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Microquasars in the Galaxy

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Abstract

Microquasars are X-ray binary stars capable of generating relativistic jets. Galactic microquasars are one of the most recent additions to the field of high energy astrophysics and have attracted increasing interest over the last decade. They are now primary targets for all space-based observatories working in the X-ray and γ-ray domains. The hope is that their study will enable us to understand some of the analogous phenomena observed in distant quasars and active galactic nuclei, which have practically the same scaled-up physics as microquasars. Microquasars are also believed to be among the sources responsible for the violent and ever-changing appearance of the γ-ray sky. This paper provides a general review of the field of microquasars, including their identification and study, and discusses the recent observational and theoretical discoveries which we regard as being of most relevance.

Resum

Els microquàsars a la galàxia constitueixen, sense cap mena de dubte, una de les més recents aportacions en astrofísica d'altes energies. L'estudi d'aquests objectes nous, estels binaris de raigs X amb ejeccions de plasma relativista, s'ha estès amb rapidesa en la darrera dècada i representa un objectiu de primera magnitud per a la generació actual d'observatoris espacials de raigs X i raigs γ. Darrere d'aquest insòlit interés, existeix l'esperança fundada que el fet d'estudiar-los pugui contribuir a comprendre millor fenòmens anàlegs en quàsars i altres nuclis de galàxies actives que comparteixen una física comuna, salvant les diferències d'escala. Es creu també que els microquàsars es troben entre els responsables del caràcter violent i mutable del firmament de raigs γ, el qual gairebé comencem a percebre. En aquest article passem revista a l'estat general sobre el tema dels microquàsars, la seva identificació i estudi, a la vegada que exposem quines han estat les troballes observacionals i teòriques recents més rellevants en la nostra opinió.

Keywords: X-rays binaries, radio continuum, stars

In recent years the concept of microquasars has come to be widely accepted when referring to a new kind of X-ray binary stars in our Galaxy, one with the ability to generate collimated beams, or jets, of relativistic plasma. The ejection takes place in a bipolar way perpendicular to the accretion disk associated with the compact star, a black hole or a neutron star. The word 'microquasar' was chosen due to the extraordinary analogy between these astronomical objects and quasars and other active galactic nuclei (AGNs) at cosmological distances [1]. This analogy will be discussed later.

The relativistic jets of plasma are probably the most reliable fingerprints of microquasar sources. They are believed to be responsible for the non-thermal emission, of synchrotron origin, that is often detected from them. The first microquasar discovered was the system SS 433 (see [2]). For many years, it was considered a mere curiosity in the galactic fauna. Its plasma jets are ejected into interstellar space at a speed of 0.26c and precess with a period of 163 days. The flight of plasma clouds along the jets can be followed spectroscopically by means of their emission lines, whose redshift or blueshift agree with a simple model of conical precession. SS 433 is the only microquasar where such lines have so far been detected, thus demonstrating the barionic nature of the ejecta in at least one case. Modern radio interferometers have allowed a direct follow up of jet motion in high angular resolution images.

The recent findings that we will discuss here have demon-

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strated that microquasars are, in fact, much more abundant than previously anticipated. Nowadays, astronomers are starting to think that all X-ray binaries with non-thermal radio emission are actually microquasars, even if we are not able to see the jets [3]. So far, whenever radio emission has been resolved, it appears with a clear elongated shape, as would be expected from a collimated jet flow. In this sense, it is very likely that the simple detection of radio emission from an X-ray binary has to be considered as a tell-tale sign of jets in the same way as X-rays are normally considered as evidence of mass accretion. However, confirming this suspicion, will require a substantial improvement in interferometers, both in terms of their sensitivity and angular resolution. The Expanded Very Large Array (EVLA) is one of the projects currently underway with the potential to achieve this.

The spectrum of microquasars extends from radio waves to probably γ-rays of very high energy. Therefore, a complete understanding of these objects necessarily requires a multi-wavelength approach using different telescopes and detectors, both ground- and space-based. Such an effort can be justified in view of the great interest raised by microquasars among astronomers. Microquasars provide an excellent laboratory for a suitable study of mass accretion and ejection phenomena in the strong gravitational field of a black hole or neutron star. For instance, it has been possible to demonstrate the direct connection between the instabilities of the accretion disk and the formation of the jets in the microquasar and black hole candidate GRS 1915+105 [4, 5]. Furthermore, microquasars may explain some of the unidentified sources of high energy γ-rays detected by the EGRET experiment on board the satellite COMPTON-GRO. The microquasar LS 5039 is the best representative of the proposed connection between microquasars and unidentified EGRET sources [6].

The microquasar population in our Galaxy

Microquasars, as X-ray binaries with relativistic radio jets, represent a growing subset of the X-ray binary population in the Galaxy. The most recent catalogue of high mass X-ray binaries (HMXBs) contains 130 sources [17], while the catalogue of low mass X-ray binaries (LMXBs) amounts to 150 objects [18]. Considering both catalogues together, there are about 50 X-ray pulsars, which are not radio emitters, and a total of 43 radio-emitting sources, some of which have been revealed to be microquasars. Recently, it has been estimated that the total number of X-ray binaries in the Galaxy brighter than 2×10^{34} erg s^{-1} is about 705, these being distributed as ~325 LMXBs and ~380 HMXBs [100]. This suggests an upper limit on the population of microquasars in the Galaxy of about one hundred systems. A decade ago there were fewer than five known microquasars. Although the situation is now much better, we do not yet have a microquasar population big enough for general results to be derived from it.

