Part 6
X-Ray Binaries

Microquasars as Sources of High Energy Phenomena

I. F. Mirabel

Centre d'Etudes de Saclay/CEA/DSM/DAPNIA/SAP
91911 Gif/Yvette, France &
Intituto de Astronomía y Física del Espacio/CONICET, Argentina

Abstract. Relativistic outflows are a common phenomenon in accreting black holes. Despite the enormous differences in scale, accreting stellar-mass black holes (X-ray binaries, collapsars) and super-massive black holes produce jets with analogous physical properties. Here I review microquasars as sources of relativistic jets, gamma-rays, cosmic rays, and high energy neutrinos.

1. The quasar-microquasar analogy

Microquasars are scaled-down versions of quasars and both are believed to be powered by spinning black holes with masses of up to a few tens that of the Sun (see Figure 1). The word *microquasar* was chosen by Mirabel et al. (1992) to suggest that we could learn about microquasars from previous decades of studies on AGN. In fact, the analogy with quasars is more than morphological, because there is an underlying unity in the physics of accreting black holes over an enormous range of scales, from stellar-mass black holes in binary stellar systems, to super-massive black holes at the centre of distant galaxies (Rees, 1998). A major difference is that the linear and time scales of the phenomena are proportional to the black hole mass.

In quasars and microquasars are found the following three basic ingredients: 1) a spinning black hole, 2) an accretion disk heated by viscous dissipation, and 3) collimated jets of relativistic particles. However, in microquasars the black hole is only a few solar masses instead of several million solar masses; the accretion disk has mean thermal temperatures of several million degrees instead of several thousand degrees; and the particles ejected at relativistic speeds can travel up to distances of a few light-years only, instead of the several million light-years as in some giant radio galaxies. In quasars matter can be drawn into the accretion disk from disrupted stars or from the interstellar medium of the host galaxy, whereas in microquasars the material is being drawn from the companion star in the binary system. In quasars the accretion disk has sizes of $\sim 10^9$ km and radiates mostly in the ultraviolet and optical wavelengths, whereas in microquasars the accretion disk has sizes of $\sim 10^3$ km and the bulk of the radiated energy comes out in the X-rays. It is believed that part of the spin energy of the black hole can be tapped to power the collimated ejection of magnetized plasma at relativistic speeds.

Because of the relative proximity and shorter time scales, in microquasars it is possible to firmly establish the relativistic motion of the sources of radiation, and to better study the physics of accretion flows and jet formation near the horizon of black holes. Jets in microquasars are easier to follow because their apparent motions in the sky are $\geq 10^3$ faster than in quasars. Because microquasars are found in our Galaxy the two-sided moving jets are more easily seen than in AGN (Mirabel & Rodríguez, 1994). However, to know how the jets are collimated in units of length of the black hole's horizon, AGN up to distances of a few Mpc may present an advantage. Biretta et al. (2002) find that the initial collimation of the non-thermal jet in the galaxy M87 of the Virgo cluster takes place on a scale of 30-100 R_S, which is consistent with poloidal collimation by an accretion disk.

At first glance it may seem paradoxical that relativistic jets were first discovered in the nuclei of galaxies and distant quasars and that for more than a decade SS433 was the only known object of its class in our Galaxy (Margon 1984). This is because that disks around super-massive black holes emit strongly at optical and UV wavelengths. Indeed, the more massive the black hole, the cooler the surrounding accretion disk is. For a black hole accreting at the Eddington limit, the characteristic black body temperature at the last stable orbit in the surrounding accretion disk will be given approximately by $T \sim 2 \times 10^7 \, M^{-1/4}$ (Rees 1984), with T in K and the mass of the black hole, M, in solar masses. Then, while accretion disks in AGN have strong emission in the optical and ultraviolet with distinct broad emission lines, black hole and neutron star binaries usually are identified for the first time by their X-ray emission. Among this class of sources, SS433 is unusual given its broad optical emission lines and its brightness in the visible. Therefore, it is understandable that there was an impasse in the discovery of new stellar sources of relativistic jets until the development of X-ray astronomy that started with the discovery of the first extra-solar X-ray source by Giacconi et al. (1962). Strictly speaking, if it had not been for the historical circumstances described above, the acronym *quasar* would have suited better the stellar mass versions rather than their super-massive analogs at the centers of galaxies.

