Microquasars

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Abstract. Microquasars are binary systems in our Galaxy which sporadically eject matter at relativistic speeds along bipolar jets. While phenomenologically similar to quasars, their vicinity allows much more in-depth studies. I review the observational aspects of microquasars, in particular the new developments on the interplay between accretion disk instabilities and jet ejection.

1. INTRODUCTION

Accreting X-ray binaries can be classified [1] in various ways, two important being those according to the nature of the compact object (neutron star or black hole) or the mass of the donor (low-mass vs. high-mass). Most of the high-mass X-ray binaries (HMXB) show X-ray pulsations thus suggesting a magnetized neutron star as the accretor. The donors usually are giants of spectral typ O or B. Low-mass X-ray binaries (LMXB) comprise X-ray bursters, globular cluster X-ray sources, soft X-ray transients and many galactic bulge sources. The donors typically are main-sequence stars of spectral types K-M. Both, neutron stars as well as black hole candidates have been found as accreting objects in LMXBs.

Radio observations with high spatial resolution during the past decade have shown that a small number of X-ray binaries display blobs which move with an apparent velocity larger than the velocity of light (superluminal motion) away from the core of the X-ray source (Fig. 2). Though the lifetime of these blobs as radio emitters is short (few days to weeks) compared to the repetition timescale of ejections, the generally accepted notion is that two-sided jets are emitted by these X-ray sources. The phenomenological similarity to radio-loud quasars led to the naming of microquasars [2].

There is no strict limit above what jet speed a system is considered to be a microquasar. Tab. 1 lists all galactic binaries with jets faster than 0.1c (though often the speed is not exactly known). As can be seen, microquasars do not belong to one of the above X-ray source categories, since they comprise both, either neutron star or black hole accretors as well as low-mass or high-mass donors.

Previous reviews with different emphasis on individual sources, jet physics and observational constraints can be found in [3, 4].

TABLE 1. Galactic binary sources showing relativistic jets ($v > 0.1$c)

Source	X-ray[(1)]	Radio[(1)]	Accretor	Donor	D (kpc)	V_{app}[(2)]	V_{int}[(3)]	Θ[(4)]	Refs.
GRS 1915+105	t	t	black hole?		10–12	1.2c-1.7c	0.92c-0.98c	66°-70°	[5, 6]
GRO J1655-40 (V1033 Sco)	t	t	black hole	F3-6 IV	3.2	1.1c	0.92c	72°-85°	[7, 8, 9]
XTE J1748-288	t	t	black hole?		8–10	0.9c-1.5c	>0.93c		[10]
XTE J1819–254 (V4641 Sgr)[(5)]	t	t			0.5?	∼0.8c			[11]
SS 433 (V1343 Aql)	t	t	neutron star	OB?	5.5	0.26c	0.26c	79°	[12, 13]
Cygnus X-3 (V1521 Cyg)	t	t	neutron star?	WR?	8–10	∼0.3c	∼0.3c	>70°	[14, 15]
CI Cam (XTE J0421+560)	t	t	neutron star?	Be?	∼1	∼0.15c	∼0.15c	>70°	[16, 17]
Circinus X-1 (BR Cir)	p	p	neutron star	MS	8.5	≥0.1c	≥0.1c	>70°	[15, 18]
1E1740.7-2942	p	p	black hole?		8–10				[2, 19]
GRS 1758-258	p	p	black hole?		8–10				[20, 21]

(1) t ≡ transient, p ≡ persistent

(2) V_{app} is the apparent speed of the highest velocity component of the ejecta.

(3) V_{int} is the intrinsic velocity of the ejecta.

(4) Θ is the angle between the direction of motion of the ejecta and the line of sight.

(5) This X-ray transient has initially been related to the optical variable GM Sgr. However, GM Sgr is a different variable, and the optical counterpart of XTE J1819–254 was named V 4641 Sgr [22].

2. THE TWO MOST IMPORTANT MICROQUASARS

Our present understanding mostly rests on the results obtained over the last years for two microquasars, namely GRS 1915+105 and GRO J1655-40. Therefore, some basics concerning these two systems will be described below.