Present census

At the time of writing, a total of 15 microquasar systems have been identified. All of them are listed in Table 1. The top part of the table is reserved for high mass X-ray binaries, while the bottom part contains those of low mass. Within each group, the objects are sorted by right ascension and the following information is given: name and position; type of system; distance; orbital period; apparent magnitude; mass of the compact object; X-ray and radio luminosities; degree of activity (persistent/transient); apparent velocity of the ejecta; intrinsic velocity; inclination and size of the jets; and relevant references. In two of the 15 microquasars, namely, GX 339-4 and XTE J1118+480, the jets have yet to be unambiguously resolved, although their microquasar identification is well supported by other hints. The information in Table 1 has been compiled from a variety of sources. Among these are, the SIMBAD database, the daily monitoring by the Green Bank Interferometer (GBI) and the Rossi X-ray Timing Explorer (RXTE), the catalogues by [17, 18], as well as the specific references quoted and other references there in. Our compilation does not aim to be complete or exhaustive, but rather representative. The X-ray and radio luminosities quoted are approximate in the keV and centimetric (0.1-100 GHz) domains, respectively. These correspond to either the normal or the flaring state of the system as a function of its emission being persistent (p) or transient (t).

Figure 1 shows the distribution in galactic coordinates of all the microquasars listed in Table 1, together with their respective names [101].

In addition to SS 433, some of the objects included in Table 1 were already famous long before the idea of microquasar was introduced. For example, Scorpius X-1 was the first extrasolar point source of X-rays to be detected [19]. Recently, and after four years of monitoring with the VLBA, [20, 21] have obtained high resolution images of Scorpius X-

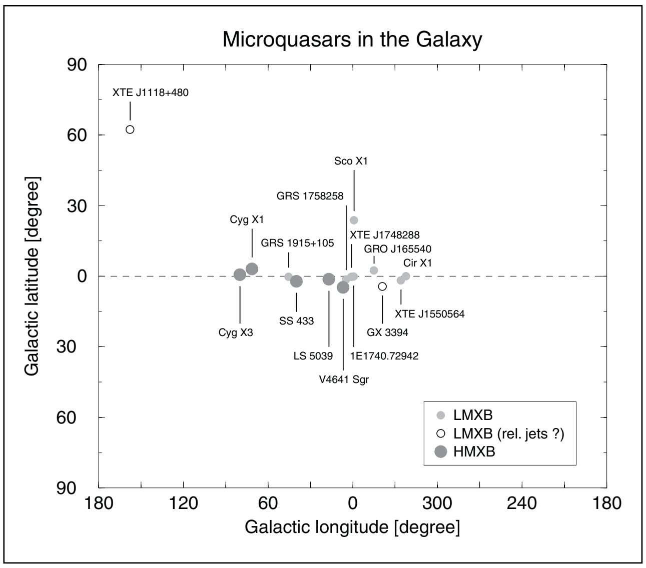

Figure 1. Distribution of known microquasars in galactic coordinates. Filled circles represent those sources where relativistic jets have been imaged, while open circles are used for those where hints of relativistic jets have been seen or are clearly suspected.

Table 1. Microquasars in our Galaxy

Name & Position (J2000.0)	Type of System	D (kpc)	P_{orb} (d)	V (mag)	M_{comp} ($M_\odot$)	Power ($erg\ s^{-1}$) X-ray	Power Radio	Activity p/t	Velocity β_{app}	Velocity β_{int}	θ (°)	Jet Size (AU)	References
High Mass X-ray Binaries													
V4641 Sgr $18^h19^m21^s.63$ –25°24'25".9	B9III +BH	10	2.8	8.5-13.5	9.6	10^{39} (2-10keV)	2×10^{33}	t	≥9.5	—	—	—	[79][80][81][82]
LS 5039 $18^h26^m15^s.06$ –14°50'54."3	O6.5V((f)) +NS?	2.9	4.1	11.2	1-3	5×10^{34} (1.5-12keV)	1×10^{31}	p	≥0.15	≥0.15	<81	10–1000	[6][83][84][85][86][87]
SS 433 $19^h11^m49^s.57$ +04°58'57".8	evolved A? +BH?	4.8	13.1	14.2	11 ± 5?	7×10^{35} (1.5-12keV)	3×10^{32}	p	0.26	0.26	79	10^4-10^6	[2][88][89][90][91][99]
Cygnus X-1 $19^h58^m21^s.68$ +35°12'05".8	O9.7Iab +BH	2.5	5.6	8.95	10.1	8×10^{36} (1.5-12keV)	1×10^{31}	p	—	>0.6	40	40	[92][93][94][95]
Cygnus X-3 $20^h32^m25^s.77$ 40°57'28".0	WNe +BH?	9	0.2	I ≅ 21	—	10^{37}-10^{38} (1-6keV)	1×10^{33}	p	0.69	0.43	73	10^4	[24][25][96][97][98]
Low Mass X-ray Binaries													
XTE J1118+480 $11^h18^m10^s.79$ +48°02'12".3	K7-M0V +BH	1.9	0.17	12.9-18.8	6.9(0.9	1.4×10^{36} (1-160keV)	5×10^{30}	t	—	—	—	≤0.03	[35][41][42][43]
Circinus X-1 $15^h20^m40^s.84$ –57°10'00".5	Subgiant +NS	5.5	16.6	B=21.4	—	1×10^{38} (0.1-100keV)	2×10^{31}	p	≥0.1	≥0.1	>70	>10^4	[44][45][46][47][48][49][50]
XTE J1550–564 $15^h50^m58^s.67$ –56°28'35".3	G8-K4III-V +BH	5.3	1.5	16.6-21.4	9.4	2×10^{37} (2-200keV)	10^{29}	t	>2	—	—	10^3	[51][52][53][54][55][56]
Scorpius X-1 $16^h19^m55^s.09$ –15°38'24".9	Subgiant +NS	2.8	0.79	12.2	1.4	2×10^{38} (2-20keV)	4×10^{30}	p	0.68	0.45	44	40	[21][36][57]
GRO J1655–40 $16^h54^m00^s.16$ –39°50'44".7	F5IV +BH	3.2	2.6	14.2-17.3	7.02	10^{37} (1-100keV)	10^{33}	t	1.1	0.92	72-85	8000	[58][59][60][61][62]
GX 339–4 $17^h02^m49^s.40$ –48°47'23".3	— +BH?	~ 4	0.6?	15-20	–	10^{35}-10^{38} (1-20keV)	2×10^{30}	t	—	—	—	<4000	[63][64]
1E 1740.7–2942 $17^h43^m54^s.82$ –29°44'42".8	— +BH?	8.5?	12.5?	K>20	–	2×10^{37} (1-200keV)	2×10^{30}	p	—	—	—	10^6	[65][66][67][68][69][70]
XTE J1748–288 $17^h48^m05^s.06$ –28°28'25".8	— +BH?	≥8	?	?	>4.5?	>10^{38} (3-25keV)	>2×10^{33}	t	1.3	>0.9	—	>10^4	[71][72][73][74]
GRS 1758–258 $18^h01^m12^s.40$ –25°44'36".1	— +BH?	8.5?	18.5?	(24	—	2×10^{37} (1-200keV)	1×10^{30}	p	—	—	—	10^6	[28][67][68][69][75]
GRS 1915+105 $19^h15^m11^s.55$ +10°56'44".8	K-MIII +BH	12.5	33.5	K(13	14(4	1×10^{39} (2-50keV)	1×10^{32}	t	1.2-1.7	0.92-0.98	66-70	10-10^4	[5][8][10][15][76][77][78]

