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Nuclear radio emission in megaparsec-size radio galaxies

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Abstract. We present high resolution radio observations of the nuclear radio emission in a sample of eight radio galaxies having Megaparsec sizes, using the European VLBI network at 18 cm. At a resolution of 25 mas we detect all the giant radio galaxies from our sample. Among them DA 240 and 1331−099 were imaged for an extended period. These observations reveal a twin-jet structure for DA 240 and one-sided core-jet morphology in 1331−099. The implications of our results in the context of the unification of quasars and powerful radio galaxies are discussed. Our results are consistent with the suggestion that powerful radio galaxies are the unbeamed counterparts of quasars.

Key words: galaxies: jets – galaxies: nuclei – radio continuum: galaxies – galaxies: DA 240; 1331-099

1. Introduction

It has been suggested that both powerful and weak 'radio-loud' active galactic nuclei (AGN) each belong to a single class of objects. The variety of their observed properties is, on this hypothesis, determined by source orientation to the line of sight (Barthel 1989; Antonucci & Ulvestad 1985; Urry & Padovani 1995 and references therein, hereinafter UP95). The suggested unifications of edge brightened radio galaxies (FR II) and quasars on the one hand, and edge darkened radio galaxies (FR I) and BL Lacs on the other are based on ample evidence for Doppler-beaming effects in quasars and BL-Lacs and the similarity of their unbeamed properties with those of FR II and FR I radio galaxies respectively (see reviews by UP95 and Antonucci (1993) for recent compilation of, and discussion on, the different investigations).

One consequence of the unification of quasars and FR II radio galaxies is that, with increasing angle of inclination to the line of sight, the jet to counter-jet flux density ratio should decrease, tending to unity for angles of 90°. Searches for counter-jets in powerful radio galaxies and quasars have yielded only a few cases, all having jet to counterjet ratio well above unity. Edge brightened giant radio galaxies (GRG), in which the dominant radio emission comes from regions extended on scales up to ten times the sizes of typical powerful radio galaxies, might better represent sources lying at large angles to the line of sight. Such a sample of GRGs can be expected to suffer only minimal projection effects. Their nuclear radio properties should therefore be in maximum contrast to those of core dominated quasars. Specifically, observed quantities such as the jet to counter-jet flux ratio and separation ratio (ratio of the extent of emission on jet side to that on the counter-jet side), the key measures of source orientation, should show marked contrast. The jet counter-jet flux ratio is much more sensitive to the orientation than the separation ratio and is consequently a better measure of the source inclination. In this paper we attempt to determine these parameters for a sample of giant radio galaxies and use the results to test the robustness of the unification schemes.

Among the radio giants only NGC 315, NGC 6251 and 3C 236 have multi-epoch radio observations of their nuclei (Venturi et al. 1993; Jones and Wherle 1994; Barthel et al. 1985). These observations have revealed a problem for the unification schemes, that of a persistence of asymmetric or one-sided radio jets among the radio galaxies, the putative unbeamed counterparts of the beamed quasars. Although the ratio of the jet to counter-jet flux density and the apparent speeds of the parsec scale components are found to decrease in going from the flat spectrum quasars, through steep spectrum quasars to radio galaxies (Bridle 1990; Hough et al., 1993) in accordance with the unification scheme, the flux ratios are never seen to be unity (on any scales) among the radio galaxies in which jets have been detected. Even the giant radio galaxies observed so far have only revealed asymmetric or one-sided jets. If the nuclei of these largest radio galaxies are identical to quasars except for their modified properties (due to orientation) then they should have bulk relativistic velocities in their jets. In this case, even at large angles to the sky plane, an apparent velocity of $\beta \approx 1$ should be seen (reference for expressions used in calculating the beaming parameters throughout this paper have been taken from Appendix A in UP 95). This has so far not been observed.

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For relativistic bulk velocities, a jet to counter-jet flux ratio of 2 and below should be seen for sources oriented at angles larger than 80° to the line of sight. Such flux ratios have so far not been observed.

