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Cygnus X-3: A Fanaroff-Riley type II microquasar?

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Abstract. We report first results, based on VLA archival data, of the discovery of two radio sources at angular distances of few arc-minutes in almost perfect alignement with the position angle of the Cygnus X-3 sub-arcsecond radio jets. We discuss how our findings resemble the double lobe structure found at the jets terminal shocks in the Fanaroff-Riley type II extragalactic radio sources. We propose these radio sources to be hot spots in the terminal radio lobes of Cygnus X-3. The confirmation of such suggested hypothesis will provide an independent way to better constrain the energetics of such sources, and it will strongly enhance the quasar-microquasar analogy.

Key words. stars: individual: Cygnus X-3 – radio continuum: stars – X-rays: binaries

1. Introduction

Observational evidence of interaction between microquasar relativistic jets and their surrounding interstellar medium (ISM) continues being a difficult task for detection. A similar configuration of hot spot/double lobe structures observable in the active galactic nuclei (AGN) jet terminal shocks, a characteristic feature of extragalactic Fanaroff-Riley type II sources (FRII; Fanaroff & Riley 1974), is naturally expected to be seen in microquasars given the analogy of the physical mechanisms at work for both systems. The absence of such observational evidences is not well understood since these Galactic sources pump significant amounts of energy into the ISM via their relativistic jets that, in turns, should cause noticeable perturbations on it.

Only in four out of the fifteen cases currently recognized as microquasars (Paredes & Martí 2003), large-scale jet structures have been detected (e.g. 1E 1740.7-2942 Mirabel et al. 1992, GRS 1758-258 Rodríguez & Mirabel 1998, XTE J1550-564 Corbel et al. 2002 and Cygnus X-1 Gallo et al. 2005).

A possible explanation for the lack of large-scale structure in these objects suggested by Heinz (2002) points to the fact that the medium where microquasars are located might be of lower density than the AGNs environ-

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ments, which will prevent the display of the expected interaction signatures.

A main goal which has driven this work was to find evidence for the hot spot/double lobe structures at the jet terminal shocks. Following this idea, we initiated a careful search by looking for fainter radio sources, not previously noticed, which could be associated with the missing large-scale radio lobes. As a representative case of well known microquasar, Cygnus X-3 was chosen as a target. It exhibits a relativistic outflow at both arcsecond and sub-arcsecond scales.

Cygnus X-3 is a X-ray binary system composed by a compact object which nature is still not well established, either a neutron star or a black hole, and a WN Wolf-Rayet star (see e.g. Fender et al. 1999) as a companion.

2. VLA archival data

We retrieved three different 6 cm wavelength data sets from the Very Large Array (VLA) archive corresponding to three distinct projects and observation dates, but sharing common amplitude and phase calibrators.

After re-analysis of the data sets, a deep integration map ($\sim$ 8h) was obtained. This map revealed additional sources fainter and further away from the microquasar core not previously detected. In particular, two faint and asymmetrically located radio sources were clearly detected at angular distances of $7\farcm07$ and $4\farcm36$ from the core in the North-South direction and in almost perfect alignement with Cygnus X-3 core along a position angle (PA) of $1\fdg8\pm0\fdg1$. The observational properties of these newly discovered radio sources are summarized in Table 1.

The PA value agrees with the PA estimated for the inner arc-second radio jets (PA=$2\fdg0\pm0\fdg4$ Martí et al. 2001). Besides, the asymmetry observed between the separation of the sources recalls the existing asymmetry between the inner jet components at arcsecond scales, explained by moderate density gradients in the two regions of the ISM. A check for the dominant emission mechanism was carried out through the computation of the source spectral index α (defined as $S_\nu \propto \nu^\alpha$, where S_ν is the radio flux density at a given frequency ν), by combining information from 6 and 20 cm VLA archival data which yielded a negative value for this index (-0.4±0.2), suggesting a non-thermal synchrotron emission mechanism.

Considered together the almost coincident PAs for the sources/core and the small-scale jets, the asymmetry of the locations of the radio sources with respect to the core (similarly to the previously noticed for the small-scale jets), and the suggested dominant non-thermal synchrotron emission mechanism of the two radio sources discovered, we propose the sources as serious hot spot candidates (hereafter HSCs) and so, possible impact sites of the Cygnus X-3 jet against the ISM.

