JETS IN SUPERMASSIVE AND STELLAR-MASS BLACK HOLES

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Relativistic outflows are a common phenomenon in accreting black holes. Despite the enormous differences in scale, stellar-mass black holes in X-ray binaries and collapsars, and super-massive black holes at the dynamic centre of galaxies are sources of jets with analogous physical properties. Synergism between the research on microquasars, gamma-ray bursts, and Active Galactic Nuclei should help to gain insight into the physics of relativistic jets seen everywhere in the Universe.

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 (1) to suggest that we could learn about microquasars from previous decades of studies on Active Galactic Nuclei (AGN). 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.

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 $\geq10^3$ faster than in quasars. Because microquasars are found in our Galaxy the two-sided moving jets are more easily seen than in AGN (2). However, to know how the jets are collimated in units of length of the black hole’s horizon, AGN

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up to distances of a few Mpc may present an advantage. (3) 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.

Figure 1. Diagram illustrating current ideas concerning microquasars, 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.

2. The microquasar gamma-ray-burst analogy

There is increasing evidence that the central engine of the most common form of gamma-ray bursts (GRBs), those that last longer than a few seconds, are afterglows from ultra-relativistic jets produced during the formation of stellar-mass black holes (4). (5) 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. 6; 7); 2) the statistical correlation between time variability and brightness (8), and 3) the statistical anti-correlation between brightness and time-lag between
hard and soft components (9). 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 (10). High collimation (11; 12) can be tested observationally (13), 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. 6), and a steepening from a power law in time $t$ proportional to $t^{-1.2}$, ultimately approaching a slope $t^{-2.5}$ (e.g. 7). 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 (5). In microquasars, these breaks and steepenings have been interpreted (14) 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. 15), 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. 16), and optical (17) 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 $\leq 10$ as in microquasars and quasars, and they reach values $\geq 100$ 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.
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 $\sim 20$ min (18). 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 (19), 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 $(13-60\text{ keV})/(2-13\text{ keV})$ is shown at the bottom of the figure. Analogous phenomena have now been observed in the quasar 3C 120 but in time scales of years (20).

3. 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 characteristic 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 (34). 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 \( \sim 5 \text{min} \), and subsequently the inner accretion disk is refilled in \( \sim 20 \text{ min} \). While the inner disk is being replenished, we observe the ejection of a relativistic plasma cloud, first at 2\( \mu \)m, 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 (35). Although VLBA images of these transient ejecta by (24) have shown that they are in fact conical jets, the model first developed for AGN is a good first approximation, and allows to demonstrate that the infrared flares that precede the radio flares are synchrotron, rather than thermal emission. This implies the presence in the jets of electrons with Lorentz factors \( \geq 10^3 \) (36; 18).

Analogous accretion disk-jet connections were observed in the quasar 3C 120 by (20). 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 relatively small when compared with the uncertainties in the data.

4. Compact jets in accreting 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*\( \sim 1\text{Jy} \)) 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. 16; 21; 22; 23). Recently, this has been confirmed by VLBI observations at AU scale resolution of GRS 1915+105 (24), and Cyg X-1 (25) in the low-hard X-ray state. VLBA images of GRS 1915+105 show compact jets with sizes $\sim 10\lambda_{\text{cm}}$ 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 (14; 26) 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 (27), and are currently used to track the path of black holes and neutron stars in our Galaxy (see 28, for a review).

5. Interaction of jets with the interstellar medium

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 (1), GRS 1758-258 (29), 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 (30) and radio wavelengths (31, 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 (30). In the radio and X-rays, the lobes reach distances of up to $1^\circ$ ($\sim 50$ 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$^{-1}$ (32), which is several orders of magnitude larger than the energy radiated in the X-rays and in the radio. (31) estimate that the kinetic energy transferred into the ambient medium is $\sim 2 \times 10^{51}$ 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 (33). 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. (33) 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.

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