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EVN e-VLBI observations of galactic transients

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e-VLBI (electronic very long baseline interferometry) is a new implementation of the VLBI technique consisting in transferring the data from the radio telescopes to the correlator over the internet and correlating them in real-time. Time-wise this is a major improvement over the traditional method. e-VLBI is thus offering new opportunities for radio transient studies. Its capability of rapid response enables a more efficient decision making process with respect to potential follow-up observations. The rapid feedback time also permits to quickly modify the observing strategy to best track the development of the transient phenomena. The results summarized here have been obtained with the EVN (European VLBI Network) in the past few years within a transient ToO programme. The targets were XRBs (X-ray binaries) undergoing periods of enhanced activity (outbursts). The EVN observations were performed at 5 GHz and were often complemented by quasi-simultaneous (within one day) data at other wavelengths (X-ray and optical). The findings reveal a complex behaviour of the accretion/ejection phenomena in the systems investigated and offer insights into the extreme physics close to a compact object.

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1. XRB transients

Collimated outflows of matter (i.e. jets) are ubiquitous phenomena in astrophysics (e.g. [41, 26, 8]). Given that in most of the cases the relevant emission mechanism at work is synchrotron radiation, and despite the self-absorption issues, the jets are probably best observed at radio wavelengths, at which very high angular resolutions can be realized. Some of these jets exhibit relativistic speeds and are in fact among the fastest flows in the Universe. They play a major role in many and varied astrophysical contexts, at different spatial scales, for instance, to name a few, in star formation processes, acceleration of high-energy cosmic rays, cooling flows issues in galaxy evolution.

An X-ray binary (XRB) is a system in which a compact object, neutron star or stellar mass black hole, accretes matter from a companion star via an accretion disc or the stellar wind. Hence, intuitively, the XRBs can be classified as neutron star XRBs (NSXRBs) or black hole XRBs (BHXRBs).

BHXRBs spend most of the time in quiescence and undergo sudden and bright, usually months-long outbursts (GRS 1915+105 is rather the exception with its ~ 15 years long, still ongoing outburst) with typical recurrence periods of years. Jets have been spatially resolved in some BHXRBs. Most spectacularly, two of the jets, GRS 1915+105 and GRO J1655-40, exhibit apparent superluminal motion [25, 34]. In fact, if the claims of larger distances are correct, a few other objects might qualify as superluminal sources, such as GX 339-4 (e.g [14]), V4641 Sgr [13], XTE J1748-288 [12].

NSXRBs are classified according to their X-ray spectral and timing properties as Z and Atoll sources. The Z class comprises a handful of objects accreting near the Eddington limit. All of them have been detected at radio wavelengths and show variable emission at cm wavelengths. For two Z sources, Sco X-1 and Cir X-1, the radio emission has been spatially resolved and evidence shows that ultra-relativistic outflows are present in these systems [9, 7, 36]. The arcsec scale jet in Cir X-1 shows in fact superluminal motion. The Atoll type NSXRBs are the largest class of XRBs and have X-ray properties similar to BHXRBs. Due to their systematically lower radio flux (at least one order of magnitude lower than for Z sources) for a given X-ray flux, compared to BHXRBs only a few have been detected in the radio regime. Flares are also common in NSXRBs and almost all of the radio observations in the literature were carried out during such active periods.

The timescales in XRBs are orders of magnitude lower than in active galactic nuclei (AGNs) (roughly, the timescale scales linearly with the mass of the compact object), thus offering good opportunities to observationally study the emergence of jets and, thus, to obtain direct information on the accretion/ejection process under extreme conditions on reasonable human timescales. Most importantly, evidence shows that XRBs can be actually viewed as scaled down versions of the AGNs (e.g. [22, 6, 21, 18, 10]), powered alike by a compact object – a stellar mass neutron star or black hole rather than a million to billion solar mass SMBH. Within the Galaxy, [19] showed that the dwarf novae can exhibit an analogous behaviour to XRBs.

