Proceedings of the 6th European VLBI Network Symposium
Ros, E., Porcas, R.W., Lobanov, A.P., & Zensus, J.A. (eds.)
June 25th-28th 2002, Bonn, Germany

3C 310 and Hercules A: The pc-scale Study

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Abstract. We present the most recent results from the analysis of the radio data on the pc-scale structure of two unique radio galaxies, namely 3C 310 and Hercules A. The radio galaxies were observed at 18 cm by the Global VLBI and the EVN arrays respectively.
Two compact components are detected at the core region of 3C 310 at 4 mas with the global VLBI with angular size $\simeq 8\times7$, and $\simeq 8.8\times3.6$ mas and position angle ≈ 14.8 and ≈ 177 degrees. The corresponding total flux density is 9.5 and 8.8 mJy respectively. A possible misalignment is also found between the pc- and kpc-scale jets.
A faint but compact radio source, was detected by the EVN at the core region of Hercules A at 18 mas resolution. The total flux density of the EVN core is 14.6 mJy. Its angular size is 18×7 mas with a position angle of approximately 139 degrees. There is also evidence for extended emission in the NW-SE direction, most probably from the eastern pc-scale jet. If this is true then there is a misalignment between the direction of the pc-eastern and the aligned kpc-scale jets of about 35 degrees.

1. Introduction

3C 310 is a nearby (z=0.054), wide double radio source. It is identified with an elliptical galaxy with a double nucleus and absolute magnitude −23.20 at the R-band (van Breugel & Fomalont, 1984, Owen & Laing, 1989). It is at the center of the Zwicky cluster Z1500.6+2559 (Jenkins, Pooley & Riley, 1977, Burns & Owen, 1979). Its total X-ray luminosity is 9.8×10^{35} W in the 1–3 keV energy band.

The radio galaxy, with a linear size of 173 kpc, is classified as an FR1.5 (Owen & Laing, 1989). Total intensity and polarization maps at 4 arcsec resolution at 6 and 21 cm using the VLA (see Figure 1, left, van Breugel & Fomalont, 1984), have shown fine-scale structure embedded in large, diffuse, almost symmetrically extended lobes which consists of shells (rings) and filaments. Its total radio power is $P_{178\,\mathrm{MHz}} \sim 3.57 \times 10^{25}\,\mathrm{WHz^{-1}}$ at 178 MHz (assuming $\mathrm{H_\circ}$=65 km s^{-1} Mpc^{-1} and $\mathrm{q_\circ}$=0 throughout this paper). The VLA data revealed an unresolved, flat spectrum core with flux $\simeq$ 140 mJy at 21 cm. It is coincident with the center of the western nucleus of the bright pair of galaxies. At 6 cm the flux density and the total radio power of the core is $\sim$ 90 mJy and $P_{6\,cm} \sim 7.25\times10^{23}\mathrm{WHz^{-1}}$ respectively with the Westerbork array (van Breugel & Jägers, 1982).

Hercules A is an extended source at the low redshift of z=0.154. It is identified with a very elongated cD galaxy (Sadun & Hayes, 1993, Baum et al., 1996), with absolute magnitude −23.75 at the R-band (Owen & Laing, 1989).

ROSAT PSPC and HRI X-ray data (Gizani, 1997, Gizani & Leahy, 1999, Gizani & Leahy, 2002a) have revealed that Hercules A is situated at the center of a centrally condensed, hot cooling flow cluster. The unabsorbed luminosity of the extended emission is 3.16×10^{37} W. Assuming a power-law spectrum the 0.1–2.4 keV luminosity of the core is 2.0×10^{36} W.

