MICROQUASARS AND JETS

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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. After remindind 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 occuring in these sources. Thereafter, I review jets at different scales: compact jets, large-scale jets, and the interactions between ejections and the surrounding medium. I finish by speaking about microblazars and ultraluminous X-ray sources.

1 Prelude to microquasars

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 Youth of microquasars: 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 characterize 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 sustended by physics? If the answer is yes, then microquasars really are "micro"-quasars. For instance, there should exist 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 benefitting 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 [a]. On the other hand the understanding of ejection phenomena in microquasars have largely benefitted from jet models developped for active galaxies.

3 Maturity of microquasars: accretion and ejection

GRS 1915+105 will once again play an important role in the understanding of microquasars. In 1997, after performing many multi-wavelength observation campaigns of this source, the link between accretion and ejection was discovered (Chaty 1998; Mirabel, Dhawan, Chaty 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, occuring 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

[a] Characteristic timescale of phenomena occuring 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.

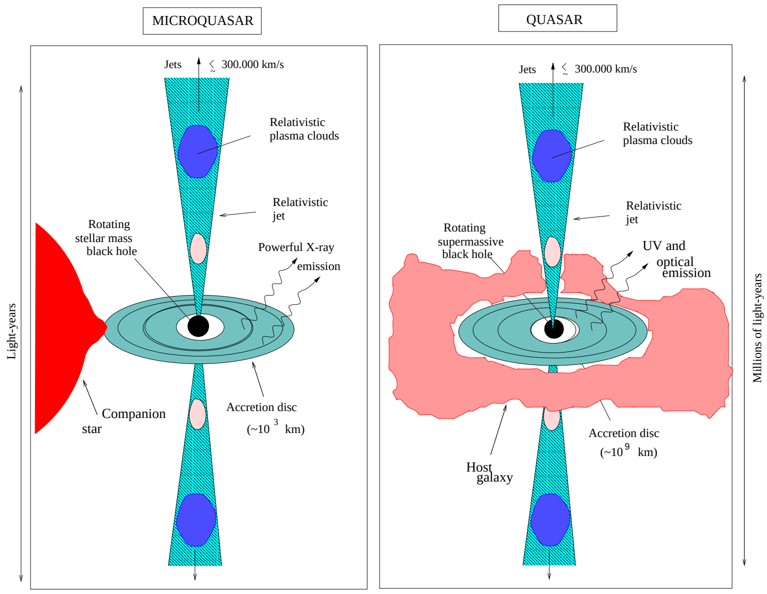

Figure 1: Schematic view illustrating analogies between quasars and microquasars (Chaty, 1998). Note the different mass and length scales between both types of objects.

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 sustended by physics[b].

4 The golden age of microquasars

We do 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 polarization observations. High energy instruments do not allow this yet, and NIR polarimetric observations are still beginning. Dubus & Chaty (2005) report NIR polarimetric observations of the microquasar XTE J1550-564, performed in 2003 at ESO/NTT. These observations were performed on the decline (at $\sim$ 2.5 count/s) of a small amplitude outburst peak (4.5 count/s) lasting about a month detected by *Rossi-XTE*/ASM (Sturner & Shrader, 2005). In NIR, it was 3.2 mag brighter 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 polarization p=0.9–2.0% perhaps due to synchrotron emission from the jet, associated with the outburst (Dubus & Chaty, 2005).

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 them, favored by its very low absorption on its line of sight

[b] Another compelling evidence of this analogy is given by the supermassive black hole at the center of our Galaxy: with a mass of $3.6 \times 10^6\ M_\odot$ it exhibits a few tens 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.

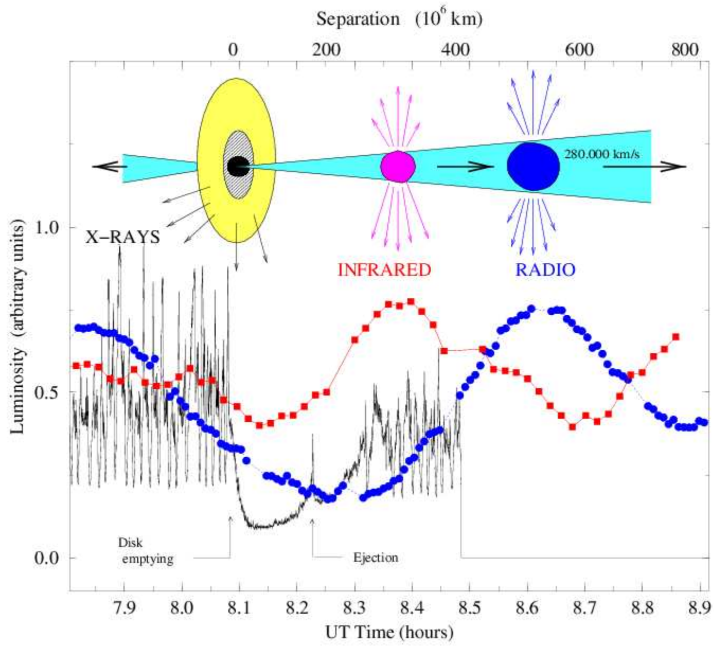

Figure 2: Observation of the link between accretion and ejection. X-ray, NIR and radio lightcurves of GRS 1915+105 during the 1997 September 9 multi-wavelength observation campaign (Chaty 1998; Mirabel, Dhawan, Chaty et al. 1998). The disappearance of the internal part of the accretion disc (decrease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

