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Radio jets and high energy emission in microquasars

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Abstract. Collimated outflows of relativistic particles emitting synchrotron radiation have been observed in both, galactic and extragalactic sources. In the most likely scenario of emission in X-ray binary systems, the stellar UV photons from the companion bright star can be up scattered by the relativistic electrons and produce high energy emission. Here, we present the main observational results, in the wavelength range from radio to very high energy γ-rays, on a group of X-ray binaries with jets (or relativistic outflows) that are γ-ray emitters or potential candidates.

Key words. X-ray: binaries – Radio continuum: stars – Gamma-rays: observations – Radiation mechanism: non-thermal

1. Introduction

In recent years, a major progress has taken place in the detection of gamma-ray emission from stellar systems. The Cherenkov telescopes H.E.S.S., MAGIC and VERITAS have contributed to the discovery of stellar sources as a class in the very high-energy (VHE) gamma-ray sky. In the high-energy (HE) gamma-ray range, *AGILE* and *Fermi* are detecting sources that have already been observed at very high energies, and also discovering new sources. Among the sources found in the HE and VHE band, there are several binary systems that contain a compact object, a black hole (BH) or a neutron star (NS), and a high-mass bright star. These systems show collimated outflows of relativistic particles emitting synchrotron radiation, which has been observed with high resolution radio interferometry.

We note that jets have been observed in systems containing white dwarfs, NS and BH of all mass scales, from stellar-mass in XB to super-massive BH in Active Galactic Nuclei (AGN); and are thought to be behind most of the energetic phenomena in the Universe (e.g., Fender et al. (2006) for a review).

2. X-ray binaries and microquasars

X-ray binaries (XB) are binary systems containing a compact object (a NS or a stellar mass BH) accreting matter from the companion star. Depending on the spectral type, the optical companions are classified into High Mass X-ray binaries (HMXB) or Low Mass X-ray Binaries (LMXB). For HMXB, the optical companion is an early type (either O or B) and mass transfer takes place via a decretion

Send offprint requests to: J.M. Paredes disc for Be stars, wind accretion or Roche lobe overflow. LMXBs, on the other hand, have an optical companion with spectral type later than B and mass transfer takes place through Roche lobe overflow. Up to now a total of 299 XBs have been catalogued, out of which 114 are HMXBs and 185 are LMXBs (Liu et al. 2006, 2007). A significant part of them, about 22% of all XB, have been detected in radio, being 9 of them HMXB and 56 LMXB (Paredes 2005). In some cases, VLBI observations have resolved the structure associated with these radio emitters, revealing the existence of relativistic jets. These XB with relativistic jets emitting non-thermal radio emission through synchrotron radiation, are known as microquasars.

Relativistic jets in these systems extract a large fraction of the total available accretion energy and are formed very close to the compact object, being unique laboratories for studying relativistic effects. The interaction of the relativistic jets with the optical companion radiation and wind or with the interstellar medium can result in GeV-TeV emission from these sources.

The mechanism(s) of steady jet production remain essentially unknown. Studies of disk-jet coupling in NS highlighted a number of quantitative differences with respect to the BH, suggesting that additional parameters other than the mass accretion rate might play a significant role in powering the jet (Migliari & Fender 2006).

In what follows we describe several characteristics of a few selected XB/microquasars that indicate the presence of accelerated non-thermal particle population susceptible to emit in the γ-ray domain. These sources either have been detected at γ-rays or are potential γ-ray emitters.

2.1. Superluminal jets: GRS 1915+105

The first clear evidence of relativistic jets in XB was found by Mirabel & Rodriguez (1994) through the detection of superluminal motion in the ejecta of the microquasar GRS 1915+105. This source has played an important role for understanding the link between the accretion disk and the formation of the jets.