3. Search for X-ray, optical and NIR counterparts

In order to discard the possible stellar or extragalactic nature of the discovered sources, we performed a search for X-ray, optical and near-infrared (NIR) counterparts at the HSC locations.

We inspected several X-ray mission archives, including ROSAT, XMM and CHANDRA. An archival ROSAT PSPC image (0.76–2.04 keV) corresponding to the field of the HSCs was found. No counterpart was detected at the inferred upper limit count rate of 6.245 counts s^{-1}.

Neither an optical counterpart was detected after astrometry of I-band images at the precise HSC locations up to a limiting magnitude of I = 22.4 mag obtained with the SITe-d15 CCD detector of the CAFOS instrument at the 2.2m Telescope at the Centro Astronómico Hispano Alemán (CAHA).

And finally, the search for a NIR counterpart was strongly justified given the strong interstellar absorption in the Cygnus X-3 region (at least about A_V = 10 magnitudes and possibly higher). After close inspection of the data from the 2 Micron All Sky Survey (2MASS) at the position of the HSCs in J, H and Ks-band, no counterpart was found within a 4 arcsec of their radio position up to upper limit magnitudes corresponding to this survey.

Table 1. Radio properties of possible hot spots associated with Cygnus X-3 derived from VLA observations

Hot spot candidate	Position $\alpha_{J2000.0}, \delta_{J2000.0}$	Frequency (GHz)	Peak Flux Density* (mJy)	Integrated Flux Density* (mJy)	Spectral Index
North	$20^h32^m26\overset{s}{.}88\pm0\overset{s}{.}01$	1.425	1.63 ± 0.13	3.3 ± 0.5	−0.4 ± 0.2
	$+41°04'32\overset{''}{.}9\pm0\overset{''}{.}2$	4.860	1.25 ± 0.11	1.9 ± 0.4	
South	$20^h32^m24\overset{s}{.}97\pm0\overset{s}{.}02$	1.425	≤ 0.6	−	≥ −0.7**
	$+40°53'05\overset{''}{.}9\pm0\overset{''}{.}2$	4.860	0.27 ± 0.04	0.45 ± 0.09	

* Corrected for primary beam decay using the AIPS task PBCOR but not for bandwidth smearing.
** Computed using the peak and 4σ upper limit values corrected for bandwidth smearing.

4. Future work

We keep searching for possible evidences of any perturbation of the ISM that could reveal hints for explaining the difficulty in detecting large-scale jet structures on microquasars. In a more general way, we search for any evidence of a perturbed ISM, in terms of density gradients, velocities, etc. One of them could be, for instance, if the jet flows have evacuated a cavity in their path from the core to the lobes.

Our next plans include to get good radio maps to check whether the sources are resolved and elongated in the direction of the jets, as it should be expected if being part of a lobe structure. New observations with the targets placed at the phase center of the array will be free for known effects such as severe bandwidth smearing and strong primary beam correction that affected the archival data, and in turns, our preliminary results.

5. Conclusions

Two radio sources have been discovered in the vicinity of Cygnus X-3 based on a deep VLA map at 6 cm wavelength. We have compiled several observational evidences to propose them to be the hot spot candidates of the microquasar relativistic jet.

These observational evidences are:

- the position angle of the line joining the two HSCs agrees within one tenth of degree with the position angle of the inner arcsecond and sub-arcsecond jets.
- their spectral index is consistent with a non-thermal emission mechanism, which would naturally be expected from synchrotron radiation in the jet bow shocks.
- we did not find evidence for a point-like optical and NIR counterpart within the sensitivity of the present data, as should be expected in case of radio sources of stellar or AGN nature.

If the hot spot nature is confirmed by our planned observations, we estimate that the extent of the jet flow would be of the order of tens of parsecs.

Such confirmation would extend the analogy quasar-microquasar well beyond the accretion/ejection region including regions of interaction of their relativistic flows with the ISM far away from the core.

And finally, by adopting the dichotomy suggested in the extragalactic domain for radiogalaxies, we could especulate of being able to classify microquasars by using the same morphological scheme proposed by Fanaroff & Riley (1974).

