The role of microquasars in astroparticle physics

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Abstract

I present an overview of past, present and future research on microquasars and jets, showing that microquasars, i.e. galactic jet sources, are among the best laboratories for high energy phenomena and astroparticle physics. After reminding the analogy with quasars, I focus on one of the best microquasar representatives, probably the archetype, namely GRS 1915+105, and present accretion and ejection phenomena, showing that only a multi-wavelength approach allows a better understanding of phenomena occurring in these sources. Thereafter, I review jets at different scales: compact jets, large-scale jets, and the interactions between ejection and the surrounding medium. I finish this review by showing that microquasars are good candidates to be emitters of astroparticles: very high energy photons, cosmic rays and neutrinos.

1 The pre-microquasar era: SS 433

In 1979 was discovered the microquasar prototype: SS 433, a high-energy source exhibiting precessing jets at frame velocity $0.26c$, with emission lines observed in the optical, showing that the jet content was baryonic (Margon, 1984). SS 433 is surrounded by a supernova remnant: W50, and there are clear signs of interaction between SS 433 jets and W50 nebula (see e.g. Dubner et al. 1998). The question which arose was then: how can a galactic object eject matter at such relativistic velocities (Γ=1.04)? This object exhibited such unusual properties, that it was probably impossible to foresee that, two decades later, jet sources would become quite common. SS 433 had everything of a microquasar, apart from the name.

2 The microquasar era: analogy with quasars

In 1990, the *SIGMA* telescope, orbiting on board *Granat*, was launched. It was designed to observe galactic black hole candidates, because its observing energy band corresponded to the energy released by accretion around compact objects. In 1992 the first so-called microquasar, 1E 1740.7-2942, was identified (Mirabel et al., 1992). This source was exhibiting bipolar radio jets spread over several light-years. This was the first such observation in our Galaxy, however jets had been already observed emanating from distant galaxies. Therefore this observation made clear the existence of a morphological analogy between quasars and microquasars.

Although there is no clear definition of a microquasar, we can characterise it as a galactic binary system –constituted of a compact object (stellar mass black hole or neutron star) surrounded by an accretion disc and a companion star– emitting at high-energy and exhibiting relativistic jets. A schematic view of a microquasar, compared with quasars, is given in Figure 1. Taking this broad definition, we observed nearly 20 microquasars in our Galaxy, and it is one of the main subjects of study by current space missions. Since each component of the system emits at different wavelengths, it is necessary to undertake multi-wavelength observations in order to understand phenomena taking place in these objects.

In 1992 the WATCH/GRANAT telescope discovered the black hole candidate GRS 1915+105 (Castro-Tirado et al., 1994), which would become the archetype of microquasars. Two years later, by observing this source with the VLA (arcsec scale), Mirabel & Rodríguez (1994) detected apparent superluminal motions, while frame velocity was $v \sim 0.92c$. It became then rapidly clear that the advantages of microquasars compared to quasars were that i) they are closer, ii) it is possible to observe both (approaching and receding) jets, and iii) the accretion/ejection timescale is much shorter. After this observation of superluminal motions, the morphological analogy with quasars became stronger, and the question was then: is this morphological analogy really subtended by physics? If the answer is yes, then microquasars really are “micro”-quasars. For instance, there should exist

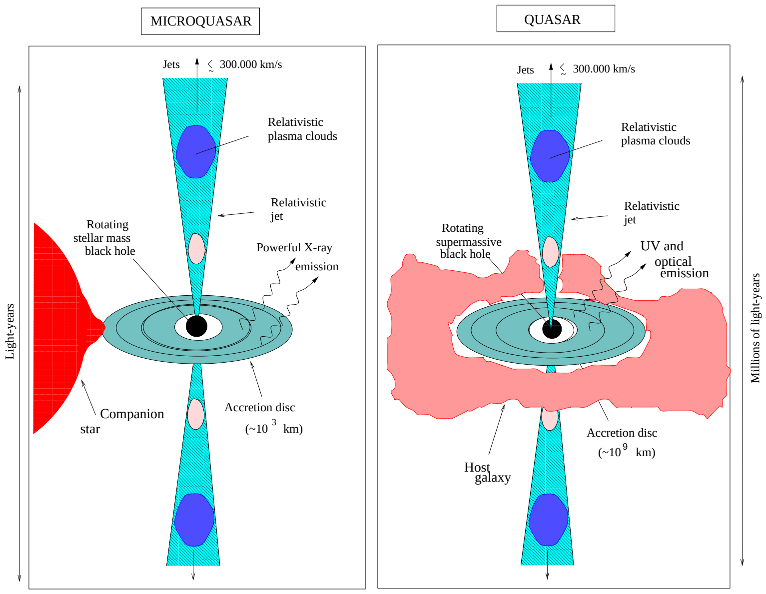

Figure 1: Schematic view illustrating analogies between quasars and microquasars. Note the different mass and length scales between both types of objects (Chaty, 1998).

microblazars (microquasar whose jet points towards the observer), in order to complete the analogy with quasars.

