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Twenty-five years of multifrequency observations of microquasars presented at the Frascati Workshops on Vulcano

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Abstract. The discovery of the first microquasar in 1979 heralded the birth of a new branch of astrophysics where multifrequency observations proved to be crucial, as they radiate throughout the entire electromagnetic spectrum, Here we review the presence of microquasars throughout the 25-year history of the Frascati Workshop by reviewing the various highlights in microquasar research as they were presented in Vulcano.

Key words. X-rays: binaries – X-rays: general – Radio continuum: stars –

1. Introduction

The first X-ray binary was discovered during a rocket flight in 1962 (Giacconi et al. 1962) and designated Scorpius X-1, indicating that it was the first X-ray source in the constellation Scorpius. Initially it was not understood what the source of X-rays from Sco X-1 and other sources like it was (many subsequent X-ray sources were discovered with the advent of satellites dedicated to X-ray astronomy in the 1970s). In the 1960s, Salpeter (1964) and Zel'Dovich (1964) independently put forward the idea that matter falling toward a black hole could heat up to emit X-rays, and in 1971 combined X-ray, optical and radio observations of Cygnus X-1 confirmed this scenario (Braes & Miley 1971; Webster & Murdin 1972). Hence it was deemed that the source of X-rays in Sco X-1 and other sources like it was the accretion of matter from a non-degenerate companion onto a stellar-mass compact object, i.e. a neutron star or a black hole.

Optical observations began to reveal the non-degenerate companions in X-ray binaries, and it was found they were divided into two groups based on the nature of the companion: high-mass X-ray binaries (HMXB), where the companion star is usually of spectral type O or B, and low-mass X-ray binaries (LMXB), where the companion is generally a main sequence or an evolved star. (There are some X-ray binaries where the companion is of intermediate mass, but they are less common.) The nature of the accretion is determined by the type of the companion: in the case of HMXBs, the compact object accretes from the stellar wind of the massive star whereas in the case of LMXBs the companion fills its Roche lobe and matter spills through the inner Lagrangian point before spiraling into a disk around the compact object.

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During the 1970s, during observations of Cygnus X-1, it was noticed that the source exhibited two distinct spectral “states”: Tananbaum et al. (1972) observed a transition from a high-intensity state to a low one in the 2–6 keV range where the average intensity decreased by a factor of 4 in less than a month, and at the same time the source intensity in the 10–20 keV range increased by a factor of 2. These two states were designated the “high” and the “low” states respectively to reflect the level of the emission. When instruments sensitive to higher energy observations were developed and launched, it was noted that during the “low” state, there was significant emission at the higher energies that before had remained undetected, and during the “high” state, there was a dearth of emission at the higher energies[1]. Hence, the “low” state came to be called the “low/hard” state to reflect the fact that there was significant emission in the harder (i.e. higher energy) energy ranges, and the “high” state came to be called the “high/soft” state to reflect the fact that, contrary to the low/hard state, the emission was dominant in the softer part of the spectrum. It was subsequently realized that, in fact, besides these two states, there are several “intermediate” states that show varying contributions in the hard and soft energy ranges. While it is generally understood that the soft X-ray emission is due to the blackbody emission from the accretion disk, there is some discussion regarding the origin of the hard X-ray emission, although one theory has it that it arises from inverse Comptonization in a hot plasma cloud of the soft disk photons.

The first time the term “microquasar”[2] appeared in relation to X-ray binaries was in 1992 when Mirabel et al. (1992) applied it to 1E1740.7−2942, known to be a hard X-ray source that exhibited different states akin to those of other accreting X-ray binaries (Sunyaev et al. 1991). They had observed 1E1740.7−2942 with the Very Large Array (VLA), and found it to be a source of relativistic radio jets. The morphological similarity to their extragalactic counterparts the quasars – central accreting black hole, relativistic radio jets – prompted Mirabel et al. (1992) to adopt the term “microquasar”..