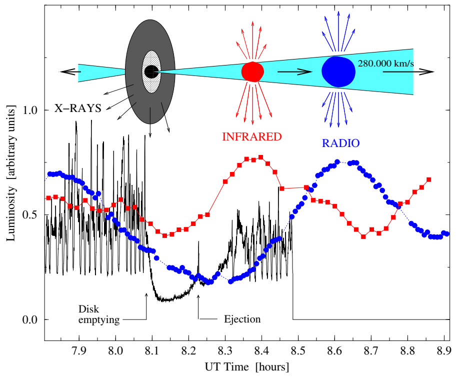

Fig. 1. Multi-wavelength behaviour of the microquasar GRS 1915+105 as observed in September 8th 1997. The radio data at 3.6 cm (grey squares) were obtained with the VLA interferometer; the infrared observations at 2.2 micron (black squares) are from the UKIRT; the continuous line is the X-ray emission as observed by RXTE in the 2–50 keV range. Figure taken from Mirabel et al. (1998)

The collimated ejections in GRS 1915+105 provide one of the best studied cases supporting the proposed disk/jet connection. In Figure 1, taken from Mirabel et al. (1998), simultaneous observations are presented at radio, infrared and X-ray wavelengths. The data show the development of a radio outburst, as a result of a bipolar ejection of plasma clouds. However, prior to the radio outburst, there was a clear precursor outburst in the infrared. The simplest interpretation is that both flaring episodes, in radio and infrared, were due to synchrotron radiation generated by the same relativistic electrons of the ejected plasma. The adiabatic expansion of plasma clouds in the jets causes losses of energy of these electrons and, as a result, the spectral maximum of their synchrotron radiation is progressively shifted from the infrared to the radio domain.

It was proposed that relativistic electron population in the jet could emit above MeV energies through Inverse Compton (IC) scattering or even direct synchrotron (Atoyan & Aharonian 1999). However, this particular source has not been detected yet in neither the GeV nor the TeV band (Saito et al. 2009; Szostek et al. 2009).

2.2. Strong radio outbursts: Cygnus X-3

Other galactic accreting sources have been best studied through their radio outbursts, as in the case of Cygnus X-3. This HMXB is formed by a Wolf Rayet star and a compact object that is thought to be a NS for orbit inclination angles above 60° or a BH otherwise (Vilhu et al. 2009). Cyg X-3 shows radio flaring levels of up to 20 Jy, and was first detected and closely observed at this level in 1972, resulting in one of the best-known examples of expanding synchrotron emitting sources. These outbursts were modeled successfully by invoking a particle injection in twin jets (Martí et al. 1992). The development of two-sided relativistic radio jets following a strong outburst were imaged at arcsecond scales with the VLA (see Fig.2) (Martí et al. 2001). Higher VLBI resolution images (at milliarcsecond scales) show also a jet morphology (Miller-Jones et al. 2004).

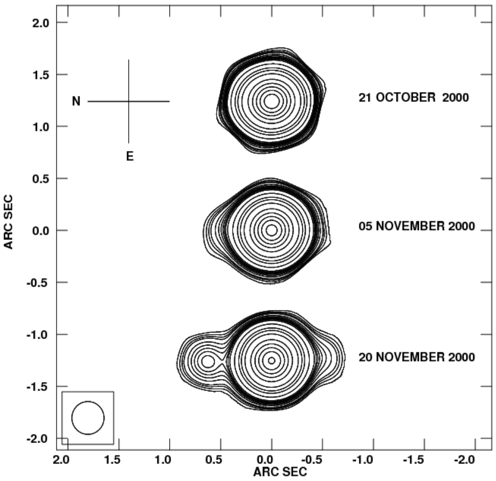

Fig. 2. Sequence of development of a two-sided relativistic radio jet in Cygnus X-3 observed with the VLA. Figure taken from Martí et al. (2001).

Long-term multiwavelength monitoring of Cyg X-3 has revealed that strong radio flares occur only when the source shows high soft X-ray flux and a hard power-law tail. If the electrons responsible for the strong radio outbursts and the hard X-ray tails are accelerated to high enough energies, detectable emission in the γ-ray energy band is possible. Recently, both the *AGILE*/GRID (Tavani et al. 2009) and *Fermi*/LAT (Abdo et al. 2009c) collaborations have published clear detections of Cyg X-3 in high energy γ-rays.

