VLBI Observations of a complete sample of radiogalaxies.

VI-The Two FR-I Radio Galaxies B2 0836+29 and 3C465

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Abstract

We present 5 GHz global VLBI observations of the two Fanaroff Riley Type I radio galaxies B2 0836+29 and 3C465 (2335+26). For 3C465 we present also 1.7 GHz and 8.4 GHz global VLBI data. In addition VLA observations were used to obtain arsecond resolution continuum and polarization maps at 5 GHz.

Both sources are very asymmetric on the parsec-scale, with a core and a one-sided jet, aligned with the main arcsecond scale jet. We place a limit on the milliarcsecond jet to counterjet brightness ratio $B_{jet}/B_{cjet} \gtrsim 20$ and $\gtrsim 30$ for B2 0836+29 and 3C465 respectively. For 3C465 the strong asymmetry holds to the kiloparsec scale.

The brightness asymmetry and the ratio between the core radio power and total radio power allow us to constrain the jet velocity close to the core and the orientation of the radio structure with respect to the line of sight. The results suggest that the plasma speed is relativistic on the parsec scale for both sources, i.e. $v_{jet} \gtrsim 0.75c$ for B2 0836+29 and $v_{jet} \gtrsim 0.6c$ for 3C465. While v_{jet} decreases from the parsec to the kiloparsec scale in B2 0836+29, in 3C465 the very high v_{jet} holds all the way to the kiloparsec-scale bright spot.

Our results are in agreement with the unification scheme suggestion that FR-I radio galaxies are the unbeamed poulation of BL-Lac objects. Furthermore, they reinforce the idea that the central engine in FR-I and FR-II radio galaxies must be qualitatively similar. The different radio morphology could then be due either to an intrinsically different nuclear power, which affects the torus geometry or to different conditions in the region beyond the parsec scale, where a significant deceleration in the FR-I jets occurs.

Subject headings: galaxies: individual (B2 0836+29, 3C465) - galaxies: nuclei - radio - continuum: galaxies - techniques: interferometric

1. Introduction

This is the sixth of a series of papers, whose main aim is to present and discuss the observational and physical properties of the parsec-scale radio emission in a sample of low-intermediate luminosity radio galaxies.

VLBI observations of radio galaxies are critical to address a number of questions, such as the properties of AGNs and the validity of the unified schemes. According to the unified models, the low luminosity Fanaroff-Riley Type I (FR-I) radio galaxies (Fanaroff & Riley, 1974) are expected to be the parent population of BL-Lacertae type objects, while the more powerful FR-II radio galaxies would be the parent population of radio loud quasars, the difference in their observed properties being entirely due to orientation effects (see Antonucci, 1993 and references therein, for an updated review of the current models and ideas). On the other hand, the intrinsic properties, such as for example the Lorentz factor γ, should be the same in the two classes.

To investigate these topics we are observing a sample of radio galaxies at VLBI resolution. The sample has been presented in Giovannini, Feretti & Comoretto (1990, Paper I), while a detailed discussion on individual sources observed thus far has been presented in the following papers: NGC315, Venturi et al., 1993, Paper II; 3C338, Feretti et al., 1993, Paper III; NGC2484, 3C109 and 3C382, Giovannini et al., 1994, Paper IV; 4C31.04 and 3C346, Cotton et al., 1995, Paper V.

In this paper we present VLBI and VLA observations of two FR-I radio galaxies in the sample, B2 0836+29 and 3C465, associated with the brightest cluster member at the center of the rich Abell cluster of galaxies A690 and A2634 respectively.

While FR-I radio galaxies are well studied on the large (kiloparsec) scale, little is known about their parsec-scale properties, mainly as a consequence of their low power radio core, which has severely limited radio observations. According to current theoretical models by Laing (1993) and Bicknell (1995), jets in FR-I radio galaxies are expected to be relativistic at their origin, as in FR-IIs, however they are strongly decelerated on the kiloparsec scale. With the present paper we want to add further information to the parsec-scale plasma speed in low luminosity radio galaxies.

A Hubble constant $H_0 = 100$ km sec^{-1}Mpc^{-1} and a deceleration parameter $q_0 = 1$ are assumed throughout the paper.

