Theoretical aspects of microquasars

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ABSTRACT: Microquasars (black hole X-ray binaries with relativistic jets) are first found by means of multiwavelengths observations with ground-based telescopes. Microquasars mimic, on a much smaller scale, many of their phenomena seen in quasars. The study about microquasars opens the door for better understanding of the relativistic jets elsewhere in the Universe, and may serve to determine the distance of the jet sources; the connection between the flow instabilities and the ejection of relativistic clouds (formation of jet); the fundamental plane of black hole activity and the black hole's spin.

INTRODUCTION

It is widely known that the quasars are the extremely bright and distant active galactic nucleus. There is now a scientific consensus that there are supermassive black holes as the central engines with surrounding accretion disks to power the quasars up to such high luminosity. According to the standard theory of the optical-thick, geometry-thin accretion disk (Shakura & Sunyaev 1976, SSD), the more massive the black hole is, 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 circular orbit (LSCO) in the surrounding accretion disk will be given approximately by $T \sim 2\times10^7 M^{-1/4}$ (Rees 1984), with T in K and the mass of the black hole , M, in solar masses. Then, while accretion disks in AGNs have strong ultraviolet and optical emission with distinct broad emission lines, the stellar mass black hole or neutron star binaries are usually identified by their thermal X-ray emission. So it will not surprise us much that many new discoveries will come to us in X-ray band with rapid developments of X-ray astronomy.

Observations in the two extremes of the electromagnetic spectrum, hard X-rays on one hand (Sunyaev et al. 1991; Paul et al. 1991), and radio wavelengths on the other hand, revealed the existence of new stellar sources of relativistic jets known as microquasars (Mirabel et al. 1992; Mirabel & Rodriguez 1998). There are two microquasars discovered in the galactic central region in 1992: 1E1740.7-2942 and GRS 1758-258 (Mirabel et al 1992; Rodriguez, Mirabel & Marti 1992). The X-ray luminosity, the photon spectrum, and the time variability of these two sources are comparable to those of black hole binary Cygnus X-1 (Churazov et al. 1994; Kuznetsov et al. 1997), and it is unlikely that they are extragalactic since no such persistent hard X-ray ultraluminous AGNs are observed (Mirabel et al. 1993). At radio wavelengths these two X-ray persistent sources located near the galactic center have a striking morphological resemblance with distant radio galaxies; they consist of compact components at the center of two-sided jets that end in weak, extended lobes with no significant radio flux variations observed in the last few years (Rodriguez & Mirabel 1999); and Mirabel et al. (1993) have argued why it would be unlikely that the radio sources are radio galaxies accidentally superposed on the X-ray sources.

The microquasars combine two relevant aspects of relativistic astrophysics: accreting black holes, which are identified by the production of hard X-ray from surrounding accretion disks, and relativistic jets, which are observed by means of their synchrotron emission. They mimic, on a smaller scale, many aspects of the phenomena observed in quasars. The physics in all systems dominated by black holes (supermassive BH or stellar mass BH) is essentially the same, and it is governed by the same scaling laws. In this context, it was proposed (Mirabel et al. 1992; Mirabel & Rodriguez 1998) that supermassive black holes in quasars and stellar mass black hole in X-ray binaries should exhibit analogous phenomena. Here we discuss some important properties of microquasars in detail:

SUPERLUMINAL MOTIONS

Some quasars are observed to periodically eject jets of relativistic particles that radiate at radio frequencies. These fast-moving jets, which at the distance of quasars typically extend no more than a tiny fraction of a second of arc, appear to exceed the speed of light. Similar superluminal motions are observed in jets streaming out of microquasars. The appearance of a velocity higher than the speed of light, however, is only a projection effect.

Consider a quasar intermittently ejecting clouds of gas moving at relativistic velocity v, at an angle θ with respect to the line of sight to Earth, as measured by an observer on Earth (see Figure 1).

