innermost stable orbit, leading to the internal shocks within the flow. Alternatively, the

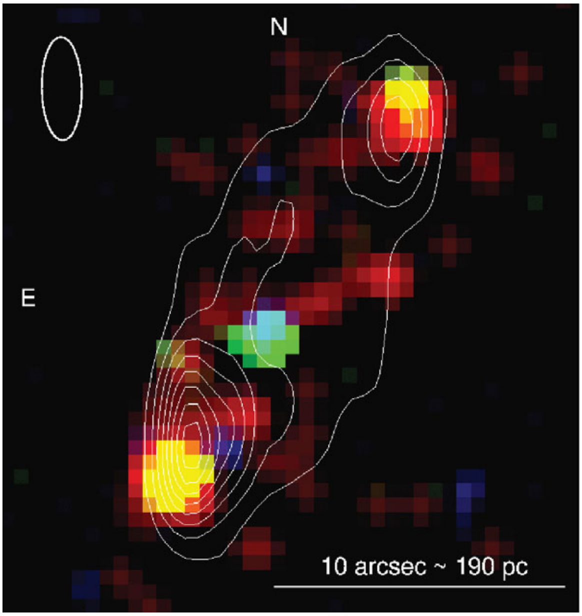

Figure 3. *Chandra*/ACIS color map of S26 (smoothed with a 1″ Gaussian core), with ATCA 5.48-GHz intensity contours. The colour coding is: red: 0.2–1 keV; green: 1–2 keV; blue: 2–8 keV. See Soria *et al.* (2010) for more details (Figure extracted from this paper).

flare itself may originate from an ejection of the coronal material (Rodriguez *et al.* 2003, 2008). For that purpose, it is of interest to note the competition in GRS 1915+105, mediating through photo-ionization and Comptonization processes, between the jets in the hard state and the accretion disk winds in the soft state (Neilsen & Lee 2009).

5. The environment of jets: bubbles and hot spots

After discrete ejection events during the hard to soft state transition (Fender *et al.* 2004b; Corbel *et al.* 2004; Fender *et al.* 2009), the moving plasma condensations are observed in the radio range for a few weeks until their emission fades below detection levels due to adiabatic expansion losses. However, beside these sub-arcsecond scale transient jets seen during the initial part of the outburst of some black holes, large scale (from few tens of arcseconds to few arc-minutes) stationary radio jets have been observed later in a few systems, probably indicating the long term action of past ejection events on the surrounding interstellar medium (Mirabel *et al.* 1992; Martí *et al.* 2002). Of significant importance, *XMM-Newton* detected 7 arc-minutes (3 to 8 pc) slowly decaying X-ray jets centered on the position of 4U 1755−33, a black hole candidate (Angelini & White 2003; Park *et al.* 2005; Kaaret *et al.* 2006). The bubble nebula W50 around SS 433 also represents the archetypical example of the action of jets on the ISM, leading to an effective way to estimate the jets total mechanical power (above 10^{39} erg s^{-1}).

Similarly, this approach is now starting to be used for estimating the total luminosity of a few ultra-luminous X-ray sources (e.g. Soria *et al.* 2006; Lang *et al.* 2007), and in the extragalactic microquasar embedded in the nebula S26 in the nearby galaxy NGC 7793 (Pakull *et al.* 2010; Soria *et al.* 2010). S26 has a morphology reminiscent of Fanaroff-Riley type II (see Fig. 3) with a mechanical power around a few 10^{40} erg s^{-1} (i.e. 4 orders of magnitude larger than the X-ray luminosity of the core and above the Eddington limit for a stellar mass black hole). This points to the possibility of an accretion mode, which

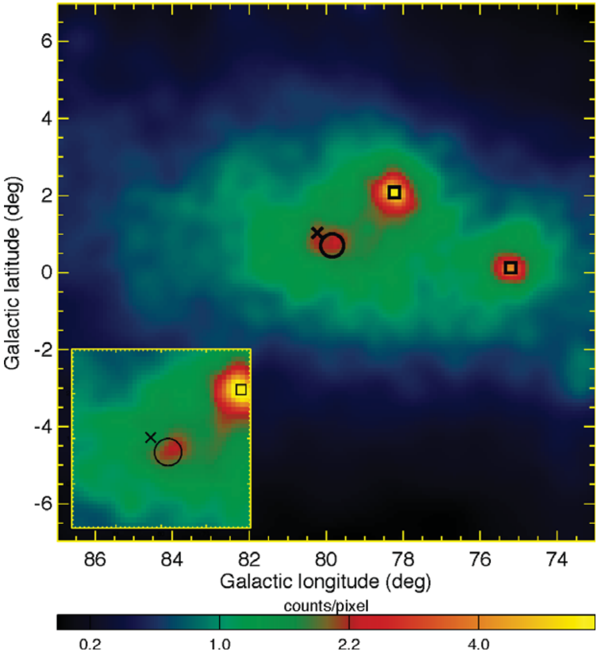

Figure 4. 200 MeV – 100 GeV *Fermi/LAT* gamma-ray counts map of a 14° × 14° region centered on the position of Cyg X−3. It shows the region around Cyg X−3 encompassing emission from three bright gamma-ray pulsars, as well as the strong Galactic diffuse emission of the Cygnus region. Inset: Similar image for the central portion (4° × 4°) corresponding to the off-pulse dataset from PSR J2032+4127 (which is not detected in the off-pulse data). See Fermi LAT Collaboration *et al.* (2009) for more details (Figure extracted from this paper).

channels most of the available power into jets, even at high mass accretion rates (Pakull *et al.* 2010; Soria *et al.* 2010).