1 which clearly show bipolar jets moving at, on average, 0.45c. Moreover, the flow of energy in the jets may be even faster (>0.95c). In the microquasar list, we also find the system Cygnus X-1, the first binary where dynamic evidence of a black hole was found [22, 23]. The case of Cygnus X-3 is also worth mentioning because, during its strong outbursts, radio emission rises by up to three orders of magnitude in just a few days [24]. Radio jets moving with relativistic

speeds are formed as a result of such flaring events. These jets can be well resolved with the VLA as illustrated in Figure 2 [25]. Finally, the microquasar family also contains the only four confirmed cases of superluminal sources in the Galaxy, namely, GRS 1915+105, GRO J1655-40, XTE J1748-288 and V4641 Sgr (see references in Table 1). We have not included the HMXB CI Cam in Table 1 because its radio emission seems to be produced in a fairly isotropic nebula [26].

It is highly likely that discoveries in the near future will increase substantially the galactic microquasar census and Table 1 will thus become obsolete. Similarly, there is no reason why microquasars might not also be identified in nearby galaxies. However, their detection will certainly be quite difficult due to the very high distances involved.

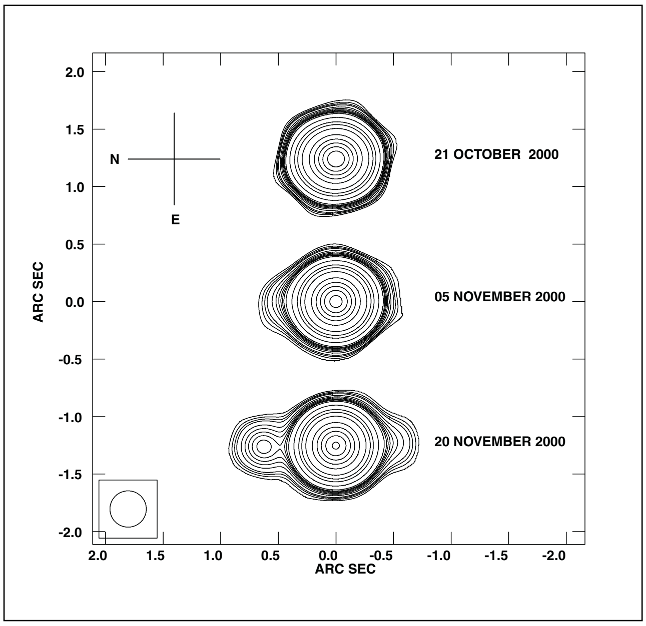

Figure 2. Sequence of radio maps of the microquasar Cygnus X-3, obtained at 6 cm with the VLA, on three consecutive epochs in the weeks after a giant outburst [25].

Search for new microquasars

The scientific potential offered by microquasar observations is still very limited by the small number of such objects so far discovered. Only for a few of them has it been feasible to take accurate measurements of the proper motions of their relativistic jets. Moreover, disappearance events of the inner regions in the accretion disk followed by immediate episodes of plasma ejection have only been observable for the microquasar GRS 1915+105. As was pointed out above, this situation makes meaningful comparisons difficult and thus hinders the long-awaited extrapolation of microquasar results to the domain of quasars and AGNs.

