Microquasars in our Galaxy

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Microquasars are stellar-mass black holes in our Galaxy that mimic, on a smaller scale, many of the phenomena seen in quasars. Their discovery opens the way for a new understanding of the connection between the accretion of matter onto black holes and the origin of the relativistic jets observed in remote quasars.

Discovered more than 30 years ago, quasars remain some of the most mysterious objects in the Universe. It is widely believed that they are powered by black holes of several million solar masses or more that lie at the centres of remote galaxies. Their luminosities are much larger than ordinary galaxies like the Milky Way, yet originate from regions smaller than the size of the Solar System. Occasionally, quasars spout jets of gas that appear to move on the plane of the sky with velocities exceeding that of light (that is, with superluminal velocities). The extreme distance of quasars introduces many uncertainties into the interpretation of the source of energy and the nature of the ejecta that appear to be moving with superluminal speeds.

The recent finding in our own Galaxy of microquasars[1–4], a class of objects that mimics—on scales millions of times smaller—the properties of quasars, has opened new perspectives for the astrophysics of black holes (see Fig. 1). These scaled-down versions of quasars are believed to be powered by spinning black holes[5] but with masses of up to a few tens times 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. As 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 solar masses, 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 microquasars[2,6] has led to a much greater acceptance of the idea that the emission from quasar jets is associated with material moving at speeds close to that of light[6]. Furthermore, simultaneous multiwavelength observations of microquasars[7,8] 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.

Superluminal sources

Superluminal motions have been observed in quasars for more than 20 years[9]. In the past, these motions had been used to argue that quasars cannot be as remote as believed, and that the use of redshifts and the Hubble expansion law to determine their distances was not fully justified. In the extragalactic case the jets are usually observed to be moving on only one side of the source of ejection, and it is not possible to know whether superluminal motions represent the propagation of waves through a slowly

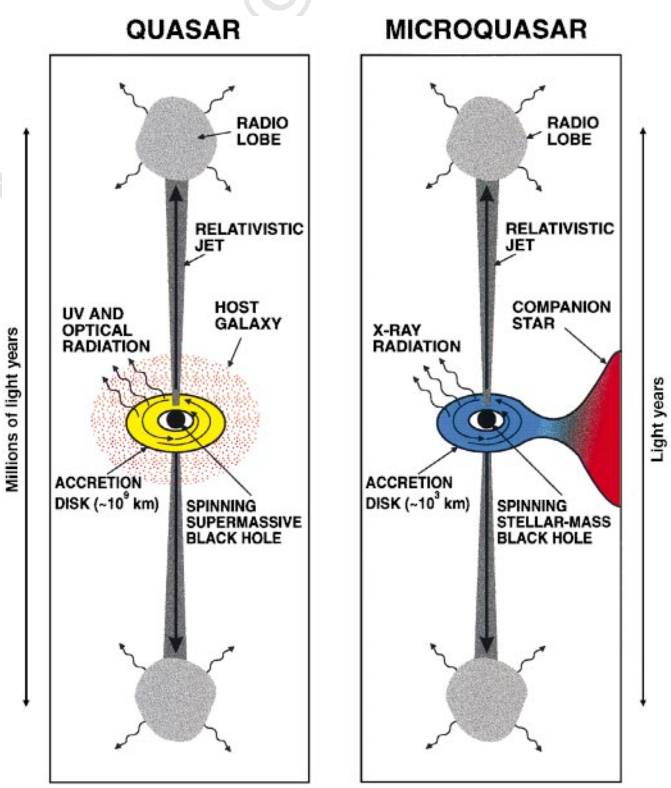


Figure 1 Diagram illustrating current ideas about quasars and microquasars (not to scale). As in quasars, the following three basic 'ingredients' are found in microquasars: (1) a spinning black hole, (2) an accretion disk heated by viscous dissipation, and (3) collimated jets of relativistic particles. But 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 a size of $\sim 10^9$ km and radiates mostly in the ultraviolet and optical wavelengths, whereas in microquasars the accretion disk has a size of $\sim 10^3$ km and the bulk of the radiation leaves as X-rays.