However, this was not the first Galactic source with radio jets discovered. High resolution radio imaging revealed that SS433, a neutron star X-ray binary, possessed a jet $\sim 1''$ in length (Spencer 1979). Nor was it the last. It is not possible to cover all aspects of microquasar research during the past 25 years, and hence, in this paper, we shall follow the advances made in step with material presented at the Frascati Workshops held on Vulcano.

2. The 1980s

As mentioned above, the first “microquasar” was technically discovered in 1979 (Spencer 1979), although it was not known as such. At the first Frascati Workshop in 1984, EXOSAT X-ray observations of SS433 were presented (Brinkmann & Doll 1985). The $\sim 2 - 17$ keV spectrum was fit with three models – a powerlaw, a thermal model, and the Sunyaev-Titarchuk comptonization model – but none of the fits was acceptable. A very strong emission line, centered at 7.4 keV, and an excess between 5.5–6.8 keV were both clearly detected in the data (see Fig. 1). These were later interpreted (Watson et al. 1986) as being the Doppler-shifted Fe 6.7 keV line expected from the kinematical jet model that had been earlier predicted for SS433 (Abell & Margon 1979). By the end of the 1980s, it was known that an X-ray binary composed of a compact object accreting matter from a donor star was capable of producing radio jets. However, the sample was very limited, consisting of one known source. It was in the 1990s that the field of microquasars really erupted.

3. The 1990s

It has already been mentioned that the first time the term “microquasar” was applied to X-ray

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[1] The distinction between soft and hard X-rays is not well defined but generally speaking the dividing line is ~10 keV, with hard X-rays >10 keV and soft X-rays <10 keV.

[2] In fact, the term “microquasar” was first used by Netzer (1990) for faint Seyferts and LINERs.

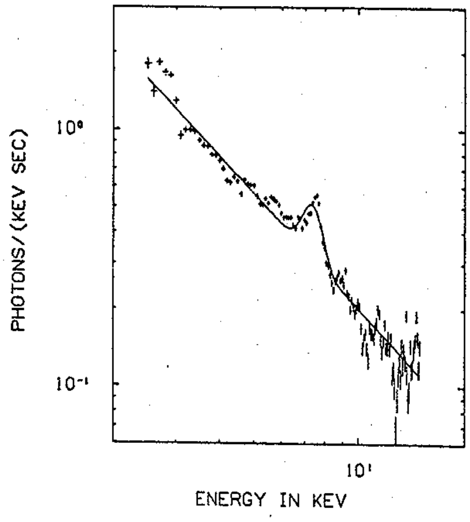

Fig. 1. The SS 433 X-ray spectrum with a powerlaw fit to the data, showing the strong emission line. Reproduced from Brinkmann & Doll (1985).

binaries was when Mirabel et al. (1992) discovered, based on VLA observations in 1992, that 1E1740.7−2942 possessed relativistic radio jets. It was speculated that the origin of the radio emission was synchrotron radiation of electrons and positrons. Then in 1994 another spectacular series of observations with the VLA of the rather recently discovered X-ray binary GRS 1915+105 (Castro-Tirado et al. 1992) showed the emanation of what were then called "plasmons", or blobs, at apparent superluminal velocities of $\sim 1.2c$, which resulted in a true velocity of $v \sim 0.92c$ after taking into account relativistic effects (Mirabel & Rodríguez 1994). This was the first time apparent superluminal motion had been observed in our Galaxy. Within a few months, the second source of apparent superluminal jets was discovered when the VLA, the Very Long Baseline Array (VLBA), and the Southern Hemisphere VLBI Experiment array observations showed repeated episodes of relativistic ejections from GRO J1655−40 (Hjellming & Rupen 1995; Tingay et al. 1995).

