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Radio observations of X-ray binaries

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Abstract. This paper describes how observations at radio wavelengths have contributed to shape our current picture of X-ray binaries as accretion powered sources in the Galaxy. A significant part of the progress during the past twenty years has been the result of modern radio interferometry. This path will certainly be continued with the construction of several improved and much more sensitive arrays. Here, I review the generalities of several observational facts which appear relevant to me for our current understanding of these accreting compact objects. Attention is also focused on new observational issues likely to provide important advances in a nearby future. These include the search for signatures of interaction between relativistic jets from X-ray binaries and the interstellar medium as well as the confirmation that these systems can be sources of high energy γ-rays.

Key words. X-rays: stars – Radio continuum: stars – ISM: jets and outflows – Gamma rays: observations

1. Introduction

X-ray binaries can be considered as end products of stellar evolution. They are formed when one of two gravitationally bound stars becomes a black hole, or neutron star, with the binary system not being disrupted in the process. The accretion of mass from the remaining non-degenerated star towards its new compact companion, either by Roche lobe overflow or stellar wind, powers the X-ray emission of the system with luminosities often approaching the Eddington limit ($\sim 10^{38}$ erg s^{-1}).

The total X-ray binary population known at present amounts to 280 objects. They are distributed into 150 and 130 systems with low-mass and high-mass donor stars, respectively (Liu et al. 2000, 2001). The first of them to be detected at radio wavelengths was the low-mass system Sco X-1 (see Hjellming & Wade 1971). The finding of such 'radio emitting' X-ray binary (hereafter REXB) occurred just a few years after this object was the first extra-solar X-ray point source ever detected (Giacconi et al. 1962). This was also a time when our understanding of X-ray binaries as stellar accreting sources started to mature around the theoretical model of Shakura & Sunyaev (1973). The remarkable progress achieved in the field of X-ray binaries since then cannot be understood without the concurrence of observational data coming through the radio window. This domain of the electromagnetic spectrum has contributed to teach us how the dynamics of accretion disks and coronae around compact objects is intimately connected to the creation of bipolar jets of relativistic plasma (see Fig. 1).

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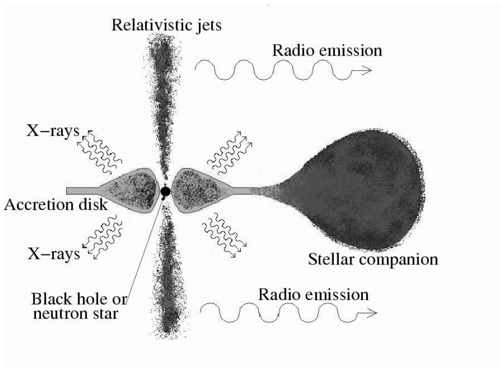

Fig. 1. Cartoon of an X-ray binary containing a normal donor star, a compact object (neutron star or black hole), accretion disk and relativistic jets emanating perpendicularly from it. When the jets are clearly detected and resolved, the X-ray binary is considered to be a microquasar.

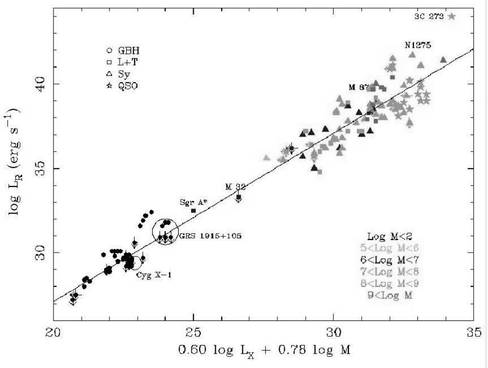

Fig. 2. Universal plane of accretion as proposed by Merloni et al. (2003).

The concept of microquasars as X-ray binaries with relativistic jets has been also widely accepted, specially after the detection in 1994 of superluminal motion in the jets of the transient X-ray binary GRS 1915+105 (Mirabel & Rodríguez 1994). The present census of galactic microquasars, a special class of REXBs, has increased significantly in recent times up to a total of at least 15 systems currently classified as such (Paredes & Martí 2003). This is roughly one third of the total REXBs known today, which in turn represents 15% of the total X-ray binary population catalogued.

