MICROQUASAR-AGN-GRB CONNECTIONS

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ABSTRACT

I review the progress made on the physics of black hole systems in the context of the analogy between AGN and microquasars that was proposed one decade ago. If the emerging empirical correlations between the observational properties of stellar and supermassive black holes will become more robust, we will use them to determine the mass and spin of black holes, independently of theoretical models. Microquasars are fossils of sources of Gamma-ray bursts (GRBs) of long duration, and their kinematics provides observational clues on the physics of collapsars. If jets in GRBs, microquasars and AGN are due to a unique universal magnetohydrodynamic mechanism, synergy between the research on these three different classes of cosmic objects will lead to further progress in black hole physics and astrophysics.

The potential contributions with INTEGRAL in this field of research are also discussed. It is shown that the Galactic Plane Survey (GPS) with INTEGRAL is unraveling new extragalactic sources of hard x-rays behind the Milky Way, as well as new black hole high-mass binaries that were hidden by large columns of gas and dust.

Key words: Black holes; x-rays; binaries; AGN.

1. PHYSICS IN BLACK HOLES OF ALL MASS SCALES

The physics in all systems dominated by black holes is essentially the same, and it is governed by the same scaling laws. The main differences derive from the fact that the scales of length and time of the phenomena are proportional to the mass of the black hole. If the lengths, masses, accretion rates, and luminosities are expressed in units such as the gravitational radius ($R_g = 2GM/c^2$), the solar mass, and the Eddington luminosity, the same physical laws apply to stellar-mass and supermassive black holes (Sams et al. 1998, Rees 2004). For a black hole of mass $M$ the density and mean temperature in the accretion flow scale with $M^{-1/2}$ and $M^{-1/4}$, respectively. For a given critical accretion rate, the bolometric luminosity and length of relativistic jets are proportional to the mass of the black hole. The maximum magnetic field at a given radius in a radiation dominated accretion disk scales with $M^{-1/2}$, which implies that in the vicinity of stellar-mass black holes the magnetic fields may be $10^4$ times stronger than in the vicinity of supermassive black holes (Sams et al. 1998). In this context, it was proposed (Mirabel et al. 1992, Mirabel & Rodríguez, 1998) that supermassive black holes in quasars and stellar-mass black holes in x-ray binaries should exhibit analogous phenomena. Based on this physical analogy, the word “microquasar” (Mirabel et al. 1992) was chosen to designate compact x-ray binaries that are sources of relativistic jets (see Figure 1).

2. SUPERLUMINAL MOTIONS IN AGN AND MICROQUASARS

A galactic superluminal ejection was observed for first time in the black hole x-ray binary GRS 1915+105, at the time of a sudden drop in the BATSE 20-100 keV flux (Giacinti et al. 1995). Since then, relativistic jets with comparable bulk Lorentz factors $\Gamma = 1/\sqrt{(1-\beta^2)}$ as in quasars have been observed in several other x-ray binaries (Mirabel & Rodríguez, 1999, Fender 2002, Paredes 2004). At present, it is believed that all x-ray accreting black hole binaries are jet sources.

Galactic microquasar jets usually move in the plane of the sky $\sim 10^3$ times faster than quasar jets and can be followed more easily than the later (see Figure 2). Because of their proximity, in microquasars two-sided jets can be observed, which together with the distance provides the necessary data to solve the system of equations, gaining insight on the actual speed of the ejecta. On the other hand, in AGN located at $\leq 100$ Mpc, the jets can be imaged with resolutions of a few times the gravitational radius of the supermassive black hole, as was done for M 87 (Biretta et al. 2002). This is not presently possible in microquasars, since such a precision in terms of the gravitational radius of a stellar-mass black hole would require resolutions a few hundreds of kilometers. Then, in terms of the gravitational radius in AGN we may learn better how the jets are collimated close to the central engine. In summary, some aspects of the relativistic jet phenomena associated to accreting black holes are better observed...
Figure 1. This diagram illustrates current ideas of what may be microquasars. These are x-ray binary systems that eject plasma at relativistic speeds.

SUPERLUMINAL MOTIONS

Figure 2. Apparent superluminal motions observed in the microquasar GRS 1915+105 at 8.6 GHz and in the quasar 3C 279 at 22 GHz.
in AGN, whereas others can be better studied in microquasars. Therefore, to gain insight into the physics of relativistic jets in the universe, synergy between knowledge of galactic and extragalactic black hole is needed.