2. The Sources

The two radio galaxies investigated here have very similar properties. They are both identified with the dominant member of a rich Abell cluster, and their total radio power is close to the upper limit of the FR-I radio power range. Their large scale radio structure shows distortions, typical of *wide angle tail* radio sources (Owen & Rudnick, 1976), probably due to the interaction of the hydrodynamic flow with the surrounding cluster medium (O'Donoghue, Eilek & Owen, 1993). This class of radio sources is characterised by radio power and morphological properties typical both of FR-Is and FR-IIs. The present sources have a rather bright core and two-sided jets, strongly asymmetric in brightness, with the main jet well collimated and with a small opening angle, as it is typical for jets in FR-II radio galaxies. In both cases one of the two jets ends in one *bright spot*, similar to the hot spots which characterise FR-II radio galaxies. Both sources are characterised by diffuse and distorted lobes, as it is observed in FR-Is

2.1 B2 0836+29

B2 0836+29 (4C29.30) is an extended, *wide angle tail* radio source. Its optical counterpart ($RA_{(1950)} = 08^h36^m13.571^s$, $DEC_{(1950)} = 29°01'14.76''$) is a multiple nuclei cD galaxy (Owen, Rudnick & Peterson, 1977), at a redshift of 0.0788, dominating the rich cluster of galaxies Abell 690 (Owen, White & Thronson, 1988). The absolute optical magnitude of the galaxy is M_V = -22.4 (Giovannini et al., 1988).

The large scale radio properties of B2 0836+29 were studied in detail by many authors (Fanti et al., 1987, O'Donoghue, Owen & Eilek, 1990, Capetti, Fanti & Parma, 1995, hereafter CFP95). Its total radio power at 408 MHz is 1.2×10^{25} W/Hz (logP = 25.08). The kiloparsec-scale radio emission is dominated by two lobes: the southern lobe has a tail-like shape extended $\sim 4'$, ($\sim$ 250 kpc), while the northern one extends for $\sim 5'$ ($\sim$ 300 kpc) and shows only minor distortions. The radio galaxy jets are asymmetric on this scale, with the counterjet shorter and weaker than the main jet. The main jet is not straight, but shows oscillations of few degrees amplitude around an average position angle of $\sim 0°$. The jet properties and the jet/counterjet brightness ratio were discussed in CFP95, who also presented and discussed the polarization properties. The plasma speed along the jet is estimated to be relativistic out to a distance of $\sim$ 5 kpc, then entrainment from the external medium causes deceleration. The radio emission in the source is polarized both along the jet and in the low brightness tails. The magnetic field geometry along the main jet switches from longitudinal to transverse, to longitudinal again. No radio variability in the radio galaxy core has been reported.

The radio galaxy is embedded in the intracluster gas, whose presence is witnessed by detected extended X-ray emission. The northern jet is coincident with a high X-ray brightness region of the cluster, while both tails are at the edge of the X-ray emission. Morganti et al. (1988)

report that the northern jet is overpressured, while both lobes are thermally confined by the intracluster gas. The nuclear X-ray emission is very faint (Bloom and Marscher, 1991), i.e. 0.03 μJy at 2 Kev.

For this galaxy we present 5 GHz global Very Long Baseline Interferometry (VLBI) data and Very Large Array (VLA) observations simultaneous with VLBI. At the distance of this source, 1 mas corresponds to 1.0 pc.

2.2 3C465

3C465 is associated with the giant D galaxy NGC7720 ($RA_{(1950)} = 23^h 35^m 58.1^s$, $DEC_{(1950)} = 26°45'15''$, Dressler, 1980) located at the center of the rich cluster of galaxies A2634 (Zhao, Burns & Owen, 1989) at a redshift z=0.0322. The optical associated galaxy, with M_V = -22.2 (Giovannini et al., 1988), exhibits distorted isophotes, with two gravitationally bound nuclei surrounded by a common envelope. De Robertis and Yee (1990) found a weak, high ionisation emission line spectrum in the nuclear region of the galaxy. Weak broad H_α is also present, and this strongly suggests the presence of faint activity in the optical nucleus in 3C465.

3C465 is the prototype of *wide angle tail* radio galaxies (Eilek et al. 1984): two aligned, strongly asymmetric jets are ejected from the radio nucleus, associated with the strongest optical component within the envelope. The fainter south-eastern jet flares out into a bright spot at $\sim 30''$ from the core, beyond which it forms a distorted lobe, extended $\sim 5'$. The main, north-western jet has a brightness peak at $\sim 30''$ from the core, then it starts bending and forms an extended ($\sim 5'$), distorted lobe. Its total power at 408 MHz is 2.0×10^{25} W/Hz (logP = 25.30). The radio jet, the spots and the low brightness tails are strongly polarized. The magnetic field remains longitudinal along the whole length of the jet, before it forms the bright spot.

