VLBI OBSERVATIONS OF LOW POWER RADIO GALAXIES

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classification: Astronomy

Invited paper at the National Academy of Sciences Colloquium: "Quasars and AGN: High Resolution Radio Imaging" - Irvine (CA) March 24 and 25, 1995

Proceedings of the National Academy of Sciences - USA in press
Abstract

The parsec scale properties of low power radio galaxies are reviewed here, using the available data on 12 FR I galaxies. The most frequent radio structure is an asymmetric parsec-scale morphology, i.e. core and one-sided jet. It is shared by 9 (possibly 10) of the 12 mapped radio galaxies. One (possibly 2) of the other galaxies has (have) a two-sided jet emission. Two sources are known from published data to show a proper motion; we present here evidence for proper motion in two more galaxies. Therefore, in the present sample we have 4 radio galaxies with a measured proper motion. One of these has a very symmetric structure and therefore should be in the plane of the sky. The results discussed here are in agreement with the predictions of the unified scheme models. Moreover, the present data indicate that the parsec scale structure in low and high power radio galaxies is essentially the same.

Introduction

The knowledge of the structure of radio galaxies on the parsec scale is important in order to test current models of jet dynamics as well as radio source unification schemes. VLBI data on powerful radio galaxies and quasars show strong evidence of relativistic jets and in many cases a proper motion with an apparent superluminal velocity has been found (see Zensus this volume; Vermeulen this volume). VLBI observations of low power radio galaxies are also necessary to compare the parsec scale properties of radio sources with different radio powers and to test the unified scheme models, which predict that also low power radio galaxies should have parsec scale jets moving at a velocity close to the speed of light. In this paper we will present and discuss the available VLBI data on extended low power radio galaxies (Fanaroff-Riley Type I, hereafter FR I, [1]). We will use the radio galaxies of the sample currently under study by us [2] observed at 5 GHz with the VLBA or the global array. This sample consists of the B2 and 3CR galaxies having a core flux density greater than 100 mJy at 6 cm at arcsecond resolution [2]. The core flux limit, imposed by observational constraints, could produce a sample biased toward objects with jets pointing toward the observer. This point is not important in discussing single objects but has to be taken in account for statistical studies. The well known FR I galaxy NGC 6251 (see [3] and references therein), not included in our sample, was added, for a total of 12 FR I radio galaxies. Some of them have been observed also at 1.6 and 8.4 GHz. Only 5 have observations at different epochs to search for a possible proper motion.

Radio galaxies in the same range of total radio power, but unresolved on the arcsecond scale, have not been properly mapped yet. Therefore, they will not be discussed here. Observations are in progress to study this class of radio sources, in order to understand their nature and connection with the more powerful CSO and CSS sources (see Readhead this volume).
A Hubble constant $H_0 = 100$ km sec$^{-1}$ Mpc$^{-1}$ and deceleration parameter $q_0 = 1$ have been used throughout this paper.

Radio Morphology

The list of radio galaxies studied so far and discussed here is presented in Table 1. A morphological analysis based on the available VLBI maps indicates that an asymmetric morphology, i.e. core and one-sided jet, is the most frequent radio structure (see for example Fig. 1a,b). It is shared by 9 (possibly 10) out of the 12 mapped radio galaxies. A clear symmetric structure is found in 3C338 (Fig. 2), while 3C272.1 shows a complex structure with a possible counter-jet close to the core (Fig. 3). The one-sided jet is always well collimated and only small oscillations or bendings are visible. The nuclear emission at 5Ghz is always the dominant component. When maps at two or more frequencies are available, the core emission shows a flat or inverted spectrum while the jet emission has a spectral index $\gtrsim 0.5$. A few peculiar sources are described in detail below.

3C264 - The one-sided jet detected at parsec resolution (Fig. 1a) is oriented within a few degrees of the optical jet visible in the Hubble Space Telescope map [8]. Unfortunately, the resolution of the radio map is too high for a detailed comparison with optical data.

