Parsec-scale properties of a complete sample of radio galaxies

By T. VENTURI[1], G. GIOVANNINI[2] L. FERETTI[1] W. D. COTTON[3] AND L. LARA[4]

[1]Istituto di Radioastronomia, CNR, Bologna, Italy
[2] Dipartimento di Fisica, Università di Bologna, Italy
[3] National Radio Astronomy Observatory, Charlottesville, VA, USA
[4] Instituto de Astrofisica de Andalucia (CSIC), Granada, Spain

We report the most important results on the parsec-scale properties of a complete sample of radio galaxies carried out at radio frequencies with the Global VLBI array and with the VLBA. Relativistic parsec-scale jets are common both in FRI and FRII radio galaxies, and their orientation to the line of sight is in agreement with the expectations from the unified schemes for radio loud AGNs. Proper motion has been detected in a few FRI galaxies in the sample. FRI and FRII radio galaxies exhibit very similar properties on the parsec-scale. Finally a few radio sources in the sample show evidence of velocity structure in the parsec-scale jet, i.e. a central spine with high Lorentz factor γ and slower layers.

1. Introduction

The study of the parsec-scale morphology and properties of radio galaxies is essential to address a number of issues. In particular it is of crucial importance *(a)* to understand the nature of the central engine and how radio jets are born and propagate thoughout the galaxy; and *(b)* to test the role of orientation and obscuration in the observed properties for this class of objects. It is now widely accepted (see for example Urry & Padovani 1995) that the observed properties of AGNs depend mostly on their orientation to the line of sight and on the presence of a thick torus surrounding the central galactic regions. According to this unified view of AGNs, FRI and FRII radio sources would be the misaligned parent population respectively of BL-Lacs and quasars. Both classes of objects are therefore expected to be aligned at large angles to the line of sight and to be characterised by relativistic speeds. Recent works of Chiaberge et al. (1999 and 2000), based on observational data in a wide range of frequencies, threw new insight on the nuclear properties of FRIs and their relation to the aligned parent population. In particular, they showed that optical compact cores exist in FRIs, suggesting that obscuration may not be relevant in these objects, and that thick tori are not an essential component of their nuclear region. Furthermore, they suggested that a two-phase jet in BL-Lacs and FRIs could account for some discrepancies still defying unification.

2. Parsec-scale imaging a complete sample of radio galaxies

In the light of the results mentioned above, the knowledge of the source orientation and plasma speed in the closest vicinity of the nucleus is particularly important. This piece of information is now available for a complete sample of radio galaxies (Giovannini et al. 1990). The sample includes 27 galaxies, including 13 FRIs, 6 FRIIs, 2 BL-Lacs, 1 compact symmetric object (CSO), one compact steep spectrum source (CSS) and four core/halo sources, with redshift ranging from 0.0021 to 0.162. All sources in the sample were observed and imaged at milliarcsecond resolution with the global VLBI array at 5 GHz during the past decade. For a number of sources 1.6 GHz and 8.4 GHz observations

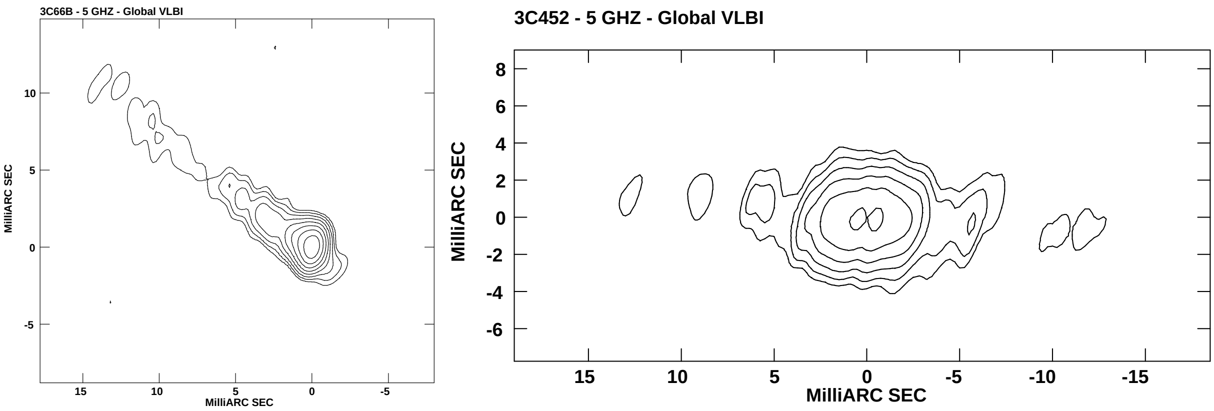

FIGURE 1. 5 GHz global VLBI images of 3C66B (left) and 3C452 (right). The restoring beam is respectively 1.6×0.8, p.a. $-15°$ and 3.1×0.7, p.a. $-13°$. In both images the rms is $\sim$ 0.11 mJy/beam and contours are -0.5, 0.5, 1, 2, 4, 8, 16 ... mJy/beam. The linear scale is 1 mas = 0.6 pc and 2 pc for 3C66B and 3C452 respectively.

and multiepoch observations are also available. The angular resolutions are of the order of $\theta_{FWHM} \sim 1-2$ mas, corresponding to linear resolutions ranging from a few tenth of parsec to a few parsecs depending on the source distance.
Here we will concentrate on our results for FRI and FRII radio galaxies.