2.1. GRS 1915+105

Already shortly after the discovery of GRS 1915+105 as a strongly variable new X-ray transient in 1992 [23] it became clear that it was an unusual source. It did not show the canonical fast-rise, exponential decay light curve, and did not show a related bright optical outburst. Later observations showed it to be X-ray active even during times of BATSE-non-detections, suggesting a strongly variable X-ray spectrum [24]. With the RXTE observations since early 1996 these spectral and temporal variations were discovered [25] to extend down to timescales of seconds to minutes (Fig. 1), leading to a variety of new interpretations (see par. 3–5), including the emptying of the inner part of the accretion disk during the stalls and its subsequent replenishment [25, 26].

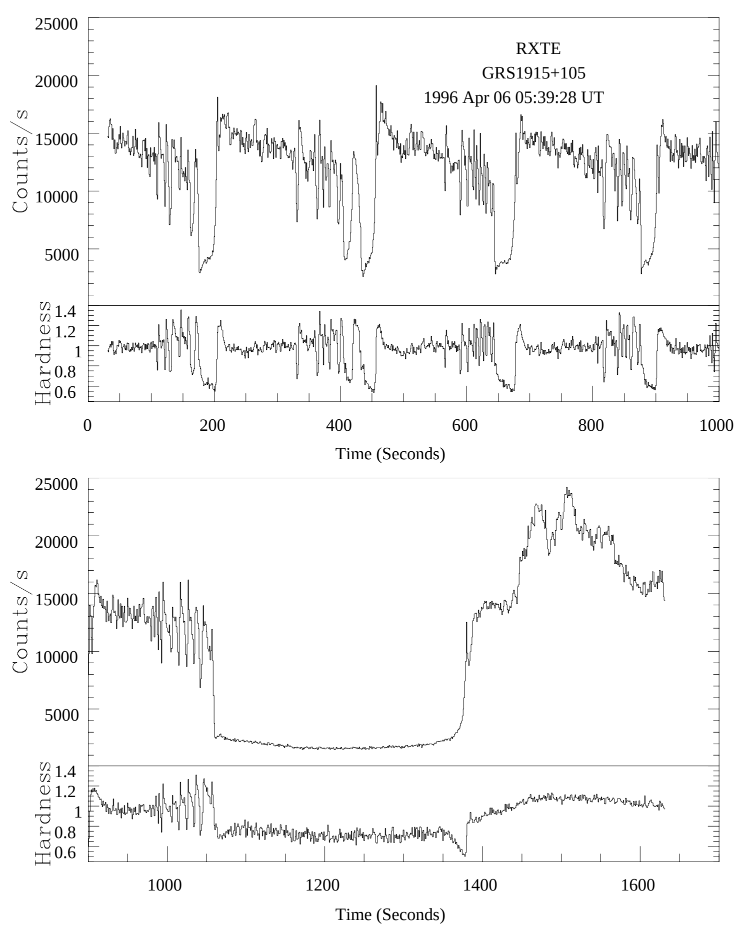

FIGURE 1. X-ray light curve of GRS 1915+105 on April 6, 1996 showing the quasi-periodically repeating pattern of 30 sec duration brightness sputters (top) and a major lull (bottom). The top panel of each plot shows the count rate while the lower panel shows the hardness ratio (count ratio in the 4.4-25 keV versus 2-4.4 keV band) at the same time resolution of 1 sec (time along the abscissa refers to the time labeled in the top panel). (Taken from [25].)

High-resolution radio observations in 1994 revealed for the first time superluminal motion of plasmons in our Galaxy [5]. Recent observations [6] revealed plasmon velocities substantially larger than those observed in 1994, and constrain the distance to less than about 11.5 kpc. Since the distance of GRS 1915+105 is not accurately known, the constraint on the bulk Lorentz factor is very loose (1.4–30). Due to its location in the galactic plane and a consequently huge visual extinction (∼25–27 mag) no decent optical studies are possible. Thus, nothing is known yet about the orbital period and the binary components.