The core flux density of 3C465 was monitored from 1976 to 1980 (Ekers et al. 1983). A marginal evidence ($\sim 3\sigma$ level) of nuclear variability was found.

The whole radio galaxy is embedded in the X-ray emission coming from the cluster (Burns et al., 1994).

We present VLBI observations of this radio galaxy at 1.7 GHz, 5 GHz and 8.4 GHz and a VLA observation at 5 GHz, obtained during the 5 GHz VLBI observation.

At the distance of the cluster, 1 mas corresponds to 0.44 pc.

3. Observations, Data Reduction and Results

3.1 B2 0836+29

3.1.1 VLBI and VLA Observations and Data Reduction

The source was observed in November 1990, at 5 GHz, with a VLBI array consisting of 8 radio telescopes. In Table 1 we report frequency, recording system, array, u-v range, duration of the observation and observing epoch. The data were recorded with the MKIII recording system (Alef, 1989), with a 28 MHz bandwidth (mode B). and were correlated in Bonn. The final u-v coverage (after editing to remove the bad data) is shown in Fig. 1a.

The VLBI data reduction was carried out following the standard procedure. The visibility amplitudes were calibrated using the gain values and the system temperatures measured during the observations at each site. Further corrections to the antenna gains, of the order of a few percent, were applied comparing the flux density of the VLBI calibrator as measured with the Bonn antenna during the VLBI observations. The calibrated data were global fringe fitted (Schwab and Cotton, 1983), self calibrated and mapped using the NRAO Astronomical

Image Processing System (AIPS). The final VLBI map is given in Fig. 2, and the map parameters are given in Table 2.

The phased VLA took part in the VLBI observations in the C configuration. The VLA antenna gains and phases were calibrated by means of standard VLA calibrators. Total and polarized VLA intensity maps were produced. Map parameters are given in Table 3.

3.1.2 The parsec-scale properties

The parsec-scale morphology of B2 0836+29 (Fig. 2) consists of a one-sided structure, i.e. an unresolved dominant component with an elongated jet, oriented to the north and aligned within a few degrees with the strongest kiloparsec-scale jet.

The total VLBI flux is the same as the arcsecond core flux, measured by us at the epoch of the VLBI observations, so we are confident we have mapped the whole parsec-scale structure. The strongest VLBI component contains $\sim$ 88% of the total VLBI flux. Such percentage should be considered an upper limit, since the beam is very elongated along the jet direction and the VLBI core flux could be contaminated by the beginning of the northern jet. The arcsecond core spectrum is inverted between 1.4 GHz and 5 GHz (CFP95), therefore we treat the strongest VLBI component as the core of the radio galaxy.

The radio emission along the jet shows three peaks respectively at $\sim$ 6 mas, at $\sim$ 12 mas and at $\sim$ 16 mas from the core. The latter one is a well separated blob, misaligned by a few degrees with the main jet direction. No counterjet is visible either in the full resolution VLBI map shown here, or in a low resolution map obtained by omitting the longest baselines. We point out that the shape of the beam, very elongated in the north-south direction, would hide a short counterjet, if present. We quantify the jet/counterjet brightness asymmetry by placing a lower limit $R = \frac{B_{jet}}{B_{cjet}} \gtrsim 20$ at 6 mas from the core.

3.1.3 The kiloparsec-scale properties

In Fig. 3 we present the map obtained with the VLA at the time of the VLBI observations. A more detailed map of the core and jets with polarized B vectors superimposed is given in Fig. 4. The different regimes in the northern jet, where the polarization vector flips from perpendicular to parallel, to perpendicular again, are clearly visible in this map. The brightness decrease along the jet and the expansion of the jet are in very good agreement with the results presented and discussed in CFP95.

We used our VLA map (Figs. 3 and 4) to determine the jet/counterjet brightness ratio R at different distances from the core. We find a value $R \sim 7$ up to 15 kpc from the core, $R \sim 4$ in the range 15-20 kpc, and $R \sim 2$ in the range 20 - 31 kpc (see Table 4). Such decrease of the ratio R as a function of the distance from the core is consistent with the trend given in CFP95.

3.2 3C465

3.2.1 VLBI and VLA Observations and Data Reduction

This source was observed with VLBI at three different frequencies, i.e. 1.7 GHz, 5 GHz and 8.4 GHz, with different recording systems. The observational parameters are given in Table 1 and the u-v coverage is given in Figs. 1b-d.