3. ACCRETION-JET CONNECTION IN MICROQUASARS AND QUASARS

Microquasars have allowed to gain insight into the connection between accretion disk instabilities and the formation of jets. In \(\sim 1\) hour of simultaneous multiwavelength observations of GRS 1915+105 during the frequently observed 30-40 min x-ray oscillations in this source, the connection between sudden drops of the x-ray flux from the accretion disk and the onset of jets were observed in several occasions (Mirabel et al. 1998; Eikenberry et al. 1998) (see Figure 3).

From these observations we have learned the following:

- a) the jets appear after the drop of the x-ray flux,
- b) the jets are produced during the replenishment of the inner accretion disk,
- c) the jet injection is not instantaneous. It can last up to several minutes,
- d) the time delay between the jet flares at wavelengths of 2\(\mu\)m, 2cm, 3.6cm, 6cm, and 21cm are consistent with the model of adiabatically expanding clouds that had been proposed to account for relativistic jets in AGN (van der Laan 1966),
- e) synchrotron emission is observed up to infrared wavelengths and probably up to x-rays. This would imply the presence in the jets of electrons with TeV energies,
- f) VLBA images during this type of x-ray oscillations (Dubner et al. 1998) showed that the ejecta consist on compact collimated jets with lengths of \(\sim 100\) AU,
- g) there is a time delay of \(\sim 5\) min between the large drop of the x-ray flux from the accretion disk and the onset of the jets. These \(\sim 5\) minutes of silence suggest that the compact object in GRS 1915+105 has a space-time border, rather than a material border, namely, a horizon as expected in relativistic black holes. However, the absence of evidence of a material surface in these observations could have alternative explanations.

After the observation of this accretion disk-jet connection in a microquasar, an analogous connection was observed in the quasar 3C 120 (Marscher et al. 2002), but in scales of years rather than minutes. This time scale ratio is comparable to the mass ratio between the supermassive black hole in 3C 120 and the stellar black hole in GRS 1915+105, as expected in the context of the black hole analogy.

4. X-RAY JETS IN AGN AND MICROQUASARS

X-ray emission has been observed with Chandra and XMM-Newton in the radio jets, lobes and hot spots of quasars and radio galaxies. X-ray photons can be produced by inverse Compton scattering from the environment of the central engine up to distances of \(\sim 100\) kpc (Wilson 2003). Synchrotron x-ray radiation has been detected in some sources, most notably in the jet of M 87.

Steady, large-scale radio jets are associated to x-ray persistent microquasars (Mirabel & Rodríguez. 1999). Extended x-ray emission associated to the radio emission was observed in the galactic source SS433/W50 up to distances of \(\sim 30\) pc from the central engine (Dubner et al. 1998) (see Figure 4). The x-rays extend in the same direction as the sub-arcsec, precessing jets. The jets in SS433 are hadronic, move with a velocity of 0.26c, and have a kinetic power of \(\sim 10^{39} - 40\) erg s\(^{-1}\). Since no hot spots have been detected in the shock regions 30 pc away from the central engine, SS433/W50 cannot be considered a scale-down analog of a FR II galaxy. Most microquasars with extended jet emission have morphologies analogous to FR I’s rather than FR II’s radio galaxies.

The recent discovery of radio (Hiellming et al. 1998) and x-ray (Corbel et al. 2002) moving jets in microquasars rise the possibility of studying the formation of radio and x-ray lobes in real time. These observations show that jets may transport energy in a “dark” way, namely, in a way that is radiatively inefficient, until shocks are produced. Synchrotron x-ray emission from shocks at large distances from the central engines imply that microquasars are potential sources of cosmic rays and electrons with up to TeV energies.

5. BLAZARS AND MICROBLAZARS

The bulk Lorentz factors \(\Gamma\) in microquasars and quasars have similar values, and it has been proposed (Mirabel & Rodríguez. 1999) that microquasars with jet axis that form angles \(\leq 10^\circ\) with the line of sight should appear as “microblazars”, showing analogous phenomena to blazars. Due to relativistic beaming, in microblazars the brightness of outbursts is enhanced by factors of \(8 \times \Gamma^3\) and the interval of time of the phenomena is reduced by factors of \(1/2 \times \Gamma^{-2}\). Then, microblazars should appear as intense sources of high-energy photons with very fast variations of flux, which makes them difficult to find and to follow. Due to this difficulty and to the relatively low statistical probability of small angles between the jet axis and the line of sight (Mirabel & Rodríguez. 1999), it is not surprising that most of the microquasars studied so far exhibit large angles (>\(30^\circ\)) between the jet axis and the line of sight.