Hercules A is the third-brightest double radio source in the northern hemisphere. Its total radio luminosity is $\sim 6.2 \times 10^{37}$ W and it is classified as an FR1.5 (Dreher & Feigelson, 1984). With a linear size of 540 kpc and a width of $\simeq$ 250 kpc, the radio galaxy possesses an unusual jet-dominated morphology, almost symmetrically extended lobes and no compact hot spots. The western jet shows partial or full ring-like features of enhanced radio brightness. In the eastern jet there is a sign of formation of features with a roughly helical appearance. Multi-frequency, multi-configuration total intensity and polarization VLA observations (see Figure 1, right, Gizani, 1997, Gizani & Leahy, 1999, Gizani & Leahy, 2002b) have revealed a strong depolarization asymmetry. Mainly, the depolarization is caused by a centrally condensed medium (most probably this is the 'X-ray' hot gas) in which Hercules A is embedded at $\simeq 50°$ to the line of sight. The spectral index analysis suggests that we may be witnessing a renewed outburst from the active nucleus (Gizani & Leahy, 2002b). The unresolved core, with the VLA, has a flux of 41 mJy at 18 cm at 1.4 arcsec resolution, it has a *steep spectrum*, it is optically thin and therefore it is apparently unusual.

2. The VLBI Observations

2.1. 3C 310

We made high resolution radio observations of the powerful extragalactic radio source, 3C 310 using the Global VLBI (the 7 element array of EVN and the VLBA), employing the phase referencing technique. With a resolution of $\sim$ 4 milliarcseconds, the observations probe the struc-

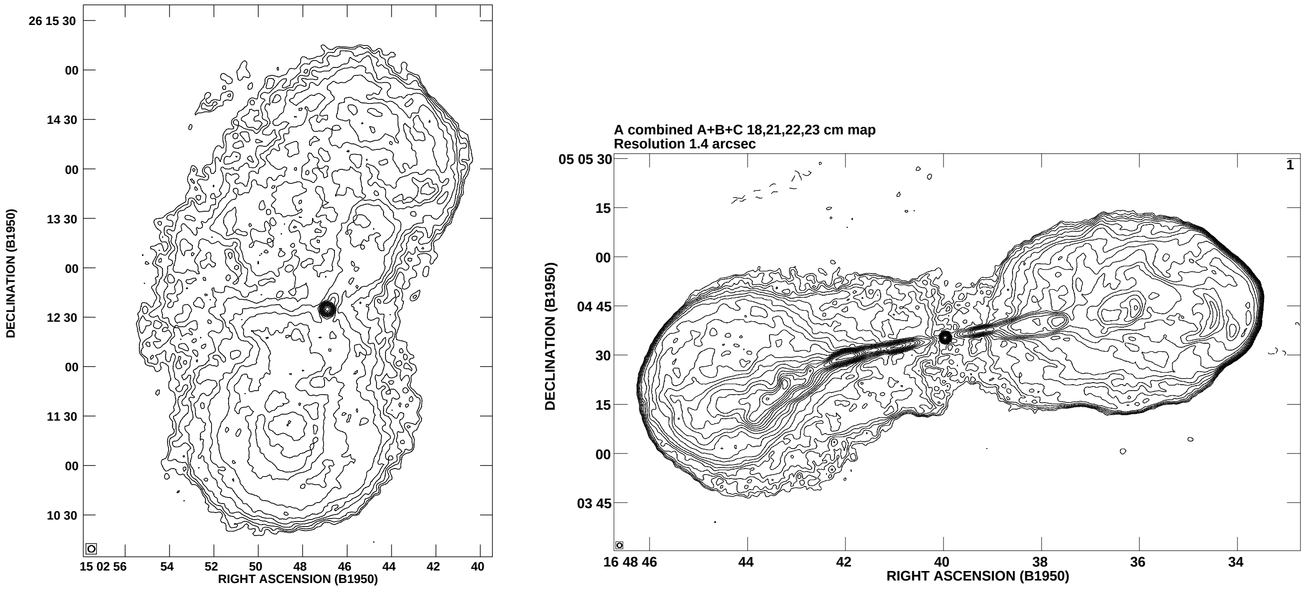

Fig. 1. Left: A total intensity VLA map of the 3C310 radio emission at 21 cm, at 4 arcsec resolution (van Breugel & Fomalont, 1984). The first non negative contour is at 0.5 mJy/beam. Right: The total intensity distribution of Hercules A at 20 cm created by combining the total intensity maps of each of the 4 frequency multi-configuration data of the L-band at 1.4 arcsec resolution. The first non negative contour is at 0.16 mJy/beam. In both images contours are logarithmic separated by factors $\sqrt{2}$.

ture of the source on 5 pc scales. At λ18cm a faint but resolved radio source was observed with an unusual structure. Two compact components and an extended emission are detected. The direction of this emission is NW, misaligned about 20° with the direction of the larger scale north-western jet in particular (see Figure 2, right).

