Proceedings of the 7th European VLBI Network Symposium
Bachiller, R. Colomer, F., Desmurs, J.F., de Vicente, P. (eds.)
October 12th-15th 2004, Toledo, Spain

Spectral Properties of the Core and the VLBI-Jets of Cygnus A

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Abstract. We present a detailed VLBI study of the spectral properties of the inner core region of the radio galaxy Cygnus A at 5 GHz, 15 GHz, 22 GHz, 43 GHz and 86 GHz. Our observations include an epoch using phase-referencing at 15 GHz and 22 GHz and the first successful VLBI observations of Cygnus A at 86 GHz. We find a pronounced two-sided jet structure, with a steep spectrum along the jet and an inverted spectrum towards the counter-jet. The inverted spectrum and the frequency-dependent jet-to-counter-jet ratio suggest that the inner counter-jet is covered by a circum-nuclear absorber as it is proposed by the unified scheme.

1. Introduction

Cygnus A is the closest ($z = 0.057$) strong FR II radio galaxy and therefore a key object for detailed studies of AGN. Its kiloparsec-scale structure in the radio bands is dominated by two prominent radio lobes which contain bright hot-spots. The radio core lies in the centre of an elliptical galaxy (Hargrave & Ryle 1974) and is powering the two thin jets and the radio lobes (e.g., Perley et al. 1984). Very Long Baseline Interferometry (VLBI) images from 1.6 GHz to 43 GHz obtained during the last 20 years (Carilli et al. 1991; Krichbaum et al. 1993; Carilli et al. 1994; Krichbaum et al. 1998; Bach et al. 2002, 2004) revealed a pronounced two-sided core-jet structure also on parsec scales. According to the unified scheme, narrow line radio galaxies, like Cyg A, should contain an obscuring torus around the central engine that blocks the emission from the broad line region (BLR) (e.g. Urry & Padovani 1995). Evidence for a hidden BLR in Cyg A comes from UV spectroscopy (Antonucci et al. 1994) and optical spectro-polarimetry (Ogle et al. 1997). Their results are supported by the detection of H I absorption near the core and on the counter-jet side (Conway & Blanco 1995). The idea of a ring or disk-like free-free absorber surrounding the nucleus is further supported from our multi-frequency VLBI studies, which show an inverted spectrum of the counter-jet and a frequency dependent jet-to-counter jet flux density ratio (Krichbaum et al. 1998; Bach et al. 2002).

In this study and with new data, we obtain further constrains for the circum-nuclear absorber. Here we show new spectral index maps of the innermost portion of the jet of Cyg A, obtained at frequencies from 5 GHz to 86 GHz.

2. Observations and Data Reduction

We carried out six multi-frequency VLBI epochs of Cyg A between 1996 and 2003, including a phase-referencing observations at 15 GHz and 22 GHz. We obtained the first VLBI image of Cyg A at 86 GHz, using the technique of fast frequency switching (Middelberg et al. 2002). A detailed observing log is given in Table 1.

The data were reduced in the standard manner using NRAO's Astronomical Image Processing System (AIPS). The imaging of the source employing phase and amplitude self-calibration was done using the CLEAN and SELFCAL procedures in DIFMAP. The self-calibration was done in steps of several phase-calibrations followed by careful amplitude calibration. A more detailed description of the data reduction can be found in Bach (2004).

Table 1. Observation log.