A the Frascati Workshop in 1995, *Rosat* observations taken shortly after the discovery outburst of GRO J1655−40 were presented as well as an overview of the multiwavelength coverage surrounding the *Rosat* observations (Greiner 1996). The *Rosat* observations improved the X-ray position of the source, and showed it to coincide with the optical and radio counterparts. Furthermore, these observations generated the discussion of whether the X-rays originated in the accretion disk or in a corona.

By the time of the Frascati Workshop in 1997, Ziółkowski (1999) listed seven Galactic sources that exhibited jets. In addition to the four sources already discussed above, the list included GRS 1758−258, Cygnus X-3 and Circinus X-1, this last being an established neutron star X-ray binary. The X-ray properties of these sources were thoroughly outlined in the paper, and are reproduced here in Table 1.

Potential microquasar candidates were also discussed in Ziółkowski (1999), and it was noted that Cygnus X-1 possessed all the characteristics of microquasars (including variable, nonthermal radio emission) but that the search for jets themselves had not yet been conclusive. The jets of Cygnus X-1 were finally detected during VLBA observations in 1997–1998 (Stirling et al. 2001).

It was also during the 1990s that more physical models in interpreting the X-ray spectra from X-ray binaries were becoming more commonplace and implemented. At the 1995 Frascati Workshop, Balucińska-Church et al. (1996) presented broadband data of Cygnus X-1 from *Rosat*/PSPC, that covered the 0.1–2.0 keV energy range, *TTM* (2–30 keV) and *HEXE* (20–200 keV), the latter two which, when taken together, covered the 2–200 keV energy range. The PSPC data were fit with a model consisting of a blackbody fit to the soft excess and a powerlaw, while the broadband data were fit with a blackbody, a powerlaw and a reflection component. Fig. 2 shows the *Rosat*/PSPC and *TTM*/*HEXE* spectra.

3.1. The age of monitoring

One key factor that propelled microquasar research forward was the era of monitoring programs, both in the X-rays and in the radio, and

Table 1. X-ray spectral properties of the known microquasars at the Frascati Workshop in 1997 (Ziółkowski 1999)

Source	Soft/disk	Hard/powerlaw	Variability	Jet speed	Comments
GRS 1915+105	Yes	Yes	Highly variable	0.92c	
GRO J1655−40	Yes	Yes	Transient	0.92c	
1E1740.7−2942	No	Yes	Variable	Steady jets	
GRS 1758−258	No	Yes	Steady	Steady jets	
SS 433	Almost all of the X-ray emission from the jets			0.26c	
Cyg X-3	Yes	Yes	Highly variable	0.3–0.99c	Highly complex
Cir X-1	Ultrasoft		Steady jet?	State transitions	

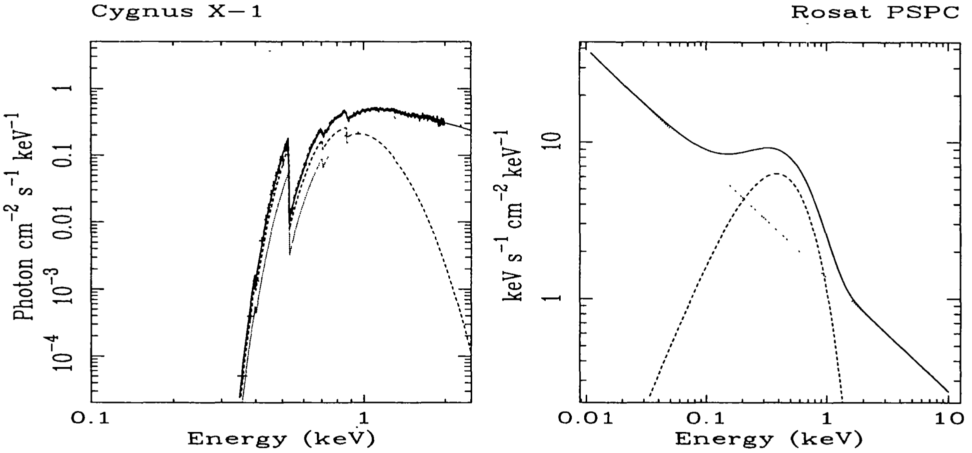

Fig. 2. *Left.* The broadband spectrum of Cygnus X-1, with the *Rosat*/PSPC spectrum showing the blackbody component used to model the soft excess. *Right.* The *TTM/HEXE* spectrum showing the total spectrum fit with a model consisting of a soft excess, a powerlaw and a reflection component. Reproduced from Balucińska-Church et al. (1996).