Table 1 shows the results from the fitting of three Gaussians to the three areas of emission detected in the core region of 3C 310. The estimated errors were produced based on the rms noise level of $6.7{\times}10^{-5}$ Jy/beam. Based solely on the calculations of the highest brightness temperature, the results from the first Gaussian correspond presumably (but this may not be the case) to the core of 3C 310. Then the implied brightness temperature is $\sim 6.6 \times 10^7$ K. The estimated flux from the core region from the natural weighted image after fitting a Gaussian is $\simeq$ 16.5 mJy. The core size is $\approx 17{\times}5$ mas. These imply a brightness temperature of $2.5{\times}10^7$ K. In any case the values of the temperature brightness are typical of the core of low luminosity AGN (LLAGN) (Falcke et al., 2000).

There is also an indication of an extended emission in the NE/SW direction. The direction of this emission makes an angle of $\simeq 68^o$ with the south-eastern direction of the kpc-scale jet (see Figure 2). However the angle increases to $\simeq 100^o$ if we take the direction of the north-western jet. The direction of the small jet emanating to the south of the VLA core (see Figure 2, left) forms an angle of $\simeq 55^o$ with the NE/SW direction. The misalignment between pc and kpc jet structures is observed in many AGN. As the case of misalignment is clearer for Hercules A, possible explanations are given there (see next section).

2.2. Hercules A

We have observed the core of Hercules A with the EVN at 18 cm employing phase referencing (Gizani, Garrett & Leahy, 2001, Gizani, Garrett & Leahy, 2002). Figure 3, top shows the EVN map obtained. Since the phase referencing did not work the axes of the map do not show absolute positions. The resolution obtained is $\sim$ 18 milliarcseconds which corresponds to a linear size of 50 pc. A faint but compact source was detected coincident with the optical center of Hercules A. The flux density is $\simeq$ 15 mJy, which indicates a radio power of 3.6 $\times 10^{22}$ W Hz^{-1}Sr^{-1}. The implied brightness temperature of the compact core is $\simeq 2 \times 10^7$ K, typical of LLAGN. The core is still unresolved at 18 mas and very weak. There is also an indication of emission from the core region in the NW/SE direction (see Figure 3, top). If this is indeed the case, then there is a misalignment between this direction (at least of the eastern pc-scale jet) with the kpc-scale jets of $\sim 35^o$. Table 2 shows the parameters from the gauss-Ian fit to the core of Hercules A.

Table 2 shows the parameters from a single Gaussian fit to the core of Hercules A. The estimated errors were produced based on the rms noise level of $3.6{\times}10^{-4}$ Jy/beam.

In the case of Hercules A, it is possible that the extended structure we see is actually a one-sided, asymmetric core-jet structure. The high resolution radio and X-ray observations Gizani & Leahy, 1999 suggest that the radio source is situated at the center of a cooling flow cluster filled with a dense intra-cluster gas. The Doppler