The 1.7 GHz and 8.4 GHz observations were carried out with the MKII recording system. The telescopes taking part to the observations are gven in Table 1. The data were correlated with the MKII Block 2 correlator at Caltech. The data were first global fringe fitted by means of the task FRING in AIPS (Schwab & Cotton, 1983), then the rest of the data reduction was carried out with the VLBI Caltech package (Pearson, 1991). The observed visibilities were first modelfitted, and the best model obtained from modelfitting was used as starting point in the self-calibration procedure. Phase self-calibration was applied at the beginning, and only when the phase corrections were stable we allowed for few cycles of amplitude and phase self calibration. Gain corrections were of the order of 5% for both datasets. The final maps were done in AIPS.

Global VLBI observations (EVN+USVN) at 5 GHz were carried out with the MKIII Mode B recording system (see *Sect. 3.1.1*) and were correlated in Bonn. The data reduction (global fringe fitting, calibration, editing and self-calibration) was carried out entirely with the AIPS package. Self-calibration started with a point source, and the final convergence between the source model and the visibilities was reached after 12 self-calibration cycles. Amplitude self-calibration was applied only in the last two cycles, when the phase corrections were stable. Gain corrections were within 5%.

The contour plots of the VLBI maps at each frequency are given in Figs. 5a-c. The 8.4 GHz map shown in Fig. 5c is convolved with a beam larger than that of the full resolution in order to emphasise the structure of the jet. The observational parameters in each map are given in Table 2.

The VLA phased array in the C configuration was used for our 5 GHz VLBI observations, allowing us to map the source at arcsecond scale. The antenna gains and phases were calibrated by means of standard VLA calibrators. Total and polarized intensity maps are shown in Fig. 6 and 7, respectively.

3.2.2 The parsec-scale morphology and spectrum

The parsec-scale morphology of 3C465 is one-sided at each frequency (Figs. 5a-c). The parameters of the VLBI maps at the various frequencies are given in Table 2. The correlated flux in the parsec-scale structure is $\sim$ 95% of the arcsecond core flux density measured from the VLA map obtained during the VLBI observations.

The milliarcsecond-scale jet in 3C465 is on the same side as the main arcsecond-scale jet. There is however a minor misalignment between the two, the VLBI jet being oriented in position angle $\sim -49° \pm 2°$ at the three frequencies, while the main arcsececond-scale jet is oriented in p.a. $\sim -56° \pm 2°$.

The brightness along the jet decreases smoothly at 1.7 GHz, with a knot of radio emission at $\sim$ 50 mas from the peak (Fig. 5a). In the 5 GHz and 8.4 GHz maps the jet is resolved in knots of radio emission (Figs. 5b and 5c). At 8.4 GHz the transverse size of the jet is at the limit of the resolution along all its length, i.e. out to $\sim$ 4 pc from the core. The brightness decreases from 20 mJy/beam at $\sim$ 1 pc to 2 mJy/beam at $\sim$ 6 pc.

We derived the jet/counterjet brightness ratio from the 8.4 GHz map, since the high resolution of the map, coupled with the knotty structure of the source at this frequency, enables us to constrain the ratio with better accuracy. At $\sim$ 1 pc from the peak ($\sim$ 2.3 mas), we obtain a lower limit $R = \frac{B_{jet}}{B_{cjet}} \gtrsim 30$.

The integrated spectrum of the VLBI structure, derived from our full resolution total intensity maps (see Table 2), is peaked around 5 GHz, being $\alpha_{1.7GHz}^{5GHz} = -0.13 \pm 0.02$ and $\alpha_{5GHz}^{8.4GHz} = 0.39 \pm 0.04$ ($S \propto \nu^{-\alpha}$).

The determination of the core and jet spectral index is difficult in both frequency ranges, though for different reasons. Between 1.7 GHz and 5 GHz we can derive only the core spectral index, because of the very different u-v coverage at these frequencies (see also Table 1 and Fig. 1). From the full resolution maps we obtain $\alpha_{1.7GHz}^{5GHz} \lesssim 0.07 \pm 0.09$. This value should be considered an upper limit, since the 1.7 GHz core flux is likely to be contaminated by the jet emission.

In order to derive the core and jet spectral index between 5 GHz and 8.4 GHz we obtained maps (not shown here) using similar u-v intervals and convolved with the same restoring beam. This procedure, however, leads to a rather poor u-v coverage at both frequencies, degrading the quality of the two maps. Furthermore the spacing sampling in the u-v plane is quite different at 5 GHz and 8.4 GHz (see Table 1 and Fig. 1), resulting in partial loss of extended structure in the high frequency map. The most reliable values we obtained are $\alpha_{5GHz}^{8.4GHz} = 0.27 \pm 0.08$ for the core and $\alpha_{5GHz}^{8.4GHz} = 0.9 \pm 0.2$ for the jet. Given the uncertainties mentioned, the jet spectral index should be considered an upper limit, and in our discussion (Sect. 4) we will use the conservative value $\alpha = 0.5$.

