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# Microquasars

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**Abstract.** Microquasars are here taken to be accreting stars with relativistic jets. The accretion disks emit thermal X-rays of a few keV, often with a power-law tail to higher energies, attributed to Compton upscattering by relativistic electrons. These electrons in turn may produce synchrotron emission - radio, IR, even X-rays. About a dozen jet sources are now established in the Galaxy, with some 30 more neutron stars and black holes detected in sporadic radio monitoring, out of $\sim$300 X-ray binaries. Many are found by high-energy satellites, and are essentially transients, though timescales range from days to years.
Selected recent VLBA observations are reviewed. The VLBA provides rapid response to transients, by dynamic scheduling; multifrequency coverage; and easy phase-referencing, with $\sim$1 mJy detectability and $\sim$1 mas astrometry. For a few objects, very rich data sets have resulted from the confluence of radio imaging, X-ray light curves from *RXTE,* and spectroscopy from *Chandra.* The time variations of disk, corona, and radio jets show the interplay of accretion and ejection in these systems. Such 'laboratory quality' data is more readily had for galactic objects, compared to distant, slowly varying AGN. The problems of imaging time-variable, moving sources await the sensitivity and snapshot coverage of the EVLA, and the New Mexico Array respectively. SKA users can look forward to the whole iceberg.

## 1. Introduction

The first microquasar, SS 433, stood alone for over a decade, though several objects were known with variable X-ray and radio emission. In the early and mid 90's, X-ray satellites supported by radio light curves and imaging, identified a distinct subset of x-ray binaries with relativistic ejecta (Mirabel & Rodriguez 1999). Accreting compact stars are now proven owners of strong magnetic fields, rapid rotation, strong gravity, high radiation pressure and gas pressure, and relativistic flow. Insights from this area are (bravely?) being applied to the ultra-luminous X-ray objects in external galaxies (Georganopoulos et al. 2002); to jets in AGN and quasars (Marscher et al 2002); and gamma ray bursts (Paczynski 1998). I focus on a few observational, partly contrasting cases. Theory and much detail is available in the references and in proceedings of the Hjellming Memorial Conference, (eds. Castro-Tirado et al. 2001). Exciting prospects abound: Corbel et al. (2002) recently reported superluminal synchrotron X-ray jets in XTE J1550-560, decelerated by interaction with the ISM. Very fast jets exist, e.g., in V4641 Sgr (Hjellming et al. 2000). And radio emission may be detectable with the SKA, from thousands of the $\sim 10^9$ isolated NS and BH adrift in the galaxy, accreting from molecular clouds (Agol & Kamionkowski, 2002; Fender & Kuulkers, 2001)

## 2. Anatomy of X-ray binary/ microquasar

To set the stage, the colour graphic (from Rob Hynes, see `http://www-xray.ast.cam.ac.uk/~sav/blackholes/stellar.html`) ties the broadband spectra to the physical components of an X-ray binary. Thermal X-rays of ~1keV come from the inner accretion disk; some of these photons are Compton upscattered to give a power-law tail out to ~100 keV. The location and geometry of the hot electron corona are debated, but could be the base of the radio synchrotron jet. A variety of X-ray modulations were discoverd by RXTE, including kHz fluctuations from Keplerian orbits in the inner accretion disk (van der Klis, 2000) and ~1Hz oscillations from the disk/corona. Several mechanisms are proposed for the latter, but they are clearly related to the radio jet (Muno et al. 2001).

In LMXB the low mass companion fills its Roche lobe, transferring matter into an accretion disk around the compact star, e.g. Cyg X-1 & GRS 1915+105, [section 4.1]. In the HMXB, the accretion is via capture of the wind from the massive donor, e.g. Cyg X-3 & SS 433, [section 4.2]. Garcia et al. (2001) report underluminous x-rays from BH accretors, compared to NS at the same $\dot{M}$, ascribed to an event horizon which swallows the influx, versus a solid re-radiating surface, respectively.

A further variable is the magnetic field - above $10^7$G or so, it disrupts the inner accretion disk by causing the accreting plasma to flow along the field lines to the poles, instead of in the equatorial plane (Li & Wilson 1999). High-field NS, or pulsars, are not expected (nor observed) to produce radio jets, while weak-B NS do, e.g. Sco X-1, (Fomalont et al 2001). A magnetic switch (Meier et al. 1997) may modulate the jet speed.