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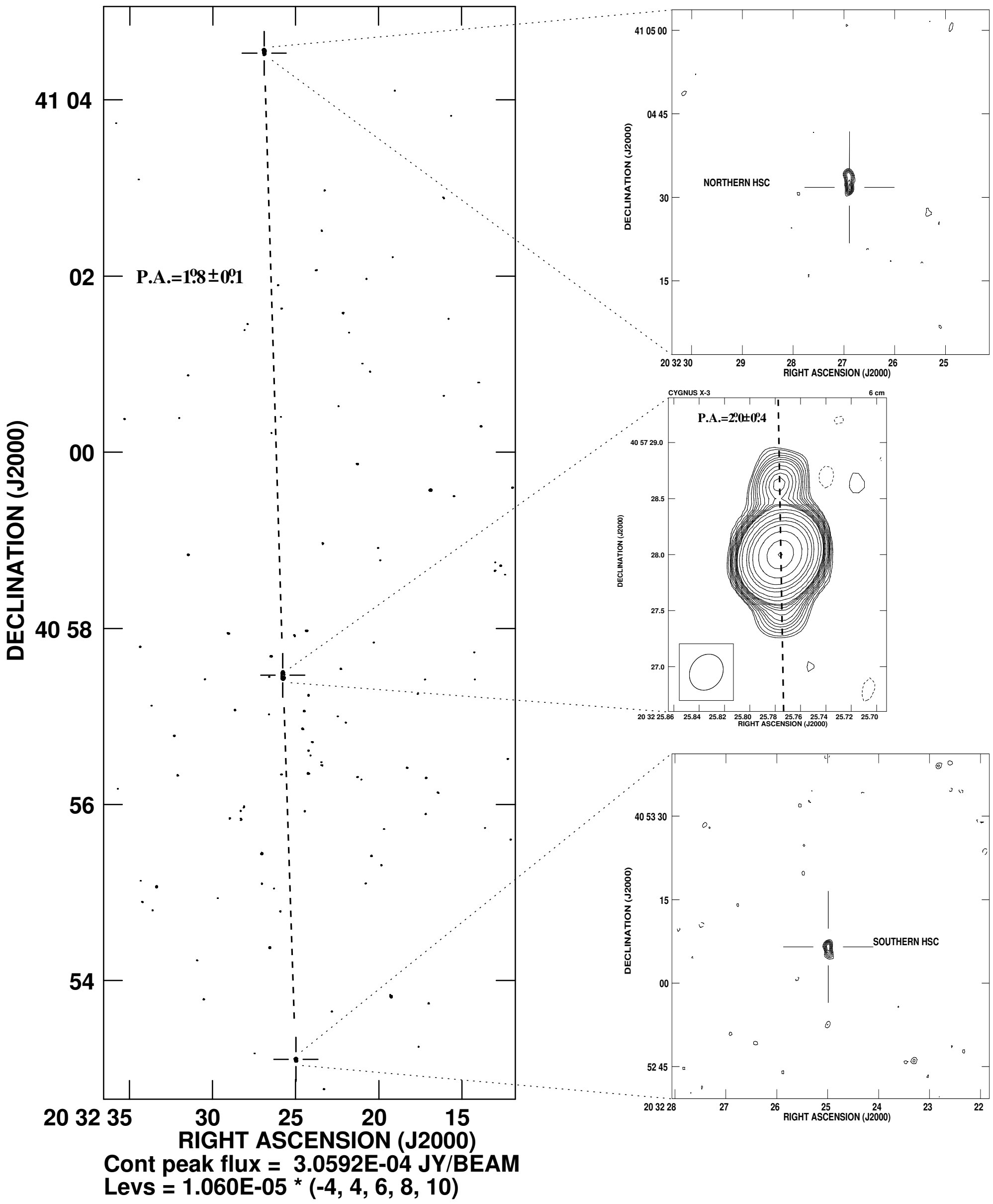

Fig. 1. Natural weight 6 cm map of the Cygnus X-3 field. This map covers almost the totality of the antenna primary beam and shows the existence of two radio sources perfectly aligned with the PA of the inner radio jets. A close-up look at the locations is given on the right top and bottom pannels. Note the remarkable effect of the bandwidth smearing that affected the archival data which caused the sources to appear elongated. The central pannel was taken from Marti et al 2001 and included for illustrative purposes corresponding to other observation of the Cygnus X-3 arc-second radio jets.

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