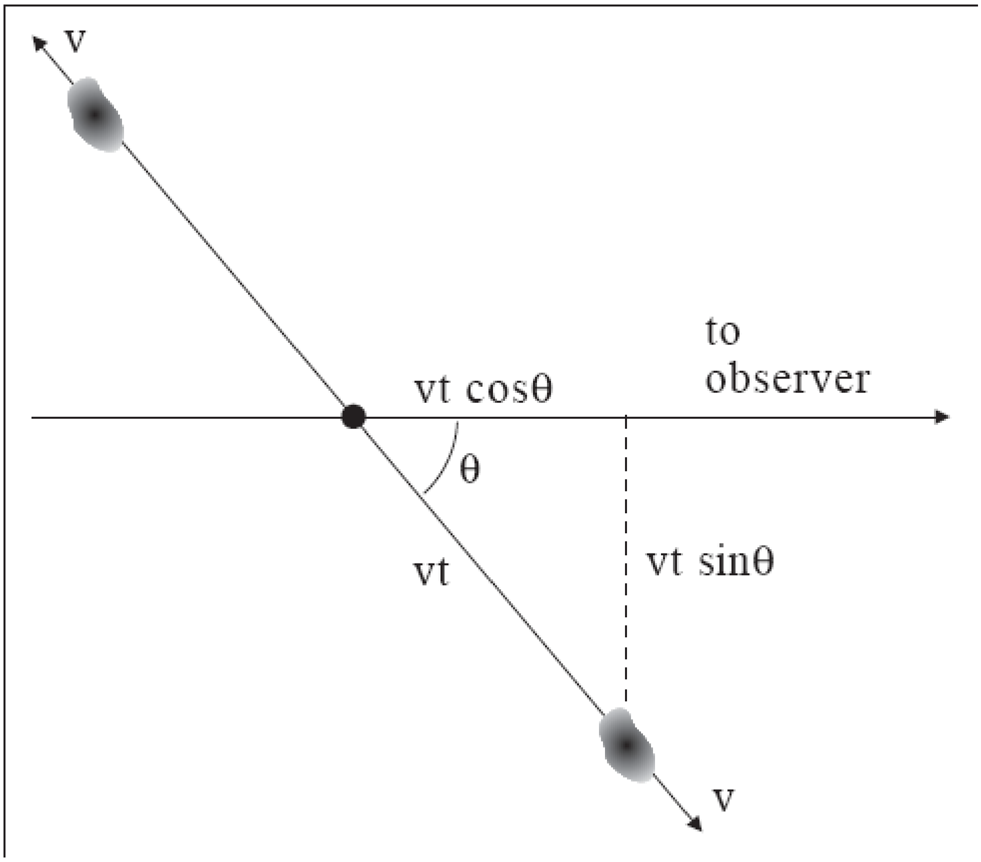

Figure 1

The apparent transverse velocity of the cloud seen from Earth is $v\sin\theta/[1-(v/c)\cos\theta]$. At sufficiently high velocity v directed close to the line of sight, where $\cos\theta$ approaches unity, the cloud will appear to have a transverse velocity exceeding the speed of light, giving rise to the name superluminal velocities. Galactic microquasars, black holes surrounded by compact accretion disks, often eject bi-lobed jets of gas in opposite directions. For a source at distant D, the proper motions of the approaching and receding clouds, respectively, μ_a and μ_r are

$$\mu_a = \frac{v\sin\theta}{[1-(v/c)\cos\theta]D} \quad \text{and} \quad \mu_r = \frac{v\sin\theta}{[1+(v/c)\cos\theta]D}, \qquad (1)$$

where D is the distance from the observer to the source. The ratio of Doppler-shifted wavelengths, respectively received from the approaching and receding jets, is then obtained as

$$\frac{\lambda_a}{\lambda_r} = \frac{1-(v/c)\cos\theta}{1+(v/c)\cos\theta}. \qquad (2)$$

Solving these three equations simultaneously yields the velocity v, angle θ, and the distance D to the source. For the microquasar GRO J1655-40 a jet velocity $v \sim 0.92c$ and a distance $D \sim 3kpc$ has been deduced this way (Mirabel & Rodriguez 1998).