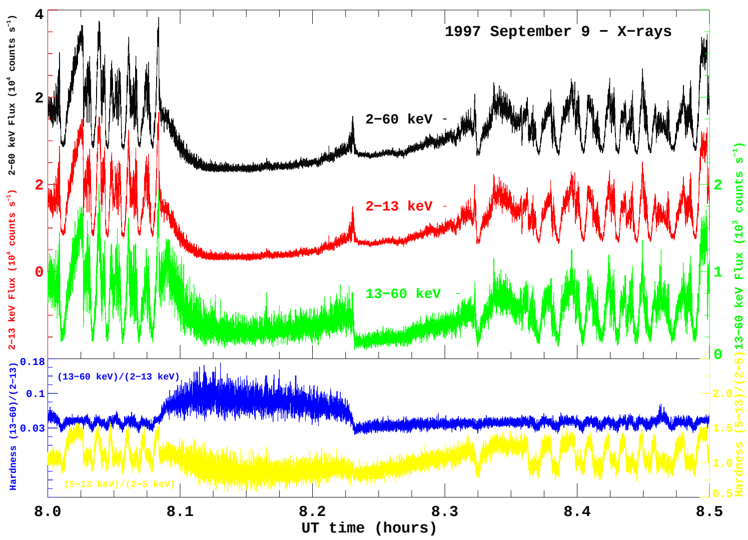

Figure 3: Same observations as above, but only X-ray observations are shown, and enlarged on the UT time interval [8.0-8.5] hours. From top to bottom: X-ray flux in 2-60 keV, 2-13 keV and 13-60 keV energy bands; hardness ratio $\frac{13-60keV}{2-13keV}$ and $\frac{5-13keV}{2-5keV}$ (Chaty, 1998).

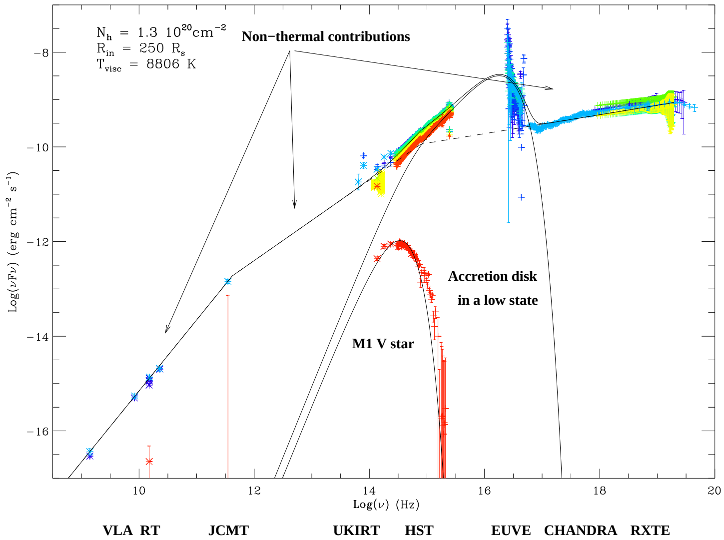

Figure 4: Spectral energy distribution of the microquasar XTE J1118+480 (Chaty et al., 2003b).

(Chaty et al., 2003b). 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. (2003b) 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., 2003b).

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 made of e^-/e^+ or e^-/p?). 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., 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.

5 The hidden face of microquasars: jets and surroundings...

Jets of microquasars can be observed at different scales, corresponding to different sizes and energy outputs involved. Observations of sporadic ejections 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 appears 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 [c]. 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 jets and the interstellar medium, one can not forget GRS 1915+105: always active, transient, and the place of very energetic ejections. 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 ejections. However it was unknown if the cocoon had been created by previous ejections, or by accumulation of ISM dust. This dust in the surroundings of this microquasar was later confirmed by *Chandra* (Lee et al., 2002) and *ISO* (Fuchs et al., 2001) observations. And what about the surroundings of GRS 1915+105, at larger scale? A low-resolution centimeter map exhibits two sources aligned with the central source (Chaty et al., 2001). By observing them at higher resolution, it appeared a strange non-thermal feature in the south-east lobe, which might be a synchrotron signature of interactions between jets and ISM. However, Chaty et al. (2001) 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 microquasars: are the jets a propagation of plasma clouds or the propagation 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 ejections in GRS 1915+105 could be described as the propagation of a shock wave forming at 1AU, with dissipative stream at $v = 0.6c$.