3.2.3 The kiloparsec-scale properties

Eilek et al. (1984) discussed the large scale properties of 3C465. Here we want to focus our attention on the jet properties as visible from our map (Fig. 6), before the jet culminates in the bright spot, at $\sim 30''$ from the core (Fig. 7). The kiloparsec-scale jets are very asymmetric, the counterjet being barely visible on our 5 GHz map.

Slices taken perpendicular to the direction of propagation of the main jet indicate that the jet remains very collimated, i.e. $\lesssim 1.1''$ out to $\sim 32''$ ($\sim$ 13.4 kpc) from the core. After a marginal expansion, recollimation occurs at $\sim 20''$ from the core. In this region the measured jet diameter is $\sim 0.6''$ and the brightness has a secondary peak, i.e. $\sim$ 3 mJy/beam.

The brightness along the jet in 3C465 suggests that there is no regime change in the jet dynamics with increasing distance from the core. This is confirmed also by the polarization map, which shows that the polarized vectors remain perpendicular to the jet direction all the way to the *bright spot.* (Fig. 7).

The jet/counterjet brightness ratio R derived from our map suggests that R remains fairly constant, i.e. $R \sim 20$, all along the jet.

4. Discussion

The two FR-I radio galaxies presented in this paper exhibit similar global radio properties. They are both characterised by straight radio jets, asymmetric in brightness, and by tails of diffuse radio emission. The distortions of the radio morphology take place along the tails, therefore for the following discussion we will assume that the jets are straight on both parsec and kiloparsec scale.

4.1 The parsec-scale asymmetry

The sources B2 0836+29 and 3C465 are asymmetric on the parsec scale. They are both characterised by a core-jet morphology, with the milliarcsecond jet aligned within few degrees with the main arcsecond scale one. As in similar cases (Giovannini et al., 1994), this is interpreted as due to Doppler favoritism in intrinsically symmetric relativistic jets. Under this assumption we will use the available data to derive constraints on the plasma speed and on its orientation to the line of sight, and we will compare the results to the predictions of the unified models.

Under the hypothesis of intrinsic symmetry for the radio jets and the observed asymmetry R due to Doppler favoritism, we can constrain the product $\beta cos\theta$ ($\beta = \frac{v}{c}$, and θ is the angle of the source radio axis to the line of sight) by means of the standard formula $\beta cos\theta = (R^{\xi} - 1)/(R^{\xi} + 1)$ (Pearson and Zensus, 1987), where the parameter ξ is defined as $\xi = \frac{1}{2+\alpha}$, α being the spectral index of the radio emission.

Assuming an isotropic jet emissivity (Giovannini et al., 1994) and a spectral index $\alpha = 0.5$ for both sources, the milliarcsecond asymmetry found for B2 0836+29 and 3C465 gives

$\beta cos\theta \gtrsim 0.54$, and $\beta cos\theta \gtrsim 0.59$ respectively. The derived allowed ranges for β and θ are given in Figs. 8a and 8b.

A second independent contraint on the angle to the line of sight and on the jet velocity is derived by means of the ratio between the 5 GHz core power and the 408 MHz total power. In order to derive an upper and lower limit for β and θ we used the correlation (Giovannini et al., 1994):

$$\beta = (K-1)(Kcos\theta - 0.5)^{-1}$$

with $K = [P_c(\theta)/P_c(60)]^{0.5}$. Here P_c is the measured (beamed) radio power, and $P_c(60)$ is the apparent (beamed) radio power for a galaxy oriented at 60° with respect to the line of sight. We have taken into account the statistical uncertainties (1σ) and a possible core flux density variability up to a factor of 2. In both sources the core is prominent, suggesting a small angle to the line of sight, as discussed below. The results of this analysis are also reported in Figs. 8a and 8b, which allow us to draw the following conclusions:

- for B2 0836+29 the core prominence is high, and this plays the main role, constraining $\theta \lesssim 37°$, and the jet velocity $v_{jet} \gtrsim 0.75c$;

- for 3C465 the combination of the core prominence and the jet/counterjet brightness ratio give $\theta \lesssim 54°$, and $v_{jet} \gtrsim 0.6c$.