In this context, it is not surprising that the hunt for new microquasars is a matter of great importance among the astrophysical community working in this field. Most microquasar discoveries have resulted from the detection of an outburst episode by a high energy satellite in Earth orbit, which triggers a quick follow-up monitoring with ground-based telescopes (e.g. GRS 1915+105, GRO J1655-40, and V4641 Sgr). This mode of discovery is expected to continue to be fruitful in the future, especially with the INTEGRAL satellite of the European Space Agency, launched in October 2002. A new feature of INTEGRAL will be its weekly scans of the Galactic Plane, that are expected to provide numerous detections of transient sources of high energy emission. The multi-wavelength monitoring of these detections will certainly lead to new identifications of microquasar systems.

However, it is also conceivable that new microquasars could be identified by carefully inspecting the many past surveys of the sky in different spectral domains. Nowadays, this information is mostly available from different public databases in electronic format and allows the selection of possible candidates for subsequent confirmation [27]. This is precisely the procedure successfully used by the present authors in identifying the microquasar LS 5039 [28, 6]. The mining of sky surveys and other databases for the purpose of microquasar hunting is, in our opinion, a valuable tool that has yet to be fully exploited.

Quasars and microquasars: an analogy over eight orders of magnitude

The quasar-microquasar analogy, shown in Figure 3, goes beyond a simple morphological resemblance. Today, there is growing evidence which suggests that the physics involved in both types of objects is the same, or at least, very similar. The key difference would be the distinct order of magnitude of the most significant parameters, especially the mass of the compact object. For instance, the observed luminosity in both cases results from the accretion of matter onto the compact object. It is believed that at the core of quasars there is a supermassive black hole of $M \sim 10^7$–10^9 solar masses ($M_\odot$). The black hole in a microquasar is a compact object of stellar origin with merely a few solar masses (typically $M \sim 10\,M_\odot$). A fraction of the kinetic energy released per unit of time by the matter accreted onto the black hole will be radiated away. For a naive estimate of the luminosity L, we can consider:

$$L \cong \frac{1}{2}\dot{M}V^2 = \frac{GM\dot{M}}{R} \quad (1)$$

where G is the universal gravitation constant, R is the radius of the compact object, $\dot{M}$ is the accretion rate of matter and $V = (2GM/R)^{1/2}$ its free fall velocity. Taking R equal to $R_s = 2GM/c^2$ (Schwarzschild radius[1]) for a black hole, we have:

$$L \cong \frac{1}{2}\dot{M}c^2 \quad (2)$$

1. The Schwarzschild radius is the radius of an object with an escape velocity equal to the light velocity. Nothing will escape if the object becomes more compact than this value, as it happens in the black holes.

In other words, the accretion of mass by a compact object provides a very efficient source of energy. According to equation 2, a significant fraction of the rest mass energy of the accreted matter can be converted into radiation. In practice, this fraction is probably closer to 10% rather than the more optimistic factor 1/2 assumed in our simple calculation. The observed luminosities reach representative values of $L \sim 10^{47}$ erg s^{-1} in quasars and $\sim 10^{37}$ erg s^{-1} in microquasars. The corresponding accretion rates involved are then $M \sim 10$ $M_{\odot}$ yr^{-1} and $\sim 10^{-9}$ $M_{\odot}$ yr^{-1}, respectively. The captured matter would come from the host galaxy in the quasar case, and from the stellar companion in a microquasar binary system.

The infall of matter onto the black hole does not normally occur in a direct way. The matter's angular momentum forces it to swirl around the black hole forming what is known as the accretion disk. Matter in the disk progressively loses angular momentum and decays towards the black hole in a roughly spiral orbit. The loss of angular momentum occurs through viscous dissipation, which implies a heating of the disk. The black body temperature reached in the last stable orbit around the black hole, accreting at the Eddington limit (2), is given by:

$$T \sim 2 \times 10^7 \, M^{-1/4} \qquad (3)$$

where T is expressed in Kelvins and M in $M_{\odot}$ [7]. The resulting temperatures are ~10^5 K and ~10^7 K for quasars and microquasars, respectively. The first temperature corresponds to the range of optical and ultraviolet radiation, while the second is more typical of the X-ray domain. It is not surprising, therefore, that quasars were discovered long before microquasars. In order to discover even luminous X-ray sources, space technology had to develop to the extent that X-ray telescopes could be placed on board satellites orbiting above the absorbing atmosphere of the Earth.

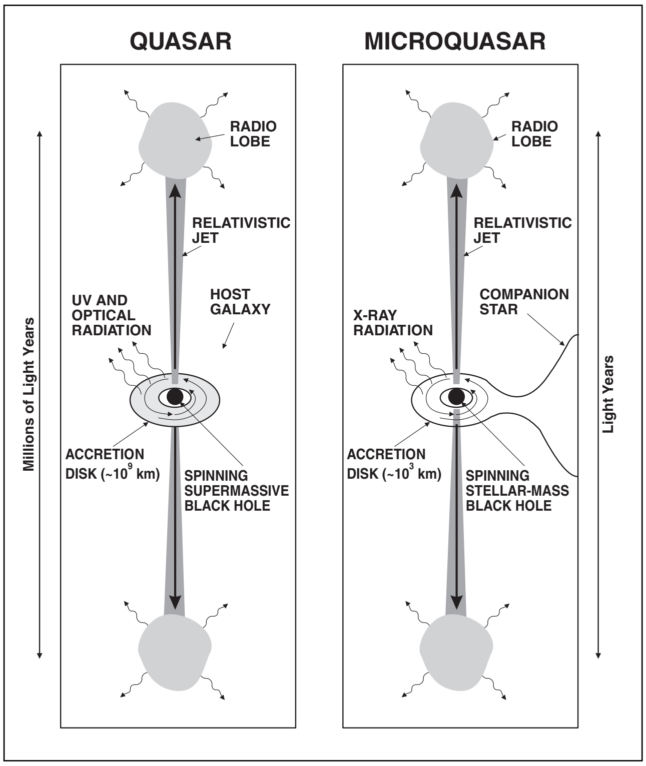

Figure 3. Comparative illustration of the analogy between quasars and microquasars in spite of the extreme differences in the order of magnitude of the physical parameters involved [5].