the mission that defines the age of monitoring is the *Rossi X-ray Timing Explorer* (*RXTE*). *RXTE* was launched at the end of 1995, and began monitoring operations in 1996 February. Besides the All-Sky Monitor (ASM), *RXTE* also carries the Proportional Counter Array (PCA) and the High-Energy X-Ray Transient Experiment (HEXTE) that allow for pointed observations of select targets. The ASM scans the whole sky several times a day, thus providing continual coverage for already known sources and allowing for the serendipitous discovery of new sources.

At the Frascati Workshop in 1997 Remillard (1999) introduced the *RXTE*/ASM and showed some highlights from the first two years of operation. Figure 3 shows a selection of new sources and known recurrent transients, showing the different morphologies in the lightcurves of the outbursts. Included amongst these sources is GRO J1655−40, the second Galactic source to exhibit apparent superluminal motion. At the time of the workshop, some 117 sources had been detected with the ASM, of which 12 were recurrent transients and ten were newly discovered sources

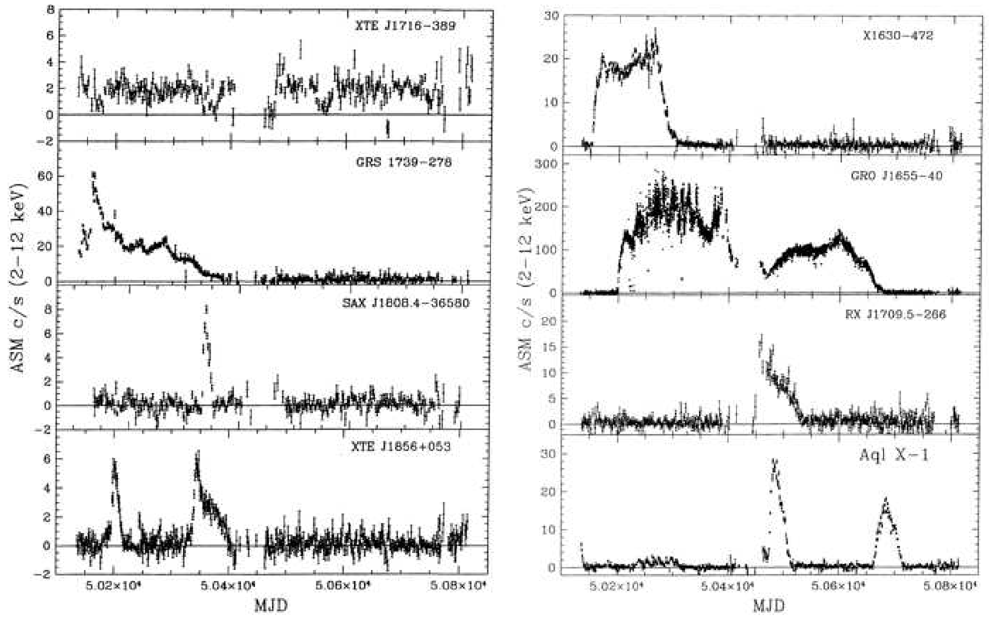

Fig. 3. *RXTE*/ASM lightcurves of four new sources (left) and four recurrent transients (right) for the period 1996–1997. Reproduced from (Remillard 1999).

(Remillard 1999). (At the time of writing, the MIT *RXTE*/ASM webpage[3] contains the lightcurves to some 1367 sources, including both Galactic and extragalactic.)