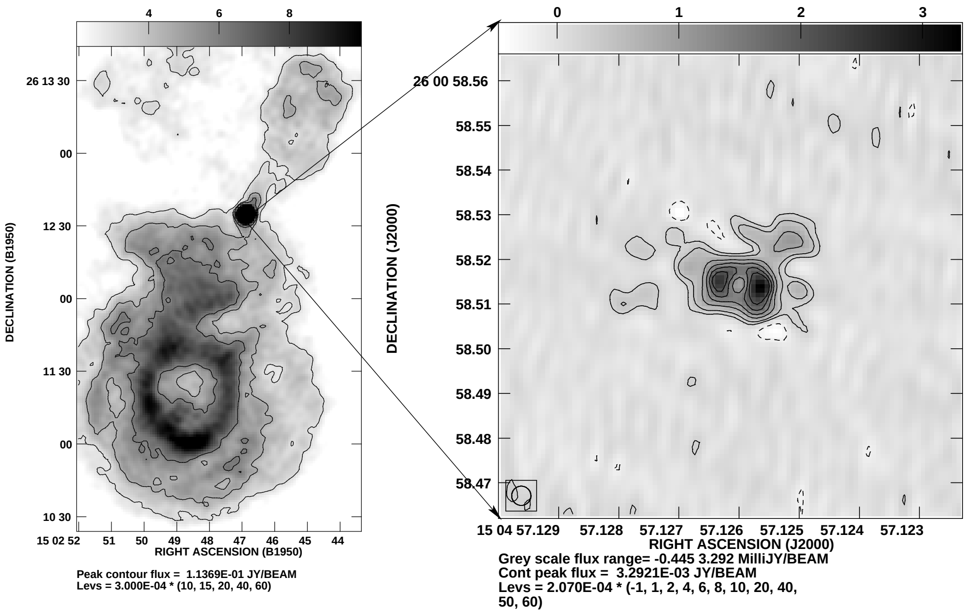

Fig. 2. Left: A grey scale VLA map of the central region of 3C310 emphasizing the jets and the ring-like features of the radio source (adapted from van Breugel & Fomalont, 1984). The total intensity contours are superimposed. Right: The global VLBI map of the central region of 3C 310 at 18 cm with 4 mas resolution. A complicated structure is revealed, see text.

Table 1. Parameters of the Gaussian fit to the global VLBI data of the core of 3C 310.

Parameters	1-Gaussian	2-Gaussian	3-Gaussian
Total Flux (mJy)	9.5±0.3	8.8±0.2	4.7±0.3
Peak Flux (mJy/beam)	2.3±0.06	3.0±0.06	1.0±0.06
Maj. Axis (mas)	8.0	8.8	11.3
Min. Axis (mas)	7.0	3.6	5.5
p.a. (degrees)	14.8	177.0	90.2

Table 2. Parameters of the Gaussian fit to the EVN data of the core of Hercules A.

Total Flux mJy	Peak Flux mJy	Maj. Axis mas	Min. Axis mas	p.a. degrees
14.6 ±0.8	9.6 ± 0.35	18	7	139

boosted eastern jet is heading towards us at a substantially large angle to the line of sight. According to this scenario the core in the EVN image would be situated at the extreme NW of the emission. The brightest component of the EVN emission would then be identified with the inner pc-scale jet directed eastwards, towards the brighter larger scale jet. However the pc-scale jet changes direction as it emerges from the core since it is decelerated. The presence of a gap between the pc- and kpc-scale jets (see Fig 3, bottom) indicates that the jets emanating from the nucleus are disrupted and this is likely to be due to the strong interaction between the energy flow and the environment. Alternatively the lack of an extended counter-jet could be explained by free-free absorption of a circum-nuclear torus.

3. Conclusions

We made high resolution Global VLBI observations of the core of the radio galaxy 3C 310 at 18 cm at 4 mas. An interesting and complicated structure was revealed consisting of two compact features with total flux density of 9.5 and 8.8 mJy, angular size $\simeq 8 \times 7$, and $\simeq 8.8 \times 3.6$ mas and position angles ≈ 14.8 and ≈ 177 degrees respectively. We assume that the component with the highest brightness temperature of $\simeq 7 \times 10^7$ K, with flux 9.5 mJy corresponds to the position of the central engine of 3C 310. An extended emission was also detected in the NW direction misaligned with the direction of the north-western kpc-scale jet. However there is an indication of another extended emission in the NE/SW direction which also seems to be misaligned with the kpc-scale jets.

We have also observed Hercules A in pc-scales with EVN at 18 cm. About 30% of the VLA flux is detected from the core area at 18 mas with angular size $\simeq 18 \times 7.0$ mas and position angle $\simeq 139^o$. Its brightness temperature is 2×10^7 K. The core remains unresolved as it is very weak. There is evidence of a possible pc-scale asymmetry. If this is indeed the case then there is a misalignment between the pc- and kpc-scale jet (at least the eastern one) of $35°$.