## 3. X-ray States and State Transitions

States are defined by the broadband X-ray spectra, characterized at the simplest level by increasing $\dot{M}$, illustrated by GX339-4 (Fig 15 in Corbel, et al. 2000). Contrary cases exist (McCollough et al. 1999)

At very low mdot, models for under-luminous black holes (Yuan et al. 2002) employ the ADAF and related schemes, augmented by a synchrotron jet to fit the radio emission. At modest mdot the 'low/hard' state is attributed to a truncated disk (innermost part missing) with a strong hot-electron corona (Esin et al. 2001; Fender 2001). This state (low x-ray counts, with prominent hard power-law) most often exhibits steady radio emission, presumably tied to the the relativistic electrons. At very high mdot, the disk radiates strongly in the soft X-rays (Gierlinski & Done 2002), near the Eddington limit of $10^{38}$ erg/s for a NS; and extends in to the innermost stable orbit (3 $R_g$ for maximally rotating hole, 6$R_g$ for non-rotating). Radio emission is not usually detected in this high/soft state, though Ballantyne et al. (2002) argue for high $\dot{M}$ in radio loud AGN. Intermediate, unstable, or oscillatory states may exist at transitions between these regimes, where gas pressure, radiation pressure, and magnetic field vie for dominance (e.g. Nayakshin et al. 2000)

## 4. Examples

### 4.1. GRS 1915+105

GRS 1915+105 is a $14M_{\odot}$ black hole (Greiner 2002), with a low-mass primary, and unstable accretion disk. Approximately once per year, [FIG.1 A] the source emerges from an extended low/hard state with x-ray and radio flares, when superluminal 'cannonballs' are ejected and decay over 3 days. Though the ejecta are hard to image with the current VLBA due to the lack of short baselines, the superluminal motion is measurable in just hours, [FIG.1 B]. The bulk and pattern speeds coincide in this case. In Sco X-1 however, (Fomalont et al. 2001) the hot-spot and flow speeds differ, familiar ghosts from the extragalactic case.

Following the flares, the disk is often wildly unstable, with oscillating X-ray and radio emission [Fig.1 C, D]. VLBA imaging shows a compact jet of length ~20–50 AU, and brightness temperature $T_B \sim 10^9$ K on scales of 0.2 - 0.6 mas. The jet varies in ~10-60 min, as the relativistic plasma is ejected from the inner disk and flows through it, radiating with a flat spectrum from radio to IR (Mirabel et al. 1998, Fender 1998, Falcke 1999).

Some other black hole systems (e.g. Cyg X-1, 1E 1740-2942, GRS 1758-258, GX 339-4, XTE J1118+48, SgrA*) have compact radio cores in the low/hard state, without flares and transient ejecta. GRS 1915+105 is the only source known to exhibit both states. The most recent RXTE/VLBA observations capture the state transition and jet birth with unprecedented clarity, (Dhawan et al. 2003, in preparation)

### 4.2. SS 433

SS 433 has an unknown primary, with a high mass, possibly WR companion, and massive wind outflow. It has famously persistent, precessing, bi-directional radio jets moving at 0.26c, but is only a modest X-ray source. Hjellming & Johnston (1988) from VLA images, fit the decay of jet flux vs. distance with slowed expansion followed by free expansion $\sim 10^4$ AU downstream. Vermeulen (1993) followed the moving ejecta with an image sequence from a VLB campaign unprecedented till then.

Recent Merlin, VLA, VLBA images illustrate the spectacular range of scales present in the jets with their ~163 day precession period. The VLA image of W50 on degree scales (Dubner, et al. 1998) shows the circular supernova remnant that presumably produced the collapsed object, with 'ears' blown out by the impact of the jet plasma. The VLA+Merlin image (Fig. 2A, from Blundell, et al. 2001) shows the jets on arcsec scales, while the VLBA image [Fig. 2B, one frame of a movie] reveals, in addition to the jets, an equatorial ruff of emission from a wind with outflow velocity 300km/s and estimated mass loss $10^{-5}$ $M_{\odot}$/yr. The equatorial outflow is poorly imaged due to the lack of short VLBA baselines, but is also seen in independent VLBA images (Paragi,