2.   The microquasar gamma-ray-burst analogy

There is increasing evidence that the central engine of the most common form of gamma-ray burst (GRBs), those that last longer than a few seconds, are afterglows from ultra-relativistic jets produced during the formation of stellar-mass black holes (McFaden & Woosley, 1999). Mirabel & Rodríguez (1999) proposed that ultra-relativistic bulk motion and beaming are needed to explain: 1) the enormous energy requirements of $\geq 10^{54}$ erg if the emission were isotropic (e.g. Kulkarni et al. 1999; Castro-Tirado et al. 1999); 2) the statistical correlation between time variability and brightness (Ramirez-Ruiz & Fenimore, 2000), and 3) the statistical anti-correlation between brightness and time-lag between hard and soft components (Norris et al. 1999). Beaming reduces the energy release by the beaming factor $f = \Delta\Omega/4\pi$, where $\Delta\Omega$ is the solid angle of the beamed emission. Additionally, the photon energies can be boosted to higher values. Extreme flows from collapsars with bulk Lorentz factors > 100 have been proposed
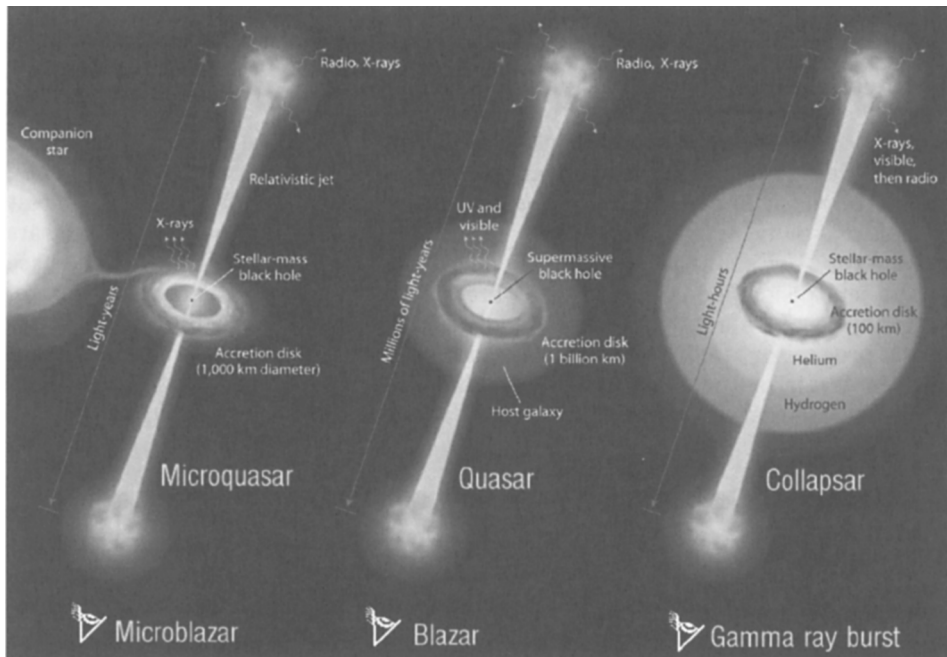
Figure 1. Diagram illustrating current ideas concerning micro-quasars, quasars and gamma-ray bursts (not to scale). It is proposed that a universal mechanism may be at work in all sources of relativistic jets in the universe. Synergism between these three areas of research in astrophysics should help to gain a more comprehensive understanding of the relativistic jet phenomena observed everywhere in the universe.

as sources of γ-ray bursts (Mészáros & Rees 1997). High collimation (Dado, Dar & de Rújula 2002; Pugliese et al. 1999) can be tested observationally (Rhoads, 1997), since the statistical properties of the bursts will depend on the viewing angle relative to the jet axis.