In this paper, several observational results are summarized which I believe are representative of the current status of the REXBs. The choice of topics is mostly based on the author's personal interest rather than being an attempt to cover extensively this growing field.

2. What have we learnt from radio observations of X-ray binaries?

It is noteworthy that a good fraction of our knowledge about the "anatomy" of these sources of highly energetic emission (X-rays and possibly γ-rays too) has been learnt through collecting the softest photons that they emit, namely those in the radio window. The main reason is understandably the higher angular resolution achieved by observing radio techniques (e.g. Very Long Baseline Interferometry or VLBI) with respect to other domains of the electromagnetic spectrum. For instance, the angular resolution achieved by X-ray telescopes not many years ago was even worse than that of Galileo's 17th century telescope at optical wavelengths. The use of the modern radio interferometers (such as the European VLBI Network (EVN), the Very Long Baseline Array (VLBA) and also the Very Large Array (VLA) among many others) are representative examples of the best tools existing to actually resolve and study the ejecta of REXBs. In parallel with high angular resolution observations, the long-term radio and X-ray monitorings of these systems have played a very important role.

All these observational efforts together have been key to develop the first semi-quantitative models to interpret how jet production, or suppresion, is related to the X-ray spectral states of the accretion disk and corona in the system. Observationally, this corresponds to a coupling between the radio and X-ray emission which appears to be better understood in the case of black hole X-ray binaries. An updated account of the X-ray/radio states where these systems can exist, and how transitions between them proceed, is described in more detail by Fender et al. (2005) but see also Gallo et al. (2005) for a review. Just to mention the basic facts, black hole X-ray bi-

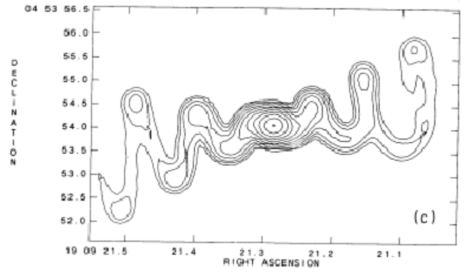

Fig. 3. An old model of the SS 433 appearance in case of slow lateral expansion of the jet (Hjellming & Johnston 1988).

Fig. 4. The deepest radio image of SS 433 taken by Blundell & Bowler (2004) showing more than one cycle of the helical pattern of the jets. Its appearance strongly resembles that of Fig. 3 based on the Hjellming & Johnston (1988) models.

naries spend most of their time in the "low-hard" state with an X-ray luminosity below a few % that of Eddington. A compact steady jet with Lorentz factor $\Gamma \leq 2$ is believed to exist whose spectrum is flat or inverted and extends from the radio to almost the infrared band. The occurrence of occasional optically thin flaring events is understood as a consequence of a transition from the "hard" state to the soft Very High State/Intermediate State. There is yet some uncertainty about the coronal or disk nature of the jet material ejected. Nevertheless, it seems clear that during these transitions the jet increases its Lorentz factor ($\Gamma \geq 2$) causing later internal shocks when encountering the slower jet material previously ejected. In particular, jets from X-ray binaries seem to be able to reach Lorentz factors as high as in Active Extragalactic Nuclei (AGN), such as the case of the neutron star system Circinus X-1 (Fender et al. 2004).

An additional lesson from the combined use of radio and X-ray observations has been the discovery of strong evidence for a "Fundamental Plane of Accretion" (Merloni et al. 2003) in the logarithmic 3D space of radio luminosity, X-ray luminosity and black hole mass (see Fig. 2). This suggests the scale invariance of the accretion/ejection processes and opens hopes for a quantitative application of X-ray binary results to AGNs.

Radio observations are also contributing significantly to determinate the dynamical properties of X-ray binaries with respect to their local environment. Here, VLBI observations over time baselines of several years are able to measure the proper motion of a system in the sky plane and, in some cases, even a trigonometric parallax as in Sco X-1 (Bradshaw et al. 1999). Such information, when combined with traditional radial velocity studies based on the Doppler effect at optical wavelengths, allows us to fully determine all components of the velocity vector of the system relative to its Local Standard of Rest (LSR).