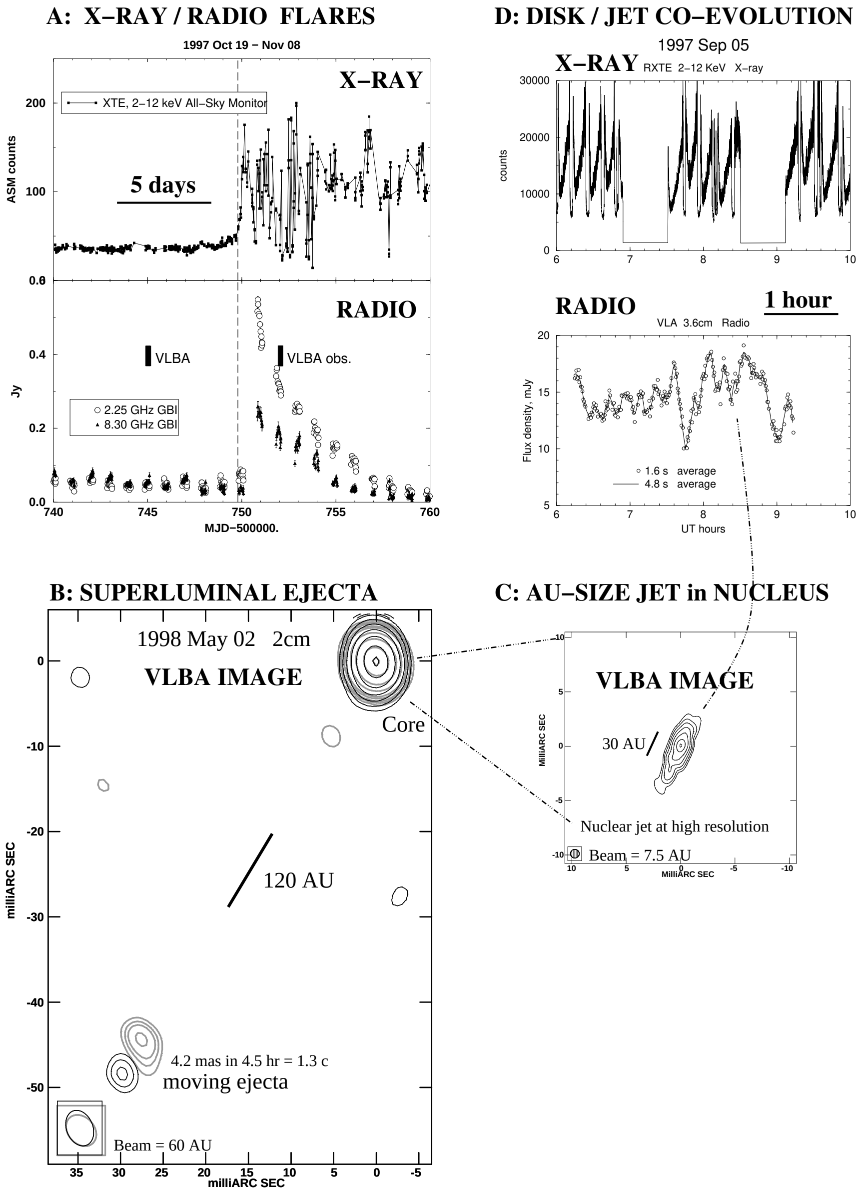


Figure 1. The disk/jet connection illustrated by GRS 1915+105.
**A**: X-ray state transition from low/hard to unstable disk, accompanied by a radio flare, imaged in a similar but later event, B.
**B**: Phase-referenced image showing the steep-spectrum 'cannonball' ejecta ∼67 hrs after the flare, and stationary flat spectrum core.
**C**: High resolution image of the nucleus, showing the AU-sized jet that varies on timescales of ∼10 min, in response to the injection and flow-through of bulk relativistic plasma.
**D**: The plasma originates with the ejection of matter from the inner disk, seen as soft x-ray dips.

et al. 1999). The wind was predicted by the evolutionary scenario of King et al. (2000), with the weak x-rays explained by the mass diversion to outflow instead of accretion.

X-ray data tightly constrain the conditions in the jets. *Chandra* detection of Doppler-shifted lines from many ionized atomic species, (Marshall et al. 2002), indicates that the jets are accelerated to terminal velocity of 0.26 c, within 0.01 AU from the star, where the temperature is $10^{7-8}$K. The electron density and density gradient in the expanding jet are measured, and the mechanical luminosity of the jet is $\sim 10^{38}$erg/s, some $10^3$ times the X-ray emission. Next, the limit on the time delay between the red and blue-shifted optical lines, restricts the size of the optical emission region with T$\sim 10^4$K to $<$100 AU - the plasma has cooled at constant bulk velocity. Further, spatially resolved Fe spectra (Migliari et al, 2002) indicate reheating of plasma to T$\sim 10^7$K, $10^4$ AU downstream, presumably by conversion of the abundant jet mechanical energy. Finally, note that there is measured circular polarization in this jet of baryonic, *not leptonic* plasma (Fender et al. 2000; Ruszkowski & Begelman 2002)

## 5. VLBA Astrometry

Though the Hipparcos tie to VLBA/ICRF included some persistent stellar sources (Lestrade et al. 1999), X-ray transients have not been well served by astrometry, but for a few cases. Sco X-1 is one famous source with a VLBA parallax distance of 2.8$\pm$0.3 kpc (Bradshaw et al. 1999). HST astrometry was used to infer the Galactocentric orbit of the XRT GRO J1655-40 (Mirabel et al. 2002). A more systematic attack is in progress, as was done for pulsars by Brisken et al. (2002). Two preliminary examples are below.