2.2. GRO J1655-40

GRO J1655-40 was discovered in July 1994 as a new X-ray transient [27], and superluminal motion of the radio blobs (Fig. 2) was discovered within a few weeks [7, 8]. However, the interpretation of the radio data is much more complicated as compared to GRS 1915+105, since the blob movement shows wiggles of about 2° around the jet axis, and the relative brightness of the receding and approaching jet does not follow the simple relativistic Doppler boosting description. Instead, the observed brightness difference is often much larger, and also flips from side to side [8]. Thus, the ejecta must be intrinsically asymmetric. Furthermore, the jet axis seems not to be perpendicular to the orbital plane, but inclined by 15° [9].

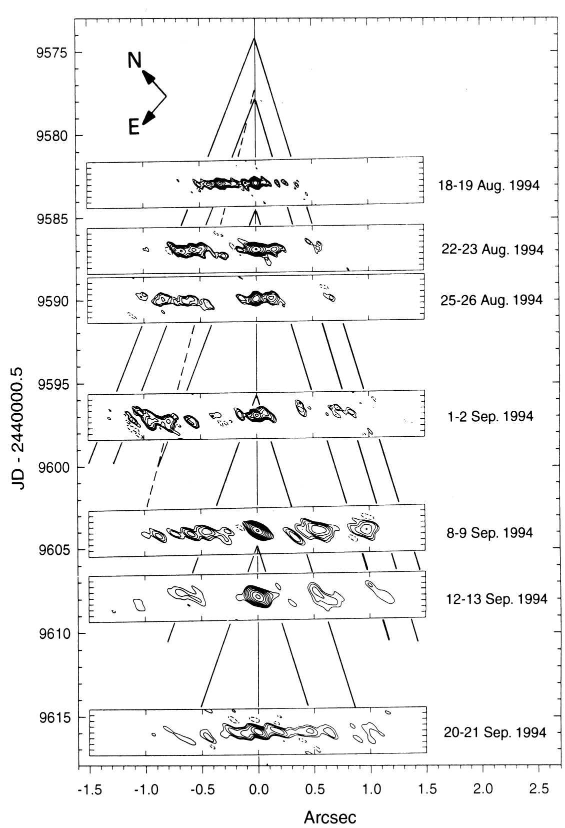

FIGURE 2. A sequence of seven VLBA images of GRO J1655-40 at 1.6 GHz, each having an agular size of 3″.0×0″.4. The vertical separation corresponds to the time elapsed between the images. The solid lines between the images identify motions of 54 mas/d (left) and 45.5 mas/d (right). The vertical line marks the central source from which the offset (in arcsec) is shown on the horizontal axis (from [8]).

The brightness ($\sim$17 mag) of the optical counterpart has allowed to determine with high precision [9] the orbital period ($2^{\rm d}_{.}621$), the inclination ($69^{\circ}_{.}5$), the mass (2.34 $M_{\odot}$) and radial velocity amplitude (228.2 km/s) of the donor, and finally the mass of the accreting object of 7.02 ± 0.22 $M_{\odot}$. With this mass estimate, the accretor in GRO J1655-40 is one of the best black hole candidates in the Galaxy.

3. QUASI-PERIODIC OSCILLATIONS

RXTE observations have revealed a perplexing variety of quasi-periodic oscillations (QPO) in the X-ray power density spectra [28, 29, 30]. Some sources show up to 7 different QPOs simultaneously spanning three decades in frequency; QPOs sometimes occur with up to 3 harmonics, and their power has a diverse energy dependence. While QPOs are believed to provide a valuable means of probing the X-ray emission region, the understanding of basic properties is still rather poor.

Often, QPOs are attributed to processes in the accretion disk, but evidence for such an origin is scarce. In several cases the properties of QPOs seem to correlate much better with those of hard X-rays, commonly believed to arise in a Comptonizing corona, rather than those of soft X-rays (accretion disk). An intriguing correlation has recently been found in GRS 1915+105 [31]: during source states with QPOs the X-ray intensity variations are mostly in the hard, power law component, while during states without QPOs intensity variations are dominated by the soft, accretion disk component. In addition, there is a strong correlation between QPO frequency (2–10 Hz) and disk temperature. This suggests a delicate interplay between accretion disk and Comptonizing corona in a way where the QPO is produced in the corona, but its frequency is determined by the state of the disk.