Epoch	ν [GHz]	$S_{\rm tot}$ [Jy]	Beam, P.A. [mas × mas], [°]	$S_{\rm peak}$ [$\frac{Jy}{beam}$]	σ [$\frac{mJy}{beam}$]	Pol.
1996.73 [a]	15.4	1.71	0.30 × 0.61, −18.3	0.40	0.36	dual
1996.73 [a]	22.2	1.48	0.24 × 0.47, −16.1	0.36	0.82	dual
1996.73 [a]	43.2	1.01	0.23 × 0.27, 3.6	0.40	1.90	dual
2002.03 [a]	4.9	0.89	0.92 × 1.54, −23.8	0.12	0.17	dual
2002.03 [a]	15.4	1.51	0.31 × 0.56, −21.3	0.28	0.12	dual
2002.51 [a]	4.9	0.91	0.87 × 1.56, −23.0	0.15	0.16	dual
2002.51 [a]	15.4	1.50	0.46 × 0.67, −14.4	0.39	0.17	dual
2003.04 [*]	15.4	1.27	0.46 × 0.73, −5.1	0.32	0.26	dual
2003.04 [*]	22.2	1.27	0.31 × 0.51, 10.4	0.34	0.45	dual
2003.24 [a]	4.9	0.99	1.10 × 1.72, −20.1	0.21	0.14	dual
2003.24 [a]	15.4	1.38	0.25 × 0.52, −23.4	0.23	0.12	dual
2003.27	14.4	1.52	0.45 × 0.68, 0.6	0.35	0.26	LCP
2003.27	43.1	0.75	0.16 × 0.26, −11.4	0.23	0.64	LCP
2003.27	86.2	0.41	0.32 × 0.36, 88.4	0.33	1.89	LCP

Note: The array used was the VLBA, unless indicated by a footnote. Epochs in bold face denote own data. a: VLBA+Eb. *: phase-referencing. Listed are the observing epoch, frequency ν, total flux density $S_{\rm tot}(\nu)$, beam size, beam position angle, peak flux density $S_{\rm peak}$, σ the rms noise of the map and polarization mode.

3. Results and Discussion

A collection of images obtained at different frequencies during 2003 is shown in Fig. 1. At 5 GHz the jet and the counter-jet extend up to ~ 50 mas from the core (1 mas $\approx$ 1.1 pc). The width of the gap of emission located $\sim 1 - 4$ mas east of the intensity maximum decreases with frequency, indicative of strong opacity effects on the counter-jet side.

The cross-identification was done using individual modelfit components along the jets. The identification was done using their relative separation from each other, their flux density and size. An upper limit of 0.2 mas for the shift of the brightest component between 15 GHz and 22 GHz could be derived from the phase-referencing observation (2003.04) and was used to constrain the identification. Component N was used as a reference point, and can be naively interpreted as being the nucleus. Our analysis, however, shows that it is more likely the first

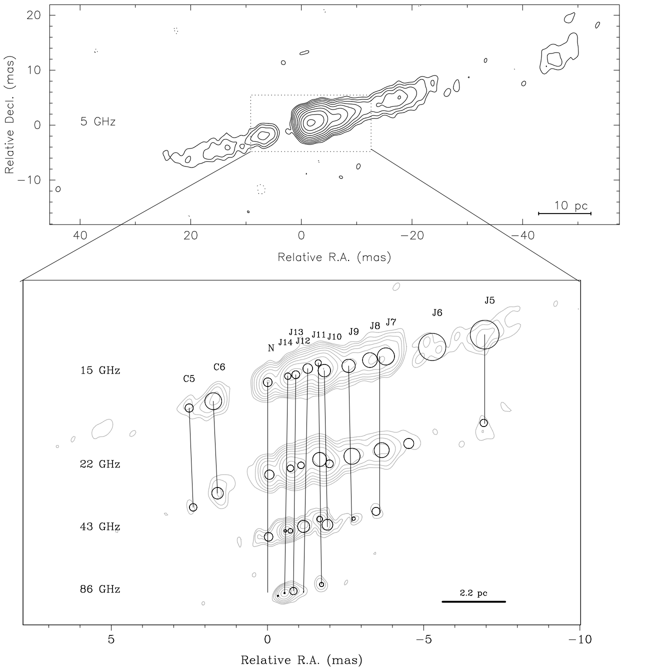

Fig. 1. VLBI images of Cyg A at 5 GHz (2003.24), 15 GHz and 22 GHz (2003.04, phase-ref.), 43 GHz (2003.27) and 86 GHz (2003.27). The beam size, peak flux density and rms noise are given Tab. 1. The lowest contours start at 3σ and increase by steps of 2. The bottom panel also shows the overlaid modelfit components and their identification between different frequencies.

counter-jet component while the true centre of activity might be located between N and J14 (Fig. 1 & Bach 2004).

