Tracking the interaction of a relativistic jet from a black hole with the interstellar medium

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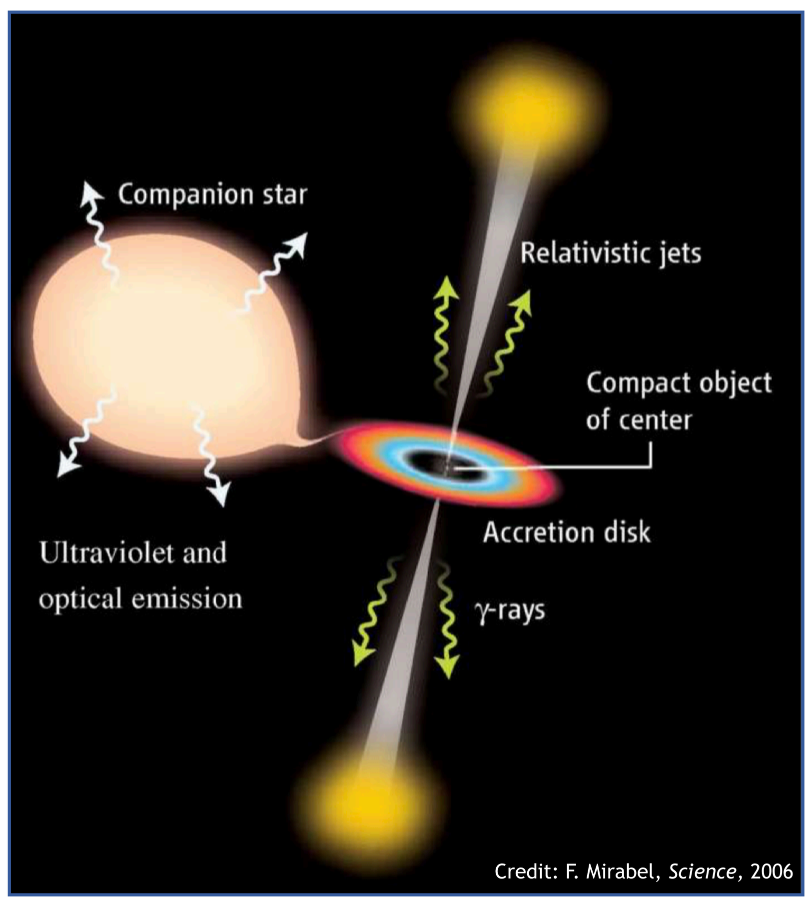
Abstract

Among the binary systems containing a neutron star or a black hole accreting matter from a companion star, microquasars are able to launch jets of plasma at relativistic speeds emitting with synchrotron emission mostly at radio frequency. We present an intensive radio monitoring campaign of the microquasar (and black hole candidate) H1743-322, in which we cover its 2003 outburst and the subsequent jet emission and motion, considering archival data from the Very Large Array (VLA) at 4.8 and 8.4 GHz. The unresolved core of the system exhibits a strong radio flare (up to ~90 mJy) which is the signature of an ejection event. From August 2003 to February 2004, we detect a ballistic jet travelling in the eastern direction, with a proper motion of 17.6 ± 0.1 microarcseconds/day. In both frequencies we see a progressive increase in the jet flux, which peaks at ~2 mJy in November 2003, and a subsequent decrease, until non detection in February 2004. The observed negative spectral index points to an optically thin synchrotron emission, which is likely the result of the interaction between plasma and the interstellar medium, producing in-situ particle acceleration up to very high energies. The next steps of the work include the study of the polarization properties of the detected radiation and the physical modelling of the jet.

1 - Microquasars



X-ray binaries are systems in which a compact object (stellar mass black hole or neutron star) accretes matter from a companion star. Flowing onto the compact object under the influence of its gravitational potential, the gas in the accretion disk reaches temperatures of ~10^7 K, and emits in X-rays with luminosities that can approach the Eddington limit (~10^{39} erg/s).

Most of these sources are transient, with outbursts lasting several months followed by years or decades of quiescence. These binary systems are important as they are potential sites for tests of general relativity in the strong field regime.

Microquasars are X-ray binary systems that are able to launch jets of plasma at relativistic speeds along the rotation axis.
As the jet impacts the interstellar medium (ISM), a strong radiative shock is likely to develop, accelerating population of relativistic electrons and producing non-thermal emission, which is detected in radio and X-rays.

