1. Abstract

Relativistic outflows are a common phenomenon in accreting black holes. Despite the enormous differences in scale, stellar-mass black holes in binaries and supermassive black holes in Galactic Nuclei produce jets with analogous properties. In both are observed two types of relativistic outflows: 1) steady compact jets with flat-spectrum, and 2) sporadic extended jets with steep-spectrum and apparent superluminal motions. Besides, the most common class of gamma-ray bursts are afterglows from ultra-relativistic jets associated to the formation of black holes at cosmological distances.

2. Origin of the idea of stellar-mass and supermassive black hole

Black holes were first predicted by John Michell (1784) in the context of Newtonian physics and the corpuscular theory of light. He proposed that these objects could be detected in binary systems by the motion of nearby luminous objects. In the fourth year of the French revolution, Pierre-Simon Laplace (1795) went even further speculating on the possible existence of both, stellar-mass and supermassive black holes. In the fourth edition of “Exposition du Système du Monde” Laplace suggested: 1) that stellar-mass black holes could be as numerous as stars -“en aussi grand nombre que les étoiles”-, and 2) that the most massive objects of the universe could be black holes-“il est donc possible que les plus grands...corps de l’univers, soient par cela même, invisibles”. In the XIXth century the ondulatory conception of light became predominant and the idea of black hole was forgotten for more than one hundred years, until it became a natural consequence of the general relativity conception of gravitation as a curvature of space-time.
Figure 1. Diagram illustrating current ideas concerning quasars and microquasars (not to scale). As in quasars, in 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 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.
3. The quasar-microquasar analogy

The idea that supermassive black holes should exist at the centre of galaxies received strong support when the redshift of a quasi-stellar-radio-source (quasar) was measured for the first time by Marteen Schmidt (1963). The cosmological distance of quasars indicated that they must be powered by the release of gravitational energy around supermassive compact objects, rather than nuclear fusion in the interior of stars. On the other hand, the first observational evidence for the existence of stellar-mass black holes came from the discovery of X-ray sources beyond the solar system by Riccardo Giacconi et al. (1962). The accurate X-ray location of Cygnus X-1 led to a precise radio position, which allowed the optical identification of the black-hole binary.

The recent finding in our own galaxy 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 (see Figure 1). 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).

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.

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. Furthermore, simultaneous multiwavelength observations of this microquasar 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 (see Figure 2).

4. Compact jets in stellar-mass and supermassive 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 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 successfully 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 unambiguously observed. VLBA images during different states of the source always show compact jets with sizes $\sim 10\lambda_{cm}$ AU along the same position angle as the superluminal large-scale jets (see Figure 3). 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.

5. 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 (Mészáros & 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

1. Belloni, T, Méndez, M, King, AR, van der Klis, M, van Paradijs, J. 1997, Ap. J. 479: L145-48
2. Castro-Tirado, AJ. et al. 1999, Science 283: 2069-73
3. Covino, S. et al. 1999, IAU Circular 7172
4. Dar, A. 1998, Ap. J. 500: L93-96
5. Dhawan, V., Mirabel, IF, Rodríguez, LF. 2000, To be submitted to Ap. J.
6. Falke, H. & Biermann, P.L. 1999, Astron. Astrophys. 342, 49
7. Falke, H. et al. 1999, astro-ph/9912436
8. Fender, R.P. et al. 1999, Ap. J. 519, 165
9. Fender, R.P., Pooley, G.G., Durouchoux, P., Tlom, R.P.J. & Brocksop, C. 2000, MNRAS in press
10. Giacconi, R.H., Gursky, F., Paolini, R. & Rossi, B.B. 1962, Phys. Rev. Lett 9: 439
11. Hjellming, RM, Johnston, KJ. 1988, Ap. J. 328: 600-09
12. Kalužná, S.R. et al. 1999, Nature 398: 389-94
13. Laplace, P.-S. 1795, Exposition du Système du Monde, second edition Volume II
14. Margon, BA. 1984, Annu. Rev. Astr. Astrophys. 22: 507-36
15. MacFayden, A.I. & Woosley, S.E. 1999, Ap. J. 524, 262
16. Mészáros, P, Rees, MJ. 1997, Ap. J. 482: L29-32
17. Michell, J. 1784, Philosophical Transactions of the Royal Society pages 35-57
18. Mirabel, IF, Dhawan, V., Chaty, S, Rodríguez, LF, Robinson, C, Swank, J, Geballe, T. 1998, Astron. Astrophys. 330: L9-12
19. Mirabel, IF, Rodríguez, LF., Cordier, B., Paul, J., Lebrun, F. 1992, Nature 358: 215-17
20. Mirabel, IF, Rodríguez, LF. 1994, Nature 371: 46-48
21. Mirabel, IF, Rodríguez, LF. 1999, Annu. Rev. Astr. Astrophys. 37: 409
22. Norris, J.P, Marani, G.F. & Bonell, J.T. 1999, submitted to Ap. J. astro-ph/9903233
23. Pugliese, G, Falcke, H, Biermann, PL. 1999, Astron. Astrophys. 344: L37-40
24. Rees, M.J. 1966, Nature 211: 468-70
25. Rees, M.J. 1984, Annu. Rev. Astr. Astrophys. 22, 471-506
26. Rees, M.J. 1998, in Black Holes and Relativistic Stars, ed. Wald, RM, University of
27. Rhoads, JE. 1997, Ap. J. 487: L1-4
28. Rodríguez, LF, Gerard, E., Mirabel, IF, Gómez, Y., & velázquez, A. 1995, Ap. J. Supp. 101: 173-79
29. Rodríguez, LF, Mirabel, IF. 1999, Ap. J. 511: 398-404
30. Sams, BJ, Eckart, A, Sunyaev, R. 1996 Nature 382: 47-49
31. Scaltriti, F, Bodo, G, Ghisellini, G, Gliozzi, M, Trussoni, E. 1997, Astron. Astrophys. 327: L29-31
32. Schmidt, M. 1963, Nature 197, 1040
Millions of Light Years

**QUASAR**

- RADIO LOBE
- RELATIVISTIC JET
- HOST GALAXY
- UV AND OPTICAL RADIATION
- ACCRETION DISK (~10⁹ km)
- SPINNING SUPERMASSIVE BLACK HOLE

**MICROQUASAR**

- RADIO LOBE
- RELATIVISTIC JET
- COMPANION STAR
- X-RAY RADIATION
- ACCRETION DISK (~10³ km)
- SPINNING STELLAR-MASS BLACK HOLE

**ACCRETION DISK** (~10^9 km)
Peak flux = 4.80E-02 JY/BEAM
Levs = 4.796E-04 * (-2, 2, 4, 8, 16, 32, 64, 96)