ACCRETION DISK INSTABILITIES

The episodes of large, sudden drop of X-ray flux are believed to be evidence for the presence of a black hole. These variation could be explained as that the inner part of the accretion disk (<200km) goes into the so-called advection-dominated mode (Narayan et al. 1997). In this mode, the infall time scale to the compact object is smaller than the time scale for the energy transfer from the ions (energy from viscosity) to the electrons (radiation energy). So the bulk of energy produced by viscous dissipation in the accretion disk is stored in the gas as thermal energy rather than being radiated. The gas along with bulk of thermal energy will be advected to the compact object. If the compact object is a black hole, the energy quietly disappears through the horizon. In contrast, if the compact object is a neutron star, the thermal energy in the gas is released as radiation when it collides with the surface of the neutron star and heats it up. A slow decay in X-ray flux is often observed in this case because the cooling time scale of the neutron star photosphere is relatively long.

During large-amplitude variation in the X-ray flux, of GRS 1915+105 for example, remarkable flux variation on time scale of minutes have also been reported at radio (Pooley & Fender 1997; Rodriguez & Mirabel 1997; Mirabel et al. 1998) and near-infrared wavelengths (Fender et al 1997; Fender & Pooley 1998; Mirabel et al. 1998). 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 jet in AGNs (van der Laan 1966).

In Figure 2 are shown simultaneous light curves in the X-ray, infrared and radio wavelengths, together with the X-ray photon index during a large amplitude oscillation. These light curves imply that the relativistic clouds emerge at the time of the dips and follow-up replenishment of the inner accretion disk. The maximum flux density at short wavelengths should be observed very shortly after the ejection, and the significant time delay only occurs in the radio wavelengths (Mirabel et al.1998). Figure 2 shows that the onset of the infrared flare occurred >200sec after the X-ray flux drop, probably at the time of the appearance of an X-ray spike (t=13min) which is associated to a sudden softening of the (13-60 kev/2-13 kev) photon index due to the drop in the hard X-ray band. Furthermore, the slow rise of the infrared flux to maximum shown in Figure 2 implies that the injection is not instantaneous and it will last up to tens of minutes.