Recent multi-wavelength studies of gamma-ray afterglows suggest that they are highly collimated jets. The brightness of the optical transient associated to some GRBs show a break (e.g. Kulkarni et al. 1999), and a steepening from a power law in time t proportional to $t^{-1.2}$, ultimately approaching a slope $t^{-2.5}$ (e.g. Castro-Tirado et al. 1999). The achromatic steepening of the optical light curve and early radio flux decay of some GRBs are inconsistent with simple spherical expansion, and well fit by jet evolution. It is interesting that the power laws that describe the light curves of the ejecta in microquasars show similar breaks and steepening of the radio flux density (Rodríguez & Mirabel, 1999). In microquasars, these breaks and steepenings have been interpreted (Hjellming & Johnston 1988) as a transition from slow intrinsic expansion followed by free expansion in two dimensions. Besides, linear polarizations of about 2% were recently measured in the optical afterglows (e.g. Covino et al. 1999), providing strong evidence that the afterglow radiation from gamma-ray bursts is, at least

in part, produced by synchrotron processes. Linear polarizations in the range of 2-10% have been measured in microquasars at radio (e.g. Rodríguez et al. 1995), and optical (Scaltriti et al. 1997) wavelengths.

The jets in microquasars of our own Galaxy seem to be less extreme local analogs of the super-relativistic jets associated to the more distant gamma-ray bursts. But the latter do not repeat, seem to be related to catastrophic events, and have much larger super-Eddington luminosities. According to the latest models, the same symbiotic disk-jet relationship as in microquasars and quasars powers the GRBs. In fact, it is now believed that the Lorentz factors at the base of the jets inside the collapsing star are ≤ 10 as in microquasars and quasars, and they reach values ≥ 100 when they break free from the infalling outer layers of the progenitor star. Because of the enormous difference in power, the scaling laws in terms of the black hole mass that are valid for the analogy between microquasars and quasars may not apply in the case of gamma-ray bursts.

3.   Compact jets in stellar-mass and super-massive black holes

The class of stellar-mass black holes that are persistent X-ray sources (e.g. Cygnus X-1, 1E 1740-2942, GRS 1758-258, etc.) and some super-massive black holes at the centre of galaxies (e.g. Sgr A* and many AGN) do not exhibit luminous outbursts with large-scale sporadic ejections. However, despite the enormous differences in mass, steadily accreting black holes have analogous radio cores with steady, flat ($S_\nu \propto \nu^\alpha$; $\alpha \sim 0$) emission at radio wavelengths. The fluxes of the core component in AGN are typically of a few Janskys (e.g. Sgr A* ~ 1Jy) allowing VLBI high resolution studies, but in stellar mass black holes the cores are much fainter, typically of a few mJy, which makes difficult high resolution observations of the core.

From the spectral shape it was proposed that the steady compact radio emission in black hole X-ray binaries are jets (e.g. Rodríguez et al. 1995; Fender et al. 1999, 2000; Corbel et al. 2000). Recently, this has been confirmed by VLBI observations at AU scale resolution of GRS 1915+105 (Dhawan, Mirabel & Rodríguez, 2000), and Cyg X-1 (Stirling et al. 2001) in the low-hard X-ray state. VLBA images of GRS 1915+105 show compact jets with sizes $\sim 10\lambda_{cm}$ AU along the same position angle as the superluminal large-scale jets. As in the radio cores of AGN, the brightness temperature of the compact jet in GRS 1915+105 is $T_B \geq 10^9$ K. The VLBA images of GRS 1915+105 are consistent with the conventional model of a conical expanding jet with synchrotron emission (Hjellming & Johnston, 1988; Falcke & Biermann, 1999) in an optically thick region of solar system size. These compact jets are also found in neutron star X-ray binaries such as LS 5039 (Paredes et al. 2000) and Sco X-1 (Fomalont et al. 2001), and are currently used to track the path of black holes and neutron stars in our Galaxy (see Mirabel & Rodrigues, 2002 for a review).