We will see in the following that this quasar/microquasar analogy became rapidly very fruitful, the field of quasars benefiting of microquasars, and vice versa. For instance, because accretion/ejection timescale is proportional to black hole mass, it is easier (because faster) to observe accretion/ejection cycles in microquasars than in quasars [1]. On the other hand the understanding of ejection phenomena in microquasars have largely benefited from jet models developed for active galaxies.

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[1] Characteristic timescale of phenomena occurring very close to the last stable orbit around the black hole of mass M is given by $\tau \sim \frac{r_g}{c} \sim M$, where r_g is the Schwarzschild radius. Therefore, this timescale is proportional to the mass of the black hole. If a stellar mass black hole exhibits accretion/ejection cycles of a few minutes, a supermassive black hole will exhibit corresponding cycles on a few thousands of years.

3 The golden age of microquasars: accretion and ejection

GRS 1915+105 will once again play an important role in the understanding of microquasars. In 1997, after performing multi-wavelength observation campaigns of this source, the link between accretion and ejection was discovered (Chaty 1998; Mirabel et al. 1998). Examining Figure 2, we can see the disappearance of the internal part of the accretion disc, shown by a decrease in the X-ray flux, followed by an ejection of relativistic plasma clouds, corresponding to an oscillation in the near-infrared (NIR) and then in the radio, the cloud becoming progressively optically thin. The analysis of X-ray fluxes and hardness ratios, shown in Figure 3, suggests that it is mainly the part emitting at higher energy which is ejected at the time of the X-ray spike. This supports the interpretation that part of the corona (surrounding the compact object in the central part of the accretion disc) is ejected during this cycle (Chaty, 1998). Each of these accretion/ejection cycles last for $\sim$ 10 min, and they are recurrent, occurring every $\sim$ 30–45 min. Not only it is interesting to point out that these observations had not been performed on quasars, even after nearly 40 years of study, but also that for the first time microquasars were taking over on the quasars, bringing new discoveries. Five years later, similar phenomena would be reported on the quasar 3C120, compiling 3 years of observations (Marscher et al., 2002). These observations from both types of objects confirmed that the morphological quasar/microquasar analogy was subtended by physics [2].

We will not discuss here the different accretion and ejection models, but refer the reader to e.g. Fender (2001) for a description of these models and how they relate to different ejection states. We simply remind that the standard model is constituted of thermal emission coming from a multicolour black body accretion disc and of non-thermal emission of plasma corona, and that jets are observed during low/hard states (historically referring to X-rays). Concurrent models invoke jet synchrotron emission from radio to X-rays. Therefore the main uncertainty in this domain concerns the underlying physical process: comptonization or synchrotron? An answer might be given by polarisation observations. High energy instruments do not allow this yet, and NIR polarimetric observations are still beginning. Dubus & Chaty (2006) report NIR polarimetric observations of the microquasar

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[2] Another compelling evidence of this analogy is given by the supermassive black hole at the centre of our Galaxy: with a mass of 3.6×10^6 $M_\odot$ it exhibits a few tens of minutes NIR quasi-periodic oscillations (QPOs; Genzel et al. 2003), when stellar mass black holes exhibit a few millisecond X-ray QPOs, consistent with the mass ratio.

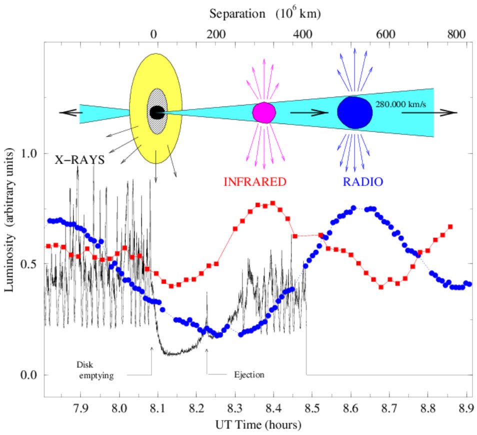

Figure 2: Observation of the link between accretion and ejection. X-ray, NIR and radio lightcurves of GRS 1915+105 during the 1997 September 9 multi-wavelength observation campaign. The disappearance of the internal part of the accretion disc (decrease in the X-ray flux) is followed by an ejection of relativistic plasma clouds (oscillation in the NIR and radio) (Chaty 1998; Mirabel et al. 1998).