Another important property of microquasars is their high variability in very short time scales. Adopting the Schwarzschild radius as the characteristic dimension of the hottest regions in the accretion disk, such time scales will be given by $\tau \sim R_s/c \propto M$, that is proportional to the mass. Accordingly, one would expect events such as accretion of matter and ejection of plasma jets to manifest themselves alongside luminosity variations on time scales roughly scaling with the mass of the black hole. Therefore, such phenomena will occur much faster in a microquasar since the black hole mass is between 6 to 8 orders of magnitude smaller. In practice, such an enormous difference implies that the observation of a microquasar for a few minutes is equivalent to decades or millenniums in a quasar's life.

By studying microquasars we are in a position to better understand phenomena that, given the relatively short time span of a human life, would be almost impossible to witness for most of the extragalactic quasars. This is one of the main reasons why microquasars are of such interest to scientists, and leads them to be considered as a kind of Rosetta stone that will improve our knowledge of quasar and AGN physics.

Relativistic effects

Modern interferometers, working at radio wavelengths, are the only instruments to have provided a direct view of the most spectacular phenomena which occur in microquasars. Particularly noteworthy among these, the VLA, VLBA and MERLIN are able to provide angular resolution well below the sub-arcsecond level. Such capabilities allow us to follow the path and brightness decay of plasma clouds (plasmons) ejected along the relativistic jets in opposite directions. The huge velocities involved imply that the effects predicted by the Theory of Special Relativity must be taken into account in order to correctly interpret the observed data. For example, the illusion of superluminal motion, together with the difference in apparent brightness between the approaching and the receding jet, must be addressed. This last effect is due to the relativistic aberration of light.

Apparent superluminal motion

Let us assume that a source ejects two identical plasma clouds in opposite directions. The ejection occurs with a velocity $\upsilon = \beta\, c$ at an angle θ with the line of sight towards the terrestrial observer. The illusion of superluminal motion occurs for an ejection velocity close to the speed of light and a rather small angle relative to the line of sight. This can be understood by considering the different positions of the plasmons as a function of time since ejection. The fact that the approaching condensation reduces its distance to the observer by an amount $\upsilon\, t \cos\theta$ makes the light travel time towards the observer progressively shorter. When finally accounting for the arrival times of the photons, the apparent velocity that we measure is given by:

$$v_{a,r} = \frac{v \sin\theta}{(1 \pm \beta \cos\theta)} \quad (4)$$

for the approaching and receding cloud, respectively. The presence of a minus sign, corresponding to the approaching case, may lead to an arbitrarily large value of υ_a provided that β and $\cos\theta$ approach unity. The first object found in our Galaxy with superluminal motion was the microquasar GRS 1915+105 [8]. Until then, such relativistic illusion had been observed only in extragalactic objects such as quasars. Figure 4 shows the time evolution of a GRS 1915+105 eruption in April 1994. Here, we can see the bipolar ejection of two plasmons going away from the central core. The kinematical distance estimates to GRS 1915+105 using neutral hydrogen suggest that it is located at 12.5 kpc from us. The observed proper motions of the plasma clouds thus translate into apparent velocities of 1.25 and 0.65 times the speed of light.

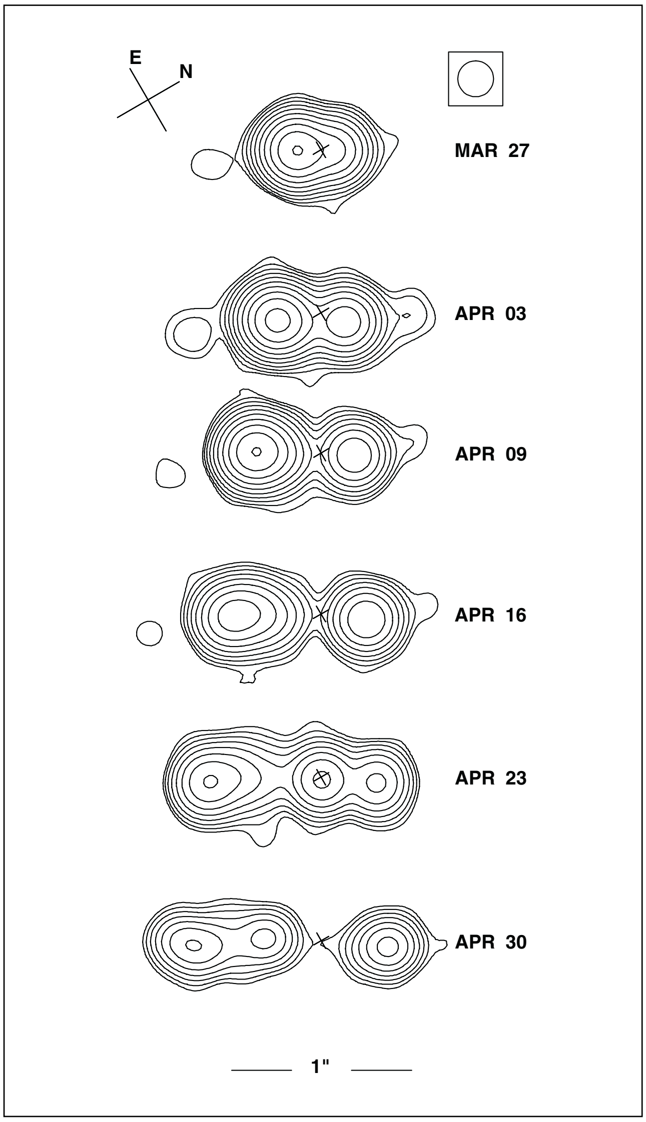

Figure 4. Sequence of images obtained by [8] showing the evolution of relativistic jets in a superluminal ejection of the microquasar GRS 1915+105. The jet approaching the observer is the one on the left, while the right one is receding. The plasma clouds in the approaching jet appear brighter, and move faster, than those in the receding one due to the relativistic effects mentioned in the text.