4.   Accretion disk origin of relativistic jets

Synergism between results from multiwavelength simultaneous observations in microquasars and quasars is providing important insights into the connection between accretion disk instabilities and the genesis of jets. Since the charac-
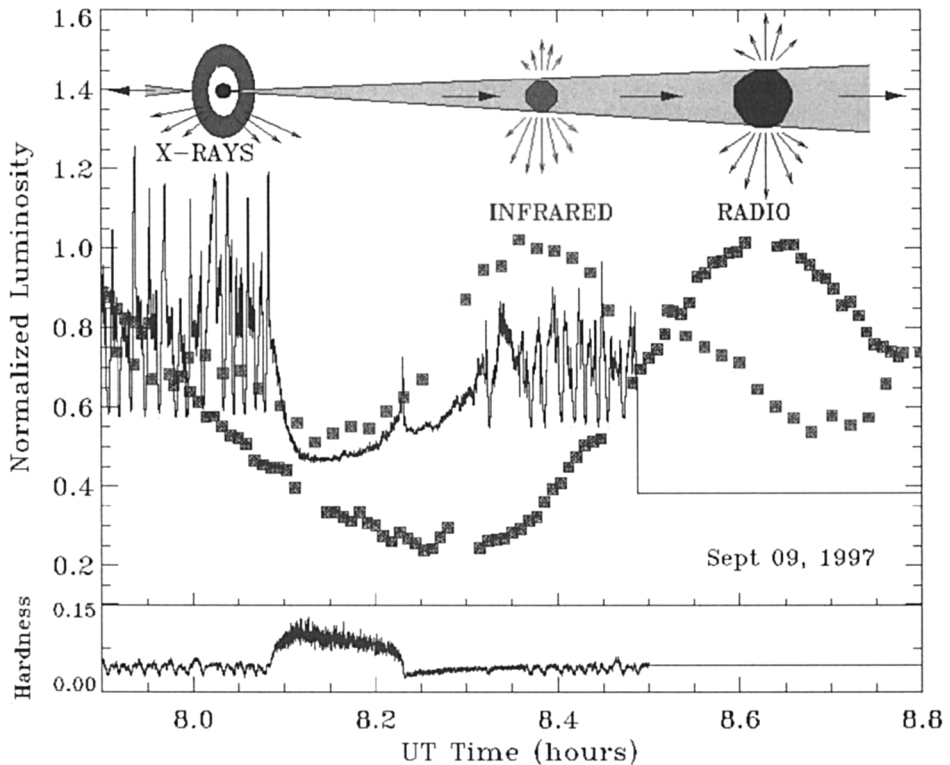
Figure 2. Radio, infrared, and X-ray light curves for GRS 1915+105 at the time of quasi-periodic oscillations with scales of time of ∼20 min (Mirabel et al. 1998). The infrared flare starts during the recovery from the X-ray dip, when a sharp, isolated X-ray spike-like feature is observed. These observations show the connection between the rapid disappearance and follow-up replenishment of the inner accretion disk seen in the X-rays (Belloni et al. 1997), with the ejection of relativistic plasma clouds observed first as synchrotron emission at infrared wavelengths, later at radio wavelengths. A scheme of the relative positions where the different emissions originate is shown in the top part of the figure. The hardness ratio (13-60 keV)/(2-13 keV) is shown at the bottom of the figure. Analogous phenomena have now been obseved in the quasar 3C 120 but in time scales of years (Marscher et al. 2002).

teristic times in the flow of matter onto a black hole are proportional to its mass, the accretion-ejection phenomena in quasars should last 10^5-10^7 longer than analogous phenomena in microquasars (Sams et al. 1996). Therefore, variations on scales of tens of minutes of duration in microquasars could be sampling phenomena that had been difficult to observe in quasars.