3.1.1. GRS 1915+105

As mentioned above, GRS 1915+105 was the first Galactic source to exhibit apparent superluminal motion. Since its discovery in 1992, GRS 1915+105 stayed "switched on" as first shown by *CGRO*, and then *RXTE*/ASM (to date the source shows continuous activity in the soft X-rays). Figure 4 shows the ASM lightcurve from the debut of the *RXTE* mission up until May 1997 (when the Frascati Workshop took place).

However, even more remarkable observations were presented by Greiner et al.

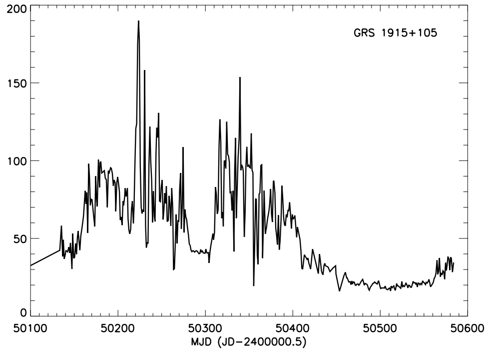

Fig. 4. The *RXTE*/ASM lightcurve of GRS 1915+105 from the start of the mission up to May 1997, the time of the Frascati Workshop.

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[3] http://xte.mit.edu/ASM_lc.html

(2002) who presented *RXTE*/PCA data of GRS 1915+105. These observations showed drastic intensity variations that were accompanied by spectral changes on the same timescales. At that stage, three types of burst had been identified in the ~ 130 PCA pointings that had been acquired to date, with one of the most intense bursts recording a bolometric X-ray luminosity of 5 × 10^{39} erg/s.

Figure 5 shows an example of PCA lightcurves of GRS 1915+105 in a "sputtering" phase and in a "lull" phase from observations undertaken on 1996 Apr 6 (the first-ever pointed PCA observation of GRS 1915+105). These were just the first manifestations of the bewildering range of activity that GRS 1915+105 would eventually reveal. The culmination of *RXTE*/PCA studies of GRS 1915+105 resulted in characterizing the variability into twelve distinct classes based on model-independent analysis (Belloni et al. 2000). However, GRS 1915+105 did not stop there: two more variability classes were identified using solely PCA data (Klein-Wolt et al. 2002) and also *INTEGRAL's* JEM-X data (Hannikainen et al. 2005). All these variability patterns reflect different accretion modes.

The high time resolution of the PCA allowed for close scrutiny of the behavior of GRS 1915+105 in terms of spectral changes. Greiner et al. (2002) (and references therein) speculate that the drastic intensity variations were attributable to inherent accretion instabilities, rather than to absorption effects. These dips in the PCA lightcurve were interpreted as due to accretion disk instabilities leading to the collapse of the inner accretion disk and related this behavior to radio flaring (see e.g. Greiner et al. 2002).

3.2. Monitoring at other wavelengths and various correlations

Although monitoring microquasars in the X-rays is very important and opened up a whole new perspective, the full picture on emission processes and their relation to source geometry can only be obtained through monitoring at all possible wavelengths. Combining long-term radio data from the Molonglo Observatory Synthesis Telescope (MOST) and hard-rays from the *Compton Gamma-Ray Observatory's* Burst and Transient Source Experiment (BATSE) with soft X-rays from the *RXTE*/ASM of the black hole X-ray binary GX 339−4, Hannikainen et al. (1998) showed that the emission from all three wavebands was correlated during a minor flaring event, suggesting a common origin for the emission. Studies dedicated to various radio-X-ray correlations followed for many sources, amongst them Cygnus X-3, a source that to this day remains a mystery. McCollough et al. (1999) used radio data from the Green Bank Interferometer and BATSE hard X-ray data to show that there is a complicated set of correlations between these energy bands in Cygnus X-3 during various states of flaring in both the ra-