2. EVN e-VLBI observations

e-VLBI is a new implementation of the very long baseline interferometry (VLBI) technique and consists in transferring the data from the radio telescopes to the correlator over the internet, and correlating them in real-time. Time-wise this is a major improvement over the traditional method, the data reaching the end-user within days instead of weeks. e-VLBI is thus offering new opportunities for radio transient studies. Its capability of rapid response enables a more efficient decision-making process with respect to potential follow-up observations, not only at radio wavelengths. The rapid turnaround time also permits to change the observing strategy in almost real-time to best track the evolution of the transient phenomenon.

At this moment, the most advanced e-VLBI facility is the European VLBI Network (EVN). Presently, a number (frequency dependent) of about 10 radio telescopes across Europe and beyond are connected to the correlator at the Joint Institute for VLBI in Europe at Dwingeloo and participate in the e-VLBI observing sessions.

In this paper we shortly present some of the results obtained within the XRB transients ToO programme active at the EVN. In some cases quasi-simultaneous observations at other wavelengths were also available. However, here we mainly focus on the results pertaining to the radio band. The full analyses of the data are presented in the references given.

2.1 Cyg X-3

Cyg X-3 is quite an exotic system. First, the nature of the compact object is not known, circumstantial evidence pointing both towards a black hole and a neutron star. Second, the companion star seems to be of the Wolf-Rayet type [17] and at the moment only two other XRBs (both extragalactic) show evidence for harbouring such a star type. The system is at a distance of 7–9 kpc [28, 20] and has an orbital period of 4.8 h [1, 27].

The first two EVN observations of Cyg X-3 were carried out in 2006 [35], several weeks after a major flare, and a few days after another flare. The second observation revealed an extended jet, whose polarization properties suggested the presence of interaction sites between the ejected matter and the surrounding medium. We observed the source with EVN in 5 other occasions, in 2007 and 2008 (Fig. 1). In order to get a general picture of the behaviour at milliarcsec scales, we have complemented the EVN observations with archival VLBA data (at 5 and 15 GHz) thus obtaining a dataset comprising all the available VLBI observations of the object (at these frequencies), from 1997 onwards. The analysis [38] showed that when the total radio emission is considered, the behaviour of Cyg X-3 at milliarcsec scales is consistent with that described at arcsec scales [33] from the point of view of the radio/X-ray coupling. However, when the radio emission is decomposed into a “core” component (compact emission) and a jet component (extended emission), it becomes evident that the radio emission from the jet dominates that from the core in active states. This has strong implications with respect to the so called disk-jet connection. Basically, the results strongly suggest that the overall radio flux from Cyg X-3 cannot be used as a direct tracer of the accretion states in the system. Generally speaking, care should be always exercised when interpreting the observations of XRBs when high-resolution radio data are not available.

Adding to the VLBI dataset archival VLA observations (at frequencies of 8.4 GHz or higher, in the A configuration) we were able to determine the proper motion of Cyg X-3 [23]. This improved ability to precisely locate the position of the compact source has already proved to be very useful in identifying the true orientation of the extended radio emission (Miller-Jones et al., in prep.).