The parsec-scale morphology and the velocity derived for the plasma speed in the vicinity of the radio nucleus for these two sources confirms the fact that FR-I and FR-II radio galaxies are indistinguishable on the parsec scale, both in their morphology and properties, as already pointed out in Paper IV. They also confirm that jets start out relativistically even in low-intermediate luminosity radio galaxies and decelerate further out, as expected by current models (Laing, 1993; Bicnkell, 1995).

BL-Lac objects are characterised by intrinsic γ factors ($\gamma = \frac{1}{\sqrt{1-\beta^2}}$) of the order of a few units (Ghisellini et al., 1993). If FR-I radio galaxies are the parent population of BL-Lac objects, the range of their intrinsic γ should be the same. We point out that for the sources presented here we have $\gamma \gtrsim 3$ if $25^\circ \lesssim \theta \lesssim 37^\circ$ for B2 0836+29, and $35^\circ \lesssim \theta \lesssim 54^\circ$ for 3C465. These numbers are in agreement with the expectations derived from the unification models, which predict $\theta \gtrsim 30^\circ$ (see Ghisellini et al., 1993).

The analysis of the X-ray emission coming from the nuclear regions and the application of the synchrotron-self-Compton (SSC) model (Marscher 1987) is being done for these two radio galaxies, as well as for the other galaxies in our sample (Giovannini, Feretti & Comoretto, 1990) using either ROSAT data or ad-hoc observations. The results will be presented in a separate paper.

No constraints can be derived from the global size of the two radio sources, since they are both characterised by a distorted morphology, possibly caused by the combination of the galaxy motion and of the density of the intergalactic medium.

The high plasma speed derived on the parsec scale makes these two sources good candidates for the detection of motion of the components along the jets. In particular, assuming that what we see on the parsec scale is the plasma flow, the standard beaming model suggests that the apparent motion β_{app} of the VLBI components is related to the intrinsic plasma speed β_{intr} by the formula

$$\beta_{app} = \frac{\beta_{intr}\, sin\theta}{1 - \beta_{intr} cos\theta}$$

(Pearson & Zensus, 1987). If we assume for both sources an angle of 35° to the line of sight, the formula reported above gives an apparent proper motion $\mu \sim 0.32$ mas/year for B2 0836+29 and ~ 0.46 mas/yr for 3C465.

In order to see if any motion is visible in the components of the parsec-scale jet, a second epoch observation at 5 GHz and 8.4 GHz respectively for B2 0836+29 and 3C465 has already been done. The results of the comparison between the first and second epoch for these two sources will be presented in the future.

4.2 The kiloparsec-scale asymmetry

We derived the constraints on θ and β along the kiloparsec scale jet under the same assumption of Doppler boosting. The straight morphology of the kiloparsec-scale jets suggests that jet bending is not prominent here, and justifies our approach.

For B2 0836+29 the jet/counterjet brightness ratio derived from our map gives a value of $\beta cos\theta$ decreasing with increasing distance from the core, i.e. from $\beta cos\theta = 0.36$ at $\sim$ 15 kpc from the core, to $\beta cos\theta = 0.14$ at $\sim$ 30 kpc (see Tab. 4). Assuming that the viewing angle θ does not change, as suggested by the source structure, the trend in $\beta cos\theta$ implies a decrease in the jet velocity at increasing distance from the core. In 3C465, $\beta cos\theta$ remains constant, i.e. 0.54, all along the jet.

If we assume that θ does not change going from the parsec to the kiloparsec scale, the derived jet velocity on the large scale for B2 0836+29 is 0.44c at 15 kpc from the core and decreases to 0.17c at 30 kpc. These numbers are in good agreement with those found by CFP95, who derived $25^\circ \lesssim \theta \lesssim 45^\circ$ at 5 kpc from the core, with a velocity in the range 0.5c - 0.85c. On the contrary, in 3C465 the jet velocity remains pretty constant, i.e. 0.7c, all the way to the *bright spot* (13 kpc from the core). The different properties of the jet velocity in the two sources, i.e. decreasing in B2 0836+29, and constant in 3C465, are in agreement with other properties of the kiloparsec scale jet, such as for example the opening angle of the jet and the direction of magnetic field vector, presented in *Sects. 3.1.3* and *3.2.3*. In B2 0836+29 the opening angle of the jet increases going further out along the jet, and the magnetic field switches from longitudinal to transverse. On the other hand, in 3C465 the jet remains very collimated all its length long, and no change in the polarization vector is observed. We want to note here that a study on a sample of 3CR quasars carried out by Bridle et al. (1994), shows evidence of deceleration from the parsec to kiloparsec scale even in high power radio jets.