Simultaneous multiwavelength observations of a microquasar revealed in an interval of time of a few tens of minutes the connection between the sudden disappearance of the inner $\sim$200 km of the accretion disk with the ejection of expanding clouds of relativistic plasma (see Figure 2). One possible interpretation of the observations shown in Figure 2 is that the plasma of the inner disk that radiates in the X-rays falls beyond the horizon of the black hole in $\sim$5min, and subsequently the inner accretion disk is refilled in $\sim$20 min. While the inner disk is being replenished, we observe the ejection of a relativistic plasma cloud, first at 2μm, and latter at radio wavelengths as the cloud expands and becomes transparent for its proper radiation at longer wavelengths. The delay between the maxima at radio and infrared wavelengths is equal to the one computed with the model for a spherically symmetric expanding clouds in relativistic AGN jets by van der Laan (1966). Although VLBA images of these transient ejecta by Dhawan et al. (2000) have shown that they are in fact connical jets, the model first developed for AGN is a good first approximation, and allows to demonstrate that the infared flares that preeced the radio flares are synchrotron, rather than thermal emission. This implies the presence in the jets of electrons with Lorentz factors $\geq 10^3$ (Fender & Pooley, 1998; Mirabel et al. 1998).

Analogous accretion disk-jet connections were observed in the quasar 3C 120 by Marscher et al. (2002). Jets were detected with VLBI after sudden X-ray dips observed with RXTE, but on scales of a few years. The scales of time of the phenomena are within a factor of 10 the black hole mass ratios between the quasar and microquasar, which is relativelly small when compared with the uncertainties in the data.

5.   Microquasars as sources of cosmic rays

If a compact source injects relativistic plasma into its environment, it is expected that some fraction of the injected power will be dissipated by shocks, where reacceleration of particles may take place. Evidences of such interactions are the radio lobes of 1E 1740.7-2942 (Mirabel et al. 1992), GRS 1758-258 (Rodríguez et al. 1992), and the two lateral extensions in the nebula W50 that hosts at its center SS 433. The interaction of SS 433 with the shells of W50 has been studied in the X-rays (Brinkmann et al. 1996) and radio wavelengths (Dubner et al. 1998 and references therein).

Besides the well known relativistic jets seen at sub-arcsec scales in the radio, large-scale jets become visible in the X-rays at distances $\sim$ 30 arcmin ($\sim$ 25 pc) from the compact source (Brinkmann et al. 1996). In the radio and X-rays, the lobes reach distances of up to $1°$ ($\sim$50 pc). These large-scale X-ray jets and radio lobes are the result of the interaction of the mass outflow with the interstellar medium. From optical and X-ray emission lines it is found that the sub-arcsec relativistic jets have a kinetic energy of $\sim 10^{39}$ erg s^{-1} (Margon, 1984), which is several orders of magnitude larger than the energy radiated in the X-rays and in

the radio. Dubner et al. (1998) estimate that the kinetic energy transferred into the ambient medium is $\sim 2\ 10^{51}$ ergs, thus confirming that the relativistic jets from SS433 represent an important contribution to the overall energy budget of the surrounding nebula W50.

Large-scale, decelerating relativistic jets from the microquasar XTE J1550-564 have been discovered with CHANDRA by Corbel et al. (2002). The broadband spectrum of the jets is consistent with synchrotron emission from electrons with Lorentz factors of $\sim 10^7$ that are probably accelerated in the shock waves formed by the interaction of the jets with the interstellar medium. Corbel et al (2002) demonstrated that in microquasars we can study in real time the formation and dynamical evolution of the working surfaces (lobes) of relativistic jets far away from the centres of ejection, on time scales inaccessible for AGN. Working surfaces of microquasar jets as in SS433 and XTE J1550-564 are potential sources of cosmic rays.