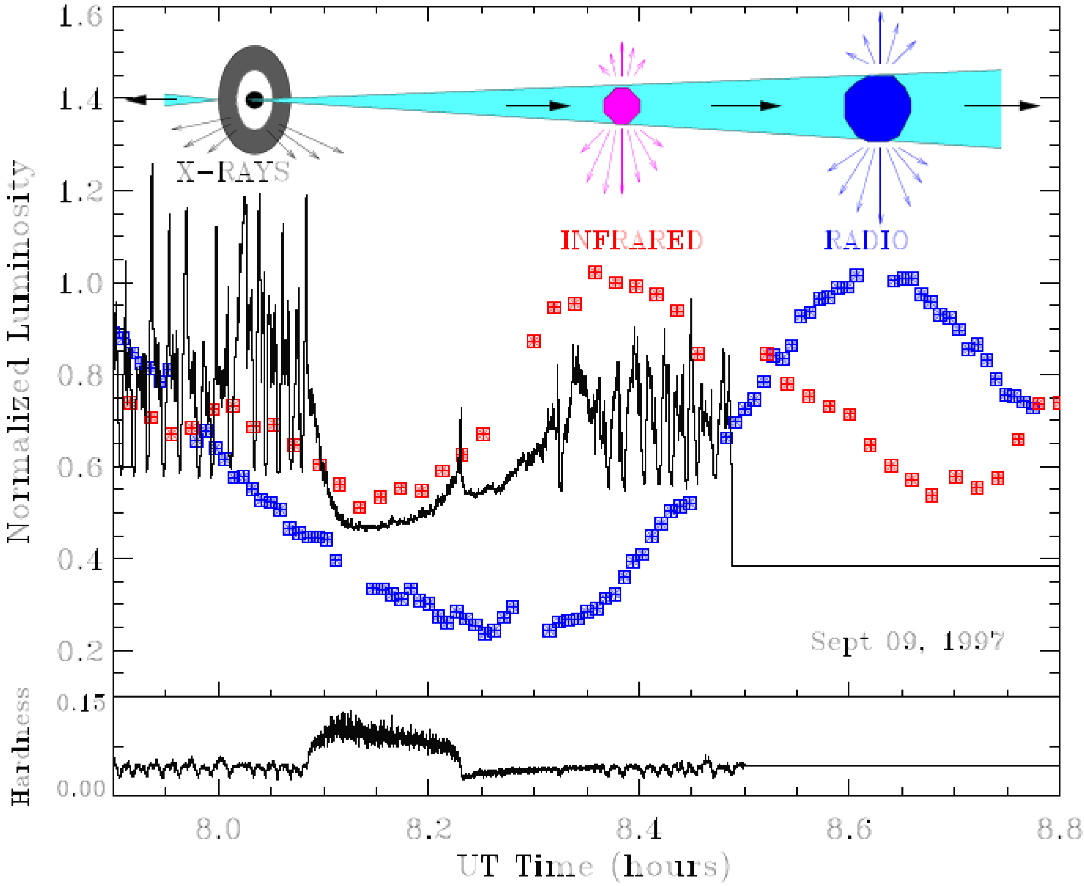

Figure 2

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 scale 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.

FORMATION OF JETS

It is widely believed that collimated jets seem to be systematically associated with the presence of the accretion disks, though the process by which jets are accelerated and collimated are still not clearly understood. However, some concepts for extragalactic jets are considered to be able to extend to galactic gets.

Blandford & Znajek (1977) proposed that it is possible to extract energy and angular momentum from a rotating black hole to produce electromagnetic fields and fast outflowing jets (Penrose 1969). However, whether BZ process can provide sufficient power in the jets is still a problem (Livio et al. 1998). A seminal model has then been established by Blandford & Payne (1982). The authors proposed that the angular momentum of the accretion disk is responsible for the acceleration of the plasma. The magnetic field lines are taken to be frozen into the disk and the plasma streams along these lines at least close to the disk. If the field line forms an small angle with the plane of the disk, the component of the centrifugal force along these lines will be larger than that of gravitational force and the plasma will be accelerated outwards. The initial “equatorial” component of the outflow will change to the dominantly “poloidal” component on larger scales.

FUNDAMENTAL PLANE OF BLACK HOLE ACTIVITY

Corbel et al. (2000, 2003) demonstrated a clear nonlinear relation between the radio luminosity L_{radio} and X-ray luminosity, L_X in the black hole binary GX 339-4, of the form

$$L_{radio} \propto L_X^{0.7} . \quad (3)$$

Gallo, Fender & Pooley (2003), compiled a larger sample of more black hole binaries and found this relation to be essentially universal. However, it should be noted that an increasing number of sources are being found at relatively high luminosities which drop off the correlation (Gallo 2007). An possible explanation is to include partial quenching or increased velocity of the jets as soft state is approached, but more data are required.

Shortly afterwards two groups (Merloni, Heinz & di Matteo 2003; Falcke, Kording & Markoff 2004) independently established the existence of a plane linking L_{radio}, L_X and mass M of all accreting black holes, from X-ray binaries to AGNs. This should be considered one of the major steps in the unification plane can be represented as:

$$L_{radio} \propto L_X^{0.6} M^{0.8} , \quad (4)$$

where the power-law indices are fitted values to a large sample of XRBs and AGNs (see Figure 3).