2.3. Jet-medium interaction: SS 433 and Cygnus X-1

For other microquasars, it has been possible to observe the interaction between their relativistic jets and the interstellar medium surrounding them. The most notable case is SS 433, a HMXB with twin relativistic precessing jets. The precession has been clearly observed in the radio domain below arcsecond scales (Stirling et al. 2002). At a larger scale, the interaction of the jets with the surrounding parent nebula W50 has deformed the originally spherical nebula into a twisting elongated shape (Dubner et al. 1998). This source is the only one for which the jets are known to contain a hadronic component after Doppler shifted iron lines were detected in spatially resolved regions corresponding to the jet and counter-jet, proving that particle re-heating in relativistic jets can affect atomic nuclei (Migliari et al. 2002). While theoretical predictions for γ-ray emission from microquasar jet-medium interactions have been made (Bordas et al. 2009), none has been detected so far.

Cygnus X-1 displays a $\sim$15 mJy and flat spectrum relativistic compact (and one-sided) jet ($v > 0.6c$) during the low/hard state (Stirling et al. 2001). Also, arcminute extended radio emission around Cygnus X-1 was found using the VLA (Martí et al. 1996). Their disposition reminded of an elliptical ring-like shell with Cygnus X-1 offset from the center. Later, as reported in Gallo et al. (2005), such structure was recognised as a jet-blown ring around Cygnus X-1 (see Fig.3). This ring could be the result of a strong shock that develops at the location where the pressure exerted by the collimated jet, detected at milliarcsec scales, is balanced by the ISM. The observed radiation would be produced by the ionized gas behind the bow shock via thermal Bremsstrahlung.

Table 1. The five X-ray binaries that are MeV and/or TeV emitters

Parameters	PSR B1259−63	LS I +61 303	LS 5039	Cygnus X-1	Cygnus X-3
System Type	B2Ve+NS	B0Ve+NS?	O6.5V+BH?	O9.7Iab+ BH	WN_e+ BH?
Distance (kpc)	1.5	2.0±0.2	2.5±0.5	2.2±0.2	~9
Orbital Period (d)	1237	26.5	3.90603±0.00017	5.6	0.2
$M_{\rm compact}$ ($M_\odot$)	1.4	1–4	1.4–5	20±5	–
Eccentricity	0.87	0.72	0.35±0.04	~ 0	~ 0
Inclination	36	30 ± 20	20?	33 ± 5	–
Peri-apoastron(AU)	0.7–10	0.1–0.7	0.1–0.2	0.2	–
Physical properties					
Radio Structure (AU)	≤2000	Jet-like (10–700)	Jet-like (10–10^3)	Jet (40) + Ring	Jet ~ 10^4
$L_{\rm radio(0.1-100GHz)}$(erg s^{-1})	(0.02–0.3)×10^{31} [(*)]	(1–17)×10^{31}	1×10^{31}	0.3×10^{31}	7×10^{32}
$L_{\rm X(1-10keV)}$ (erg s^{-1})	(0.3–6)×10^{33}	(3–9)×10^{33}	(5–50)×10^{33}	1×10^{37}	$(3.9 - 7.9) \times 10^{37}$
$L_{\rm VHE}$ (erg s^{-1})	2.3×10^{33} [(a)]	8×10^{33} [(a)]	7.8×10^{33} [(b)]	12×10^{33} [(a)]	–
$\Gamma_{\rm VHE}$	2.7 ± 0.2	2.6 ± 0.2	2.06 ± 0.05	3.2 ± 0.6	–
Periodicity					
Radio	48 ms and 3.4 yr	26.496 d and 4.6 yr	persistent	5.6 d	persistent and strong outbursts
Infrared	–	27.0±0.3 d	variable	5.6 d	–
Optical	–	26.4±0.1 d	–	5.6 d	–
X-ray	variable	26.7±0.2 d	variable	5.6 d	0.2 d
> 100 MeV	–	variable	variable ?	–	variable ?
> 100 GeV	variable	26.8±0.2 d	3.9078±0.0015 d	flare	–

[(*)] Unpulsed radio emission
[(a)] 0.2 <E< 10 TeV
[(b)] Time averaged luminosity.