In this way, it has been discovered that some REXBs are remarkably high velocity objects ($v_{\rm LSR} \geq 100$ km s^{-1}). This statement is true for both high and low-mass REXBs, such as the the runaway microquasar LS 5039 (Ribó et al. 2002) and the black hole candidate in the Halo XTE J1118+480 (Mirabel et al. 2001), respectively. For the periodic REXB and microquasar LSI+61°303, the use of VLBI has made possible to determine that it was ejected in the past from the stellar cluster IC 1805 (Mirabel et al. 2004). In contrast, VLBI observations of the classical black hole candidate Cygnus X-1 have provided a very slow velocity of this microquasar with respect to its LSR (Mirabel & Rodrigues 2003). This suggests that black holes can also form quietly in situ, while other compact objects seem to be formed with a significant natal kick likely due to a supernova explosion. All these observed facts need now to be theoretically interpreted and understood in the context of binary star formation and evolution.

3. What do we expect from future radio instrumentation?

The field of REXBs is expected to benefit a lot from the increase both in sensitivity and angular resolution of the new generation of radio interferometers being currently upgraded or build in the world (such as the EVLA, SKA, eMERLIN or eVLBI among others). The authors's opinion here is that the improvement in sensitivity will likely be the most scientifically rewarding. A large fraction of X-ray binaries in the Milky Way, if not all, will become detectable as radio sources even during faint quiescent states. REXBs in the Magellanic clouds and nearby galaxies as well will shift within our detection capabilities, at least during radio flares. This would fully open the search window for extragalactic microquasars. Statistically robust comparisons of microquasar properties should be finally possible and no longer being based on merely a handful of systems. The correlation between X-ray and radio emission will also be tested up to very low accretion rates and therefore very low luminosities. A more extended account of future perspectives with very sensitive instruments can be found in Fender (2004).

Just to put an example of the amount of progress expected, the following analogy could be illustrative here. Nearly a quarter of a century ago, the precessing jets of the microquasar SS 433 were already imaged with remarkable detail by Hjellming & Johnston (1981). At that time, theoretical models for the expanding jets of SS 433 allowed to calculate the expected appearance of the jet helical pattern. In particular, Fig. 3 displays how it would look like in case of slow lateral expansion and hence small adiabatic energy losses of the radio emitting electrons. This is also equivalent to what should be seen with incredibly good sensitivity in the more realistic case of higher adiabatic losses. An image showing more than one loop of the SS 433 corkscrew could hardly be dreamed of in 1988. Remarkably, a very deep VLA integration carried out by Blundell & Bowler (2004) does clearly reveal more than one corkscrew cycle allowing to study the subtle velocity differences of the ejected plasma at large distances from the binary system. Images with this quality (see Fig. 4) and the science being possible with them should hopefully become routine with future instruments.

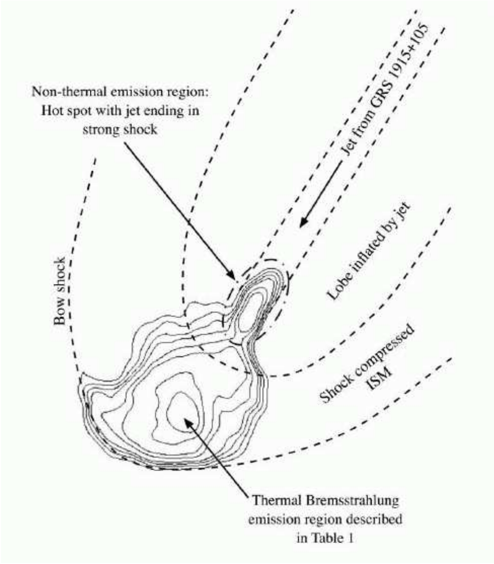

Fig. 5. Sketch of the hot spot and extended lobe interpretation proposed by Kaiser et al. (2004) based on previous observations by Rodríguez & Mirabel (1998) of two IRAS sources aligned with the jet axis of the microquasar GRS 1915+105.