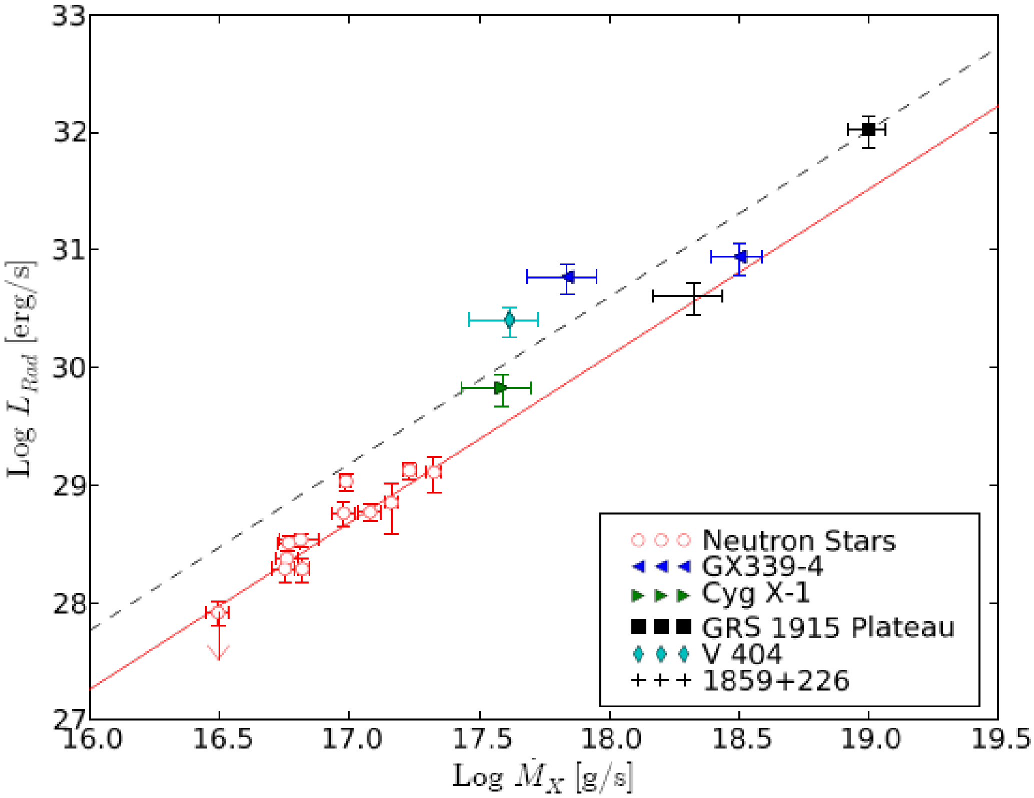

Figure 3

The following is probably the most straightforward interpretation of the fundamental plane.

If

$$L_{radio} \propto \dot{m}^{1.4}, \tag{5}$$

which have been demonstrated in Kording, Fender & Migliari (2003) (see Figure 4), and

$$L_X / L_{Edd} \propto (\dot{m} / \dot{m}_{Edd})^2, \tag{6}$$

which is a general approximate solution for radiatively inefficient accretion flow. Then we rearrange these terms and have:

$$L_{radio} \propto L_X^{0.7} M^{0.7}, \tag{7}$$

which is within in power-law indices of the fitted plane.

The above argument only works if the fundamental plane is dominated by radiatively inefficient sources. Kording, Fender & Migliari (2006) argue that this is indeed the case.