These systems are mostly observed in our Galaxy and allow us to study the jet formation and emission on **timescales much shorter than what is typical for quasars**, making it possible **to unveil the mechanisms that link accretion and ejection in compact objects.** The injected energy heats the ISM, generates interstellar turbulence, produces high-energy cosmic rays. The motion of the blobs of bright plasma within the jets usually **appears to be superluminal**, a projection effect due to special relativity, for which the jet could travel with an apparent speed greater than the speed of light.

Recent scenarios include the jets propagating almost without interactions through a cavity of low ISM density until they reach the cavity's walls. The discontinuity in the ISM density profile causes the formation of external shocks responsible for the acceleration of the particles which produces the radio to X-ray emission.

Despite large recent progress, our understanding of microquasars is still far from being complete.

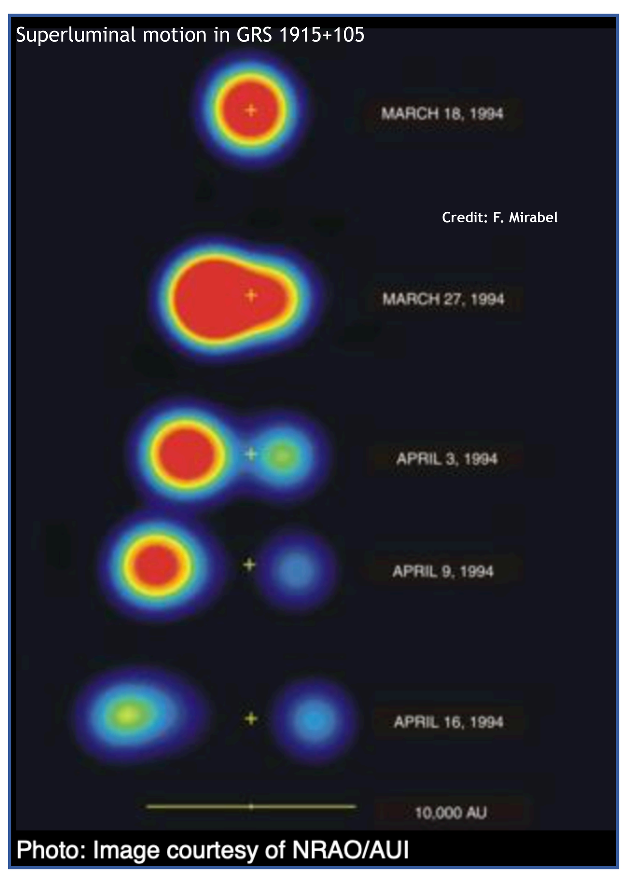


Photo: Image courtesy of NRAO/AUI

2 - The project: VLA observations of H1743-322

Credit: A. Savello (NRAO)

In the radio frequency domain, small structures like jets can only be observed with **aperture-synthesis interferometry,** a technique that coherently combines signals from a collection of antennas to produce images with the same resolution of an instrument having the size of the largest separation between the antennas that are considered. The output of a radio-interferometer is the Fourier transform of the spatial distribution of the brightness of the source. The **Very Large Array** is a radio interferometer that consists of 27 antennas with a diameter of 25 m, located in New Mexico. The antennas can be arranged in various Y-shaped configurations, the largest one allowing a sub-arcsecond resolution.

Discovered in 1977, **the microquasar H1743-322** is a black hole candidate which has been in outburst several times during the past decades. After its reactivation in 2003, a bright radio flare (likely associated with a massive ejection event) was observed on April 2003. During the outburst, H1743-322 went through several X-ray states with properties typical of accreting black holes. There are now strong evidences supporting the picture of a ~10 M_{sun} non rapidly spinning black hole at ~8.5 kpc of distance.

Two large-scale jets have been detected in radio (ATCA) and X-rays (Chandra) by Corbel et al (2005). However, we have a **large amount (~70) of archival and unpublished Very Large Array (VLA) observations** of the same source, spanning from April 2003 to April 2004.
A deep analysis of this large set of observations will allow us to better understand the formation, the dynamical evolution of the relativistic jets and their interaction with the interstellar medium.