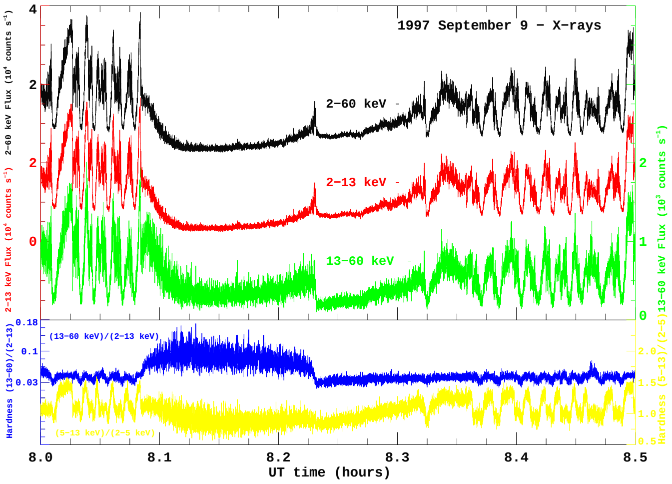

Figure 3: Same observations as above, with only X-ray observations, and enlarged on the UT interval [8.0-8.5] hours. From top to bottom: 2-60 keV, 2-13 keV and 13-60 keV X-ray flux; hardness ratio $\frac{13-60keV}{2-13keV}$ and $\frac{5-13keV}{2-5keV}$. These observations suggest that it is a part of the corona which is ejected at the time of the X-ray spike (Chaty, 1998).

XTE J1550-564, performed in 2003 at ESO/NTT. These observations were performed on the decline (at ~ 2.5 count/s) of a small amplitude outburst peak (4.5 count/s) detected by *Rossi-XTE*/ASM (Sturner & Shrader, 2005) and which lasted about a month: it was 3.2 mag brighter in NIR than in quiescence. XTE J1550-564 polarisation is inconsistent with other stars of the field of view at the 2.5σ level, suggesting an intrinsic NIR polarisation p=0.9–2.0% perhaps due to synchrotron emission from the jet, associated with the outburst (Dubus & Chaty, 2006).

To understand accretion/ejection models, it is therefore necessary to undertake a multiwavelength approach and get the spectral energy distribution (SED) of various sources. There is a small number of microquasars for which this has been done intensively, the jet source and black hole XTE J1118+480 being one of the best examples, favoured by the very low absorption on its line of sight (Chaty et al., 2003). In Figure 4 I report the SED of this source, including 6 different epochs of simultaneous multi-wavelength observations from radio to X-rays, performed with 8 different instruments. On this Figure I overplot the thermal emission of the multicolour black body accretion disc, the emission from the companion star, and non-thermal emission which appears to be necessary to account for radio, NIR and X-ray domains. In Chaty et al. (2003) it has been shown, by using a non-linear Monte-Carlo simulation, that the presence of hot spherical plasma in the centre can account for the emission of the source from optical to X-rays. However other models show that this emission can also be described by a jet emitting from radio to X-rays, as in the case of active galaxies (Markoff et al., 2001). This question about the jet contribution is therefore still a matter in the debate.

It is interesting to compare XTE J1118+480 and GRS 1915+105 SEDs. During large multiwavelength campaigns from radio to hard X-rays, Ueda et al. (2002) and Fuchs et al. (2003) have shown the presence of a flat radio spectrum, during the “plateau” (or low/hard) state of GRS 1915+105. They also confirm that the jet contributes to the emission in the NIR domain. A comparison of the accretion/outflow energy ratio of both sources XTE J1118+480 & GRS 1915+105 shows that they both fall into the regime of radio-quiet quasars (Chaty et al., 2003).