One of the simple predictions based on the existence of a Comptonizing corona is the time lag of hard X-ray photons with respect to soft ones. This is indeed observed [32]. Moreover, the observed time lag scales roughly logarithmically with photon energy, as would be expected from a Comptonization process. However, a detailed QPO waveform analysis for 4 QPOs in GRS 1915+105 has shown that the mean waveform does not exhibit the profile smearing that would be caused at the delayed higher energies [28].

A "stable" QPO has been seen in both, GRS 1915+105 (67 Hz) and GRO J1655-40 (300 Hz) with varying strength. If associated with the Keplerian motion at the last stable orbit around a (non-rotating) black hole according to f (kHz)$= 2.2/M_{\rm BH}$ ($M_{\odot}$) gives $M_{\rm BH} \sim 7$ $M_{\odot}$ for GRO J1655-40, in surprising agreement with the optically determined mass! However, the strong increase of the fractional rms towards larger energies (up to 25 keV) is incompatible with an origin in the disk which has an effective temperature of 2 keV. Alternatively, three other models have been proposed, all resorting on relativistic effects (e.g. [32] for an overview): (i) diskoseismic oscillations [33, 34], (ii) frame dragging [35] and (iii) oscillations related to a centrifugal barrier [36]. At present, it is not clear which of these models, if any, provides a correct description.

4. ROTATING BLACK HOLES?

The X-ray spectra of microquasars consist of (at least) four different components [37]: (1) a thermal component with effective temperature of 2–3 keV which usually is attributed to the emission of the accretion disk, (2) a hard, power law component extending up to 600 keV [38] without any obvious cut-off which is generally interpreted as comptonization of the accretion disk spectrum by hot electrons in a corona above the disk, (3) iron features which have been interpreted as absorption lines of He- and H-like iron [39, 40], and (4) an additional component comprising of excess emission in the 10–20 keV range which has been interpreted as Compton reflection hump.

The effective temperature of the thermal component is very high when compared to the neutron star binaries (≈1.2 keV) or canonical black hole soft X-ray transients (≈0.7–1.1 keV). If interpreted according to the standard accretion disk prescription of Shakura & Sunyaev [41], where T (keV) = $1.2\ (\dot{M}/\mathrm{M})^{1/4}$, the observed temperatures of 2–3 keV would correspond to a mass of the central object of much less than 1 $M_\odot$. Such a low mass, however, seems unacceptable given the high luminosities and non-thermal spectra up to 600 keV. Thus, either a different cooling process is active in microquasars, or the implicit assumption of the last stable orbit at 3 Schwarzschild radii for the above $T(M)$ relation is not valid. In fact, for prograde rotating black holes the innermost stable orbit is closer to the hole, thus allowing higher temperatures of the disk. Application to GRO J1655-40 with its known parameters yields a nearly maximally rotating black hole (a=0.93) [42]. For GRS 1915+105, assuming a mass of 30 $M_\odot$ (based on the lower QPO frequency and luminosity arguments), a similar high rotation rate is deduced (a=0.998). Note that this black hole spin is not inconsistent with the Thirring-Lense interpretation of the QPOs.

5. DISK INSTABILITIES AND JET EJECTION

The variability of the X-ray intensity and spectrum can be rather complex. In GRS 1915+105 (Fig. 1) periodically repeating stalls, short outbursts, rapid oscillations with large amplitude have been observed occasionally while at other times the emission is practically constant [25]. In most cases, intensity variations are coupled to spectral variability. While not all of the variability is understood yet, some patters are most probably due to instabilities in the accretion disk. During the repeating stalls (Fig. 1) the spectrum softens dramatically (factor of ∼2 in effective temperature) which has been interpreted as the vanishing of the inner part of the accretion disk [25, 26] (note, however, that this interpretation has been called into question because temperature ≡ inner-disk-radius variations are imitated by a change of the hardening factor $T_{\rm col}/T_{\rm eff}$ when the accretion rate changes [43]). After a few minutes the disk hole is refilled, and the disk temperature and X-ray intensity goes back to its normal, high value. The whole cycle of emptying and