It has been proposed that microblazars may be more frequently found in High Mass X-ray Binaries (HMXBs) (Paredes et al. 2000; Romero et al. 2003). In such binaries, gamma-rays can be produced by inverse Compton of the jet particles with the UV photons radiated...
Figure 3. Direct evidence for the disk-jet connection in the black hole x-ray binary GRS 1915+105 (Mirabel et al. 1998). When the hot inner accretion disk disappeared, its x-ray brightness abruptly diminished. The ensuing x-ray recovery documented the inner disk’s replenishment, while the rising infrared and radio emission showed plasma being ejected in a jet-forming episode. The sequence of events shows that material indeed was transferred from the disk to the jets. Similar transitions have been observed in the quasar 3C 120 (Marscher et al. 2002), but in time scales of years, rather than minutes.

Figure 4. VLA radio image at 1.5 GHz (grey scale) superimposed on the ROSAT x-ray contours of SS433/W50 (Dubner et al. 1998). The radio counterpart of the microquasar is the bright unresolved source at the center of the image. The lateral E-W extension of the nebula over ~1° (~50 pc) is caused by the injection of relativistic jets from SS 433.
by the massive donor star. In fact, the three microquasars so far proposed as counterparts of variable EGRET unidentified sources are HMXBs with similar properties (Combi et al. 2004a).

6. EXTRAGALACTIC MICROQUASARS AND SUPER-EDDINGTON X-RAY SOURCES

GRS 1915+105 and SS 433 have been invoked (King 2002) as the Milky Way counterparts of the two most numerous classes of super-Eddington x-ray sources (ULXs) in external galaxies. GRS 1915+105 is a long lasting transient outburst x-ray binary with an evolved donor of ~1 M☉, whereas SS 433 is a persistent black hole HMXB (Hillwig et al. 2004). SS 433 type of ULX’s are preponderantly found in starburst galaxies like the Antennae, whereas luminous x-ray sources of low mass as GRS 1915+105 may also be found in galaxies with a low rate of star formation.

Most of the ULX’s would be stellar-mass black hole microquasars with the following possible properties:

1) HMXBs that host massive stellar black holes (M ≥ 40 M☉) with isotropic radiation (Pakull 2003).

2) HMXBs and LMXBs that host stellar black holes (M ∼ 10 M☉) with anisotropic radiation (King 2002).

3) A few (≤ 1%) may be microquasars with relativistic boosted radiation. These should be very bright, highly time-variable, and have a hard x-ray/γ-ray photon spectrum (Mirabel & Rodríguez, 1999).

Although less numerous, it is not excluded that some ULX’s could be accreting black holes of intermediate-mass (100-1000 M☉).

7. X-RAY/RADIO CORRELATIONS IN LOW POWER BLACK HOLES OF ALL MASSES

Several teams of researchers are exploring interesting x-ray/radio correlations.

Microquasars in the low-hard state exhibit radio/x-ray correlations (Gallo et al. 2003). In the low-hard state the power output of quiescent black holes is jet-dominated and when the system moves to a high soft state the radio jets are quenched. The same seems to take place in AGN (Maccarone et al. 2003). A scheme to unify low-power accreting black holes has been proposed (Falcke et al. 2003), where the black holes in Sgr A*, LINERs, FR I, and BL Lac would be analogous to microquasar black holes in the low-hard state.

Following studies (Heinz & Sunyaev 2003) of correlations between radio and bolometric luminosities, a fundamental plane of black hole activity in terms of the black hole mass and x-ray and radio core luminosities is proposed (Merloni et al. 2003). This correlation holds for radiatively inefficient accretion, not for bright thin synchrotron emitting states.

At present, these empirical correlations have large scatters. However, if they became more robust, the mass of black holes could be inferred from the x-ray and radio fluxes, independently of theoretical models.

8. TIME VARIATIONS OF FLUX AND THE MASSES OF BLACK HOLES

Time variations of flux may be correlated with the mass of the black hole.