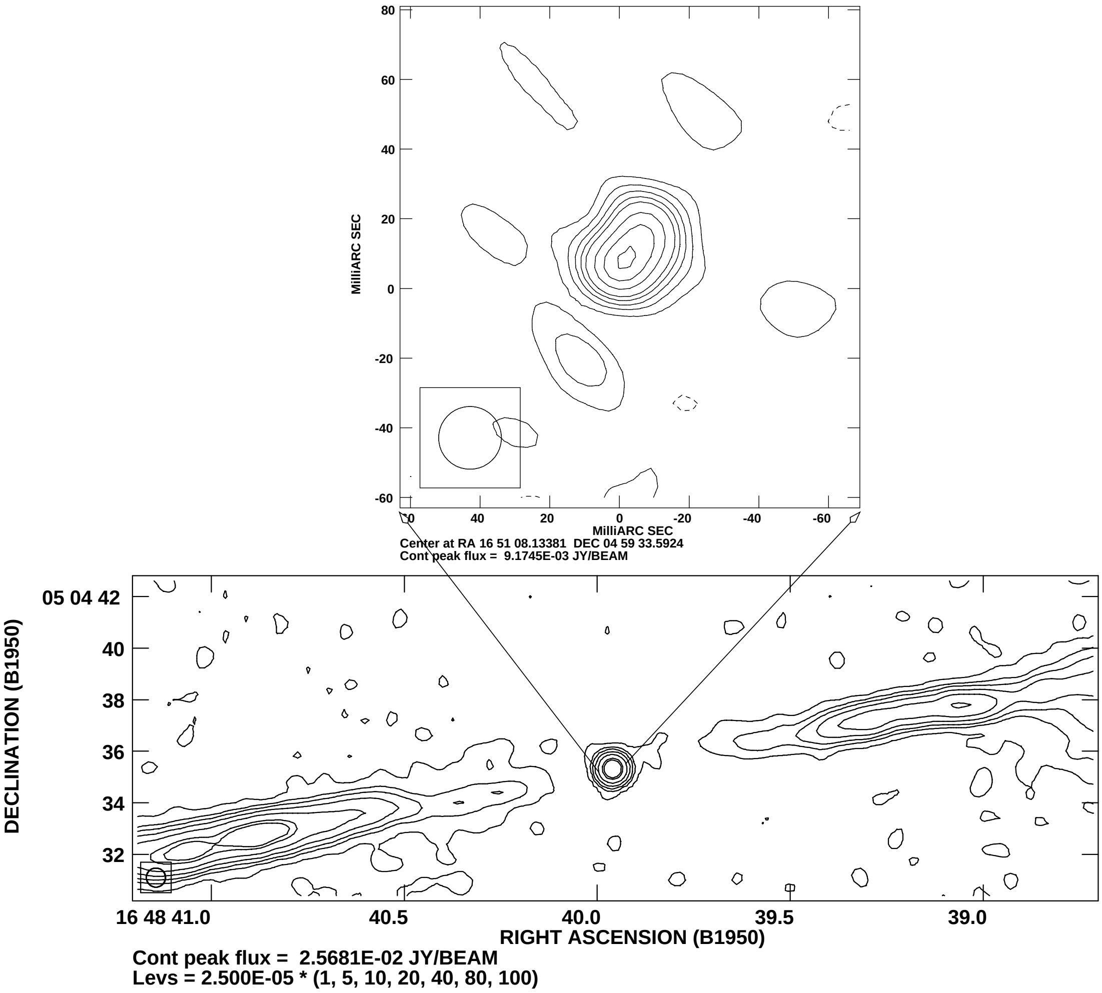

Fig. 3. Bottom: Total intensity contours of the radio emission of Hercules A with the VLA at 3.6 cm with 0.74 arcsec resolution emphasizing the central kpc-scale region of the radio galaxy. The core is unresolved. Top: The EVN map of the core region at 18 cm at 18 mas resolution. There is evidence for extended emission in the NW/SE direction, see text.

The resolution of the observations is not sufficient in order to find out what is the most likely interpretation for this small scale asymmetry.

Acknowledgements. The European VLBI Network is a joint facility of European and Chinese radio astronomy institutes funded by their national research councils. This research was supported by the European Commission's IHP Programme "Access to Large-scale Facilities", under contract No. HPRI-CT-1999-00045. We acknowledge the support of the European Union - Access to Research Infrastructure action of the Improving Human Potential Programme. NG also acknowledges her post-doc grant PRAXIS XXI/BPD/18860/98 from the Fundação para a Ciência e a Tecnologia, Portugal. M.A.G. acknowledges partial support from the EC ICN RadioNET (Contract No. HPRI-CT-1999-40003).

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