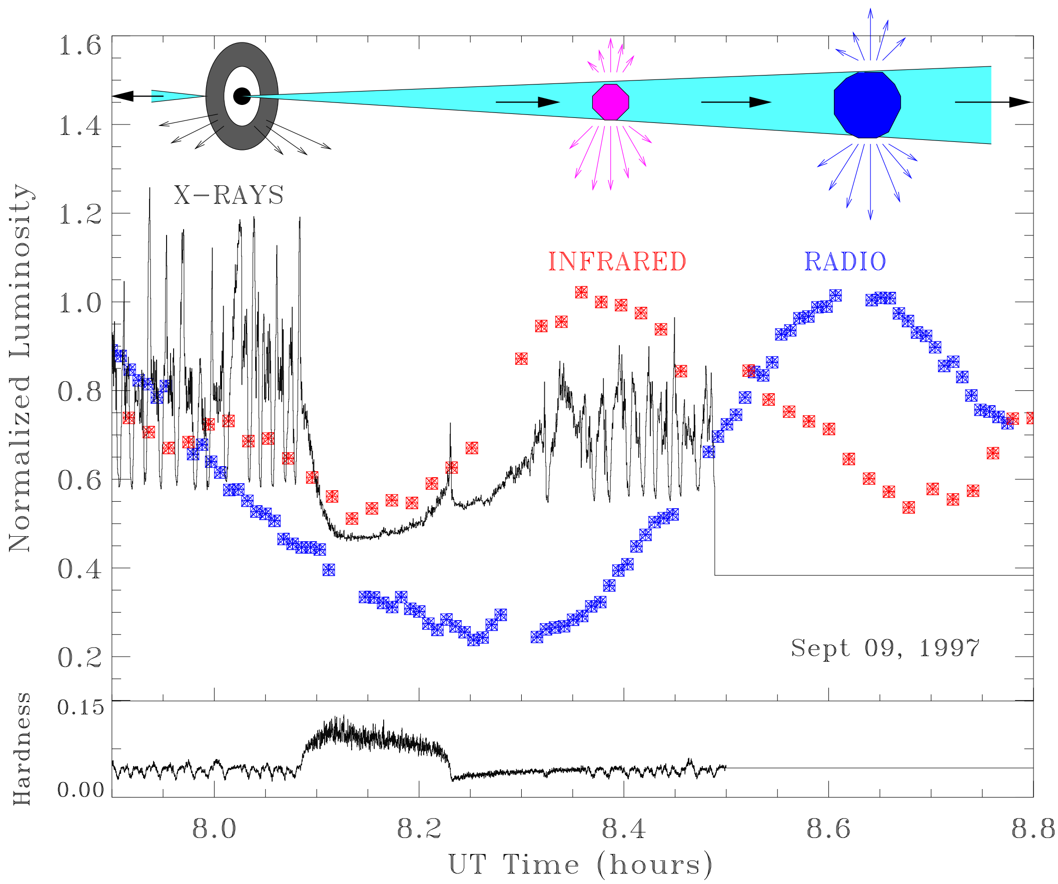

FIGURE 3. Contemporaneous X-ray (solid line) radio (dark squares), infrared (grey squares) light curves (top panel) and X-ray hardness ratio (bottom panel) for GRS 1915+105 on 9 Sep 1997 [45]. The sudden drop in X-ray intensity combined with the X-ray spectral change suggest an emptying of the inner accretion disk [25, 26]. The temporal displacement of the infrared and radio curves is consistent with being due to synchrotron emission from an adiabatically expanding plasmon. (from [45])

replenishment of the inner disk is governed by only one parameter, namely the radius of the disk ring which empties. The larger the radius, the deeper the stall, the cooler the measured temperature of the remaining disk and the longer the time to refill the hole [26], just as expected for a radiation-pressure dominated disk.

How, if at all, are these instabilities related to a transient radio emission and jet ejection? It has been known for several years that transient radio emission is associated to X-ray state transitions. Direct radio imaging, discrete peaks in the radio light curves as well as rapidly evolving radio spectra (to optically thin) suggest that the transient radio emission is related to discrete ejections. The most dramatic observation showing the relation of transient radio emission to the disk behaviour was made for GRS 1915+105 in September 1997 (Fig. 3) when radio and infrared oscillations have been found to follow large-amplitude X-ray variations [45] similar to those described above (Fig. 1). These radio/infrared oscillations have been interpreted as synchrotron emission from repeated small ejections suffering adiabatic expansion losses [44, 45]. The time delay between the infrared and radio maximum is consistent with what one expects from an adiabatically expanding plasma cloud. Together with the above described accretion disk instability cycle this strongly suggests that the inner part of the accretion disk disappears as X-ray radiating source, and possibly is accelerated and ejected away from the system. First-order estimates suggest that up to $\approx$10% of the mass involved in the disk instability may get ejected [26, 44, 45].