Relativistic aberration

This effect is usually known in astronomic literature as Doppler boosting. Assume that the two plasma clouds ejected in opposite directions are identical, as mentioned before, with a radiation flux density S_0 in their respective reference frame. The synchrotron spectrum of each cloud, as a function of frequency ν, is characterised by a power law of the type $S_0 \propto \nu^{\alpha}$, α being what is known as the spectral index (usually $\alpha \cong -0.7$). When transforming to the reference frame of the observer, the resulting flux density appears to be different from S_0. Let $S_{a,r}$ be the flux density observed from the approaching and receding cloud, respectively. The relationship between the emitted and observed flux density is then given by:

$$S_{a,r} = \frac{S_0}{\left[\gamma(1 \pm \beta \cos\theta)\right]^{k-\alpha}} \quad (5)$$

where $\gamma = (1 - \beta^2)^{-1/2}$ is the Lorentz factor and the constant k takes the values 3 or 2 depending on whether it refers to discrete clouds or a continuous jet, respectively.

If θ is small ($\leq 10°$) and β close to unity, the brightness of the approaching cloud is considerably boosted and it may appear thousands of times brighter than the receding one. This is what is known as Doppler favouritism, which only allows one side of the jet condensations in very distant quasars to be seen, and where a strong amplification is needed for the emission to be detectable. In Figure 4 the same effect is seen, although not so strong, when the approaching plasma jet seems to be faster and clearly brighter than the opposite counter jet due to relativistic aberration.

Accretion disk and jet ejection

The existence of jets of relativistic plasma in X-ray binary systems has recently acquired growing importance. Indeed, modern observations show how wide the spectral range of the synchrotron emission from these collimated beams is, ranging from radio to near infrared and possibly even shorter wavelengths. Moreover, the luminosity directly associated with the jets represents at least ~10% of the total [3]. The astrophysical community is gradually becoming convinced that the process of mass accretion onto a black hole cannot be understood without taking into account the presence of jets. The so called "symbiosis" between accretion disks and jets is probably the most outstanding expression of this belief [102].

The theoretical models which aim to understand how the jets are formed and identify their relationship to the accretion disks received a seminal contribution thanks to the works by [9]. These authors explored the possibility of extracting energy and angular momentum from the accretion disk by means of a magnetic field whose lines extend towards large distances from the disk surface. Their main result was confirmation of the theoretical possibility that a flow of matter could be generated from the disk itself towards the outside, provided that the angle between the disk and the lines was smaller than 60°. Subsequently, the flow of matter is collimated at a large distance from the disk by the action of a toroidal component of the magnetic field. In this way, two opposite jets could be formed flowing away perpendicularly to the accretion disk plane.

In the [9] scenario there is a direct link between the accretion disk and jet genesis. However, it is far from easy to confirm this observationally. The collimated ejections in the superluminal microquasar GRS1915+105 provide one of the best studied cases in support of these ideas, i.e., the proposed disk/jet connection. Figure 5, taken from [5], shows simultaneous observations at radio, infrared and X-ray wavelengths. The data show the development of a radio outburst, with a peak flux density of about 50 mJy, as a result of a bipolar ejection of plasma clouds observed with the VLA. However, prior to the radio outburst there was a clear precursor outburst in the infrared. The simplest interpretation of these light curves is that both flaring episodes, radio and infrared, were due to synchrotron radiation generated by the same relativistic electrons of the ejected plasma. The adiabatic expansion of plasma clouds in the jets causes these electrons to lose energy and, as a result, the spectral maximum of their synchrotron radiation is progressively shifted from the infrared to the radio domain.

No less important in Figure 5 is the behaviour of X-rays and their associated hardness index. The emergence of jet plasma clouds, that produces the infrared and radio flares, seems to be accompanied by a sharp decay and hardening of the system's X-ray emission (8.08-8.23 h UT in the figure). The X-ray fading is interpreted as the disappearance, or emptying, of the inner regions of the accretion disk [10]. Part of the matter content in the disk is then ejected into the jets, perpendicularly to the disk, while the remainder is finally captured by the central black hole. Additionally, [5] suggest that the initial time of the ejection coincides with the isolated X-ray spike just when the hardness index suddenly declines (8.23 h UT). The recovery of the X-ray emission level at this point is interpreted as the progressive refilling of the inner accretion disk with a new supply of matter until the last stable orbit around the black hole is reached.

This kind of behaviour in the light curves of GRS 1915+105 has been repeatedly observed by different authors (e.g. [4, 11]), thus providing solid evidence of disk/jet symbiosis in accretion disks. All observed events took less than half-an-hour to occur and their equivalent in quasars, or AGNs, would need a much longer time span (at least a few years). Despite the complexity in the GRS 1915+105 light curves, the episodes of X-ray emission decay with associated hardening are very reminiscent of the low/hard state typical of persistent black hole candidates (Cygnus X-1, 1E 1740.7-2942, GRS 1758-258 and GX339-4). The transitions towards this state are often accompanied by radio emission with flat spectrum, interpreted as being due to the continuous creation of partially self-absorbed compact synchrotron jets. One such transitions is illustrated in Figure 6, corresponding to the black hole candidate and microquasar GX 339-4 [12].