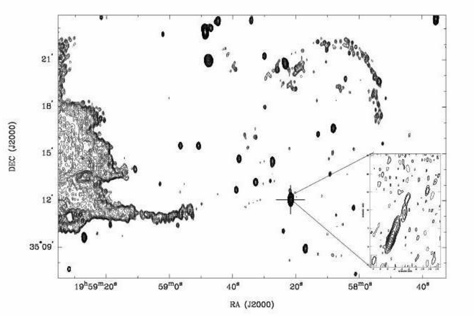

Fig. 6. Extended arc of radio emission around the black hole candidate Cygnus X-1 detected by Gallo et al. (2005) using the Westerbork Synthesis Radio Telescope at the 20 cm wavelength.

Another issue where increased sensitivity will be a key factor is in the interaction of the REXBs relativistic jets with its surroundings which is discussed in a special section below.

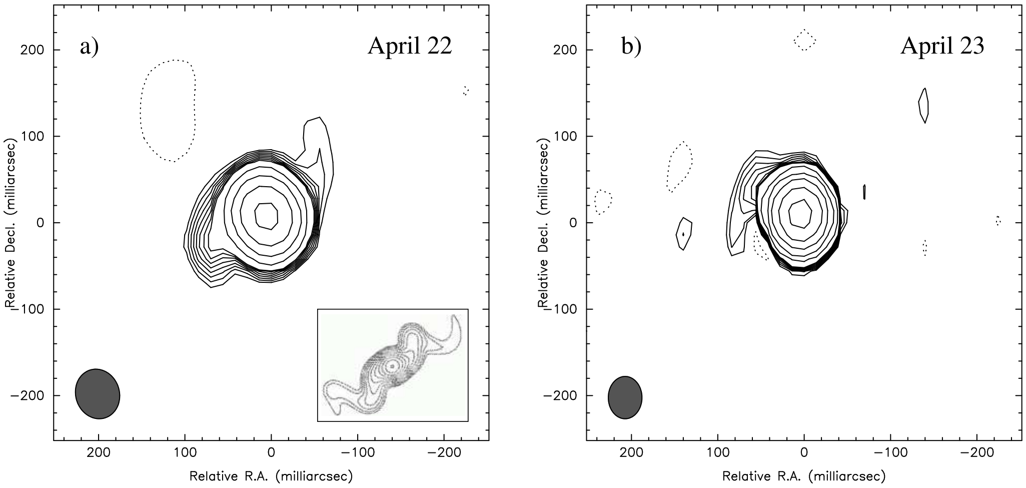

Fig. 7. Detection of a radio jet in the high-mass Be X-ray binary LS I+61°303 (Massi et al. 2004) with apparent variations of position angle in time scales of a day. The inset in the left panel is one of the SS 433 models by Hjellming & Johnston (1988) inserted for comparison. The clear detection of jets confirms the microquasar nature of LS I+61°303. Moreover, the apparent changes would be consistent with models of the short term EGRET variability based on fast precession of the relativistic jet.

4. The interaction of relativistic flows with the interstellar medium

Microquasar jets are believed to pump enormous amounts of energy into the interstellar medium (ISM). For the superluminal microquasar GRS 1915+105, Fender & Pooley (2000) suggest that $\sim 10^{51}$ erg (i.e. comparable with a supernova explosion) could be injected into the ISM over its total ejecting lifetime. Surprisingly, it is observationally very difficult to search for evidence of interaction between the relativistic jets and the ISM. Clear examples of such interaction are only seen in a few cases. Among others, these include the two galactic center microquasars 1E 1740.7−2942 and GRS 1758−258 with parsec scale extended radio lobes (Mirabel et al. 1992; Rodríguez et al. 1992). Additional indication that such indication must occur is the deceleration observed in the jet components of some microquasars as in the remarkable example of XTE J1550−564 (Corbel et al. 2002).

