Magnetism in microquasars

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Magnetism in microquasars

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Microquasars are stellar-mass black holes with relativistic jets that mimic, on a much smaller scale, many of the phenomena seen in quasars. Because of their proximity, their study opens the way for a better understanding of the relativistic jets seen elsewhere in the Universe. In microquasars the jets are accelerated and collimated by magnetic activity rather than radiation pressure, and the structure and evolution of the ejecta is determined by magnetic fields. In clouds expelled during quasi-periodic oscillations of tens of minutes in GRS 1915+105, equipartition magnetic fields have values of *ca.* 10 G. In ejecta with bulk motion speeds greater than or equal to $0.9c$, linear polarizations of up to 10% have been measured, and as in quasars, far from the central engine the magnetic field is well ordered and aligned at right angles to the jet axis.

Keywords: radio continuum stars; superluminal motion; X-ray binaries; magnetic field; plasma physics

1. Introduction

Black holes were first predicted by John Michell (1784) in the context of Newtonian physics and the corpuscular theory of light. He was the first to suggest that they could be detected by the motion of nearby luminous objects. In the fourth year of the French Revolution, Pierre-Simon Laplace (1795) speculated on the possible existence of both stellar mass and supermassive black holes. In the *Exposition du Sytème du Monde* Laplace proposed: (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 19th century the ondulatory conception of light became predominant and the idea of black holes was forgotten for more than a century, until it became a natural consequence of general relativity.

The recent finding in our own galaxy of *microquasars* (Margon 1984; Mirabel *et al.* 1992; Mirabel & Rodríguez 1994) has opened new perspectives for the astrophysics of black holes (see figure 1). These scaled-down versions of quasars are believed to be powered by spinning black holes but 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 centres of distant galaxies (Rees 1998).