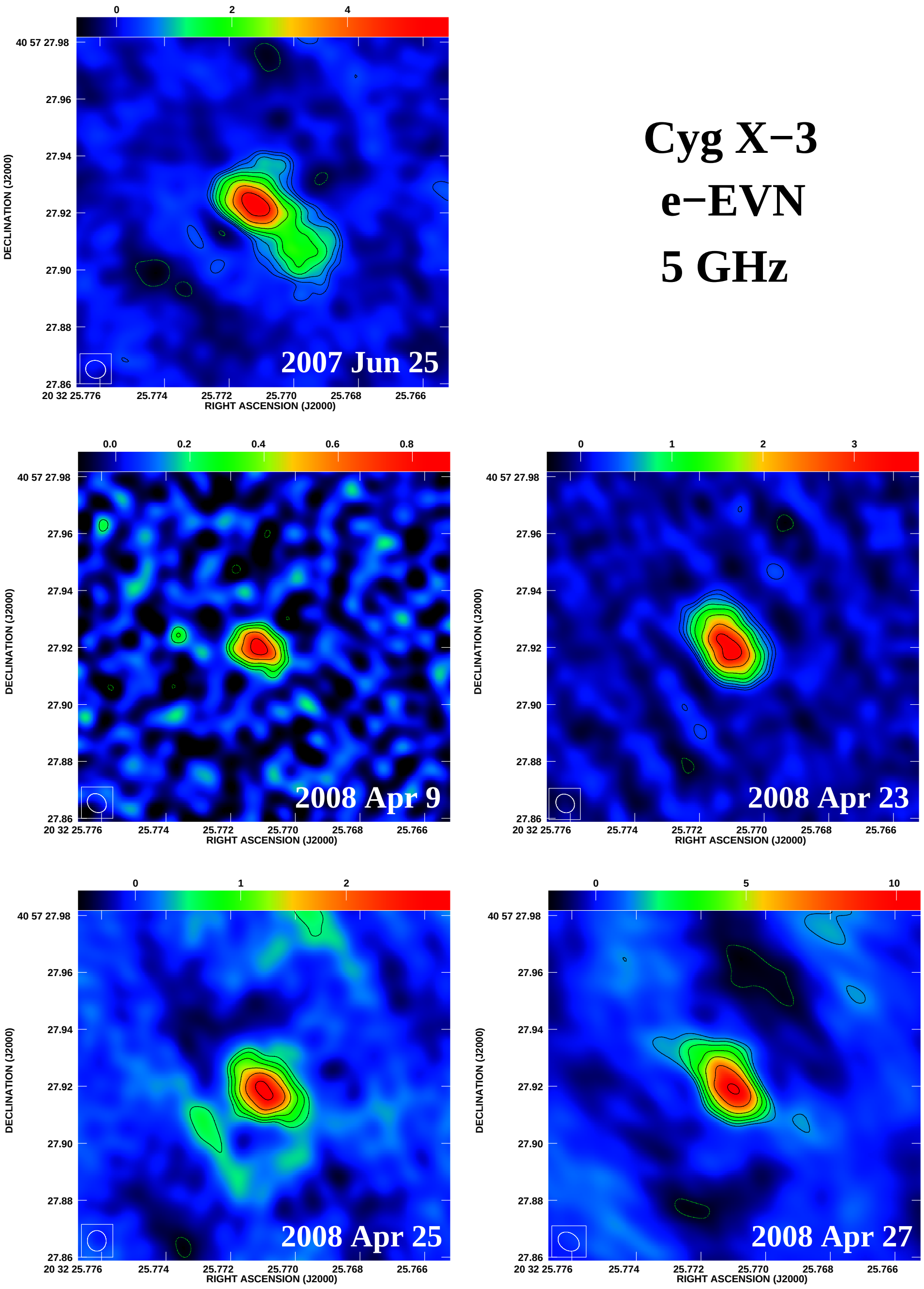

Figure 1: 5 GHz e-EVN radio maps of Cyg X-3. The contour levels are at -2.8, 2.8, 4, 5.6, 8, 11, 16, 23, 32, 45, 64, 90 times the rms noises of respectively 0.15, 0.07, 0.10, 0.17 and 0.45 mJy/beam. The colour code bars are expressed in mJy/beam. From [38].

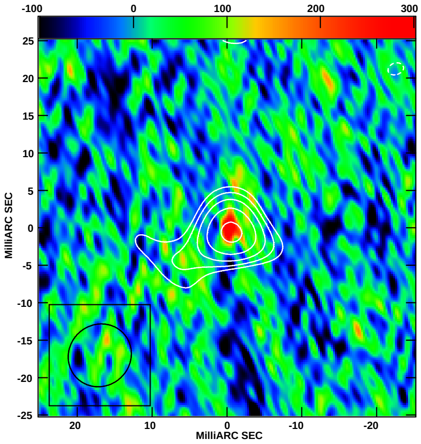

Figure 2: 8.4 GHz VLBA radio map of Aql X-1, with 5 GHz e-EVN contours overlaid. The contours are at the levels of $\pm(\sqrt{2})^n$ times the rms noise of 37 μJy/beam. The colour code bar is expressed in μJy/beam. From [24].