In the GRS 1915+105 case, two otherwise normal HII regions have been proposed as possible extended lobes being excited by the relativistic jets as shown in Fig. 5 (Rodríguez & Mirabel 1998; Kaiser et al. 2004). The physical interpretation behind such conclusion is mainly based on applying a scaled down model for large-scale structure of jets in extragalactic radio sources (Kaiser & Alexander 1997). Nevertheless, only the good alignment with the jet position angle and a non-thermal radio feature pointing towards GRS 1915+105 remain as the only proofs of such connection. A similar scenario has been also suggested for the microquasar Cygnus X-3 (Martí et al. 2005; Pérez-Ramírez et al. 2005). The total energy output needed to sustain the possible double lobe/hot spot radio features in both GRS 1915+105 and Cygnus X-3 is estimated to be $\sim 10^{36}$-10^{37} erg s^{-1}. These values are believed to be consistent with the total energy injection rate of their respective collimated outflows when averaged over time scales of many years.

It is intriguing why, excluding some of the examples quoted above, most microquasar jets fade and dissapear before deceleration and bow shock formation is observed. This situation is considerably different when comparing with collimated outflows from young stellar sources (YSOs). Thermal jets from YSOs display a wide variety of bow-shock structures with hundreds of cases being catalogued as Herbig Haro objects. It has been proposed that this happens because relativistic jets from microquasars propagate in a much less dense medium, in a dynamical sense, than those of YSOs (Heinz 2002).

In any case, new interferometric arrays will certainly increase our chances of detecting the physical signatures of the REXBs jets/ISM interactions thus allowing a direct 'calorimetric' determination of the total energy rate injected by these systems. An example of observational surprises encountered, even in well studied sources when good signal-to-noise ratio and angular resolution is achieved below 0.1 mJy beam^{-1}, is the detection of an arc-shaped feature around the classical black hole candidate Cygnus X-1 by Gallo et al. (2005) (see Fig. 6). This radio arc, which traces part of a more extended elliptical ring-like shell (Martí et al. 1996), could be the result of interaction of the Cygnus X-1 jets with ambient gas and strongly deserves future in depth studies.

5. X-ray binaries and high energy γ-ray sources

The REXB LS 5039, likely associated with an EGRET source (Paredes et al. 2000), brought the hypothesis that microquasars could account for some fraction of the unidentified high energy ($\geq$ 100 MeV) γ-ray sources at low galactic latitudes detected by the EGRET instrument on board the COMPTON-GRO satellite (Hartman et al. 1999). Further observational and theoretical work has provided additional support to such idea (Kaufman-Bernadó et al. 2002; Bosch-Ramon et al. 2005; Ribó et al. 2005). The emission mechanism producing the γ-ray emission is modelled as inverse Compton scattering of stellar photons interacting with the same relativistic jet electrons. Variability could be naturally induced here through jet precession.

More recently, the discovery of precessing jets in LS I+61°303 (see Fig. 7) has provided another case of very likely association of a microquasar with an unidentified and short term variable EGRET source (Massi et al. 2004). The connection is futher strengthen given the

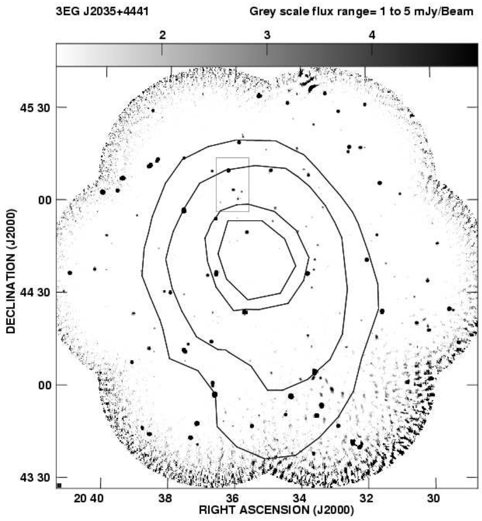

Fig. 8. WSRT observations of the field of 3EG J2035+4441 at the 20 cm wavelength during 2003 (Paredes et al. 2005). The black lines represent the EGRET contours of 50, 68, 95 and 99% confidence for the position of the unidentified γ ray emitter and many radio sources are detected inside them. The small rectangle is displayed in more detail in Figs. 9 and 10, whose comparison reveals a clearly variable radio source inside the 95% confidence contour.

possible detection of a common period around 26.5 days in both the radio and EGRET light curves (Massi 2004).