4.3 The unified models

The similarity of the parsec-scale properties in B2 0836+29 and 3C465, compared to the differences found on the large scale, suggests that the central engine in these two radio galaxies may be the same, but that differences in their interaction with the surrounding medium could be responsible for the different morphology and properties of the kiloparsec-scale jets.

In Paper IV we have shown that FR-I and FR-II radio galaxies are very similar on the parsec scale, despite their large differences on the large scale. The results presented in this paper, together with other examples in the literature for other FR-Is (i.e. M87, Biretta 1993, and NGC6251, Jones & Wehrle, 1995) reinforce the growing evidence that the central engine in FR-Is and FR-IIs must be similar. The different radio morphology could then be due either to an intrinsically different power and torus (Falcke et al., 1995), or to different conditions in the region beyond the parsec scale, where a significant deceleration in the FR-I jets occurs (De Young, 1993; Bicknell, 1995). We point out that Maraschi & Rovetti (1994) showed that BL-Lacs and flat spectrum radio quasars can be linked together in a single beamed population, their parent unbeamed population including FR-Is, FR-IIs and steep spectrum radio quasars.

More radio observations, at sub-arcsecond resolution (using for example the MERLIN or an upgraded VLA) and at very high resolution (with satellite VLBI) are necessary to firmly discriminate between these two hypothesis.

5. Conclusions

We can summarize the results presented in this paper as follows.

1. The parsec-scale core-jet morphology found for B2 0836+29 and for 3C465 confirms that this is the most common parsec-scale strucure found in low-intermediate luminosity radio galaxies, and that this class of radio sources is indistinguishable from the more luminous FRIIs on the small scale.

2. The values derived for the plasma speed are $\beta \gtrsim 0.75$ for B2 0836+29 and $\beta \gtrsim 0.6$ for 3C465. The limits to the angle to to line of sight are $\theta \lesssim 37^\circ$ and $\theta \lesssim 54^\circ$ respectively for B2 0836+29 and 3C465. These angles are consistent with a Doppler factor $\gamma \gtrsim 3$.

3. The intrinsic velocities derived for the plasma speed are in agreement with the expectations, both theoretical and observational, that jets start out at relativistic speed even in low-intermediate luminosity radio galaxies and decelerate on the kiloparsec scale.

4. Both the velocities and the angles to the line of sight derived in these two sources support the idea that low luminosity radio galaxies are the unbeamed parent population of BL Lac radio sources.

5. Finally, the results presented in this paper support the idea that the central engine in FRI and FRII radio galaxies is essentially the same, and that the differences in the large scale properties for the two classes of radio sources could be related to an intrinsically different core power or/and differences in the environment outside the nuclear region of the associated

optical galaxy.

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Figure Captions

Figure 1 - uv-coverage of our VLBI data sets. a) B2 0836+29 at 5 GHz; b) 3C465 at 1.7 GHz; c) 3C465 at 5 GHz; d) 3C465 at 8.4 GHz.

Figure 2 - Contour plot of B2 0836+29 on the VLBI scale. The peak flux in the map is 128 mJy/beam. Contour levels are -0.4, 0.4, 0.6, 0.8, 1, 1.5, 2, 3, 4, 5, 7, 10, 20, 30, 50, 70, 100, 120 mJy/beam. The restoring beam is 1.9×0.7 mas in p.a. $0°$.

Figure 3 - VLA C array total intensity map of B2 0836+29 at 5 GHz. The peak flux is 145 mJy/beam. Contour levels are -0.2, -0.1, 0.1, 0.2, 0.3, 0.5, 1, 2, 5, 10, 20, 30, 50, 100, 120 mJy/beam. The restoring beam is $3.67'' \times 3.58''$ in p.a. $-84.5°$. The noise in the map is 0.03 mJy/beam.

Figure 4 - Percentage of polarization for B2 0836+29, superimposed to the total intensity map. 1 arcsec corresponds to 5×10^{-5} Jy/beam. The total intensity peak is 145 mJy/beam. Contour levels are -0.1, 0.1, 0.5, 1, 5, 30, 100 mJy/beam. The restoring beam is $3.67''\times3.58''$ in p.a. $-84.5°$.