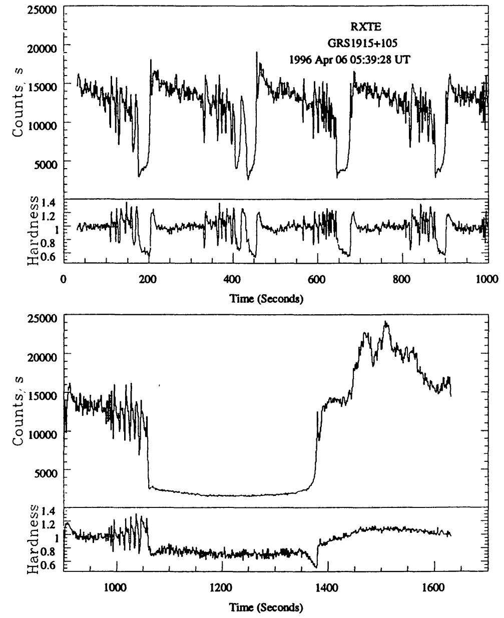

Fig. 5. PCA data of GRS 1915+105 from 1996 Apr 6. The top panels of each plot show the lightcurves while the bottom panels show the hardness ratio (4.4–25 keV / 2 – 4.4 keV), both with a time resolution of 1 second. In the upper plot we see the characteristic sputtering behavior of GRS 1915+105 and in the lower plot we see a "lull". Even during the lull, the background (at 5 ct/s) is negligible with respect to the source count rate. Reproduced from (Greiner et al. 2002).

dio and the hard X-rays This is work that continues to this day in an attempt to shed light on this source (see Koljonen et al., these proceedings).

3.3. Wrap-up of the 1990s

At the end of the 1990s, the following was known or discussed about microquasars, and contributed greatly to the studies that followed:

- Accretion disk + corona geometries not so straightforward
- Some XRBs capable of accelerating jets to relativistic velocities
- Timing/QPOs (not discussed in this paper) give invaluable insight into the behavior
- Accretion/ejection connections are complex
- Could disk instabilities contribute to the jet material?

4. The 2000s

The 2000s very much ushered in the era of comprehensive multiwavelength campaigns, or at least the pulling together of observations at different wavelengths.

4.1. Gamma-ray binaries

To being with, VLA observations of the massive X-ray binary LS 5039 resolved its bipolar jets thus classifying it as a microquasar (Paredes et al. 2002). But even more striking was the association of LS 5039 with the EGRET source 3EG J1824−1514 (Paredes et al. 2002). Figure 6 shows the VLBA and VLA radio map of LS 5039 and the EGRET contours. This in itself spawned a whole field dedicated to studies of the very high energy emission from X-ray binaries. Amongst the theories proposed to explain the very high energy emission is that the jets interact with the dense stellar wind from the companion, generating the gamma-rays.

4.2. Shock-in-jet vs synchrotron bubble

The generally accepted picture at the end of the 1990s was that the radio spectral evolution in microquasars was due to the "synchrotron bubble" model first proposed by van der Laan (1966) to explain the behavior of extragalactic sources. This model was then modified for and adapted to microquasars (Hjellming & Johnston 1988; Ball & Vlassis 1993; Hjellming & Han 1995). In this scenario, the radio emission arises from an adiabatically expanding cloud of relativistic electrons and randomly oriented magnetic field. The model predicts that the emission at the higher frequencies peak before the emission at lower frequencies. Moreover, the peak flux density is predicted to be higher for the higher frequencies, and that the radio spectrum is initially inverted and self-absorbed and as the outburst progresses becomes optically thin as the cloud expands.