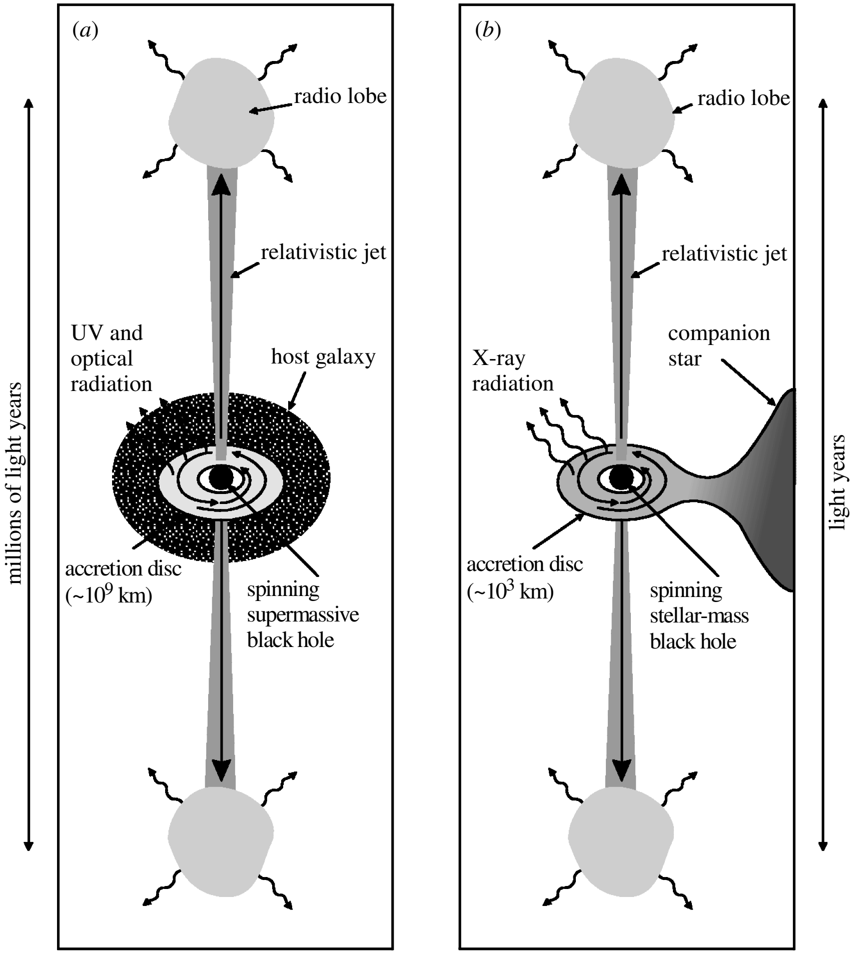

Figure 1. Diagram illustrating current ideas concerning (*a*) quasars and (*b*) microquasars (not to scale). As in quasars, in microquasars the following three basic ingredients are found: (1) a spinning black hole; (2) an accretion disc heated by viscous dissipation; and (3) collimated jets of relativistic particles. However, in microquasars the black hole is only a few solar masses instead of several million solar masses; the accretion disc 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 disc 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 disc has sizes of *ca.* 10^9 km and radiates mostly in the ultraviolet and optical wavelengths, whereas in microquasars the accretion disc has sizes of *ca.* 10^3 km and the bulk of the radiation comes out in 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 SS 433 was the only known object of its class in our galaxy (Margon 1984). The reason for this is that discs around supermassive black holes emit strongly at optical and UV wavelengths. Indeed, the more massive the black hole, the cooler the surrounding accretion disc is. For a black hole accreting at the Eddington limit, the characteristic black-body temperature at the last stable orbit in the surrounding accretion disc will be given by *ca.* $T \sim 2 \times 10^7 M^{-1/4}$ (Rees 1984), with T in kelvins and the mass of the black hole, M, in solar masses. Then, while accretion discs in active galactic nuclei have strong emissions in the optical and ultraviolet with distinct broad emission lines, black holes and neutron-star binaries are usually 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.

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 lifetime. 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 (Mirabel *et al*. 1998; Eikenberry *et al*. 1998) 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.

2. Magnetic fields and jet formation

The processes by which the jets are accelerated and collimated are still not clearly understood, but it is believed that several of the concepts proposed for extragalactic jets can be extended to galactic jets.

Blandford & Znajek (1977) take advantage of the fact that, in principle, it is possible to extract energy and angular momentum from a rotating black hole (Penrose 1969), to produce electric and magnetic fields and possibly fast outflowing jets. A magnetized accretion disc around the Kerr black hole brakes it electromagnetically. However, Ghosh & Abramowicz (1997) and Livio *et al*. (1998) have called into question the idea that the Blandford–Znajek process can provide the primary power in the jets. The Blandford & Znajek (1977) mechanism requires very large magnetic fields and in this respect it may be important in the upper limit of 7×10^4 G for the magnetic field at $770 R_\odot$ in the jet source Cygnus X-3 found by Ogley *et al*. (1999).

A seminal idea that has been followed by many researchers in the field is that of the magnetohydrodynamical model of Blandford & Payne (1982). These authors proposed that the angular momentum of a magnetized accretion disc around the collapsed object is responsible for the acceleration of the plasma. The magnetic-field lines are taken to be frozen into the disc and the plasma is assumed to follow them like a 'bead on a wire', at least close to the disc. If the field line forms an angle with the plane of the disc smaller than 60°, the displacements of the plasma from its equilibrium position become unstable. This happens because along these field lines the component of the centrifugal force will be larger than the component of the gravitational force and the plasma will be accelerated outwards. Then, in its origin, the outflow motion has an important 'equatorial' component, while on larger scales the jets are observed to have a motion that is dominantly 'poloidal'. In other words, after the acceleration a collimating mechanism is required to change the wide-angle centrifugal outflow into a collimated jet.