Simultaneous multi-wavelength observations of both types of objects, namely microquasars and quasars, will eventually bring severe constraints on accretion-ejection models (e.g. Blandford-Payne, Blandford-Znajek, Magneto-Rotational Instability...), and on the nature of the jets (are they baryonic or leptonic?). For instance, putting together radio and X-ray observations suggests that a coupling exists between both domains, $F_{\rm rad} \propto F_{\rm X}^{+0.7}$, for galactic (Gallo et al., 2003) and extragalactic jet sources (Falcke et al.,

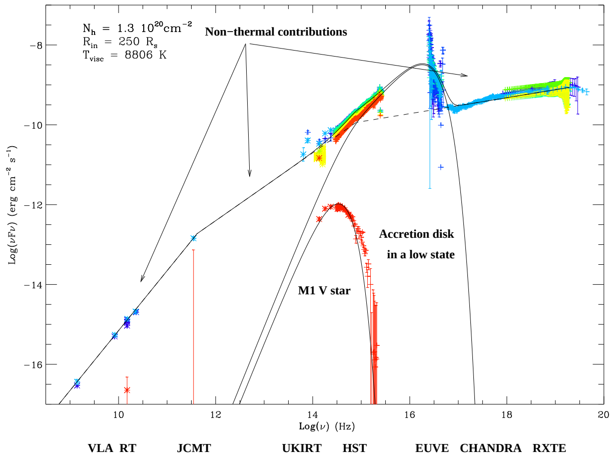

Figure 4: Spectral energy distribution of the microquasar XTE J1118+480 which can be described by the sum of emission from the multicolour blackbody accretion disk, a non-thermal contribution from an outflow and the M1 V companion star (Chaty et al., 2003).

2004), but a good understanding of this coupling still misses. Some answers might also come from the detection of (Doppler- shifted?) annihilation emission lines, and also from observations of QPOs in microquasars.

4 The hidden face of microquasars: interaction with their surroundings

Jets of microquasars can be observed at different scales, corresponding to different sizes and energy outputs involved. Observations of sporadic ejection at large scale were performed first, as described in Section 2. A steady compact jet has been observed in a few microquasars, for instance in GRS 1915+105 (at the milli-arcsec scale, where 10mas = 1AU; Dhawan et al. 2000; Fuchs et al. 2003; Ribó et al. 2004). Since these jet sources eject a large amount of matter in the interstellar space, which is far from being empty, it appeared fruitful to look for interactions between jets and surroundings of the microquasar. The first example is 1E 1740.7-2942, which exhibits a steady jet, probably due to the braking of its continuous jet in the interstellar medium. The signature of such an interaction might be the observation, directly in the jets, of a narrow annihilation line at 511 keV, due to e^+ colliding with the interstellar medium [3]. Large-scale jets are now regularly observed in X-rays. Corbel et al. (2002) have observed such jets emanating from the microquasar XTE J1550-564, at $45''$ of the central source. To emit at such energy, the particles have to be accelerated up to TeV energy, again strengthening the analogy with quasars.

By studying the interactions between the jets and the interstellar medium, one can not forget GRS 1915+105: always active, transient, and the place of very energetic ejection. Such interactions in the surroundings of GRS 1915+105 had already been suggested nearly 10 years ago by Mirabel et al. (1996). In August 1995, during a strong and long X-ray outburst of GRS 1915+105, the radio source was resolved in 2 jets, and the NIR emission increased significantly between 2 and 5 days after the radio burst. Mirabel et al. (1996) interpreted this as the presence of an extended cocoon of dust, heated by ejection. This dust in the surroundings of this microquasar was later confirmed by *Chandra* (Lee et al., 2002) and *ISO* (Fuchs et al., 2001) observations. However it is still unknown if the cocoon has been created by previous ejection, or by accumulation of ISM dust. What about the surroundings of GRS 1915+105, at larger scale? A low-resolution centimetre map exhibits two sources aligned with the central source (Chaty et al., 2001). By observing them at higher resolution, Chaty et al. (2001) discovered a strange non-thermal feature in the south-east lobe, which might be a synchrotron signature of interactions between jets and ISM. However, they concluded that even if, based on the energy output, the interaction is a possibility, there is no observational fact allowing to confirm that this strange feature is the signature of interaction between jets and interstellar medium.

Finally, all these observations of jets bring us to another important question in the field of jet sources: are the jets a propagation of plasma clouds or of shock waves? The first interpretation is usual among the microquasar community, and the second one among the extragalactic community. By applying 3C273 model to GRS 1915+105, Türler et al. (2004) have shown that ejection in GRS 1915+105 could be described as the propagation of a shock wave forming at 1AU, with dissipative stream at $v = 0.6c$.

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[3] Annihilation lines have been reported on this source (therefore also called "the great annihilator of the Galaxy") but likely coming from the central source, and therefore related to the accretion process (Bouchet et al., 1991).

5 Microquasars and their role in astroparticle physics

In this review I have shown that microquasars are the site of accretion, ejection and interaction of jets with the interstellar medium. Microquasars are therefore high-energy laboratories which encompass all necessary ingredients in order to emit astroparticles: VHE photons, cosmic rays and neutrinos.