Box 1 Determining distances with special relativity

The superluminal motions can be fully understood in terms of a relativistic illusion in the observation of ejecta moving at close to the speed of light. The ejecta is moving so fast that it nearly catches up with its own radiation. After a time t from the moment of ejection, the plasma clouds, with a true velocity v, have moved a distance vt. As seen in projection by the observer, the displacement seems to be $vt \sin\theta$, where θ is the angle between the line of sight and the axis of ejection (see Box Figure). However, because the approaching condensation is now closer to the observer by a distance $vt\cos\theta$, the time t' in which the observer sees the condensation move from the origin to its present position is smaller than t and is given by $t' = t - (vt\cos\theta/c)$. The apparent velocity of the approaching condensation is then $v_a = v\sin\theta/(1-(v\cos\theta/c))$, that can exceed c. By a similar reasoning, the apparent velocity of the receding condensation is then $v_r = v\sin\theta/(1+(v\cos\theta/c))$. If one can measure the proper motions in the sky of the approaching and receding ejecta, μ_a and μ_r, two independent equations are obtained:

$$\mu_a = \frac{v\sin\theta}{(1-(v/c)\cos\theta)D}$$

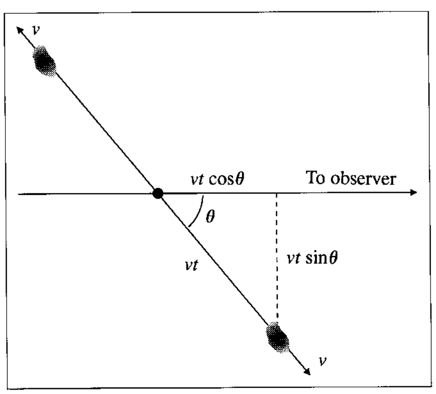
$$\mu_r = \frac{v\sin\theta}{(1+(v/c)\cos\theta)D}$$

where μ_a and μ_r are in units of rad s^{-1}, v is the true velocity of the ejecta, θ is the angle between the line of sight and the ejection axis, and D is the distance to the source.

Measuring the wavelength $\lambda_{a,r}$ of spectral lines (with rest wavelength λ_{rest}) arising in either the approaching or receding jets, a third equation can be chosen from:

$$\frac{\lambda_{a,r}}{\lambda_{rest}} = \frac{1 \mp (v/c)\cos\theta}{[1-(v/c)^2]^{1/2}}$$

One can then resolve the system of three equations and find the three unknowns: v, θ and D, the distance to the source. The physical configuration is shown in the Box Figure.



Additionally, for an object moving at relativistic speeds, the emitted radiation 'focuses' in the direction of motion (the so-called relativistic beaming), an effect that makes the approaching condensation look brighter than the receding condensation. In remote objects, such as quasars, the approaching ejecta can be observed more easily when their apparent brightness is very highly enhanced due to beaming to the observer. This Doppler-favouritism for the approaching jet implies the opposite effect for the receding jet, often rendering it undetectable in practice.

With the new technological capabilities in astronomy, this relativistic method to determine distances may be applied first to black-hole jet sources in binaries, and in the decades to come to quasars. The history of science shows that new methods to determine distances have been crucial in astronomical revolutions.

moving jet, or whether they reflect the actual motion of the sources of radiation.

In the context of the microquasar analogy, one then may ask if superluminal motions could be observed from black-hole binary systems known to lie in our own Galaxy. Among the handful of black holes of stellar mass known so far, the X-ray sources GRS1915+105 (ref. 10) and GRO J1655-40 (ref. 11) have indeed been identified at radio wavelengths as transient sources of superluminal jets[2–4]. The jets in the two sources move at 0.92 times the velocity of light and still hold the 'speed record' in the galaxy. GRO J1655-40 is known to be at a distance of 10,000 light years, and the apparent transverse motions of the ejecta in this source are the largest observed up to now from an object beyond the Solar System.

Special relativity

The observation of superluminal double-sided jets in GRS1915+105 confirmed the existence of highly relativistic ejections of matter in the Universe and gave support to the microquasar analogy. Fig. 2 shows a significant ejection event observed from GRS1915+105 in March–April 1994. The brighter cloud (to the left) appears to move faster than the fainter cloud (to the right). This asymmetry in apparent motion and brightness can be explained in terms of relativistic aberration (see Box Figure). In all five main ejections observed so far from GRS1915+105, the clouds move with the same motions and approximately along the same direction on the sky[6]. The observation of counterjets in this microquasar allows a comparison of the parameters of the approaching and receding ejecta: this comparison shows that the emission arises in moving material and rules out the possibility of other explanations[6], such as only rapid propagation of waves through a slowly moving jet.

As shown in Box 1, if the proper motions of the twin ejecta and the Doppler shift of spectral lines can be measured in the approaching and/or receding ejecta, the parameters of the system—in particular its distance—can be obtained[12]. The main observational difficulty resides in the detection of lines that are strongly Doppler broadened as they arise from plasma clouds that not only move but also expand at relativistic speeds.