3C272.1 - The core radio power in this nearby galaxy is low with respect to the total radio power, so we expect that this source is very close to the plane of the sky (see next section). The VLBI map shows a complex structure with a curved jet on the side of the main kpc jet (North) and a possible short counter-jet (Fig. 3) on the opposite side.

3C274 - See Biretta (present volume) for a detailed discussion of this source.

1144+35 - This source shows at kpc scale a dominant core and two slightly asymmetric faint jets [9]. The core is strongly variable. Several measurements of the flux density [2] at 1.4 and 5 GHz show that it was about 300 mJy in 1974.0 while now (1995.1) it is 540 mJy after reaching a maximum of 610 mJy in 1991. Simultaneous multifrequency observations show that the core spectrum is flat between 1.4 and 5 GHz but strongly steepens between 5 and 8.4 GHz. The VLBI structure consists of two main components (A and C) with an inverted spectrum between 1.7 and 5 GHz and low brightness, jet-like features departing from them (Fig. 4). A comparison between our data and the 5 GHz VLBI map obtained in the second Caltech-Jodrell Bank VLBI survey [10] shows that: a) the component A is probably variable, therefore we tentatively identify it as the core; in this case the parsec scale structure would be in the direction of the fainter kpc scale jet. However, owing to the complexity of this source and the slight asymmetry of the faint kpc scale jets, the definition of a main jet may be ambiguous; b) the separation between A and C increases between the two observing epochs. This proper motion is clearly visible also comparing the model given by [10] with our visibilities. The data are consistent with a proper motion of component C with respect to A with an apparent superluminal velocity $= 1.2c$ ($H_0 = 100$). The snap-shot data obtained by us [2] are in agreement with this
motion.

**3C338** - This source has a very steep global spectrum and is associated with the multiple-nuclei cD galaxy NGC6166. Even for this source the arcsecond core flux density is strongly variable in time. At pc resolution, this source shows a flat spectrum core with two symmetric jets oriented in the E-W direction (Fig 2). We observed this source at 1.6, 5 and 8.4 GHz, and second epoch observations are available at 5 and 8.4 GHz. While the analysis of the 5 GHz data is still in progress, a preliminary comparison between the 8.4 GHz maps of the two epochs (Fig. 5) shows a clear change in the source structure. It is not obvious in such a complex structure how to determine an unambiguous proper motion; however the present data suggest a possible motion corresponding to an apparent velocity of 0.5 c.

**3C465** - This giant Wide Angle Tail radio galaxy has a total radio power intermediate between low and high power radio galaxies. The parsec scale map (Fig. 1b) shows a core emission and an asymmetric jet in the same direction of the main kpc jet. A faint counter jet is visible only in VLA maps at arcsecond resolution.

**Discussion**

**A - Jet velocity and orientation**

In all the sources discussed here the parsec scale jet is oriented on the same side of the main kpc scale jet with the exception of 1144+35 whose interpretation is still uncertain (see before). This correlation implies either that jets are intrinsically asymmetric or that parsec and kpc scale jets are both relativistic. The presence of relativistic jets in strong radio sources is now widely accepted ([11] and Zensus present volume). Furthermore, a detailed study of the inner kpc scale properties of low power radio galaxies (Laing present volume) and the evidence of proper motion at high velocities in some galaxies (see below) suggest that radio jets in FR I radio galaxies are initially relativistic. For these reasons, we interpret the radio structures presented here as affected by Doppler favoritism and will use the available data to constrain the possible values of the jet velocity ($\beta = v/c$) and of the orientation of the radio source with respect to the line of sight ($\theta$). We can constrain these two parameters in a four different ways: a) from the jet to counter-jet brightness ratio, b) from the prominence of the core radio power with respect to the total radio power, c) from comparing the observed X-Ray nuclear emission with that expected by the Self Compton Model, d) from imposing an upper limit on $\theta$ to restrict the maximum intrinsic radio source size to 1.5 Mpc. A detailed discussion on these methods can be found in [5]. The allowed values for the jet velocity $\beta$ and its orientation with respect to the line of sight $\theta$ are given in Table 2.

