JETS IN QUASARS, MICROQUASARS AND GAMMA-RAY BURSTS

I.F. Mirabel

Centre d’Etudes de Saclay/ CEA/DSM/DAPNIA/SAP
91911 Gif/Yvette, France &
Intituto de Astronomía y Física del Espacio. Bs As, Argentina

ABSTRACT

Relativistic outflows are common in accreting and forming black holes. Despite the enormous differences in scale, stellar-mass black holes in X-ray binaries and supermassive black holes in Galactic Nuclei produce jets with analogous properties. In both are observed two types of relativistic outflows: 1) quasi-steady compact jets with flat-spectrum, and 2) episodic large-scale ejections with steep-spectrum and apparent superluminal motions. Because of the short time scale of the phenomena in black hole binaries, the formation of synchrotron jets is associated to changes in the X-ray thermal emission from the accretion disk. Besides, the most common class of gamma-ray bursts can be conceived as extreme microquasars, since they are afterglows from ultra-relativistic jets associated to the formation of black holes at cosmological distances.

KEYWORDS: Black holes, jets, quasars, microquasars, gamma-ray bursts

1. THE MICROQUASAR ANALOGY

The discovery of microquasars (Margon, 1994; Mirabel et al. 1992) with apparent superluminal motions (Mirabel & Rodríguez, 1994) has opened new perspectives for the astrophysics of black holes (Mirabel & Rodríguez, 1999 for a review). These scaled-down versions of quasars are believed to be powered by spinning black holes with masses of up to a few tens that of the Sun. The word microquasar was chosen to suggest that the analogy with quasars is more than morphological, and that 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 supermassive black holes at the centre of distant galaxies (Rees, 1998).

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 radiation 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. This analogy between quasars and microquasars resides in the fact that in black holes the physics is essentially the same irrespective of the mass, except that the linear and time scales of phenomena are proportional to the black hole mass. 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.

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). The reason for this is that disks around supermassive 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 AGNs 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 these sources, SS 433 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 recent developments in X-ray astronomy. Strictly speaking and 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. COUPLING BETWEEN ACCRETION DISK AND JET

Since the characteristic times in the flow of matter onto a black hole are proportional to its mass, variations with intervals of minutes in a microquasar correspond to analogous phenomena with durations of thousands of years in a quasar of $10^9 M_\odot$, which is much longer than a human life-time Sams et al. (1996). Therefore, variations with minutes of duration in microquasars could be sampling phenomena that we have not been able to study in quasars. The repeated observation of two-sided moving jets in a microquasar (Rodríguez & Mirabel, 1999) has led to a much greater acceptance of the idea that the emission from quasar jets is associated with moving material at speeds close to that of light.

On the other hand, simultaneous multiwavelength observations of GRS 1915+105 are revealing the connection between the sudden disappearance of matter through
the horizon of the black hole, with the ejection of expanding clouds of relativistic plasma. Radio, infrared, and X-ray light curves of GRS 1915+105 at the time of quasi-periodic oscillations on 1997 September 9 (Mirabel et al. 1998) have shown that the infrared flares occur during the recovery from X-ray dips. These simultaneous multiwavelength observations have shown the connection between the rapid disappearance and follow-up replenishment of the inner accretion disk seen in the X-rays (Belloni et al. 1997), and the ejection of relativistic plasma clouds observed as synchrotron emission at infrared wavelengths first and later at radio wavelengths.

3. COMPACT JETS IN X-RAY BINARIES AND GALACTIC NUCLEI

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 supermassive black holes at the centre of galaxies (e.g. Sgr A* and many AGNs) 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 AGNs 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 less than a few mJy, which makes difficult high resolution observations of the core.

Although there have been multiwavelength studies and speculation about the nature of the faint and steady compact radio emission in X-ray black hole binaries (e.g. Rodríguez et al. 1995; Fender et al. 1999, 2000), GRS 1915+105 is the black hole binary where the core has been sucessfully imaged at AU scale resolution (Dhawan, Mirabel & Rodríguez, 2000). GRS 1915+105 is the only X-ray binary where both, a compact core with steady fluxes $\geq$20 mJy, as well as large-scale superluminal ejections are unambigously observed. VLBA images during different states of the source (quiescent and QPO states) always show compact jets with sizes $\sim 10\lambda_{cm}$ AU along the same position angle as the superluminal large-scale jets. The length of the compact jet and the period of the oscillations are consistent with bulk motions $\geq 0.9c$, comparable with the velocities of the large-scale superluminal ejecta (Mirabel & Rodríguez, 1994). As in the radio cores of AGNs, 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; Falke & Biermann, 1999) in an optically thick region of solar system size.