Worth mentioning here is a recently published observa-

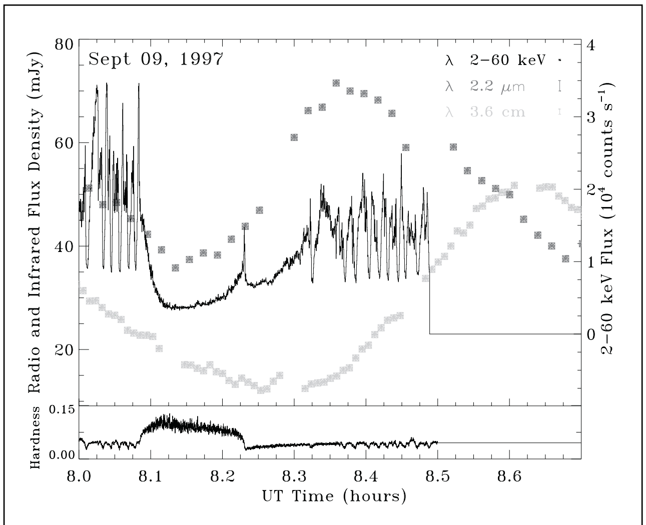

Figure 5. Multi-wavelength behaviour of the microquasar GRS 1915+105 as observed on September 8, 1997 [5]. The radio data at 3.6 cm (grey squares) were obtained with the VLA interferometer; the infrared observations at 2.2 micron (black squares) are from the UKIRT; the continuous line is the X-ray emission as observed by RXTE in the 2-50 keV range. These observations demonstrated the connection between the emptying, and subsequent refilling, of the inner accretion disk with the ejection of relativistic plasma clouds whose synchrotron emission is detected later at radio and infrared wavelengths.

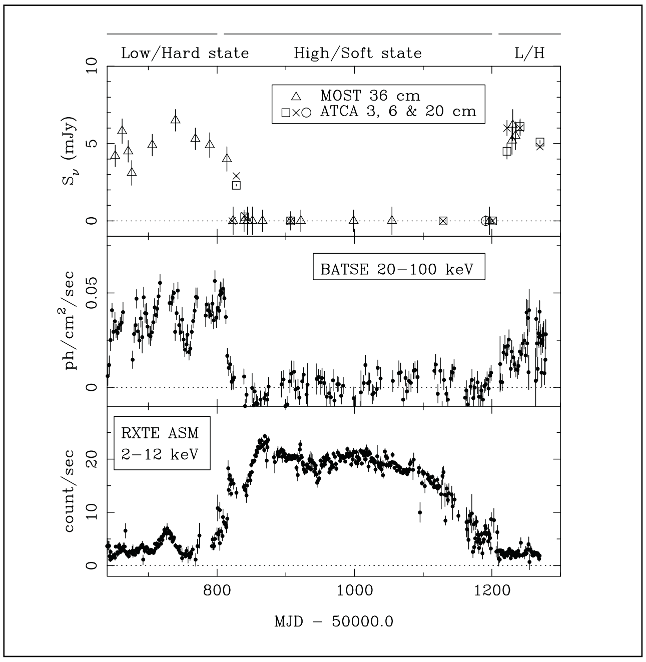

Figure 6. Observations of the black hole candidate GX339-4 (Fender et al. 1999b) obtained over two years at radio (ATCA and MOST), hard X-rays (BATSE) and soft X-rays (RXTE). The data show how a transition from the high/soft state to the low/hard state implies the onset of radio emission due to the appearance of persistent relativistic jets.

tional study by [13] who presented evidence of disk/jet symbiosis in an AGN as well. In the active galaxy 3C120, they observed episodes of ejection of superluminal plasma, using VLBI techniques, just after the decay and hardening of its X-ray emission. This is precisely the kind of behaviour displayed by GRS 1915+105. The events in 3C120 seem to be recurrent with an interval of one year, which is consistent with a compact object mass of ~$10^7\ M_{\odot}$. Such observations strongly support the idea of continuity between galactic microquasars and the other AGNs in the Universe.

Clearly, a lot of work remains to be done before a satisfactory interpretation of the physical mechanisms involved in the formation of jets and their connection to the accretion disk is achieved. However, theoretical progress since [9] has been very encouraging. As of today, the existence of jets begins to be a mandatory ingredient in serious accretion disk models. For example, the recent results by [14] indicate that both the jets and the magnetic field, anchored to the accretion disk close to the black hole horizon, play a fundamental role in extracting black hole rotational energy. Which fraction of the luminosity emitted by one of these systems comes from the rotation energy of the black hole is a question that remains to be answered. The issue of the barionic or non-barionic nature of the jet plasma is likely to depend on whether the formation mechanism is magnetohydrodynamic or purely electromagnetic.

Last but not least, the study of accretion disks in microquasars would not be complete without an understanding of the quasi-periodic oscillations (QPOs) in their X-ray emission. QPOs are detected observationally as peaks in the power spectrum of the X-ray emission by using Fourier techniques. In the microquasars GRS1915+105 and GROJ1655-40, very stable QPO frequencies have been measured at 67 and 300 Hz, respectively [15, 16]. It has been proposed that these frequencies are associated with the last stable orbit around the central black hole and, therefore, must be related to fundamental parameters such as mass and angular momentum. In this sense, it is very likely that disk-seismologic methods will contribute substantially to the determination of such elusive parameters.