**B - Proper motion**

While a proper motion of well defined features inside the radio jets is firmly established and well studied in strong radio galaxies, quasars and BL-Lac type objects (Vermeulen
this volume; Zensus this volume), the situation is still unclear for low power radio galaxies. A few galaxies (5) among those presented here have at least two observations at different epochs that can be used to look for the existence of a proper motion.

The galaxy 3C274 shows evidence of stationary knots as well as structures moving at a sub-relativistic velocity; moreover some sub-structures seem to move with an apparent velocity larger than \( c \) (Biretta this volume). NGC6251 could have both a stationary knot and one moving at \( v = 1.2c \), the same velocity we have found for the component C in 1144+35. 3C338 has certainly changed its structure and a proper motion with \( v \sim 0.5c \) is compatible with data but it needs to be confirmed. For NGC315 an upper limit of 0.5c on the jet velocity was derived in [4].

We appear to see stationary as well as subluminal and superluminal knots in the jets of low power radio galaxies. This could reflect the presence of oblique shocks and complex situations where the measured velocity could be much lower than the jet velocity (Begelman this volume). More data are therefore necessary to properly discuss this point, but in any case the detection of proper motion in some low power radio galaxies confirms that also in this class of radio galaxies parsec scale jets are relativistic.

C - Unified Models

The present data and the derived values for \( \beta \) and \( \theta \) are in agreement with the expectations from unified models. In fact in all the low power radio galaxies presented here, observational data are in agreement with the presence of a parsec scale jet with a Lorentz factor \( \gamma \geq 3 \), viewed at angles larger than 30° with respect to the line of sight. This is consistent with FR I sources being the parent population of BL-Lac type objects.

Moreover we note that the parsec scale properties of FR I radiogalaxies are very similar to the parsec scale properties of FR II radio galaxies and quasars. The large morphological difference between FR I and FR II radio galaxies at the kpc-scale does not exist at the pc scale. This similarity suggests that the nature and the power of the nuclear engine is the same in low power and high power sources. The kpc scale differences seem to arise from conditions far from the nuclei and could be related to a different interaction with the surrounding medium. A similar result was deduced by De Young [12] in an optical study of FR II and FR I galaxies and by Maraschi and Rovetti [13] who compared BL-Lac type objects and flat spectrum radio quasars.

Acknowledgments

We thank the staffs at the telescopes for their contribution to these observations and the staffs at the Bonn and VLBA correlator where the data have been correlated absentee. The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under contract with the National Science Foundation.
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### Table 1 - VLBI Radio Galaxies

| Name     | z    | Log P$_{408}$ | VLBI morphology | Reference          |
|----------|------|---------------|-----------------|--------------------|
| 0055+30  | NGC 315 | 0.0167       | 23.95           | One-sided          | [4]                |
| 0104+32  | 3C31  | 0.0169       | 24.50           | One-sided          | present paper      |
| 0206+35  | 4C35.03 | 0.0375       | 24.28           | One-sided          | present paper      |
| 0755+37  | NGC2484 | 0.0413      | 25.04           | One-sided          | [5]                |
| 0836+29  | 4C29.30 | 0.0790       | 25.08           | One-sided          | [6]                |
| 1142+20  | 3C264 | 0.0206       | 24.85           | One-sided          | present paper      |
| 1144+35  | 0.0630 | 24.15        | One-sided?      | present paper      |
| 1222+13  | 3C272.1 | 0.0037       | 23.27           | Two-sided?         | present paper      |
| 1228+12  | 3C274 | 0.0037       | 25.07           | One-sided          | Biretta present volume |
| 1626+39  | 3C338 | 0.0303       | 25.25           | Two-sided          | [7] and present paper |
| 1637+82  | NGC6251 | 0.0230       | 24.55           | One-sided          | [3]                |
| 2335+26  | 3C465 | 0.0301       | 25.39           | One-sided          | [6]                |