In fact, Heinz & Sunyaev (2002) propose that if microquasar jets contain cold protons and heavy ions (as in the case of SS433) thay can produce a small but measurable contribution to the cosmic ray spectrum in the range of 3-10 GeV. These authors propose that if the cosmic ray microquasar proton component is ruled out by observations, one could put interesting constraints on the particle content in microquasar jets by the observation of the 511 keV line with INTEGRAL. The process of cosmic ray production in microquasar jets is fundamentally different from the cosmic ray production in the non relativistic shocks of supernovae remnants.

6.   Microquasars as sources of high energy neutrinos

If the energy content of the jets in transient sources is dominated by electron-proton plasma as in SS433, Levinson and Waxman (2001) predict that an outburst of several hours of 1-100 TeV neutrinos should preceed the radio and infrared flares associated with major ejection events as the one observed by Mirabel & Ridríguez (1994) in GRS 1915+105. These high energy neutrinos are produced by the interaction of the high energy protons with synchrotron photons emitted by the shock-accelerated electron. These neutrinos would provide further probe of the microquasar jet physics.

Guetta et al. (2002) estimate the neutrino fluxes produced in the jets of a sample of identified microquasars and microquasar candidates. They demonstrate that in several of the sources considered, the neutrino flux at Earth, produced in events similar to those observed, can exceed the detection threshold of a km^2 neutrino detector. Neutrino and gamma-ray emission may be the way to identify microquasars candidates with jets directed along our line of sight.

7.   Microquasars as transient and persistent sources of gamma-rays

Microblazars should exist and be found with the developement of new tools in astronomy. Mirabel & Rodríguez (1999) proposed that for objects with angles between the line of sight and the jet axis $\theta \leq 10°$ one expects the timescales to be shortened by $2\gamma^2$ and the flux densities to be boosted by $8\gamma^3$ with respect to the values in the rest frame of the condensation. For instance, for motions

with $v = 0.98c$ ($\gamma = 5$), the time-scale will shorten by a factor of $\sim$50 and the flux densities will be boosted by a factor of $\sim 10^3$. Then, for a galactic source with relativistic jets and small θ we expected fast and intense variations in the observed flux. Microblazars are hard to detect in practice, both because of the low probability of small θ values and because of the fast decline in the flux.

Recently, several flares were detected with Konus from a region that contains Cygnus X-1 (Golenetskii et al. 2002), later confirmed with the BATSE data base as gamma-ray transients (Schmidt, 2002). These events have been interpreted by Romero, Kaufman Bernadó & Mirabel (2002) in the context of the ideas of Georganopoulos, Aharonian, & Kirk (2002), as non-thermal emission by inverse Compton interaction between relativistic electrons in a precessing jet and external photon fields, with a dominant contribution from the companion star field (Kaufman Bernadó, Romero & Mirabel, 2002). Another microblazar could be V4641 Sgr, which exhibits outbursts with rapid optical variations (Uemura et al. 2002) and seems to be a source of jets with apparent speeds $\geq$10 (Orosz et al. 2001).

Paredes et al. (2000) found that the runaway persistent microquasar LS 5039 (Ribó et al. 2002) is inside the error box of the unidentified Egret source 3EG J1824-1514. In addition, a TeV source inside the core of the OB association Cygnus OB2 and at the edge of the 95% error circle of the EGRET source 3EG J2033+4118 has been reported by Aharonian et al (2002). No counterpart for the TeV source at other wavelengths has so far been identified, and one could envisage gamma -ray production via a jet-driven termination shock. Although most may be isolated neutron stars, a microquasar sub-population of EGRET sources is at this time a working hypothesis.

I point out that Cygnus X-1, V4641 Sgr, and LS 5039 are all three confirmed sources of relativistic jets in high mass X-ray binaries. In this class of sources the jets initially move inside the UV photon field of the massive donor stars and inverse Compton of the jets with the UV photons is unavoidable.

INTEGRAL and other space and ground based observatories for gamma-rays as well as km^2 neutrino telescopes will in the next decade enhance the number of known microquasars providing unprecedented insights into the physics of high energy processes and phenomena in accreting stellar-mass black holes.

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