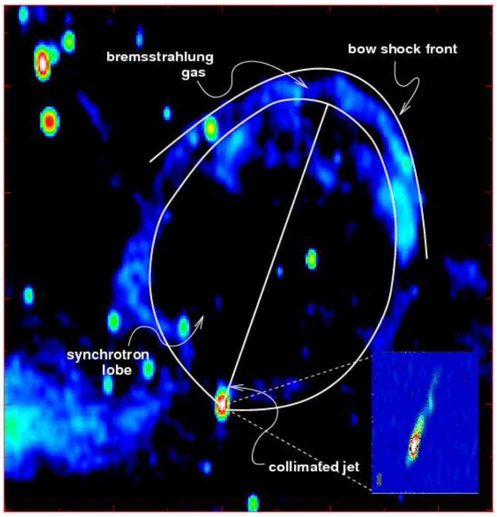

Fig. 3. A jet-blown ring around Cygnus X-1. Figure taken from Gallo et al. (2005).

2.4. Morphological and astrometrical variablity in the radio: LS I +61 303 and LS 5039

LS I +61 303 shows periodic non-thermal radio outbursts, on average, every $P_{\rm orb}$=26.4960 d (Taylor & Gregory 1982). Massi et al. (2004) reported the discovery of an extended jet-like and apparently precessing radio emitting structure at angular extensions of 10–50 milliarcseconds. VLBA images obtained during a full orbital cycle show a rotating elongated morphology (Dhawan et al. 2006), which may be consistent with a model based on the interaction between the relativistic wind of a young non-accreting pulsar and the wind of the stellar companion (Dubus 2006) (see nevertheless Romero et al. (2007) for a critical analysis of this scenario).

The radio emission of LS 5039 is persistent, non-thermal and variable but no strong radio outbursts or periodic variability have been detected so far (Ribó et al. 1999, 2002). VLBA observations led the detection of an elongated radio structure, which is interpreted as relativistic jets (Paredes et al. 2000). The discovery of this bipolar radio structure, and the fact that LS 5039 was the only source in the field of the EGRET source 3EG J1824−1514 showing X-ray and radio emission, allowed to propose the physical association of both sources (Paredes et al. 2000).

High-resolution radio images at two different orbital phases and using the phase-referencing technique, have shown a changing morphology between the two images suggesting a behaviour similar to LS I +61 303. However, the astrometric results were not conclusive (Ribó et al. 2008) and precise phase-referenced VLBI observations covering a whole orbital cycle are necessary to advance in the understanding of this peculiar system.

2.5. Interaction between a pulsar wind and a Be star with a circumstellar disc: PSR B1259−63

PSR B1259−63 is the first variable galactic source of VHE γ-rays ever discovered. It contains a 47.7 ms radio pulsar orbiting around its massive companion every 3.4 years in a very eccentric orbit. Up to now, no elongated radio structure of synchrotron origin has been detected. It is possible that PSR B1259−63 has this kind of structure but has not yet been detected with the present sensitivity and resolution of the instruments available in the southern hemisphere

The radiation mechanisms and interaction geometry in this pulsar/Be star system was studied in Tavani & Arons (1997). In a hadronic scenario, the TeV light-curve, and radio/X-ray light-curves, can be produced by the collisions of high energy protons accelerated by the pulsar wind and the circumstellar disk (Neronov & Chernyakova 2007). A very different model is presented in Khangulyan et al. (2007), where the TeV light curve can be explained by an IC scenario of γ-ray production.