This collimation is proposed to be achieved as follows. Inside an inner region, the magnetic-field energy density is larger than the kinetic energy density of the flow, but at some distance from the disc (the Alfvén surface) this situation reverses and the flow stops corotating with the disc. This causes a loop of toroidal (azimuthal) field to be added to the flow for each rotation of the footpoint of the field line. The tension of this wound-up toroidal field that is formed external to the Alfvén surface produces a force directed toward the axis (the 'hoop stress'). Most models for the production of jets in the astrophysical context use elements of MHD acceleration and collimation.

Recently, several groups (Spruit *et al*. 1997; Lucek & Bell 1997; Begelman 1998) have pointed out that the toroidal field traditionally held responsible for collimating jets in the MHD mechanism is unstable and cannot collimate the jets effectively. It has been proposed alternatively that the collimating agent is the poloidal component of the magnetic field. Koide *et al*. (1998) have performed for the first time full general relativistic MHD numerical simulations of the formation of jets near a black hole. Their results suggest that the ejected jet has a two-layer structure with an inner fast gas-pressure-driven component and an outer slow magnetically driven component. The presence of the inner fast gas-pressure-driven component is a result of the strong pressure increase produced by shocks in the disc through fast advection flows inside the last stable orbit around a black hole. This feature is not seen in non-relativistic calculations.

Within the uncertainties of the small sample, the velocity of the jets seems to show a bimodal distribution, with some sources having $v_{\mathrm{jet}} \simeq 0.3c$ and others having $v_{\mathrm{jet}} \geqslant 0.9c$. Two explanations have been offered in the literature. On one hand, Kudoh & Shibata (1995) suggest that the terminal velocity of the jet is of the order of the Keplerian velocity at the footpoint of the jets; that is that the fastest jets probably come from the deepest gravitational wells (Livio 1998). However, recent observations suggest that Sco X-1, which is a neutron-star binary, has $v_{\mathrm{jet}} \sim 0.5c$ (E. B. Fomalont 1999, personal communication), departing from the bimodal distribution. On the other hand, Meier *et al*. (1997) propose that the velocity of the jets is regulated by a magnetic 'switch', with highly relativistic velocities achieved only above a critical value of the ratio of the Alfvén velocity to the escape velocity. The determination of the mass of the collapsed object in a larger number of jet sources would discriminate between these two models.

While it seems that a steady-state MHD model can account for the formation of continuous relativistic jets, the events discussed by Mirabel *et al*. (1998), Belloni *et al*. (1997) and Fender & Pooley (1998), which seem to involve a connection between the disappearance of the inner accretion disc and the sudden ejection of condensations, may require a different mechanism. Clearly, the time seems to be ripe for new theoretical advances on the models of formation of relativistic jets that take into account the observational features found in stellar jets.

Another characteristic that the jet models must account for is the production of relativistic particles that will produce the synchrotron emission that is observed in several sources. As in other astrophysical contexts, it is believed that the acceleration of electrons to relativistic speeds takes place in shocks (Blandford & Ostriker 1978). On the other hand, most of the X-ray binaries are 'radio-quiet', implying that relativistic electrons and/or magnetic fields are not always present in sufficient amounts.

It is possible to estimate the parameters of the ejected condensations using the formulation of Pacholczyk (1970) for minimum energy, correcting for relativistic effects and integrating the radio luminosity over the observed range of frequencies. Rodríguez & Mirabel (1999) estimate for the bright 1994 March 19 event in GRS 1915+105 a magnetic field of *ca.* 50 mG and an energy of *ca.* 4×10^{43} erg in the relativistic electrons. Assuming that there is one (non-relativistic) proton per (relativistic) electron, one gets a proton mass estimate of the order of 10^{23} g. To estimate the peak mechanical power during the ejection we need a value for the time over which the acceleration and ejection took place. Mirabel & Rodríguez (1994) conservatively estimate that the ejection event must have lasted less than or equal to three days, requiring a minimum power of *ca.* 5×10^{38} erg s^{-1}, a value comparable with the maximum observed steady photon luminosity of GRS 1915+105, which is *ca.* 3×10^{38} erg s^{-1} (Harmon *et al.* 1994).