6 Ubiquity of microquasars

Even if microquasars are not everywhere, they are more and more present! We have seen in Section 2 that microblazars should exist if the analogy with quasars was sustended by physics. However the problem with microblazars is that they are difficult to observe since flares, although strong, are short [d]. Jet precession could produce intermittent microblazars (see e.g. Massi et al. 2004). There are some hints that some microblazars have been observed. The source V4641 Sgr exhibited a one-day flare, becoming for a short time the brightest X-ray source of the sky, increasing from 1.6 to 12.2 Crab, and in optical from 14 to 8.8 magnitudes, exhibiting a wind velocity of 5000 km/s (Chaty et al., 2003a). This source was claimed to be a microblazar, since at a distance of 6 kpc, the jets would have had an apparent velocity of $v \sim 10c$. However this apparent velocity is based on the uncertain motion of the radio lobe, due to lack of good observing coverage, therefore there is no conclusive evidence that this source is a microblazar.

Ultra-luminous X-ray sources (ULXs) are observed near active galactic nuclei at high stellar formation rates. Are they beamed jets from microquasars (and in this case microblazars

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

[d] For a microblazar with a jet frame velocity $v = 0.98c$, the time of the outburst is shortened by a factor 10, the flux multiplied by 1000, and the photon energy increased compared to a microquasar.

would not be missing to the family anymore), or black holes of intermediate mass ($\sim 1000 M_{sol}$) (Körding et al., 2002)? Are there ULXs in our Galaxy? There are claimed associations between galactic microquasars and gamma-ray sources: e.g. LS 5039 (Paredes et al., 2000), and hundreds of unidentified gamma-ray sources still exist... so this field is still full of discoveries to come.

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References

Bouchet L. et al., 1991, ApJ, 383, L45

Castro-Tirado A. J. et al., 1994, ApJSS, 92, 469

Chaty S., 1998, PhD thesis, University Paris XI

Chaty S., Charles P. A., Martí J. et al., 2003a, MNRAS, 343, 169

Chaty S., Haswell C. A., Malzac J. et al., 2003b, MNRAS, 346, 689

Chaty S., Rodríguez L. F., Mirabel I. F. et al., 2001, A&A, 366, 1041

Corbel S. et al., 2002, Science, 298, 196

Dhawan V., Mirabel I., Rodríguez L., 2000, ApJ, 543

Dubner G., Holdaway M., Goss M., Mirabel I. F., 1998, AJ, 116, 1842

Dubus G., Chaty S., 2005, MNRAS subm.

Falcke H., Körding E., Markoff S., 2004, A&A, 414, 895

Fender R. P., 2001, MNRAS, 322, 31

Fuchs Y. ., Mirabel I. F. ., Ogley R. N., 2001, Astrophysics & Space Science Suppl., 276, 99

Fuchs Y., Rodriguez J., Mirabel I. F., Chaty S. et al., 2003, A&A, 409, L35

Gallo E., Fender R. P., Pooley G. G., 2003, Mon. Not. R. astr. Soc., 344, 60

Genzel R. et al., 2003, Nat., 425, 934

Körding E., Falcke H., Markoff S., 2002, A&A, 382, L13

Lee J. C. et al., 2002, ApJ, 567, 1102

Margon B., 1984, Annu. Rev. A&A, 22, 507

Markoff S., Falcke H., Fender R., 2001, A&A, 372, L25

Marscher A. P. et al., 2002, Nature, 417, 625

Massi M., Ribó M., Paredes J. M. et al., 2004, A&A, 414, L1

Mirabel I. F., Dhawan V., Chaty S. et al., 1998, A&A, 330, L9

Mirabel I. F., Rodríguez L. F., 1994, Nature, 371, 46

Mirabel I. F., Rodríguez L. F., Chaty S. et al. 1996, Astrophys. J., 472, L111

Mirabel I. F., Rodríguez L. F., Cordier B., Paul J., Lebrun F., 1992, Nature, 358, 215

Paredes J. M., Martí J., Ribó M., Massi M., 2000, Science, 288, 2340

Ribó M., Dhawan V., Mirabel I. F., 2004, in Proceedings of the 7th European VLBI Network Symposium, 111 (astro-ph/0412657)

Sturner S. J., Shrader C. R., 2005, ApJ subm.

Türler M., Courvoisier T. J.-L., Chaty S., Fuchs Y., 2004, A&A, 415, L35

Ueda Y., Yamaoka K., Sánchez-Fernández C., Dhawan V., Chaty S. et al. 2002, ApJ, 571, 918