Many details of the disk-jet coupling are still unknown. The expected time delay between the infrared flare and the ejection (X-ray event) is only 10^{-3} sec, and thus it is unclear which X-ray feature would relate to the ejection. Alternatively, one could interprete this observed time delay as the duration of a continuous ejection event [45]. Then, the ejection time scale would be related to the viscous time scale of the disk rather than the dynamical one. Is indeed a fraction of the inner disk ejected while falling onto the black hole, or does the innermost disk gets geometrically thick during the instability? What is the role of magnetic fields?

6. DIFFERENCES AND SIMILARITIES BETWEEN MICROQUASARS AND QUASARS

There are two distinct differences between microquasars and quasars:

- Jets of quasars are oriented within a few degrees towards us while those of microquasars are mostly perpendicular. This is a pure observational bias: statistically one expects the same number of objects with angles between 0°–60° and between 60°–90°. For quasars, however, the jet emission is intrinsically too faint to be visible without the Doppler boosting at small angles (factor $>10^4$ flux enhancement). This is also the reason why quasar jets are one-sided only while in microquasars they are two-sided. It is interesting to speculate how a microquasar would look like if its beam is directed towards us!
- The masses of the accreting objects in microquasars are a factor of 10^{6-9} smaller than those of quasars. Most of the basic observable parameters scale with this mass. Thus, microquasars provide the fortunate circumstance that the timescale of accretion and jet ejection is much better adapted to the human lifetime than that of quasars.

The surprising finding that the two microquasars GRO J1655-40 and GRS 1915+105 may contain maximally rotating black holes actually fits nicely into our picture of quasars. Black hole rotation has long been considered as a way to explain the radio-loud vs. radio-quiet dichotomy in AGN [46]. While the impact of the black hole spin on jet ejection has still to be clarified, this relation provides one of the many examples that the similarities between microquasars and quasars go beyond their names.

7. OUTLOOK

For the near future one can expect further substantial progress because the good observability of the "right" timescales of the jet-disk coupling (seconds to minutes as compared to many years in quasars) combined with a series of new generation instrumentation at X-ray (Chandra, XMM, Astro-E) and Earth-bound (8–10 m class telescopes) optical wavelength opens new perspectives to attack some of the major unsolved questions:

- If it is possible to identify emission lines originating in the jets and to measure their Doppler motion, a new and independent method for distance determination would be available [5].
- Our present understanding allows a much better prediction of the disk-jet interaction which in turn will improve the ability to obtain much improved simultaneous coverage of the jet ejection events.
- X-ray observations with high spectral resolution will provide new insight into the dynamics of matter flow and emission processes in the strong gravitational field near black holes. One may expect that the spin and the mass of black holes could be determined thus providing the basis for the understanding of the energy source of jet ejection and acceleration to relativistic speeds.
- The new correlations found between QPO properties and spectral characteristics will eventually lead to a better theoretical understanding of the origin of QPOs which in turn promises to measure the spin and the mass of black holes and the intimate connection between accretion disk instabilities and jet ejection.

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REFERENCES

1. Lewin W.H.G., van Paradijs J., van den Heuvel E.P.J., 1995, *X-ray binaries*, Cambridge Astrophysics Series 26, Cambridge Univ. Press, Cambridge
2. Mirabel F., Rodriguez L.F., Cordier B., Paul J., Lebrun F., 1992, Nat 358, 215
3. Mirabel F., Rodriguez L.F., 1999, ARAA 37 (in press)
4. Fender R., 2000: *Astrophysics and Cosmology: A collection of critical thoughts*, Lecture Notes in Physics, Springer (in press)
5. Mirabel F., Rodriguez L.F., 1994, Nat 371, 46
6. Fender R., Garrington S.T., McKay D.J. et al. 1999, MN 304, 865
7. Tingay S.J., Jauncey D.L., Preston R.A. et al. 1995, Nat. 374, 141
8. Hjellming R.M., Rupen M.P., 1995, Nat 375, 464
9. Orosz J.A., Bailyn C.D., 1997, ApJ 477, 876