2.2 Aql X-1

Aql X-1 is a recurrent XRB with a relatively high rate of outbursts, about 1 per year. The compact object in the system is a neutron star and is accompanied by a main sequence star [3]. Aql X-1 is also an accretion-powered millisecond X-ray pulsar, a class of objects with only about 10 members known so far. The system has an orbital period close to 19 h [40] and lies at a distance of 4–6.5 kpc [3, 31, 15].

The first attempt to detect Aql X-1 with EVN came during an outburst at the beginning of 2009. It was unsuccessful [37]. Later on, at the end of the same year the opportunity appeared again: Aql X-1 was in an active state. This time the object was detected, a first in this case, at milliarcsec scales [24]. Quasi-simultaneous (within 1 day) VLBA observations were also available, enabling an unprecedented view of the system at VLBI scales (Fig. 2). Most interestingly, the EVN image showed a marginally significant extended emission component towards south-east. However, the VLBA map (at higher frequency) was consistent with an unresolved source. Simulations showed that a possible explanation for this discrepancy is that the faint extended emission seen by the EVN is resolved out by the VLBA. Alternatively, it is just an artifact.

This outburst has also been monitored with the VLA. These data, together with the VLBI observations, show that the radio emission in Aql X-1 is consistent with a compact, steady jet. The internal shock mechanism believed to produce the optically thin transient radio ejecta seen in BHXRBs does not seem to be active in this NSXRB.

2.3 GRS 1915+105

GRS 1915+105 is one of the most well-known BHXRB systems. The companion to the ~ 14 $M_\odot$ black hole is a K-M III star [11]. The system is at a distance of 6.5–14 kpc [25, 29, 16] and has an orbital period of 33.5 d [11], the longest of any low-mass XRB.

The EVN observation took place in 2006 during a period of relative radio quietness. However, during the run, a rapidly decaying (at timescales of a few hours) radio flare have been detected

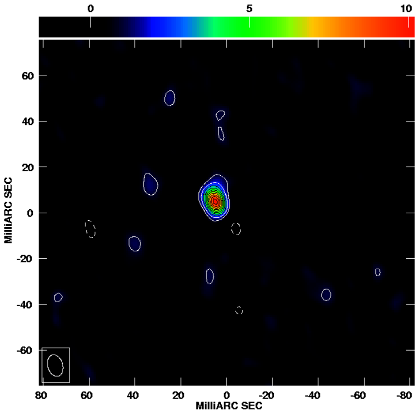

Figure 3: 5 GHz e-EVN radio map of GRS 1915+105. The contour levels are at -1, 1, 2, 4, 6, 8, 10 times 1.0 mJy/beam (rms noise level of 0.3 mJy/beam). The colour code bar is expressed in mJy/beam. From [30].

[30]. The source appeared marginally resolved (Fig. 3). The extended component was at a position angle similar to that observed during previous large-scale ejections.

The data were also used to estimate the energy content of the flare, based on some common assumptions, i.e. equipartition.

2.4 SS 433

SS433 is definitely one of the most exotic XRBs in the Galaxy. The compact object is likely a black hole and the companion perhaps a high-mass star [4]. What makes this object special is the radio nebula (W50) in which it is embedded and the cork-screw shape of the precessing large-scale jets that plunge into it. The XRB has an orbital period of 13.1 d [5] and is situated at a distance of about 5.5 kpc [2].

We observed SS 433 with the EVN for 3 epochs during a period of increased activity in 2008 (Fig. 4). The radio maps revealed in great detail the behaviour of the system at milliarcsec scales.