3. HE and VHE γ-ray sources

Among the VHE sources detected with the Cherenkov telescopes, there are three that are clearly associated to X-ray binaries. These binary TeV sources, PSR B1259−63 (Aharonian et al. 2005a), LS I +61 303 (Albert et al. 2006) and LS 5039 (Aharonian et al. 2005b), have a bright high-mass primary star, which provides an intense UV seed photon field for IC scattering of particles accelerated within or close to the binary system. All of them have been detected at TeV energies in several parts of their orbits and show variable emission and a hard spectrum. The emission is periodic in the systems LS 5039 and LS I +61 303, with a period of 3.9078±0.0015 days and 26.8±0.2 days, respectively (Aharonian et al. 2006; Albert et al. 2009), consistent with their orbital periods (Casares et al. 2005a,b; Aragona et al. 2009). These two sources also share the distinction of being the only two known high-energy emitting X-ray binaries that are spatially coincident with sources above 100 MeV listed in the Third EGRET catalog (Hartman et al. 1999). LS 5039 is associated with 3EG J1824−1514 (Paredes et al. 2000) and LS I +61 303 with 3EG J0241+6103 (Kniffen et al. 1997). Both sources have also been detected by the *Fermi* observatory (Abdo et al. 2009a,b). In the case of PSR B1259−63, the periodicity at TeV energies has not yet been determined because the long orbital period (3.4 years) requires an extensive monitoring over several years with the Cherenkov telescopes. The source was not detected by EGRET.

Another HMXB, Cygnus X-1, was observed with MAGIC during a short-lived flaring episode, and strong evidence (4.1σ post-trial significance) of TeV emission was found (Albert et al. 2007). The detected signal is point-like, consistent with the position of Cygnus X-1, and excludes the nearby radio nebula powered by the relativistic jet. The upper limit to the steady γ-ray emission from this object is $\lesssim 1\%$ of the Crab nebula flux above 500 GeV (Saito et al. 2009). In the energy range 100 MeV-3 GeV, the *AGILE* team reported an episode of significant transient γ-ray emission detected on 2009 October 16, and the source position is compatible with Cygnus X-1 (Sabatini et al. 2010).

Cygnus X-3 is the latest XB to join the group of HE/VHE γ-ray XB. The *AGILE* and *Fermi* satellites detected transient γ-ray emission above 100 MeV from Cygnus X-3 (Tavani et al. 2009; Abdo et al. 2009c), making it the first microquasar detected unambiguously at high energy γ-ray. During the γ-ray active periods, the emission is correlated with strong radio flares, which are associated to the ejections of relativistic jets. The detections of Cygnus X-3 by *AGILE* and *Fermi* demostrate that Cygnus X-3 is a new HE γ-ray source. The fact that the γ-ray emission detected by *Fermi* is modulated with the orbital period of Cygnus X-3, makes the association of the γ-ray source with Cygnus X-3 secure. The detections occurred when Cygnus X-3 was in the high soft X-ray state and the modulation was found only during high γ-ray activity periods. At TeV energies, Cygnus X-3 has not been detected yet by the new generation of Cherenkov telescopes (Aleksic et al. 2010).

The nature of the compact object is well determined only in two sources. In the case of Cygnus X-1, it is a BH and, in the case of PSR B1259−63, a NS. For LS I +61 303, LS 5039 and Cygnus X-3, there is no strong evidence yet supporting either the BH or the NS nature of the compact objects.

See Table 1 for a summary of the properties of these five X-ray binaries detected at HE and/or VHE γ-rays.