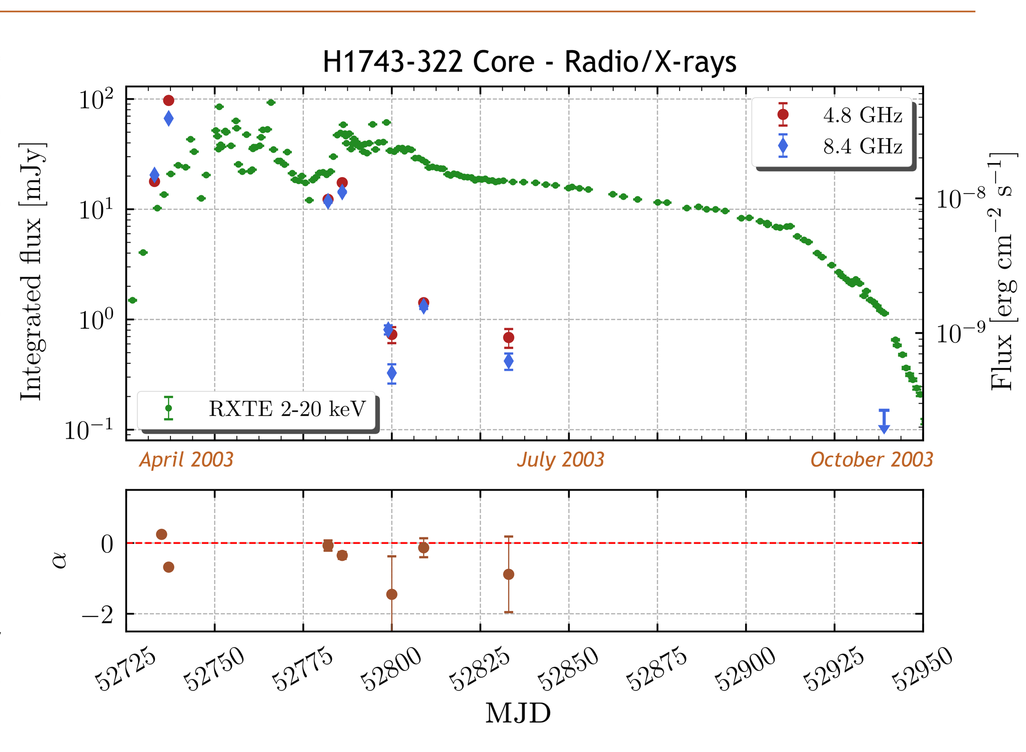
From April to July 2003, we detect the core at 4.8 and 8.4 GHz, covering the strong radio flare, which peaks at ~90 mJy in April. We also plot the X-rays light curve of the RXTE satellite from McClintock et al. (2009) in the 2-20 keV band. It provides information on the transitions between different spectral states, which depend on modifications in the accretion flow onto the black hole.

The obtained negative spectral index, defined as

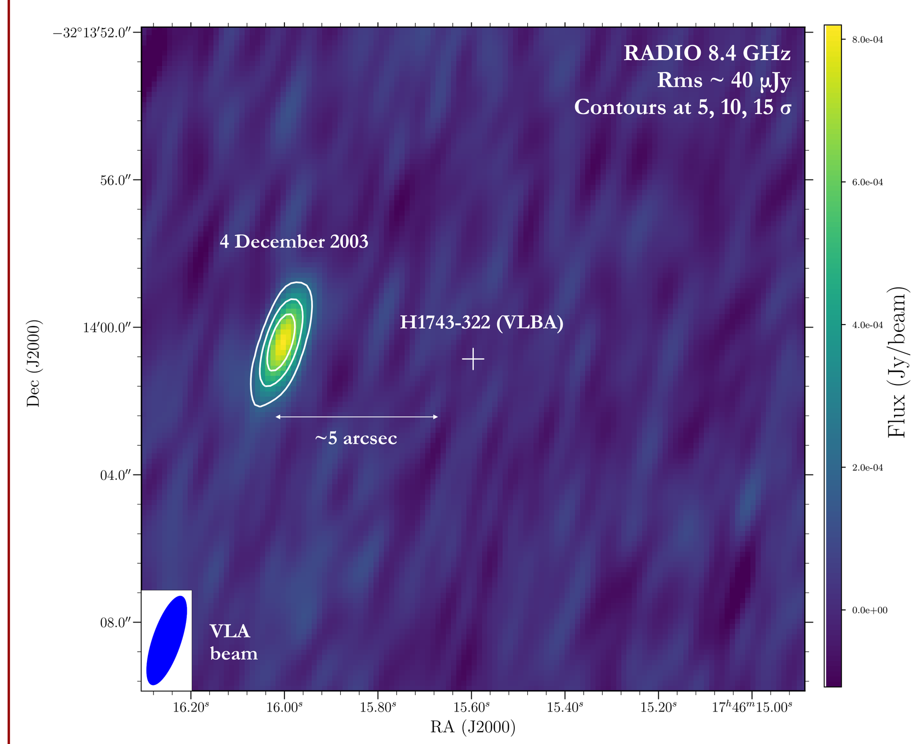
$$S_\nu \propto \nu^\alpha$$

where S is the flux density, points to an optically thin emission.