Beside inflating bubble nebulae, the action of the jets on the ISM can also be revealed by the detection of (moving or not) hot-spots, the working sites of the jet interactions. In Sco X−1, an unseen underlying, highly relativistic, flow is energizing the hot spots (Fomalont *et al.* 2001b,a). The interaction may eventually lead to X-ray emission, as indicated by the *Chandra* detections of X-ray jets in XTE J1550−564, H 1743−322 or Cir X−1 (Corbel *et al.* 2002, 2005; Heinz *et al.* 2007; Soleri *et al.* 2009; Sell *et al.* 2010). The broadband spectra of these jets in XTE J1550−564 and H 1743−322 are usually consistent with synchrotron emission from high-energy (up to 10 TeV) particles accelerated in the shocks formed by the interaction of the jets with the ISM (Corbel *et al.* 2002; Kaaret *et al.* 2003; Tomsick *et al.* 2003; Hao & Zhang 2009).

6. Jets emission at high and very high energy

The detection of high (or very high) energy emission from a Galactic accreting binary has been a long awaited observation. Indeed, in the early 1970s and 1980s, detections of Cyg X−3 were reported in the MeV to PeV energies, which generated considerable excitements. However, the detections remained doubtful mainly because a more sensitive generation of telescopes and satellites failed to confirm these detections (Ong 1998). In 2009, the *Fermi* Large Area Telescope (*LAT*) and the *AGILE* satellite reported the detection of a variable high energy source (Fig. 4) coinciding with the position of the microquasar Cyg X−3 (Fermi LAT Collaboration *et al.* 2009; Tavani *et al.* 2009). The identification with Cyg X−3 is secured by the detection by *Fermi* of its orbital period in gamma rays, as well as the correlation of the *LAT* flux with radio emission from the relativistic jets of Cyg X−3 (Fermi LAT Collaboration *et al.* 2009). The gamma-ray emission can be explained by inverse Compton scattering of UV photons from the Wolf-Rayet (WR) star off of high energy electrons from the relativistic jets of Cyg X−3 (Fermi LAT Collaboration *et al.* 2009) or in a recollimation shocks associated with the strong wind from the WR star (Dubus *et al.* 2010).

In addition to Cyg X−3, low significance gamma-ray flares have been reported by MAGIC (Albert *et al.* 2007) and associated with the black hole binary Cyg X−1. According to the binary parameters of the system, this very high energy flare is believed to occur in a configuration with the black hole behind the high-mass star companion. The huge gamma-ray absorption should normally prevent any detection above few tens of GeV in this configuration, although Romero *et al.* (2010) propose a possible interpretation based on the interaction of the Cyg X−1 jets with the clumpy wind of the high-mass star. We note that AGILE has recently reported high energy gamma-ray flares from Cyg X−1 (e.g. Sabatini *et al.* 2010), that have, however, not been confirmed by Fermi †.

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† e.g. http://fermisky.blogspot.com/2010/03/lat-limit-on-cyg-x-1-during-reported.html

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Discussion

Fendt: What do we know about the collimation degree of compact jets?

Corbel: The constraints are very pooor as only two sources have imaged compact jets. It is less than 2° in the case of Cyg X-1. This is also consistent with the compact jets in the plateau state for GRS 1915+105.

de Gouveia Dal Pino: Regarding the point you reported about X-ray bubbles carried by jets at different scale (from galactoc compact sources to AGN FR II radiogalaxies) I just would like to comment that there is a poster outside by Falceta-Goncalves *et al.*, where we have performed 3D MHD simulations of the radio jet that seats in the center of the Perseus cluster of galaxies and inflate bubbles in the X-ray distribution of gas in the surrroundings, and distribute energy all over $\sim$ 100 kpc scales - and stopping the cooling flow un the core of this galaxy cluster.

Corbel: Thanks for the comment.

Kundt: Pakull *et al.*'s energy estimate of S26 in the Sculptor galaxy may be overestimated by a factor of order 10^3 by the assumption that their lobes emit homogeneously, rather than by small-filling-factor thermal inclusions, of filling factor $f \approx 10^{-3}$.

Corbel: Yes, I agree that it is a possibility.

Yuan: Most of the estimation of the power of the ejected blob are time-averaged values. Is there any estimation to a single ejection event?

Corbel: Estimates do exist such as the ones done for the impulsive jets of GRS 1915+105 (see Fender *et al.* 1999) or even in the case of the decelerating jets in XTEJ1550-564 (Tomsick *et al.* 2003). With some cautions, this can be at least more than 10^{38}erg s^{-1}, i.e., a significant fraction of the accretion power.