### 5.1. GRS 1915+105

The black hole is located to $\sim$1 mas. After accounting for the secular parallax due to Galactic rotation, a velocity of 20–40 km s$^{-1}$ is found for its motion with respect to its neighbourhood, implying that this 14M black hole has received a modest kick at birth (Dhawan et al 2003 in prep). A more precise but finite velocity might rule out evolutionary schemes in which the massive star collapses directly to the black hole with no supernova and hence no birth kick. (Belczinski & Bulick, 2002)

### 5.2. XTE J1118+480

This unusual x-ray nova at high Galactic latitude was observable in all wave bands. Though the radio emission lasted only 3 months, significant proper motion was measurable with the VLBA. With the optical radial velocity, the 3-dimensional orbit was found to be similar to that of halo objects (Mirabel et al. 2001). A disk origin for this binary (7$M_\odot$ primary) is not excluded, but it would require an extreme kick in the originating supernova, and is inconsistent with the age of the system. It thus may be a wanderer ejected from a globular cluster, one of many dark halo objects that happened to brighten in a mass transfer episode.

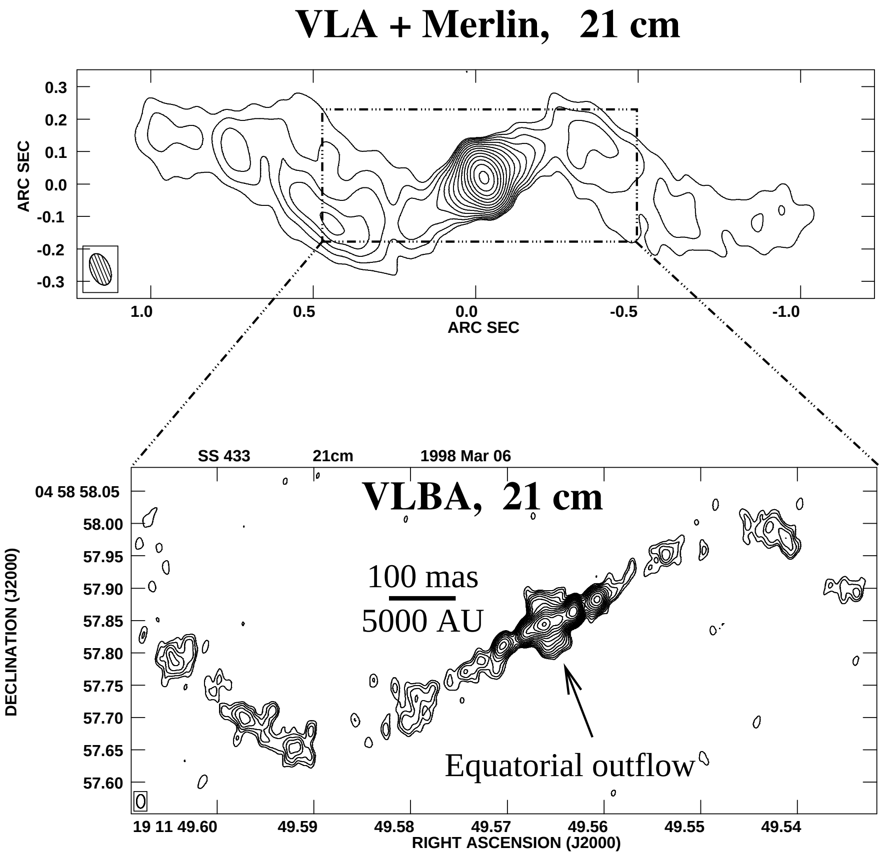


Figure 2. **A:** Precessing Jets; **B:** Equatorial Outflow in SS 433: both features have low surface brightness, and would benefit from a larger UV range than can be mustered at present. (Contours are 1, 1.4, 2%... with total flux ∼500mJy. Courtesy A.J. Mioduszewski, from Blundell et al. 2001)

## 6. Conclusion

Microquasars complement distant AGN:

- They offer a speedup, proportional to mass, of $>10^6$, comparable to the advantage to biology of *e.coli* vs. humans. However, the timescales demand new ways of scheduling and coordinating multiple observatories; and the spatial scales demand wider UV range, and better snapshot coverage for radio imaging.
- Galactic objects are close, and brighter by upto $10^3$ in X-rays, allowing detailed spectroscopy of the disk and jet contents. Radio imaging has milliarcsec resolution, but needs sensitivity to thermal material. The advantage in linear resolution in units of $R_g$ per beam lies with big AGN, the best case being Sgr A$^*$.
- For Sgr A* and many extragalactic black holes, the $\dot{M}$ is low. Accreting binaries yield more examples at high $\dot{M}$. Conditions in the accretion region are more directly measurable, unlike in most extragalactic cases - see next item.
- Unification faces more diversity: NS, accreting millisecond pulsars, magnetars, white dwarfs, in addition to BH. On the other hand, this variety may be key to controlled experiments, by comparing the effects of event horizons and and magnetic fields. Also, the physical quantities are more likely to be understood in galactic objects. e.g. M, (Bailyn, et al. 1998; Galloway et al. 2002), $\dot{M}$, evolutionary history, metallicity, age, binary orbit, inclination, distance (by VLBA parallax). One can hope to measure B directly as in pulsars and CV, from cyclotron lines, (Coburn et al. 2002) or from the period derivative $\dot{P}$ (Cheng 1989). The spin period P of the central mass is measured from radio or x-ray pulses, while Fe line profiles are diagnostic of rotation and GR effects in the inner disk (Martocchia et al. 2000).

## References

Agol & Kamionkowski 2002, MNRAS, 334, 553

Bailyn et al. 1998, ApJ, 499, 367

Ballantyne, Ross, & Fabian 2002, MNRAS, 332, L45

Belczynski & Bulick, 2002, ApJ, 574, L147

Blundell et al. 2001, ApJ, 562, L79

Bradshaw et al. 1999, ApJ, 512, L121

Brisken et al. 2002, ApJ, 571, 906

Castro-Tirado, Greiner, & Paredes 2001 (eds) Granada Microquasar Workshop, 11-13 September 2000.

Cheng 1989, ApJ, 337, 803

Coburn et al. 2002, ApJ, 580, 394

Corbel et al. 2000, A&A, 359, 251
Corbel et al. 2002, Science, 298, 196
Dhawan, et al. 2000 ApJ, 543, 373
Dubner et al. 1998, AJ, 116, 1842
Esin et al. 2001, ApJ, 555, 483
Falcke & Biermann, 1999, A&A, 342, 49
Fender 2001 MNRAS, 322, 31
Fender et al. 2000, ApJ, 530, L29
Fender & Kuulkers, 2001, MNRAS, 324, 923
Fender & Pooley, 1998, MNRAS, 300, 573
Fomalont et al. 2001, ApJ, 558, 283
Galloway et al. 2002, ApJ, 576, L137
Garcia et al. 2001, ApJ, 553, L47
Gierlinski & Done, 2002, MNRAS, 331, L47
Greiner, et al. 2001, Nature, 414, 522
Hjellming et al. 2000, ApJ, 544, 977
King, Taam, & Begelman 2000, ApJ, 530, L25
Lestrade et al. 1999, A&A, 344, 1014
Li, J. & Wilson, G. 1999, ApJ, 527, 910
Markoff, Falcke, & Fender 2001, A&A, 372, L25
Markwardt, Swank, & Taam 1999, ApJ, 513, L37
Marscher et al 2002, Nature, 417, 625
Marshall et al. 2002, ApJ, 564, 941
Martocchia et al. MNRAS2000, 312, 817
McCollough et al. 1999, ApJ, 517, 951
Meier et al. 1997, Nature, 388, 350
Migliari et al. 2002 Science, 297, 1673
Mirabel et al. 1998 A&A, 330, L9
Mirabel et al. 2001 Nature, 413, 139
Mirabel et al. 2002 A&A, 395, 595
Mirabel & Rodríguez 1999 ARA&A, 37, 409
Muno et al. 2001, ApJ, 556 515.
Muno, Morgan, & Remillard 1999, ApJ, 527, 321
Nayakshin, Rappaport, & Melia 2000, ApJ, 535, 798
Paczynski 1998 ApJ, 494, L45
Paragi et al. 1999 A&A, 348, 910
Ruszkowski & Begelman 2002, ApJ, 573, 485
van der Klis 2000, ARA&A, 38, 717
Vermeulen et al. 1993 A&A, 270, 177
Yuan, Markoff, & Falcke 2002, A&A, 383, 854