3. Results and discussion

3.1. *Radio morphologies*

Most FRI and FRII radio galaxies in the sample are characterised by asymmetric morphology on the parsec-scale, with the mas jet aligned with the dominant arcsecond scale one. In those cases where multifrequency observations are available, the most compact component turned out to be the core of the radio emission (Cotton et al. 1999; Giovannini et al. 1999a; Lara et al. 1997; Venturi et al. 1995; Giovannini et al. 1994).
We also found two symmetric sources, i.e. the FRI 3C338 (Giovannini et al. 1998 and references therein) and the FRII 3C452 (Venturi et al. 2000; Giovannini et al. in preparation). The latter is a narrow line radio galaxy, and its two-sided parsec-scale morphology is consistent with the idea that it is oriented at a large angle to the line of sight. For this source we derived $\theta \geq 60°$. Observational constraints for 3C338 suggest that this source lies almost in the plane of the sky, i.e. $\theta \sim 85°$. It is interesting to note that HST images for the host galaxy show the presence of a compact nuclear component (Chiaberge et al. 1999), therefore obscuration is negligible for this object.
In Figure 1 we show the VLBI radio images of two typical radio galaxies in the sample, i.e. the one-sided 3C66B and the symmetric 3C452. Most parsec-scale jets in our images are similar to that in 3C66B, where the jet brightness is centrally peaked. In some cases the jets show high brightness knots; in other cases the jet brightness smoothly decreases along the jet propagation direction (Venturi et al. 1995).

There are however two remarkably different cases: for B2 1144+35, shown in Figure 2, and MKN 501 (Giovannini et al. 1999a and 2000 respectively) the jets are limb-

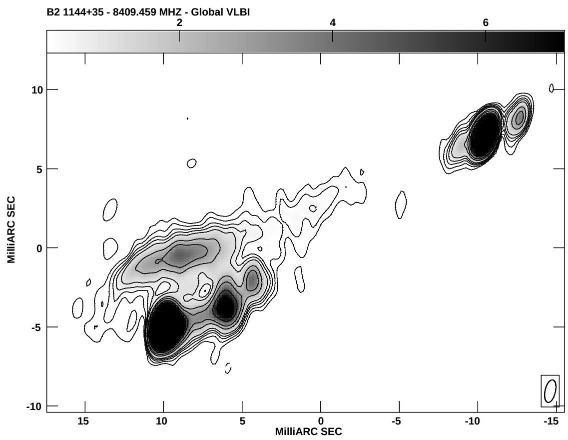

FIGURE 2. 8.4 GHz global VLBI image of B2 1144+35. The restoring beam is 1.45×0.66, p.a. −13°; the rms is ∼ 0.05 mJy/beam and contours are -0.2, 0.15, 0.2, 0.7, 0.7, 1, 2, 3, 5, 7, 10, 20, 30, 50 mJy/beam. Greyscale ranges from 0 to 7 mJy/beam. The linear scale is 1 mas = 1.62 pc.

brightened. This could be explained assuming that the jet consists of two different components, i.e. a fast central spine, deboosted if seen under viewing angles $\theta < \gamma^{-1}$, and a surrounding shear-layer with slower, but still relativistic, speed. This result is in agreement with the central spine-shear layer model predicted by Laing (1996) for parsec-scale jets, and with the suggestion made by Chiaberge et al. (2000).

3.2. *Superluminal motion*

A major result found from our study is the detection of parsec-scale proper motion in FRI radio galaxies. Beyond the well known case of the accelerating superluminal jet in 3C274 (Biretta et al. 1999), we found proper motion for three more FRIs in the sample, i.e. NGC315 (Cotton et al. 1999), B2 1144+35 (Giovannini et al. 1999a), 3C338 (Giovannini et al. 1998) and for the two BL-Lacs (Giovannini et al. 1999b, 2000). The proper motion, β_{app}, found for the three FRIs ranges from ∼ 0.9 (3C338) to 2.7 (B2 1144+35). For the two BL-Lacs we found β_{app} = 1.5 and 6.7 for MKN 421 and MKN 501 respectively.
It is noteworthy that there is evidence of an accelerating parsec-jet in NGC315 (Cotton et al. 1999), where the intrinsic speed along the jet increases from $\beta_{intr} \sim 0.75$ to 0.95 going from ∼ 3.4 to 9.5 mas from the core.

3.3. *Orientation and Lorentz factors*

Assuming that the observed morphologies and properties of the galaxies in our sample are due to Doppler boosting in an intrinsically symmetric source, we derived possible ranges for the viewing angle θ and for the intrinsic speed β_{intr} of the radio emitting plasma using standard beaming indicators (Giovannini et al. 1994, and in preparation):
(a) the jet to counterjet brightness ratio;

(b) the 5 GHz arcsecond scale core dominance with respect to the source total power at 408 MHz;
(c) the superluminal motion, where available.

The viewing angles we derived both for FRIs and FRIIs are consistent with the idea that both classes of sources are oriented at moderate to large angles to the line of sight, i.e. $\theta \geq 30°$, in agreement with unification. The only exceptions to this rule are B2 1144+35 and 3C274 (see Giovannini et al. 1999a and Biretta et al 1999 for more details). The intrinsic velocities found for FRIs are at least mildly relativistic, with lower limits ranging from $\beta_{intr} \geq 0.4$ to 0.95.
Similar results are found for the FRIIs, reinforcing the idea that FRIs and FRIIs are indistinguishable on the parsec-scale.
The limits to the Lorentz factors we derived are in the range 3 -10, in agreement with the results obtained by Chiaberge et al. (2000), who require γ in the range 3 - 7 to account for the different orientation properties in FRIs and BL-Lacs.

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