The ejection events that preceded and followed the 1994 March 19 outburst are estimated to have masses of the order of 10^{21-22} g (Rodríguez & Mirabel 1999; Gliozzi *et al.* 1999). Finally, if the repetitive events observed with periods of tens of minutes in GRS 1915+105 (Rodríguez & Mirabel 1997; Pooley & Fender 1997; Mirabel *et al.* 1998; Eikenberry *et al.* 1998) are interpreted as mini-ejection episodes, the mass associated with them is of order 10^{19} g. We crudely estimate that, on average, GRS 1915+105 injects energy of the order of 10^{23} g per year in the form of relativistic ($0.92c$ to $0.98c$), collimated outflows. This corresponds to an average mechanical energy of $L_{\mathrm{mech}} \sim 10^3 L_\odot$. In contrast, SS 433, as a result of its more continuous jet flow, has $L_{\mathrm{mech}} \sim 10^5 L_\odot$ (Margon 1984), despite having a lower flow velocity than GRS 1915+105. The GRS 1915+105 bursts are thus very energetic but more sporadic.

As emphasized by Hjellming & Han (1995), relativistic plasmas are difficult to confine and synchrotron radiation sources in stellar environments will tend to be variable in time. Then, one of the behaviours most difficult to account for is the relative constancy of the radio flux in some sources, of which Cyg X-1 is the extreme example. The presence of a steady outflow that is too faint to be followed up in time as synchrotron-emitting ejecta could be consistent with the lack of large variability in this type of source.

Recently, there has been evidence that during some events the synchrotron emission in GRS 1915+105 extends from the radio into at least the near-infrared (Mirabel *et al.* 1998; Fender *et al.* 1997). Then the synchrotron luminosity becomes significant, reaching values of 10^{36} erg s^{-1}.

3. Microquasars in our galaxy

We list in table 1 the sources of relativistic jets in the galaxy reported as of December 1998. The first six are transients, whereas the next four are persistent X-ray sources. Proper motions of the relativistic ejecta have been determined with accu-

Table 1. *Sources of relativistic jets in the Galaxy reported as of December 1998*

(V_{app} is the apparent speed of the highest velocity component of the ejecta. V_{int} is the intrinsic velocity of the ejecta. Θ is the angle between the direction of motion of the ejecta with the line of sight.)

source	compact object	V_{app}	V_{int}	Θ	references
GRS 1915+105	black hole	$1.2c$–$1.7c$	$0.92c$–$0.98c$	66–70°	Mirabel & Rodríguez (1994); Fender *et al.* (1999); Dhawan *et al.* (1999)
GRO J1655-40	black hole	$1.1c$	$0.92c$	72–85°	Tingay *et al.* (1995); Hjellming & Rupen (1995); Orosz & Bailyn (1997)
XTE J1748-288	black hole	$1.3c$	$> 0.9c$		Hjellming *et al.* (1998)
SS 433	neutron star ?	$0.26c$	$0.26c$	79°	Margon (1984); Spencer (1984)
Cygnus X-3	neutron star ?	$\sim 0.3c$	$\sim 0.3c$	> 70°	Schalinski *et al.* (1993); Martí *et al.* (2000)
CI Cam	neutron star ?	$\sim 0.15c$	$\sim 0.15c$	> 70°	Mioduszewski *et al.* (1998); García *et al.* (1998)
Scorpio X-1	neutron star	$\sim 0.5c$			E. B. Fomalont (1999, personal communication)
Circinus X-1	neutron star	$\geqslant 0.1c$	$\geqslant 0.1c$	> 70°	Stewart *et al.* (1993); Fender *et al.* (1998)
1E1740.7-2942	black hole				Mirabel *et al.* (1992); Rodríguez & Mirabel (1999)
GRS 1758-258	black hole				Rodríguez *et al.* (1992)
Sgr A*	black hole				Lo *et al.* (1998)

racy in GRS 1915+105, GRO J1655-40, XTE J1748-288 and SS 433. Besides these four sources, proper motions were also measured—but with less accuracy—for moving features in Cygnus X-3 (Schalinski *et al*. 1995; Martí *et al*. 1999), Scorpius X-1 (E. B. Fomalont 1999, personal communication), Circinus X-1 (Fender *et al*. 1998) and CI Cam (XTE J0421+560; Hjellming & Mioduszewski 1998; Mioduszewski *et al*. 1998). Jet structures have been reported to be associated with Cygnus X-1, but these results are still uncertain.