4. MICROBLAZARS AND GAMMA-RAY BURSTS

In all three galactic microquasars where $\theta$ (the angle between the line of sight and the axis of ejection) has been determined, a large value is found (that is, the axis of ejection is close to the plane of the sky). This result is not inconsistent with the statistical expectation since the probability of finding a source with a given $\theta$ is proportional to $\sin \theta$. We then expect to find as many objects in the $60^\circ \leq \theta \leq 90^\circ$
range as in the $0^\circ \leq \theta \leq 60^\circ$ range. However, this argument suggests that we should eventually detect objects with a small $\theta$. For objects with $\theta \leq 10^\circ$ we expect 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 timescale 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 $\theta$ we expect fast and intense variations in the observed flux. These microblazars may be quite hard to detect in practice, both because of the low probability of small $\theta$ values and because of the fast decline in the flux.

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 black holes (McFadden & Woosley, 1999). Mirabel & Rodríguez (1999) propose 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, in Vth Compton workshop on GRBs 1999), and 3) the statistical anticorrelation 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 as sources of $\gamma$-ray bursts (Meszáros & Rees 1997). High collimation (Dar 1998; 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 multiwavelength studies of gamma-ray afterglows suggest that they are highly collimated jets. The brightness of the optical transient associated to GRB 990123 showed a break (Kulkarni et al. 1999), and a steepening from a power law in time $t$ proportional to $t^{-1.2}$, ultimately approaching a slope $t^{-2.5}$ (Castro-Tirado et al. 1999). The achromatic steepening of the optical light curve and early radio flux decay of GRB 990510 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 afterglow of GRB 990510 (Covino et al. 1999), providing strong evidence that the afterglow radiation from gamma-ray bursters 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.

In this context, 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 bursters. However, there are caveats to this analogy and gamma-ray
bursters are different to the microquasars found so far in our own Galaxy. The former do not repeat, seem to be related to catastrophic events, and have much larger super-Eddington luminosities. Therefore, the scaling laws in terms of the black hole mass that are valid in the analogy between microquasars and quasars do not seem to apply in the case of gamma-ray bursters.

REFERENCES

- elloni, T, Méndez, M, King, AR, van der Klis, M, van Paradijs, J. 1997, Ap. J. 479: L145-48
- astro-Tirado, AJ et al. 1999, Science 283: 2069-73
- tino, S. et al. 1999, IAU Circular 7172
- ar, A. 1998, Ap. J. 500: L93-96
- hawan, V, Mirabel, IF, Rodríguez, LF. 2000, To be submitted to Ap. J.
- alke, H. & Biermann, P.L. 1999, Astron. Astrophys. 342, 49
- alke, H. et al. 1999, astro-ph/9912379
- ender, R.P et al. 1999, Ap. J. 519, 165
- ender, R.P., Pooley, G.G., Durouchoux, P., Tilanus, R.P.J. & Brocksop, C. 2000, MNRAS in press
- jellming, RM, Johnston, KJ. 1988, Ap. J. 328: 600-09
-ulkarni, S.R. et al. 1999, Nature 398: 389-94
- argon, BA. 1984, Annu. Rev. Astr. Astrophys. 22: 507-36
- acFayden, A.I. & Woosley, S.E. 1999, Ap. J. 524, 262
- száros, P, Rees, MJ. 1997, Ap. J. 482: L29-32
- irabel, IF, Dhawan, V, Chaty, S, Rodríguez, LF, Robinson, C, Swank, J, Geballe, T. 1998, Astron. Astrophys. 330: L9-12
- irabel, IF, Rodríguez, LF, Cordier, B., Paul, J., Lebrun, F. 1992, Nature 358: 215-17
- irabel, IF, Rodríguez, LF. 1994, Nature 371: 46-48
- irabel, IF, Rodríguez, LF. 1999, Annu. Rev. Astr. Astrophys. 37: 409
- orris, J.P. Marani, G.F. & Bonell, J.T. 1999, submitted to Ap. J. astro-ph/9903233
- ugliese, G, Falcke, H, Biermann, PL. 1999, Astron. Astrophys. 344: L37-40
- ies, MJ. 1966, Nature 211: 468-70
- ies, MJ. 1984, Annu. Rev. Astr. Astrophys. 22, 471-506
- ies, MJ. 1998, in Black Holes and Relativistic Stars, ed. Wald, RM, University of Chicago, 79-101
- hoads, JE. 1997, Ap. J. 487: L1-4
- dríguez, LF, Gerard, E., Mirabel, IF, Gómez, Y., & velázquez, A. 1995, Ap. J. Supp. 101: 173-79
- dríguez, LF, Mirabel, IF. 1999, Ap. J. 511: 398-404
- ans, BJ, Eckart, A, Sunyaev, R. 1996 Nature 382: 47-49
- altriti, F, Bodo, G, Ghisellini, G, Gliozzi, M, Trussoni, E. 1997, Astron. Astrophys. 327: L29-31