Columns 1,2: radio galaxy names; Col. 3: total radio power at 408 MHz; Col. 4: parsec scale radio morphology; Col. 5: reference for the radio morphology.
Table 2 - Jet velocity and orientation

| Name, Radio Galaxy | allowed $\beta$ | allowed $\theta$ | $\theta$ if $\gamma \geq 3$ |
|-------------------|-----------------|-----------------|-------------------------|
| 0055+30 NGC 315   | 0.7 - 1.0       | 30 - 40         | 30 - 40                 |
| 0104+32 3C31      | 0.5 - 1.0       | 25 - 60         | 50 - 60                 |
| 0206+35 4C35.03   | 0.6 - 1.0       | 0 - 50          | 35 - 50                 |
| 0755+37 NGC2484   | 0.5 - 1.0       | 0 - 55          | 40 - 55                 |
| 0836+29 4C29.30   | 0.7 - 1.0       | 0 - 40          | 30 - 40                 |
| 1142+20 3C264     | 0.5 - 1.0       | 0 - 55          | 40 - 55                 |
| 1144+35           | 0.4 - 1.0       | 0 - 60          | 45 - 60                 |
| 1222+13 3C272.1   | 0.4 - 1.0       | 60 - 80         | 75 - 80                 |
| 1626+39 3C338     | 0.0 - 1.0       | 0 - 90          | 85 - 90                 |
| 1637+82 NGC6251   | 0.9 - 1.0       | 40 - 45         | 40 - 45                 |
| 2335+26 3C465     | 0.6 - 1.0       | 0 - 50          | 35 - 50                 |

Columns 1,2: radio galaxy names; Col. 3: allowed range for $\beta = v/c$ in parsec scale jets; Col. 4: allowed range for the source angle in degree with respect to the line of sight $\theta$ corresponding to the jet velocity range given in Col. 3; Col. 5: as Col. 4 but for a jet with a Lorentz factor $\gamma \geq 3$. 
Figure Captions

**Fig. 1** - a) VLBI map of 3C264 at 5.0 GHz. The HPBW is $3.5 \times 2.1$ mas in PA $11^\circ$. The peak flux is 135 mJy/beam; contour levels are: -0.3 0.3 0.5 0.8 1.5 2 5 10 25 50 100 mJy/beam. The arrow shows the direction of the main kpc scale jet.

b) VLBI map of 3C465 at 8.4 GHz. The HPBW is $2.52 \times 0.83$ mas in PA $-9.7^\circ$. The peak flux is 132 mJy/beam; contour levels are: -0.75 0.75 1.5 2 3 5 10 20 50 100 mJy/beam. The arrow shows the direction of the main kpc scale jet.

**Fig. 2** - VLBA map of 3C338 at 5 GHz. The HPBW is $2.2 \times 2.2$ mas. The peak flux is 44.4 mJy/beam; contour levels are: -0.5 0.5 0.7 1 1.5 2 3 4 6 8 10 20 30 40 mJy/beam. The two-sided arrow shows the direction of the symmetric kpc scale jet.

**Fig. 3** - VLBI map of 3C272.1 at 5 GHz. The HPBW is $5.3 \times 1.2$ mas in PA $-5^\circ$. The peak flux is 168 mJy/beam; contour level are: -0.7 0.7 1 2 3 5 7 10 20 50 100 150 mJy/beam. The arrow shows the direction of the main kpc scale jet.

**Fig. 4** - VLBI map of 1144+35 at 5.0 GHz. The HPBW is $2.5 \times 0.8$ mas in PA $5^\circ$. The peak flux is 255 mJy/beam; contour levels are: -1.5 1.5 3 5 7 10 15 20 50 100 200 mJy/beam. The arrow shows the direction of the main kpc scale jet (but see text).

**Fig. 5** - upper: VLBI map at 8.4 GHz of 3C338 obtained on 1991.3. The peak flux is 62.7 mJy/beam; contour levels are: -0.3 0.3 0.5 0.7 1 1.5 2 5 10 40 60 mJy/beam; bottom VLBA map of 3C338 at 8.4 GHz obtained on 1994.92. The peak flux is 25.8 mJy/beam; contour levels are: -0.3 0.3 0.5 0.7 1 1.5 2 5 10 15 20 mJy/beam. The HPBW is $2 \times 1$ mas in PA $0^\circ$ in both maps which have been plotted in the same scale.