1) The duration of the x-ray flares observed in stellar-mass black holes and in Sgr A* seem to be proportional to the mass of the black holes. In Cygnus X-1 and other x-ray black hole binaries, flares with durations of 1-10 ms are observed (Gierlinski & Zdziarski 2003). On the other hand in Sgr A*, x-ray flares lasting 400-10,000 sec have been observed with Chandra (Baganoff et al. 2003) and XMM-Newton (Belanger et al. 2003). As expected, the time ratios of the power variations are comparable to the black hole mass ratios.

2) For a given black hole spin, the maximum frequencies of quasi periodic oscillations (QPOs) of flux are expected to be proportional to the mass of the black hole. In 4 microquasars, 3:2 twin peak x-ray QPOs of maximum frequency in the range of 100-500 Hz have been observed, from which angular momenta a = J/(GM/c²) = 0.6-0.9 have been derived (Abramowicz et al. 2004). On the other hand, 17 min infrared QPOs have been reported in Sgr A*, from which it has been inferred an angular momentum a = 0.52 (Genzel et al. 2003). As expected, these QPOs appear to scale with the mass of the black hole. If the 17 min QPO in Sgr A* is confirmed as a component of a twin peak QPO of maximum frequency, this correlation could be used to derive black hole masses, and in particular, those of the super-Eddington x-ray sources in external galaxies (Abramowicz et al. 2004).

3) Some properties of the aperiodic variability (noise) in AGN and x-ray binaries seem to be correlated with the mass of the compact objects. The break time scale in the power spectra density of black holes seems to scale linearly with the mass of the black hole (Uttley & McHardy 2001). The broad band break time in the Sey 1 NGC 3516 scales linearly with that of Cyg X-1 in the low-hard state (McHardy et al. 2003). If this type of correlation is confirmed it could also be used to estimate the mass of black holes in extragalactic super-Eddington x-ray sources.

9. RELATIVISTIC IRON LINES IN STELLAR AND SUPERMASSIVE BLACK HOLES

AGN frequently exhibit broad iron Kα lines skewed to low energies (Tanaka et al. 1995). The shape of these lines is consistent with emission from the surface of an
accretion disk extending from about 6 to more than 40 gravitational radii. Occasionally the red wing of the line extends below 4 keV and the current explanation is that the disk extends within 6 gravitational radii implying that the black hole is rapidly spinning. Now it is widely believed that this spectral feature is a probe of the immediate environment of black holes (Fabian et al. 2000). Until recently, only smeared edges with little evidence for line emission had been observed in Galactic black hole binaries. But after Chandra, XMM-Newton and Beppo-SAX, similar emission iron lines to those in AGN were found, even in the ASCA archive (Miller et al. 2004a).

Besides emission lines skewed to low energies, analogous spectra to AGN-like warm absorbers are observed in some x-ray binaries (Miller et al. 2004b). The absorption is variable and it is believed to be produced in a dense local disk wind rather than in the ISM. A finding possibly related to these absorption lines is the discovery with INTEGRAL of black hole binaries with strong x-ray absorption, much larger than that derived from optical and infrared observations, which also implies that the absorption is local rather than in the ISM.

The iron line in stellar black hole binaries can be used to investigate:

1) the physical models of the $K_\alpha$ line. Because of the short dynamical time scales, the shape of the line can be correlated with the x-ray state of the accretion disk, and corona-disk interactions.

2) the dense plasma outflows from accreting black holes. The study of warm absorber lines similar to those seen in Seyferts may be important to estimate the mass outflows in x-ray binaries.

3) the spin of the accreting black hole. This is important to test models where the jets are powered by the spin of the black hole.

At present, the main constrain to derive the slope of the iron lines is due to the uncertainties on the shape of the continuum at energies $\gtrsim$8 keV.

10. MICROQUASARS AND ULX’S AS FOSSILS OF GAMMA-RAY BURST SOURCES

GRBs of long duration may be caused by the formation of a black holes in collapsars (MacFadyen & Woosley 1999) or highly magnetized neutron stars (Vietri 1998). It is estimated that half of the compact objects are produced in primordial binaries and that after their formation a significant fraction ($\sim$20%) remain in binary systems (Belczynski et al. 2004), leaving microquasars as remnants.

It is believed that GRBs take place in close massive binaries because:

1) the core must be spun up by spin-orbit interaction in order to provide enough power to the jet that will drill the collapsing star all the way from the core up to the external layers (Izzard et al. 2004; Podsiadlowski et al. 2004).