The central engine

Multiwavelength monitorings of the galactic superluminal sources have shown that hard X-ray emission is a necessary, but not sufficient, condition for the formation of collimated jets of synchrotron radio emission. In GRS1915+105, the relativistic ejection of pairs of plasma clouds have always been preceded by unusual activity in hard X-ray[13]. More specifically, the onset of the main ejection events seems to be related to the sudden drop from a luminous state in the hard X-ray[14,15] band. However, not all unusual activity and sudden drops in the hard X-ray flux appear to be associated with radio emission from relativistic jets. In fact, in GRO J1655-40 there have been several hard X-ray outbursts observed without subsequent radio flare/ejection events[16].

What is the current belief as to how these relativistic jets are generated? Black holes, both in quasars and microquasars, are thought to be surrounded by an accretion disk. In the case of microquasars the disk is fed by magnetized gas drawn from a star that accompanies the black hole, forming a gravitationally bound binary system (Fig. 1). Finding a mechanism that creates a collimated flow that approaches the speed of light is a theoretical challenge faced more than two decades ago when extragalactic radio jets were first discovered. One possibility is magnetohydrodynamic acceleration in the accretion disk itself[17]. An alternative model is one that involves the enormous rotational energy of a spinning black hole[18]; the energy drawn from the black hole accelerates the magnetized plasma coming from the disk, and ultimately propels it into jets.

We next consider why some black-hole systems produce powerful jets while others apparently do not. The answer may reside in the spin of the black hole. In a unification scheme[19], black-hole sources of powerful collimated jets are rotating black holes with threading magnetic fields maintained by co-rotating accretion disks. Ejection of relativistic jets will take place preferentially in those sources where the spin of the black hole is close to its maximum value.

Accretion onto the black hole

The X-ray power of the superluminal source GRS1915+105 shows a large variety of quasi-periodic oscillations (QPOs). Of particular interest is a class of oscillations with a maximum stable frequency of 67 Hz that has been observed many times, irrespective of the X-ray luminosity of the source[20]. It is believed that this fixed maximum frequency is a function of the fundamental properties of the black hole, namely, its mass and spin. However, this particular frequency could be related to the last stable circular orbit around the black hole[20], to a radial mode in general relativity disk seismology[21], or to the relativistic dragging of the inertial frame around the fast-rotating collapsed object[22]. Theoretical work to distinguish between these alternatives will be important to estimate the spin of the black holes with masses that have been independently determined.

The episodes of large-amplitude X-ray flux variations on time-scales of seconds and minutes, and in particular, the abrupt dips observed in GRS1915+105 (see Fig. 3) are believed to be strong evidence for the presence of a black hole[23–25]. These variations could be explained if the inner part of the accretion disk goes temporarily into an advection-dominated mode[26]. In this mode, the time taken