In the meantime, the extragalactic community had shifted towards a model that invoked shock waves propagating down a relativistic jet to explain the synchrotron emission (Marscher & Gear 1985). The first microquasar for which it was noted that it exhibited outbursting behavior in the radio that differed from the synchrotron bubble model was GRO J1655−40 (Hannikainen et al. 2000). Simultaneous multifrequency radio data from the Molonglo Observatory Synthesis Telescope and the Australia Telescope Compact Array spanning frequencies from 843 MHz to 9.2 GHz showed that during a major radio outbursting event in 1994 (in fact, when VLA and VLBA imaging showed the presence of collimated, relativistic jets) the flux densities at all observing frequencies increased simultaneously after the initial rise and peaked simultaneously (Hannikainen et al. 2000), which is inconsistent with the synchrotron bubble model. Stevens et al. (2003) studied GRO J1655−40 in more depth and showed that this behavior is in fact in accordance with the Compton/growth stage in the generalized shock model. The synchrotron emission arising during radio flaring in GRS 1915+105 and Cygnus X-3 was also

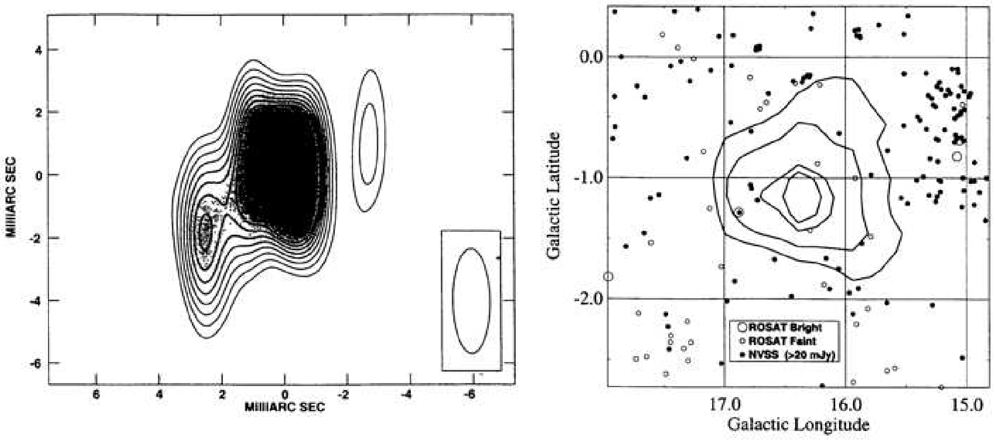

Fig. 6. *Left.* The VLBA and VLA radio map at 6cm of LS 5039 showing the bipolar structure. *Right.* Location map of 3EG J1824−1514; the only source with X-ray and radio emission well inside the EGRET 95% contour is LS 5039. From Paredes et al. (2002).

shown to be better described by the shock-in-jet model (or a generalization thereof; Türler et al. 2004; Lindfors et al. 2007). These results were partly summarized at the Vulcano Workshop in 2005 (Hannikainen et al. 2006).

4.3. Unifying multiwavelength behavior

The 2000s really heralded the era of comprehensive multiwavelength campaigns, partly due to the successful long-running X-ray missions such as *RXTE* but also due to an increased awareness that multiwavelength coverage is necessary in order to obtain as complete an understanding as possible of the physics governing microquasars. Some of these multi-effort observing programs led to the realization that microquasars undergoing transient outbursts follow specific patterns in what are known as "hardness-intensity diagrams", or HIDs, where X-ray intensity is plotted along one axis (usually the y-axis) and X-ray hardness is plotted along the other axis. Specifically, multiwavelength data of GX 339−4 showed that the source traced a "Q" shape in the HID as it undergoes transient outbursts. The source starts in quiescence in the lower right of the diagram (designating low X-ray luminosity and a hard spectrum, see Figure 7). When the outburst starts, the source's X-ray luminosity begins to increase, but the source remains at approximately the same hardness level, and the source moves up the right-hand branch of the Q. It is usually in this state that low-luminosity compact jets are observed (e.g. Fuchs et al. 2003 for GRS 1915+105). At the peak of the intensity in the outburst, the source becomes softer all the while remaining at the same, bright X-ray luminosity level. At some point during this transition towards the high/soft state, the source crosses what is known as the "jet line" (see e.g. Fender et al. 2004) and giant relativistic ejections such as those from GRS 1915+105 and GRO J1655−40 are observed. Following this, the source luminosity decreases, and slides down the left branch of the Q back into quiescence.