10. Hjellming R.M., 1998, (Paris workshop)
11. Hjellming R.M., Rupen M.P., Mioduszewski A.J., 1999, (see URL page http://-www.aoc.nrao.edu/~ rhjellmi/gmsgr.html)
12. Margon B.A., 1984, ARAA 22, 507
13. Spencer R.E., 1984, MN 209, 869
14. Molnar L.A., Reid M.J., Grindlay J.E., 1988, ApJ 331, 494
15. Stewart R.T., Caswell J.L., Haynes R.F., Nelson G.J., 1993, MN 261, 593
16. Mioduszewski A.J., 1998 (Paris workshop)
17. Garcia M., 1998, (Paris workshop)
18. Fender R.P., Spencer R., Tzioumis T. et al. 1998, ApJ 506, L121
19. Sakano M., Imanishi K., Tsujimoto M., Koyama K., Maeda Y., 1999, ApJ 520, 316
20. Rodriguez L.F., Mirabel I.F., Marti J., 1992 ApJ 401, L15
21. Marti J., Mereghetti S., Chaty S. et al. 1988, AA 338, L95
22. Green D.W.E. (ed.), 1999, IAU Circ. 7277
23. Castro-Tirado A.J., Brandt S., Lund N., 1992, IAU Circ. 5590
24. Greiner J., Harmon, B.A., Paciesas W.S., Morgan E.H., Remillard R.A., 1997, ASP Conf. Ser. 121, p. 709
25. Greiner J., Morgan E.H., Remillard R.A., 1996, ApJ 473, L107
26. Belloni T., Mendez M., King A.R., van der Klis M., van Paradijs J., 1997, ApJ 488, L109
27. Zhang N.S., Wilson C.A., Harmon B.A., et al. 1994, IAU Circ. 6046
28. Morgan E.H., Remillard R.A., Greiner J., 1997, ApJ 482, 993
29. Chen X., Swank J.H., Taam R.E., 1997, ApJ 477, L41
30. Remillard R.A., Morgan E.H., McClintock J.E., Bailyn C.D., Orosz J.A., 1999, ApJ 522, 397
31. Muno M.P., Morgan E.H., Remillard R.A., 1999, ApJ (in press; astro-ph/9904087)
32. Cui W., 1999, in *High-energy processes in accreting black holes*, eds. J. Poutanen & R. Svensson, ASP Conf. Ser. 161, p. 97
33. Perez C.A., Silbergleit A.S., Wagoner R.V., Lehr D.E., 1997, ApJ 476, 589
34. Nowak M.A., Wagoner R.V., Begelman M.C., Lehr D.E., 1997, ApJ 477, L91
35. Cui W., Zhang S.N, Chen W., 1998, ApJ 492, L53
36. Titarchuk L., Lapidus I., Muslimov A., 1998, ApJ 499, 315
37. Greiner J., Morgan E.H., Remillard R.A., 1998, eds. R.N. Ogley, J. Bell Burnell, New Astron. Rev. 42, p. 597
38. Tomsick J.A., Kaaret P., Kroeger R.A., Remillard R.A., 1999, ApJ 512, 892
39. Ebisawa K., 1997, in *X-ray imaging and spectroscopy of cosmic hot plasmas*, Univ. Acad. Press, Tokyo, p. 427
40. Ueda Y., Inoe H., Tanaka Y., et al. 1998, ApJ 492, 782
41. Shakura N.I., Sunyaev R.A., 1973, AA 24, 337
42. Zhang N.S., Cui W., Chen W., 1997, ApJ 482, L155
43. Merloni A., Fabian A.C., Ross R.R., 1999, (in press; astro-ph/9911457)
44. Fender R.P., Pooley G.G., 1998, MN 300, 573
45. Mirabel I.F., Dhawan V., Chaty S., et al. 1998, AA 330, L9
46. Wilson C.A., Colbert E.J.M., 1995, ApJ 438, 62