All these features are known signatures of the ejection of relativistic jet along the rotation axis.

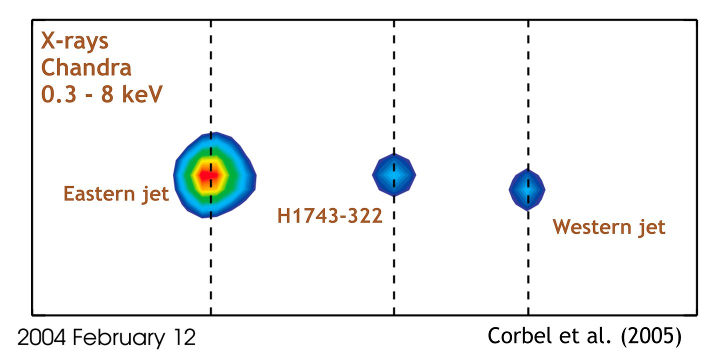


3 - The eastern jet



We considered 27 epochs so far, where the source has been observed at 4.8 and 8.4 GHz, using the CASA data reduction software. The data are calibrated in flux and phase and an image from each epoch is produced using the TCLEAN deconvolution algorithm. Particular attention has been taken in flagging data contaminated by environmental radio-frequency interference (RFI). A natural weighting scheme has been applied to the correlated data coming from all the baselines.

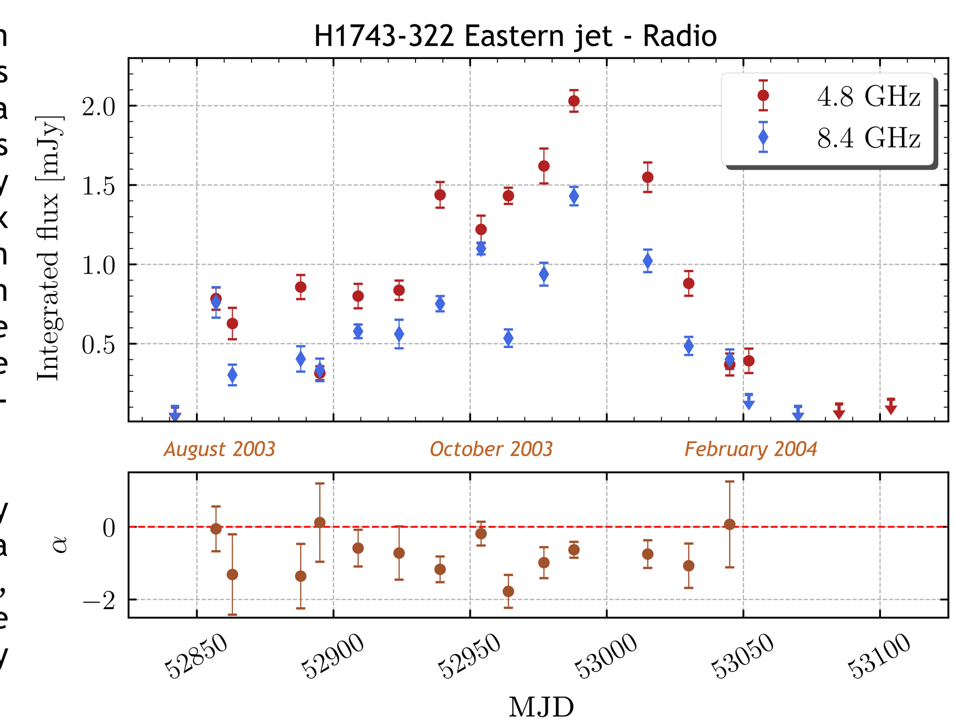
The jet is detected in ~20 epochs, from August 2003 to February 2004. A detection from the 4 December 2004 is shown. We clearly detect with high significance a radio emission displaced from the core position, which is obtained with high resolution Very Long Baseline Interferometry (VLBI) measurements.The emission comes from an unresolved point-source.