It is interesting that the ejecta from the black-hole binaries GRS 1915+105, GRO J1655-40 and probably also XTE J1748-288 have velocities greater than $0.9c$, while the ejecta from the four sources believed to be neutron-star binaries have velocities less than or equal to $0.5c$. From their models of magnetically driven jets, Kudoh & Shibata (1995) have proposed that jet velocities such as those listed in table 1 are comparable with the Keplerian rotational velocities expected at the base of the jets, close to neutron stars and black holes, respectively. Livio (1998) has also stressed the similarity between the velocity of jets and the escape velocity of the gravitational well from where they were ejected. If this notion is confirmed, jet velocities could then be used to discriminate between neutron stars and black holes, with jet velocities close to the speed of light produced only in black-hole binaries.

Another possible source of relativistic jets in the galaxy is, of course, Sgr A*, the presumed black hole of 2.5 million solar masses at the galactic centre (Eckart & Genzel 1997). The radio source is always present at about the 1 Jy level and exhibits a flat spectrum with relatively small variations, a behaviour similar to that of the faint compact mJy radio sources associated with Cygnus X-1 (Martí *et al*. 1996) and GRS 1915+105 in its plateau state at times when no strong outburst/ejection events take place: a state that in the latter source can last from days to weeks (Pooley & Fender 1997). This type of radio emission could arise from a jet in a coupled-jet–disc system (Falcke *et al*. 1993), from electrons in an advection dominated flow (Narayan *et al*. 1998; Mahadevan 1998), or from shocks in massive winds (Blandford & Begelman 1999). Despite heavy interstellar scattering at radio wavelengths, recent VLBA observations at 7 mm may have resolved Sgr A* in an elongated radio source of 72 Schwarzschild radii, suggesting the presence of a jet (Lo *et al*. 1998).

4. Microblazars and gamma-ray bursts

It is interesting that in all three sources where θ (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). These values are $\theta \simeq 79^\circ$ (SS 433; Margon 1984), $\theta \simeq 66^\circ$–70° (GRS 1915+105; Mirabel & Rodríguez 1994; Fender *et al*. 1999), $\theta \simeq 85^\circ$ (GRO J1655-40; Hjellming & Rupen 1995) and $\theta \geqslant 70^\circ$ for the remaining sources. This result is not inconsistent with the statistical expectation, since the probability of finding a source with a given θ is proportional to $\sin\theta$. We then expect to find as many objects in the $60^\circ \leqslant \theta \leqslant 90^\circ$ range as in the $0^\circ \leqslant \theta \leqslant 60^\circ$ range. However, this argument suggests that we should eventually detect objects with small θ. For objects with $\theta \leqslant 10^\circ$ we expect the time-scales to be shortened by 2γ 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 time-scale will shorten by a factor of about 10 and the flux densities will be boosted by a factor of about 10^3. Then, for a galactic source with relativistic jets and small θ 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 θ values and because of the fast decline in the flux. Gamma-ray bursts are at cosmological distances and ultra-relativistic bulk motion and beaming appear as essential ingredients to solve the enormous energy requirements (see, for example, Kulkarni *et al.* 1999; Castro-Tirado *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 greater than 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 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 (Harrison *et al.* 1999). 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 (§ 7; 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 *ca.* 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 (Rodríguez *et al.* 1995; Hannikainen *et al.* 1999) and optical (Scaltriti *et al.* 1997) wavelengths.