4. Scenarios for the radio and γ-ray emission

There exist two main scenarios to explain the radio and high energy emission. These scenarios are based on the different engines, accretion or pulsar wind, for powering the relativistic particles. These particles are responsible for the HE/VHE emission, which is basically interpreted as the result of IC up scattering of stellar UV photons by relativistic electrons, while the radio emission is synchrotron radiation from these relativistic electrons. Historically, models based in these scenarios were developed to explain the radio and high energy emission of LS I +61 303/2CG 135+01. On one hand, the accretion model proposes that the radio outbursts of LS I +61 303 are produced by streams of relativistic particles powered by episodes of accretion onto a compact object in a highly eccentric orbit, embedded in the mass outflow from the companion B-star (Taylor & Gregory

(1982), Bosch-Ramon et al. (2006)). On the other hand, the pulsar model assumes that LS I +61 303 might contain a non-accreting young pulsar in orbit around a mass-losing B-star, powered by the pulsar wind (Maraschi & Treves 1981). This model was reinforced by the discovery of PSR B1259−63 and the subsequent studies of the interaction of the pulsar wind with the circumbinary material from its companion star (Tavani et al. 1994). The VLBI observations showing a rotating jet-like structure in LS I +61 303 (Dhawan et al. 2006) have been interpreted as a result of the interaction between the relativistic wind from a young pulsar and the wind from its stellar companion, the scenario accepted for PSR B1259−63.

In certain pulsar models (e.g. Dubus (2006)), a cometary-like nebula of radio emitting particles would be expected. This structure would rotate along the orbit pointing away from the companion star. The interaction of the relativistic wind from a young pulsar with the wind from its stellar companion has been considered to be a viable scenario for explaining the observations of LS 5039 (in addition to PSR B1259−63 and LS I +61 303) (Dubus (2006), Dubus et al. (2008)). It has been noted that hydrodynamical simulations of pulsar/star wind interactions (Romero et al. (2007), Bogovalov et al. (2008)) do not show such elongated shape seen in the VLBI radio images of LS I +61 303, previously cited as strong evidence in favor of a pulsar/star wind interaction scenario.

A feature at very high energies that would render the distinction between the accretion and the pulsar scenarios is a line-type energy spectrum formed by the Comptonization of stellar photons by a mono-energetic pulsar wind, as shown for PSR B1259−63/SS2883 by Khangulyan et al. (2007). This has been also calculated for the cases of LS I +61 303 and LS 5039 by Cerutti et al. (2008), although electromagnetic cascades were not accounted for, which was otherwise done by Sierpowska-Bartosik & Torres (2007) in the case of LS 5039.

The HE γ-ray modulation detected in Cygnus X-3 in the high energy active periods can be originated by anisotropic IC scattering. In order to avoid strong absorption with the bright X-ray emission produced at the base of the jet or in the inner accretion disc, it is thought that the HE γ-ray emission should take place beyond $\sim 10^{10}$ cm above the compact object, i.e., in the jet. However, the observed orbital modulation imposes that the emission should not originate at large distances from the compact object. On the contrary, in the case of VHE the strong photon-photon absorption produced in the vicinity of the Wolf-Rayet implies that any possible detection of VHE photons would come from a location far from the binary system (Bednarek 2010). A model based on Doppler-boosted Compton emission from energetic pairs in an inclined and mildly relativistic jet has been developped by Dubus et al. (2010) to explain the orbital modulation of the > 100 MeV flux from Cygnus X-3.

Another interesting fact is that Cygnus X-1 and LS 5039 show TeV emission around the superior conjunction of the compact object, when the largest γ-ray opacities are expected. To investigate the implications of these detections, given the role of the magnetic field for the occurrance of electromagnetic cascading in these systems, the absorbed luminosity due to pair creation in the stellar photon field for different emitter positions has been computed (Bosch-Ramon et al. 2008). The results suggest that the TeV emitters in Cygnus X-1 and LS 5039 are located at a distance $> 10^{12}$ cm from the compact object. This would disfavor those models for which the emitter is well inside the system, like the innermost-jet region (microquasar scenario), or the region between the pulsar and the primary star (standard pulsar scenario) (Bosch-Ramon et al. 2008). Similar results concerning the location of the emitter in the case of LS 5039 were previously discussed by Khangulyan et al. (2008) based on acceleration efficiency arguments.

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