Figure 5 - Contour plot of 3C465 on the VLBI scale. **a)** 1.7 GHz map. The peak flux in the map is 165 mJy/beam. Contour levels are -1, 1, 1.5, 2, 3, 5, 10, 20, 30, 50, 100 mJy/beam. The restoring beam is 12.5×11.2 mas in p.a. $85°$. The noise in the map is 0.45 mJy/beam. **b)** 5 GHz map. The peak flux in the map is 133 mJy/beam. Contour levels are -0.75, 0.75, 1.5, 2, 3, 5, 10, 20, 30, 50, 100 mJy/beam. The restoring beam is 2.52×0.83 mas in p.a. $-9.7°$. The noise in the map is 0.33 mJy/beam. **c)** 8.4 GHz map. The peak flux in the map is 132 mJy/beam. Contour levels are -0.75, 0.75, 1.5, 2, 3, 5, 10, 20, 30, 50, 100 mJy/beam. The restoring beam is 2.52×0.83 mas in p.a. $-9.7°$. The noise in the map is 0.35 mJy/beam.

Figure 6 - 5 GHz VLA C array total intensity map of 3C465. The peak flux is 242 mJy/beam. Contour levels are -0.2, 0.2, 0.5, 1, 2, 3, 4, 6, 10, 15, 20, 30, 50, 100, 200 mJy/beam. The restoring beam is $3.87'' \times 3.54''$ in p.a. $-80.7°$. The noise in the map is 0.05 mJy/beam.

Figure 7 - Percentage of polarization for 3C465 superimposed to the total intensity map. 1 arcsec corresponds to 3.3×10^{-4} Jy/beam. The total intensity peak is 242 mJy/beam. Contour levels are 0.1, 0.3, 0.5, 1, 3, 5, 10, 50, 100, 200 mJy/beam. The restoring beam is $3.87'' \times 3.54''$ in p.a. $-80.7°$.

Figure 8 - Constraints on the angle θ and the intrinsic jet velocity β for **a)** B2 0836+29 and **b)** 3C465. A and A′ respectively the lower and upper limits derived from the ratio between the core flux density and the total flux density. B is the limit derived from the jet/counterjet brightness ratio. The allowed region is the undashed one.

Table 1. Observational Parameters

(1) Source	(2) ν MHz	(3) Mode	(4) Array	(5) uv-range Mλ	(6) Obs. Time hr	(7) Epoch
0836+290	4990.99	MKIIIB	EU-US[a]	5-150	12	Nov. 90
3C465	1662.99	MKII	Y,VLBA[b]	0.2-12	12	Jan. 92
	4990.99	MKIIIB	EU-US[c]	4-150	10	Mar. 92
	8416.99	MKII	LNM,Y,VLBA[b]	1-260	12	Jan. 92

[a] EU = Bonn, WSRT, Onsala, Jodrell Bank, Medicina

US = Green Bank, Owens Valley, VLA Phased Array

[b] VLBA = KP,PT,LA,FD,NL,BR,OV

[c] EU = Bonn, WSRT, Jodrell Bank, Medicina, Noto

US = Haystack, Green Bank, Pie Town, North Liberty, VLA Phased Array

Table 2. VLBI Flux Densities

(1) Source	(2) ν MHz	(3) Beam mas, ($\circ$)	(4) Noise mJy/b	(5) S_{core} mJy	(6) S_{total} mJy
0836+290	4990.99	1.9×0.7, (0)	0.18	146 ± 7	167 ± 8
3C465	1662.99	12.5×11.1, (85)	0.45	181 ± 9	203 ± 10
	4990.99	2.52×0.83, (−9.7)	0.33	168 ± 7	234 ± 12
	8416.99	2.52×0.83,(−9.7)	0.35	146 ± 7	191 ± 10

Table 3. VLA Data

(1) Source	(2) RA_{core} (J2000)	(3) DEC_{core} (J2000)	(4) ν MHz	(5) Beam $''$,$^\circ$	(6) rms mJy/b	(7) S_{core} mJy
0836+290	$08^h39^m15.827^s$	$28^\circ50'38.86''$	4990.99	3.67×3.58, -84.5	0.025	161 ± 8
3C465	$23^h38^m29.376^s$	$27^\circ01'53.31''$	4990.00	3.87×3.54, -80.7	0.05	246 ± 12

Table 4. Jet Constraints

	VLBI		VLA		
	$\beta cos\theta$	d (pc)	$\beta cos\theta$	d ($''$)	D (kpc)
B2 0836+29	$\gtrsim$0.54	6	0.36	$\leq$ 15	$\leq$ 15
			0.27	15-20	15-20
			0.14	20-31	20-31
3C465	$\gtrsim$0.59	1	0.54	$\leq$ 30	$\leq$ 13