5.1 Microquasars as emitters of VHE photons

Many models exist which predict the emission of VHE photons by the microquasars. A recent one is the broad-band leptonic model for gamma-ray emitting microquasars by Bosch-Ramon et al. (2006), in which the jet is dominated dynamically by cold protons, radiatively by relativistic leptons, and the magnetic field is at equipartition. In this model the emission from radio to VHE is due to synchrotron, relativistic Bremsstrahlung and Inverse Compton processes. It provides predictions about the shape of the SEDs and points to microquasars as VHE sources.

There are some observations of GeV emission from EGRET (Paredes et al. 2000) to VHE TeV γ-rays with HESS (Aharonian et al. 2005) emanating from the microquasar candidate LS 5039. A second example is the detection of variable VHE $\gamma - ray$ emission from the microquasar candidate LS I +61 303, with MAGIC. However, it is not clear if the high energy emission is coming from the jets of these sources, or from the interaction between radiation of the compact object (if it is a neutron star) and the wind of their early spectral type companion star as proposed by Dubus (2006)[4]. In the latter case no jet would be needed, and these sources would not be microquasars.

5.2 Microquasars as neutrinos emitters

The model by Romero & Orellana (2005) predicts neutrino and gamma-ray emission from misaligned microquasars, if the jet is misaligned with the perpendicular to the orbital plane (which could be usual: for instance, the jet is inclined of 35° from orbital plane for V4641 Sgr; there is some precession in SS 433, LSI +61 303, and Cygnus X-3), and if the donor star is an early-type star. If both conditions are met, then the jet collides with the stellar wind, and a standing shock between the compact object and the stellar surface is created. Finally, if the jet has an hadronic content, TeV protons might

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[4] This kind of object has been nicely called "pulsars in disguise" by this author.

diffuse into an inner, dense wind leading to γ-ray emission. This model predicts an enhancement and periodic variability of γ-ray TeV signal (which could be detected by HESS, MAGIC, Veritas) and also a neutrino signal at 3 σ (ICECUBE, AMANDA, ANTARES) for an observation time of 15 years of a source located at 2 kpc... only if there is a close alignment of the jet with the line of sight, in order to obtain a duty cycle of 20%.

Therefore even if the microquasars are emitters of TeV neutrinos, their possible detection will probably only be feasible with km^2 neutrino telescopes. To see what could be the signal, we can take the model of Distefano et al. (2002), where there is photopion production in the jet, with the conditions that the jets are protonic, and that a fraction of a few percents of the jet energy is dissipated on a sufficiently small scale. In this case, we would expect a signal of 252 neutrinos coming from SS 433, with a 1 year integration time. We could probably even identify new microquasars by their neutrino and γ-ray emission, if they exhibit large bulk Lorentz factors, and if the jets are directed along our line of sight.

5.3 Microquasars as cosmic rays emitters

If the jets contain cold protons and heavy ions (as it is the case in SS 433), cosmic rays from microquasars could represent a narrow component at 3-10 GeV to the Cosmic ray spectrum (Heinz & Sunyaev, 2002). For instance, a single microquasar as GRS 1915+105, if it is active for 10^7 years, with a luminosity of 10^{38}ergs/s, and located at a distance of 1 kpc, would produce detectable signal in the galactic CR background spectrum. On the other hand, their prediction is that if there is no such detection, this means that the jets are leptonic...

6 Conclusions

We have seen that microquasars are excellent laboratories for high energy physics, and are the key to many still pending questions, related to accretion-ejection mechanisms, interaction between the jets and interstellar medium, and their propagation. To answer to these questions, it will be necessary to simultaneously study multi-wavelength emissions from various microquasars at different stages. This will also allow to better measure what is the contribution in the SED of non-thermal (synchrotron) emission coming from the jets. One of the key questions, perhaps the most important one, is whether the jets are baryonic or leptonic. Indeed, we have seen that microquasars will not have the same role in astroparticle physics in both cases, since there is much more chance for them to be VHE photons, cosmic rays and neutrinos emitters if the jets are of baryonic nature.

We are at an era where the whole electromagnetic spectrum can be explored, from the radio to VHE photons, along with cosmic rays, and we will be able soon to observe neutrinos. Putting everything together and linking these observations with theory and models might help us in a better understanding of these exciting sources.

I would like to take here the opportunity to thank the organisers for their invitation to give this review on microquasars and their role in astroparticle physics, and also for a very nice organisation of this workshop, in an idyllic place and atmosphere, fruitful to arise scientific discussions and new ideas!

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