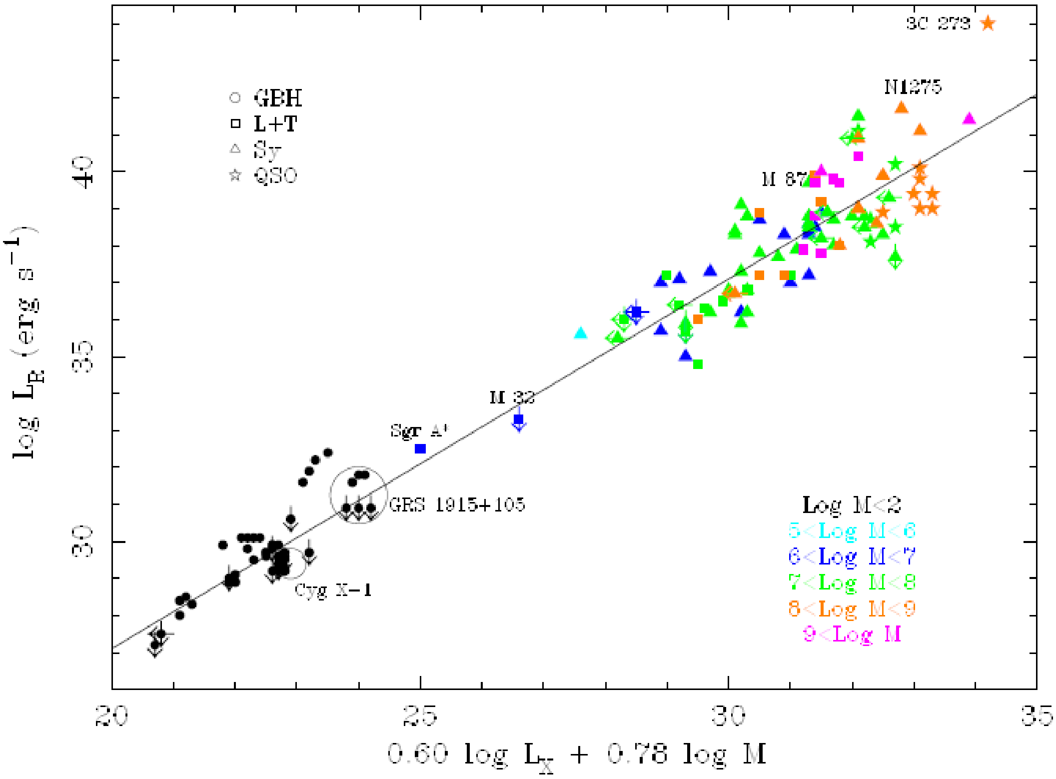

Figure 4

THE VARIATION OF FLUX AND MASS OF BLACK HOLE

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 400-10000 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 variability are comparable to the black hole mass ratios.

The X-ray power of the superluminal sources exhibits a large variety of quasi-periodic oscillations (QPOs) of high frequency. One possible interpretation is that these frequencies correspond to the last stable circular orbit around the black hole. This frequency depends on the black hole's mass and spin, as well as on the rotation direction of the accretion disk. For a given black hole spin, the maximum frequencies of 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 momentum a=J/(GM/c^2)=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 angular momentum a=0.52 has been inferred (Genzel et al. 2003). As expected, these QPOs appears to scale with the mass of the black hole. If the 17 min QPOs 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 mass (Abramowicz et al. 2004). In addition, with masses determined independently, it also offers a promising way to determine the spin of black holes.

CONCLUSIONS

The analogy between quasars and microquasars lead to the discovery of superluminal sources in our own galaxy. Because the microquasars have two-sided ejecta, it allows us to overcome the ambiguities in the physical interpretation of one-sided moving jets in quasars. From the study of the two-sided moving jets in one microquasar, the velocity, the angle and the distance to the Earth can be derived.
Provided relative short dynamical time scale of the matter flow around stellar black holes, one can sample phenomena that we can not observe in quasars. One of the most interesting issues is to about the formation of jet. A possible clue for that is to explore the connection between accretion instabilities observed in the X-rays, with the ejection of relativistic clouds in the radio and infrared bands.

Microquasars in the low-hard state exhibit radio/X-ray correlations. 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. Following studies show that there is fundamental plane of black hole activity in terms of the black hole mass, X-ray and radio core luminosities. This correlation only holds for radiatively inefficient accretion phase. The goal for us to test such correlation is that we can use the relatively rapid evolution of black hole X-ray binaries to understand something about the life cycles of AGN. E.g. we can estimate the total amount of kinetic feedback associated with the accretion process (Merloni & Heinz 2007).

The spin of stellar mass black hole could be derived from the observed maximum stable frequency of QPOs observed in the X-rays, provided the mass has been determined independently. However, theoretical work is needed to distinguish between the alternative maximum stable frequencies of QPOs which have been proposed in the context of general relativity.

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