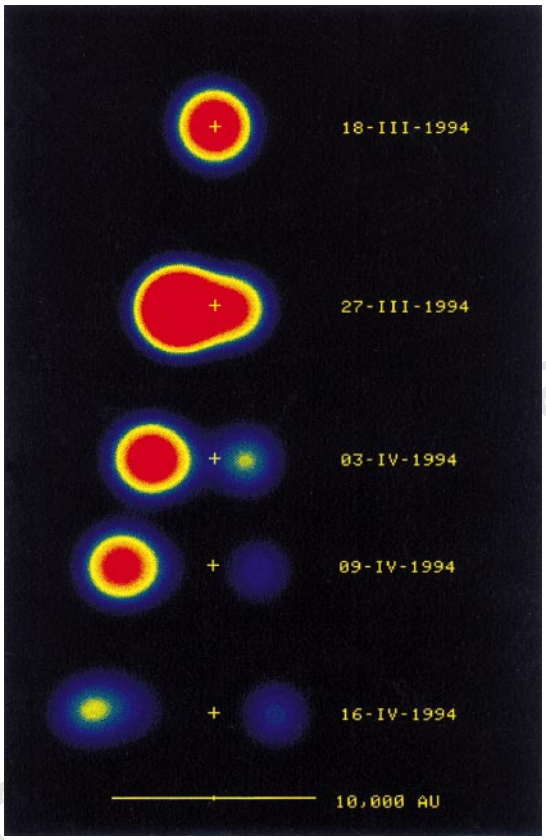


Figure 2 A pair of plasma clouds expelled from the microquasar GRS1915+105, the first superluminal source detected in the galaxy[2]. The observations were made at radio wavelengths, where red denotes the most intense emission. The cloud to the left appears to move away from the centre of ejection (yellow cross) at 125% the speed of light (1.25*c*). An observer in the frame of one of these clouds would see the other receding at 0.997*c*. It has been shown[2] that the asymmetries in velocity and brightness between the cloud to the left and the cloud to the right can be explained in terms of an antiparallel ejection of pairs of twin plasma clouds moving with bulk speeds of 92% that of light, at an angle of 70° with respect to the line of sight. These maps were obtained at intervals of ~1 week with the Very Large Array of NRAO at a wavelength of 3.5 cm. At a distance of 40,000 light years from Earth, in 1 month the clouds moved apart in the plane of the sky a distance equivalent to 10,000 astronomical units (AU; 1 AU equals the mean radius of the Earth's orbit around the Sun).

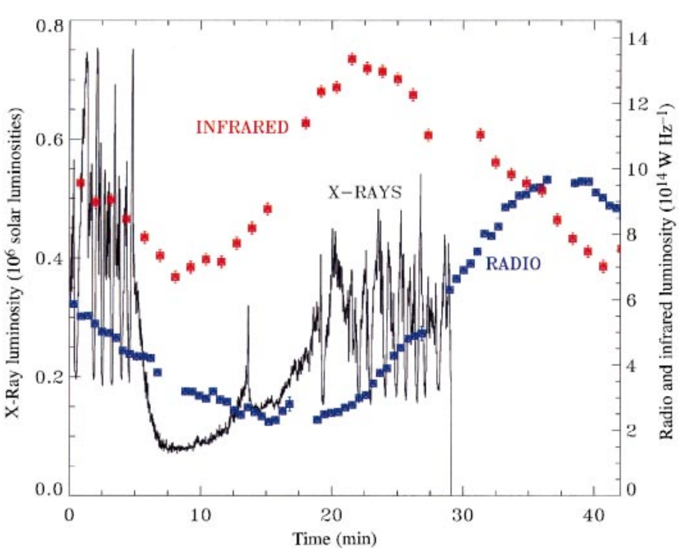


Figure 3 Oscillations in the luminosity at X-rays (2–60 keV), infrared (2 μm) and radio (6 cm) wavelengths of the galactic source of superluminal jets CRS1915+105 (ref. 7). The disappearance of the inner accretion disk (marked by the X-ray dip 7 min after the start of the set of observations shown in here), coincides with the beginning of the ejection of a relativistic plasma cloud (marked by the start of the infrared flare). As the ejected cloud expands it becomes transparent to radio waves, with a peak radio-wave flux that is delayed by 15 min relative to the infrared peak. The absence of X-ray data after 29 min is due to occultation of the source by the Earth.

for the energy transfer from ions (that get most of the energy from viscosity) to electrons (that are responsible for the radiation) is larger than the time of infall to the compact object. Then, the bulk of the energy produced by viscous dissipation in the disk is not radiated (as happens in standard disk models), but instead is stored in the gas as thermal energy. This gas, with large amounts of stored energy, is advected (transported) to the compact object. If the compact object is a black hole, the energy quietly disappears through the horizon, and one can observe sharp decays in the X-ray luminosity. In contrast, if the compact object is a neutron star, the thermal energy in the superheated gas is released as radiation when it collides with the surface of the neutron star and heats up. The cooling time of the neutron-star photosphere is relatively long, and in this case a slow decay in the X-ray flux is observed. Then, one would expect the luminosity of black-hole binaries to vary over a much larger range of values than that of neutron-star binaries for an interval of time of a few seconds.

The formation of jets

During large-amplitude variations in the X-ray flux of GRS1915+105, remarkable flux variations on timescales of minutes have also been reported at radio[27,28] and near-infrared[29] wavelengths (see Fig. 3). These rapid flares are thought to come from expanding magnetized clouds of relativistic particles. Simultaneous observations in X-ray, infrared and radio wavelengths show that the ejection of relativistic clouds of plasma[7,8] takes place when the matter of the inner accretion disk suddenly disappears through the horizon of the black hole. Recent interferometric observations during episodic ejections with the Very Long Baseline Array by Dhawan and us, and with the British radio interferometer MERLIN by Fender *et al.* may show the evolution of the ejecta on timescales of hours and with spatial resolutions of tens of astronomical units.

Microquasars offer new opportunities to gain a general understanding of the relativistic jets seen elsewhere in the Universe. We expect that in the future they will also be used to investigate the physics of strong-field relativistic gravity near the event horizon of black holes. □

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