2) GRBs seem to be associated to SNe Ic. This is the class of SNe that do not show H and He lines, implying that before the explosion the progenitor of those GRBs had lost the H and He layers. These layers are more easily lost if the progenitor was part of a massive binary that underwent a common envelope phase (Izzard et al. 2004; Podsiadlowski et al. 2004). Furthermore, SNe Ic exhibit 4-7 % polarization, which are an indication of asymmetric explosions probably caused by collimated jets.

11. MICROQUASAR KINEMATICS AND THE CORE-COLLAPSE

It is believed that stellar black holes can be formed in two different ways: Either the massive star collapses directly into a black hole without an energetic supernova explosion, or an explosion occurs in a protoneutron star, but the energy is low enough to form the system with a runaway velocity, no matter the explosion being symmetric or asymmetric. Therefore, the kinematics of microquasars can be used to constrain theoretical models on the explosion of massive stars that form black holes.

Using this method it has been shown that the x-ray binary Cygnus X-1 was formed in situ and did not receive an energetic trigger from a nearby supernova (Mirabel & Rodrigues 2003). If the progenitor of the black hole and its parent association Cygnus OB3 are coeval, the progenitor mass was greater than 40 $M_\odot$, and during the collapse to form the 10 $M_\odot$ black hole of Cygnus X-1, the upper limit for the mass that could have been suddenly ejected is $\sim$1 $M_\odot$, much less than the mass ejected in a typical supernova. Theoretical models suggest that larger mass remnants are associated to subluminous supernovae (Balberg & Shapiro; Fryer et al. 2002).

Furthermore, the kinematics of GRS 1915+105 derived from VLBI proper motion of the compact jet for the last 5 years (Dhawan & Mirabel 2004) show that the 14±4 $M_\odot$ black hole (Greiner et al. 2001) in this x-ray binary probably was formed promptly, as the black hole in Cygnus X-1. Of course, these observations do not exclude the possibility that high mass stellar black holes could also be formed with strong natal kicks, and runaway as unbound solitary black holes, which would be difficult to detect.

On the other hand, the kinematics of GRO J1655-40 has been a confirmation (Mirabel et al. 2002) of the indirect evidence for an energetic supernova explosion in the formation of this low-mass black hole, inferred earlier from the chemical composition of the donor star (Israelian et al. 1999). More recently, the observation of
the compact object may have had a mass of massive stars IC 1805 and that the progenitor of stellar mass and supermassive black holes are very accreting black holes. The observed hard x-ray proper-

ties of stellar mass and supermassive black holes are very interesting that IGR J16393-4643 is, as the microquasars LS 5059 and LSI +61°303, inside the error circles of EGRET sources of high-energy gamma-ray emission, and that these three microquasars have similar properties. The number of detections of AGN in the GPS is smaller than expected on the basis of the sensitivity of INTEGRAL, and some of the newly discovered hard x-ray sources may be extragalactic. In fact, after the discovery with GRANAT of a Seyfert 1 galaxy at a redshift of 0.021 behind the Galactic Center (Martí et al. 1998), INTEGRAL is detecting new hard x-ray AGN. Figure 6 shows that IGR J21247+5058 is the hard x-ray counterpart of the radiogalaxy 4C 50.55 (Ribó et al. 2004). The source IGR J18027-1455 is probably also an AGN, because the photometric properties of the infrared and optical counterpart are not consistent with those of a stellar object (Combi et al. 2004b). The multiwavelength approach to the hard x-ray sources revealed by INTEGRAL is in progress.

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Figure 5. A unique universal mechanism may be responsible for three types of astronomical objects: microquasars (left); quasars (center); and collapsars (right), the massive, suddenly collapsing stars believed to cause some gamma-ray bursts. Each contains a black hole (probably spinning), an accretion disk (which transfers material to the black holes), and relativistic jets (which emerge from a region just outside the black holes, carrying away angular momentum). Microquasars and quasars can eject matter many times, while collapsars form jets but once. When the jet is aligned with an observer’s line of sight these objects appear as microblazars, blazars, and gamma-ray bursters, respectively. The components of each panel are not drawn to scale; scale bars denote jet lengths. (Sky & Telescope, May 2002, 32)

Figure 6. NVSS image at 1.4 GHz of the radiogalaxy 4C 50.55 detected in the Galactic Plane Survey of INTEGRAL as IGR J21247+5058. The core of the radio source is within the 90% uncertainty error circle of the hard x-ray source (Ribó et al. 2004).