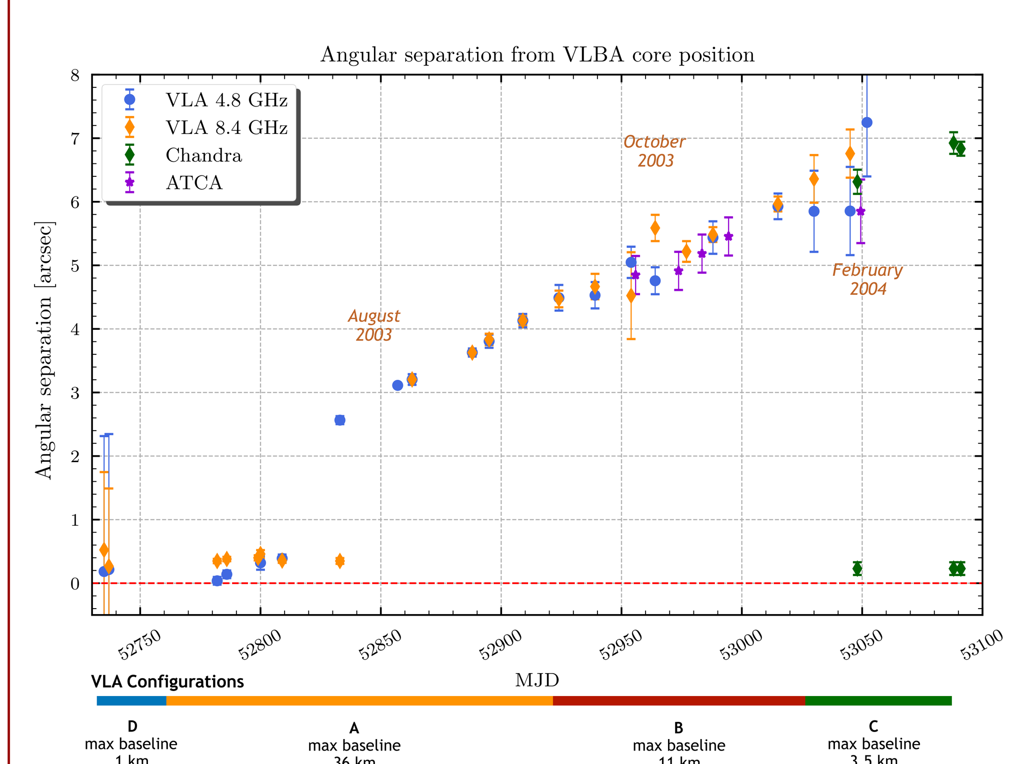
From Corbel et al. (2005), we have Chandra X-ray detections of the core and of the pair of jets, with the eastern showing a flux of ~10^{-14} erg/cm² s.The western jet, rising during the decay of the eastern, is unfortunately not seen by the VLA, since its emission is very faint and in February/March 2004 the array was not in the optimal configuration in terms of resolution.

We cover the entire jet emission period, from the rising to the decay phase. The jet flux is obtained with an elliptical Gaussian fit for a point source in the image plane. The peak is reached at ~2 mJy in November 2003, but way less variability with respect to core flux. The flux density at 4.8 GHz is almost always larger than the one at 8.4 GHz, pointing to a steep spectrum resulting from an optically thin emission, as we can see to the negative spectral index in the range ~[0, -2]. The upper limits on the non-detections are at 3σ level.

As for Corbel et al. (2005), the spectral energy distribution of the jet is consistent with a synchrotron spectrum from radio up to X-rays, that can be explained as radiation from the non-thermal electrons in the adiabatically expanding ejecta.



To track the jet that travels and interacts with the surrounding interstellar medium, we compute the angular separation (as great circle distance) between the position of the peak inferred from the fit and the position of the core obtained by Miller-Jones et al. (2012) with VLBI measures (VLBA instrument).



$RA_{core} = 17\ 46\ 15.59637 \pm 0.00006\ s$
$DEC_{core} = -32\ 14\ 00.860 \pm 0.002$

The first points on the left are the core detections, showing that our accuracy is limited around ~0.3 arcsec. Nevertheless, our measurements are consistent with the position obtained by Corbel et al. (2005) with ATCA and Chandra.

In its first detection, the jet is already at ~2.5 arcsec of separation, which is consistent the picture of a blob of plasma shocking the ISM. From then, the jet steadily travels away from the core. If, for simplicity, we assume no deceleration, we obtain a proper motion of 17.6 ± 0.1 μas/day, consistent with the 15.2 ± 1.6 μas/day obtained by Corbel et al. (2005).

4 - Future work

Work in progress: in order to improve our understanding of the jet dynamics and morphology for the 2003 ejection event of H1743-322, the next steps include:

- Data reduction and imaging of the other ~40 epochs left, from April 2003 to March 2004, to get a full coverage of the microquasar outburst and jet trajectory, in particular to clearly identify the date of ejection.
- Study of the polarization properties of the jet emission, to be able to infer the possible presence and orientation of magnetic field inside the jet plasma.
- Comparison with other known jets and test of the model on the parsec scale ISM cavities around the system.

Main references

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