SS 433 has been observed extensively in radio at arcsec scales. The morphology of the radio emission is well described by the so called “kinematic model”, which predicts the position of any knot assumed to have been ejected at a particular moment in time. This is not as straightforward as it sounds because the jets of SS 433 precess with a period of 162.5 d, slightly complicating the geometry of the system. The “kinematic model” does an excellent job in reproducing the radio observations at arcsec scales, however, it has been tested only in a relatively few occasions at milliarcsec scales. The EVN observations offered a good opportunity. For generating the model we used the precession parameters from [32] and the nodding parameters from [39]. The predictions of the model are overlaid on the radio maps in Fig. 4 as red plus signs. The calculations considered a time interval between ejections of 1 day. The symbols furthest away from the core of the system (which is located close to the center of the maps) correspond roughly to an ejection time of 50 days before the time of the observations. A good agreement was obtained between the model and the observations.

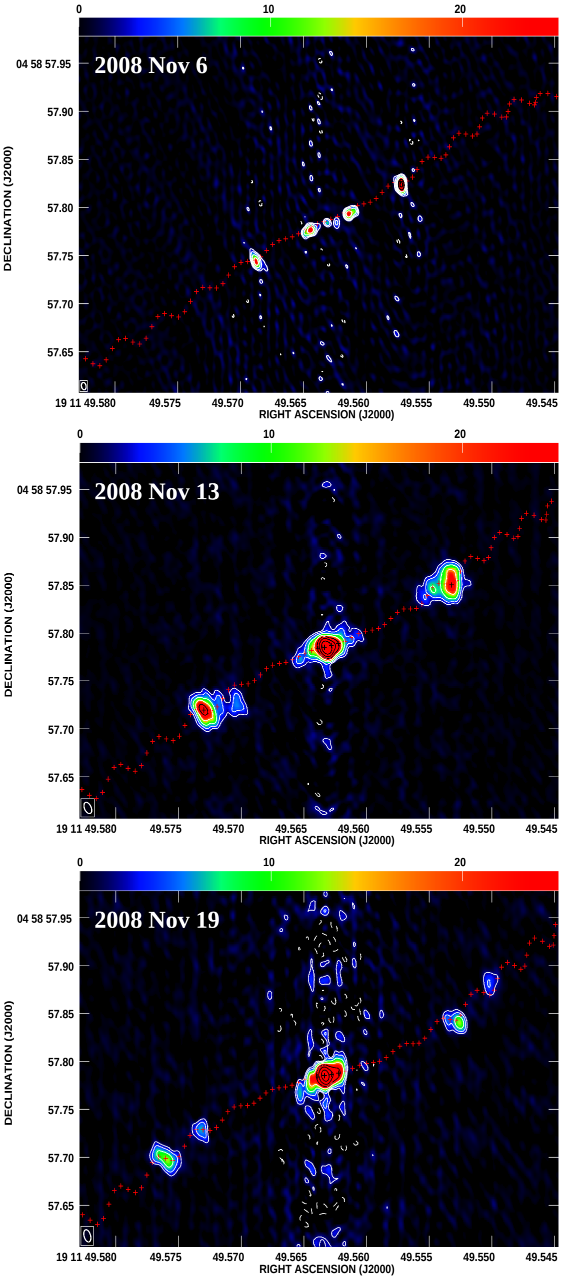

Figure 4: 5 GHz e-EVN radio maps of SS 433. The contour levels are at -1, 1, 2, 4, 8, 16, 32, 64 times the average rms noise of 2.0 mJy/beam. The colour code bars are expressed in mJy/beam. The images are at the same scale. Overlaid are the predictions of the “kinematic model”. Tudose et al., in prep.

3. A glimpse towards the future

A radio facility capable of round the clock monitoring of the whole sky has never been available. With the advent of LOFAR and later on SKA, this will change. The possibility of detecting and then observing a radio transient at an early stage during its evolution will definitely offer a fresh insight into the physics of these phenomena. LOFAR will be invaluable and SKA even more so, given its higher observing frequencies which will allow "catching" the transients at an earlier phase. This would mean brighter, more compact emission, probing regions closer to the compact object.

The EVN proved to be a reliable network facility for studying the XRB transients at high resolutions. If the efforts towards developing and improving this technique will continue, and the commitment of the EVN to support transient science will increase even further, the EVN will play an important role in this kind of science, in the new "golden age" of radio astronomy ahead.

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