In this context, microquasars in our own galaxy seem to be less extreme local analogues of the super-relativistic jets associated to the more distant gamma-ray bursters. However, gamma-ray bursters are different to the microquasars found so far in our own galaxy. The former do not repeat and 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.

5. Conclusions

1. The large kinetic power of the sudden, short and rather discontinuous ejections in microquasars exceeds by more than a order of magnitude the maximum steady photon luminosity of the source, suggesting that a radiation acceleration mechanism of the ejecta is unlikely (Rodríguez & Mirabel 1999). In this context, several MHD models have been proposed.

2. During quasi-periodic oscillations of tens of minutes, equipartition magnetic fields of *ca.* 10 G and energies of *ca.* 10^{40} erg have been derived for the expanding plasma clouds in the microquasar GRS 1915+105 (Fender *et al.* 1997; Mirabel *et al.* 1998).

3. Linear polarizations in the range of 2–10% have been measured in microquasars at radio (Rodríguez *et al*. 1995; Hannikainen *et al*. 1999) and optical (Scaltriti *et al*. 1997) wavelengths. Linear polarization measurements indicate that close to the central engine the magnetic field is predominantly parallel to the jets, whereas at large distances the magnetic field becomes predominantly perpendicular to the jet axis. This is consistent with flux conservation and geometry in conical jets, where the magnetic-field components parallel and perpendicular to the jet decrease as r^{-2} and r^{-1}, respectively. Similar polarizations are observed in extragalactic sources.

4. Using minimum energy conditions, Rodríguez & Mirabel (1999) found in GRS 1915+105 that four days after a major ejection the ejecta had a magnetic field of 50 mG aligned along the outflow axis. Twenty-three days after ejection the magnetic field dropped to 7 mG and was preponderantly perpendicular to the outflow axis.

5. Microquasars in our own galaxy may be less-extreme local analogues of the super-relativistic jets that seem to be associated with distant gamma-ray bursters. Linear polarizations of *ca.* 2% were recently measured in the optical afterglow of a gamma-ray burst (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.

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Discussion

R. D. Blandford (*Caltech, Pasadena, USA*). There are two infrared sources associated with GRS 1915+105 aligned with the jet. Do you believe that they are associated?

I. F. Mirabel. We have studied them thoroughly with the VLA, ISO, UKIRT, etc. These infrared sources at a few hundred light years are located at the same position angle as the sub-arcsec jets. They are at about the same distance as GRS 1915+105. However, we did not find clear evidence for a physical association of these ‘infrared lobes’ with GRS 1915+105.

R. E. Pudritz (*McCaster University, Canada*). Microquasars, as you said, are ideal labs for testing origins of relativistic jets. Is there evidence to suggest that jets may originate from the inner disc radius, as opposed to a spinning black hole?

I. F. Mirabel. There is clear evidence that in the jets in GRS 1915+105 and GR 01655-40—the first two superluminal sources—the jet formation seen in the radio and infrared wavelengths is connected to disc instabilities seen in the X-rays. In this context, the jets in microquasars may be powered by magnetohydrodynamic mechanisms arising in the accretion disc. However, we cannot rule out the spin of the black hole as the source of power.

A. Shukurov (*University of Newcastle, UK*). Is there any continuous jet seen in synchrotron emission in GRS 1915+105?

I. F. Mirabel. There is a continuous laminar jet of a few hundred astronomical units in length that seemed to be almost always present.

E. Harflaftis (*National Observatory of Athens, Greece*). Could there be an effect on the structure of the jet (continuous flow or cloud ejection) depending on the type of compact object? In SS 433 with a likely neutron star as the compact object we observe a continuous jet flow, whereas in GRS 1915 with a likely black hole as the compact object we observe cloud ejection.

I. F. Mirabel. In SS 433 there are also discrete ejections of clouds on top of a continuous outflow. The same may occur in GRS 1915+105, but the sporadic ejections are more marked. In fact, there are not enough sources studied to answer your question. Furthermore, there is no consensus on whether SS 433 contains a neutron star or black hole.