However, not all sources follow this pattern, with some exhibiting larger departures

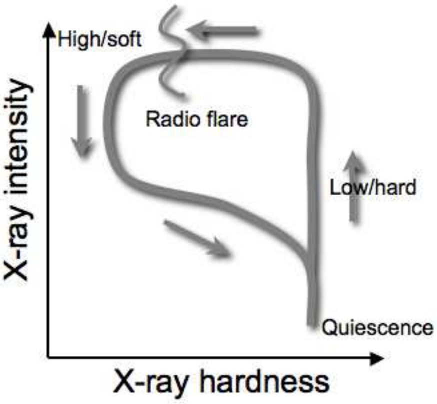

Fig. 7. Hardness-intensity diagram showing the path a microquasar traces during an outburst. See the text for details. Based on Gallo (2009).

and some less. First of all it must be stressed that this pattern is traced by black hole X-ray binaries during their outbursts (neutron stars exhibit entirely different outbrusts and behavior patterns). But there are black hole X-ray binaries that do not necessarily follow this pattern strictly and the deviations are being studied (e.g. XTE J1818−245, Cadolle Bel et al. 2009). Then there are those microquasars that do not exhibit transient behavior, but are constantly in a state of flaring (to varying degrees, of course) in the X-rays and radio, such as Cygnus X-3 (see Koljonen et al., these proceedings for further information on Cygnus X-3's multiwavelength behavior).

Broadband spectra obtained during multiwavelength campaigns also provide a plethora of information. It is with these that detailed modeling of the physical processes involving the accretion disk, outflows, coronae, etc. can be undertaken and further inroads into understanding the geometry of these sources can be made.

5. Open questions

There are obviously many open questions associated with microquasars, although many have been addressed. Amongst these are

- what is the composition of the jets
- are the jets made up of accretion disk matter, coronal matter, or neither
- how are the jets collimated and accelerated
- what is the origin of the hard X-ray emission (inverse Compton scattering in the corona vs. synchrotron from the jet vs. something else)
- what is the origin of the very high energy emission
- do all microquasars obey the shock-in-jet model

Also, please note that neutron stars were not dealt with in great detail in this paper, and there are several neutron stars that have also exhibited relativistic jets (e.g. the prototype SS 433).

6. Conclusions

The Frascati Workshops dedicated to the Multifrequency Behavior of High Energy Cosmic Sources have been going strong for a quarter of a century. During this time, we learned that X-ray binaries are capable of accelerating matter to relativistic speeds. We learned that accretion geometries are not so straightforward. We learned that outbursts do not all follow the same pattern. Mainly, we learned that without true multifrequency coverage it is very difficult to derive a complete picture of the behavior of these sources. But we also learned that the rich multifrequency world of microquasars will never cease to amaze us.

7. DISCUSSION

FILIPPO FRONTERA: You review many nice results on microquasars, yet you never mention Beppo-SAX. Can I ask why?

DIANA HANNIKAINEN: I realize this is a serious omission, and I'm very sorry about this. I tended to concentrate on the work that I have been involved in in one way or another over the years or the missions that I am more familiar with. Unfortunately I have not worked with Beppo-SAX data, but I can rectify this (or at least try to!) in the future.

GENNADY BISNOVATY-KOGAN: You mentioned the source 1E1740.7−2942 and referred to it as ”The Great Annihilator”. OSSE failed to detect the annihilation line first reported by Granat/SIGMA.

DIANA HANNIKAINEN: True. I was just using its familiar name, but I realize that this might create the wrong impr

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