During the last years, a combined effort by several observers is being carried out in an attempt to identify additional examples of X-ray binaries with likely emission of high energy γ-ray photons. A possible approach is to focus on highly variable EGRET sources in terms of variability indices as defined by Torres et al. (2001). Such selection should hopefully exclude neutron star pulsars and supernova remnants, which are non-variable objects during the time scale of observations, and maximize the chances that a microquasar is being responsible for the high energy emission. Its identification should then proceed by observing in the radio most of the solid angle included within the 95% confidence contour of the EGRET source position. If it is really a microquasar,

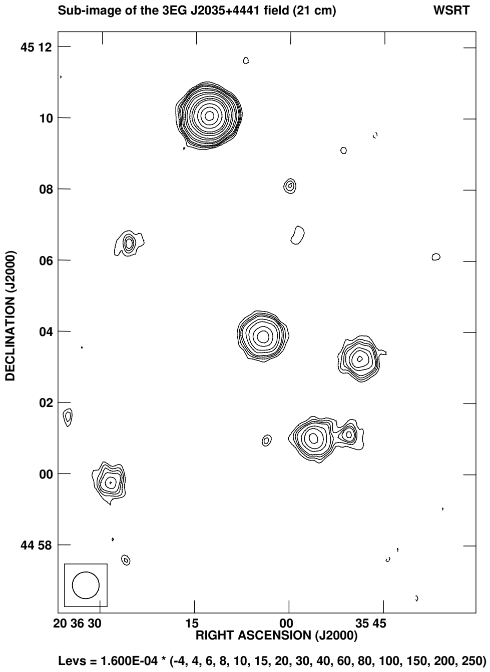

Fig. 9. Zoomed view of the small rectangle in the WSRT map of 3EG J2035+4441 shown in Fig. 8.

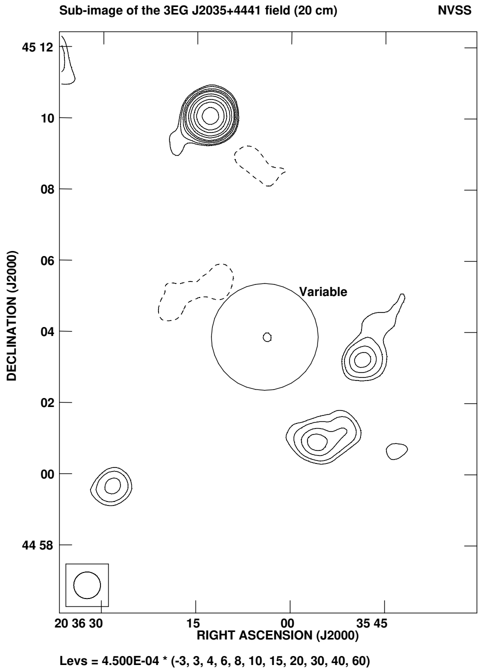

Fig. 10. The same field of Fig. 9 as it appears in the NRAO VLA Sky Survey at practically the same wavelength. The circle indicates the clear discovery of a strongly variable radio source.

one would naturally expect to detect a variable radio source in the field.

Considering that the typical size of the EGRET 95% confidence contour is about one degree, one needs to observe at low radio frequencies with a mosaicing technique in order to cover all of the solid angle required. In Fig. 8, an example of such observation is shown for the unidentified EGRET source 3EG J2035+4441 (Paredes et al. 2005). The observations were obtained with the Westerbork Synthesis Radio Telescope (WSRT) and a mosaicing technique. A clearly variable radio source has been already identified in the field as illustrated by the comparison of the zoomed maps in Figs. 9 and 10, both at similar wavelengths. Further observations are in progress to confirm the possible identification.

6. Conclusions

1. Radio observations with interferometric arrays provide a key tool for a unified understanding of X-ray binaries in the context of accretion powered sources in the Universe. The discovery of correlations connecting the observational properties of both X-ray binaries and AGNs, together with the masses of their respective compact objects, strongly points in this direction.
2. The future perspectives offered by the very sensitive interferometric arrays under construction will allow us to address new astrophysical issues about the interaction of relativistic jets with the galactic ISM.
3. In addition, there is growing evidence that X-ray binaries could be the counterpart of some unidentified sources of high energy γ-rays. However, additional identification efforts are still needed to confirm such association beyond any reasonable doubts.

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