Microquasars as γ-ray sources

It is widely accepted that relativistic jets in AGNs are strong emitters of γ-rays with GeV energies (e.g. [29]). Generally speaking, and allowing for their similarity, one could also expect the jets in microquasars to be GeV γ-ray emitters. Based on the physical parameters derived from observations of outbursts in GRS 1915+105, the expected γ-ray flux has been estimated from inverse Compton scattering of the same radio photons of synchrotron origin [30]. The resulting fluxes could hardly be detected by EGRET, but they are within the sensitivity of the future GLAST mission.

The recent discovery of the microquasar LS 5039, and its possible association with a high energy γ-ray source (E>100 MeV), provides the first observational evidence that microquasars could also be sources of high energy γ-rays [6]. This finding opens up the possibility that other unidentified EGRET sources could also be microquasars. LS 5039 is the only X-ray source from the bright ROSAT catalogue whose position is consistent with the high energy γ-ray source 3EG J1824-1514. LS 5039 is also the only object simultaneously detectable in X-ray and radio which displays bipolar radio jets at sub-arcsecond scales. Taken together, this evidence strongly suggests that LS 5039 is emitting in very different parts of the electromagnetic spectrum, from radio to γ-rays. It is important to point out that this is the first time an association between a microquasar and a high energy γ-ray source has been reported.

The mechanism of the γ-ray emission, with a luminosity of L_{γ} (>100 MeV) ~10^{35} erg s^{-1}, is likely to originate from inverse Compton effect by the ultraviolet photons from a hot companion star scattered by the same relativistic electrons responsible for the radio emission. The energy shift in this process is given by $E_{\gamma} \sim \Gamma^2 E_{f}$, where the energies of the γ-ray and the stellar photon are related by the Lorentz factor of the electrons squared. For an O6.5 star in the main sequence, most of its luminosity is radiated by photons with E_f ~10 eV. In order to scatter them into γ-ray photons with Eγ ~100 MeV, electrons with a Lorentz factor of $\Gamma \sim 10^3$, or equivalently with energy ~10^{-3} erg, are required.

While only one EGRET source has so far been identified (to a high degree of confidence) with a microquasar system (LS 5039), the instrument COMPTEL (also on board the Compton Gamma-ray Observatory), did detect other microquasars at several MeV energies. For example, Cygnus X-1 has been detected several times and it may be even brighter above 1 MeV in the soft/high state [31]. GRO J1655-40 has also been detected up to ~1 MeV [32]. In the extreme energy range of TeV γ-rays, a flux in the order of 0.25 Crab was detected from GRS 1915+105 during the period May-July 1996 when the source was in an active state [33]. Given the marginal confidence of this detection, this result needs further confirmation.

Further consequences of the relativistic effects discussed above indicate that, for relativistic sources with small θ, the flux density becomes greatly amplified by a factor of $8\gamma^3$ and the time squeezed by a factor of 2γ. It has been proposed [1] that microquasars where the ejecta forms a small angle with the line of sight should behave as microblazars, analogous to blazars in the unified model of AGNs. As a consequence, their flux density should be strongly boosted and highly variable. The possibility of finding microblazars among the unidentified variable sources in the EGRET catalogue has been suggested by [34].

Microquasars in the galactic halo

A recent topic of great interest in the microquasar field has been the measurement of high spatial velocities for some of these objects (runaway microquasars). In particular, XTE J1118+480 [35] is reported to move at 200 km s^{-1} in an eccentric orbit around the Galactic Center. Its age is comparable to that of the Galactic Disk. It has been proposed that only an extraordinary kick, due to a supernova explosion, would be able to launch the system from its birth place in the Galactic Disk into the Galactic Halo. Another possibility is that the system was formed in the Halo itself. Similarly, the microquasar Scorpius X-1 has a position and spatial velocity in the Galaxy which also suggest that it is a halo object [36]. Other microquasars, such as GRO J1655-40 and Cygnus X-1, also display significant space velocities [37, 38]. The most recent case of a runaway microquasar is that of LS 5039, with a systemic velocity of 150 km s^{-1}. This object is escaping from its local environment (the Regional Standard of Rest) with a very high velocity component perpendicular to the Galactic Plane [39]. Such behaviour may be the result of the supernova explosion which created the compact object in this binary system. According to its computed trajectory, LS 5039 could reach a galactic latitude of –12 degrees. Taking into account the possible association of this microquasar with the high energy gamma-ray source 3EG J1824-1514 [6], one would expect to detect gamma-ray microquasars up to galactic latitudes greater than 10 degrees. In particular, as suggested by [40] and [35], some microquasars with high spatial velocity could be related to the faint, soft and variable unidentified EGRET sources above the Galactic Plane.

Concluding remarks

We have broadly described present knowledge about microquasars. Recent observational results have established these systems as being a new type of stellar object in the Galaxy that merits additional in-depth studies. It is hoped that their existence will make a significant contribution to a unified understanding of accretion and ejection phenomena in the vicinity of collapsed objects, both in terms of stellar mass and supermassive black holes in X-ray binary stars and quasars, respectively. Observational results, such as those by [5] and [13], clearly point in this direction. However, it remains unclear how long it will take for this to become a reality. Nevertheless, in addition to the efforts made by observers and theoreticians, this enterprise will undoubtedly lead to better communication and exchange of ideas among astrophysicists working on very different domains.

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