Spectral index profiles of the inner region around the core are presented in Fig. 2 and show clearly the different behaviour of the spectral index at different frequency pairs. Most of the jet emission has a steep spectrum, whereas the counter-jet spectrum is flatter. The spectral properties in the core region, $(-2 \leq r \leq 1)$ mas, are much more complex, showing a highly inverted spectrum between 5 GHz and 15 GHz and also highly inverted regions at the higher frequency pairs, but always at different locations.

Synchrotron self-absorption can produce spectral indices of up to 2.5, but between $(-3 \leq r \leq 0)$ mas the spectral index between 5 GHz and 15 GHz exceeds this maximum significantly. The most likely explanation is that in this region the lower frequencies become affected by free-free absorption as observed, e.g., prominently in the lower-luminosity system NGC 1052 (e.g., Kadler et al. 2004). Recent simulations of radiative transfer models for obscuring tori in active galaxies which were applied to Cyg A (van Bemmel & Dullemond 2003) show that the spectral energy distribution (SED) is best fitted by an inclined ($\sim 50°$) torus of 10 pc to 30 pc, which is in good agreement with our results.

We estimate the absorption using fits of free-free absorbed synchrotron emission to the jet spectra. At the positions where we think free-free absorption is most relevant the resulting optical depth at 5 GHz is on average 4.3 ± 1.0. Assuming a typical temperature of 10^4 K and a path length of about 5 pc for the absorber, this correspond to an absorbing column density of $\sim 7 \times 10^{23}$ cm, which is within the uncertainties of the measurements in good agreement with the column density inferred from X-ray absorption of 4×10^{23} cm^{-2} (Young et al. 2002).

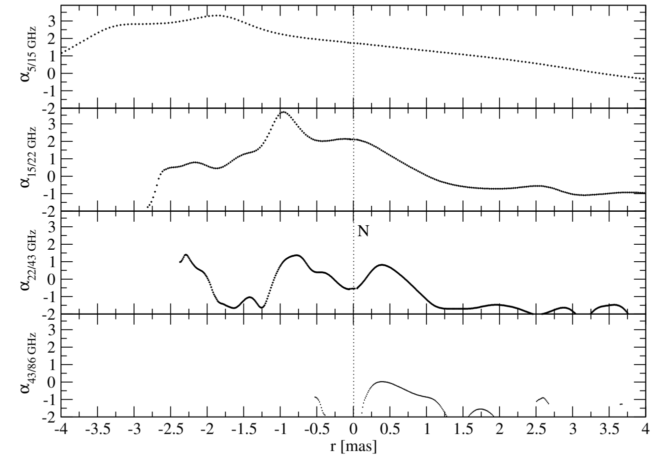

Fig. 2. Spectral index profiles between frequency pairs at (5, 15, 22, 43, and 86) GHz. The profiles represent cuts through spectral index maps along the ridge-line of the jet. The dotted line marks the position of component N.

To summarize, the emission gap between the jet and the counter-jet at 5 GHz seems to be the imprint of a circum-nuclear absorber which might cover also a large fraction of the counter-jet up to 20 mas and becomes optically thin further out, where the counter-jet shines through.

Acknowledgements. We thank the group of the VLBA 2cm Survey for providing their data. This work made use of the VLBA, and of the 100 m telescope at Effelsberg, which is operated by the Max-Planck-Institut für Radioastronomie in Bonn. U.B. acknowledges partial support from the EC ICN RadioNET. M.K. is supported for this research through a stipend from the International Max Planck Research School (IMPRS) for Radio and Infrared Astronomy at the University of Bonn.

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