However, if the jets are relativistic, even the approaching jet is de-amplified to values lower than the intrinsic power, provided the angle to the line of sight is larger than some critical value. For a Lorentz factor of 2 this angle is 55 degrees; for higher factors, this angle is even smaller. The jets in sources oriented at relatively large angles to the line of sight will therefore be hard to detect. For NGC 315 and NGC 6251 to have jets with flux ratios as large as 50 and 100 implies, for Lorentz factors of 4 (UP95; assuming they are identical to BL Lacs), angles to the line of sight of 48° and 41° respectively. While this prospect does not make the unprojected linear sizes unacceptably large this raises the question of where one can find sources that are in the sky plane, or close enough for us to test for the two-sidedness of jets with flux ratios approaching unity.

With this in mind, as well as looking for nuclear radio properties that contrast most sharply with those of flat spectrum quasars, we observed a sample of eight radio galaxies (Table 1) with apparent sizes larger than 1.5 Mpc (H_0 = 50 km s^{-1} Mpc^{-1}) with the EVN at 18 cm.

Sects. 2 and 3 give the details of the sample, and the observations and results respectively. In Sect. 4 the implication of these results are discussed.

2. Sample

The main criterion for selecting a source for our purpose was for the apparent linear size to be larger than 1.5 Mpc so that we would be dealing with the largest radio sources. All such sources known with radio core flux densities larger than 10 mJy at 1.7 GHz and declinations above $-10°$ were selected. Of the eight sources, three have core flux densities of 15 mJy, with the rest having core flux densities larger than 30 mJy. The resulting set of sources included both FR I and FR II types. We also restricted the sources to only those which were not previously studied in detail.

3. Observations and results

We observed the sources at 1.67 GHz with the MK3 (Mode B) recording system giving a bandwidth of 28 MHz using 6 telescopes of the EVN. The observations were made on 1994 November 16. For the six sources with no previously published VLBI observations we made short observations of about 1 hour. Since some of the sources were weak we observed nearby calibrators frequently (for 3 minutes every 10 minutes) to reference in delay and fringe-rate (Porcas 1994) to circumvent difficulty in fringe fitting on these weak sources. DA 240 and 1331$-$099 were observed for a total of 6 hours each. The data were correlated at MPIfR-Bonn. Further data processing was carried out in the NRAO AIPS software package and the Caltech DIFMAP package.

The resultant resolution was 25 milliarcsecond. All the six previously unobserved sources were detected. Table 1 gives the coordinates used for correlation and the total correlated flux density at 1.67 GHz. Only the compact core is detected in each of these sources. We observe 3C 326 at two positions to find out the position of the core. We detected emission at 3C 326A (See Table 1) and none from 3C 326B suggesting that the core is located at 3C 326A. 1245+673 has an unusually bright core (249$\pm$10 mJy), no other structure is detected within a field of view of 0.5$\times$0.5 arcsec. There is marginal evidence that the core may be extended in PA 180°.

Naturally weighted maps (256 $\times$ 256; pixel size of 5 mas) were made for 1331$-$099 and DA 240. A circular gaussian restoring beam of 25 mas was used. Below we describe these results in more detail.

3.1. DA 240

The pilot observations at 6 cm reported by Graham et al. (1981) show the structure on a scale of 20 mas and below. We have detected two components (at 12σ) on either side of the core (Fig. 1 left). These two components (NW and SE) are unlikely to be artifacts of data analysis since they are not symmetrically located around the core. More interestingly, these two components, which we refer to as jet (NW, in PA 72°) and counter-jet (SE, in PA -117°), are almost aligned with the overall position angle of the radio galaxy (64°; Willis et al. 1974). The two jets are asymmetrically located with separation from core of 55 mas for the NW jet and 62 mas for the SE jet.

The total flux density of the source is 105$\pm$10 mJy with most of the flux density in the core. The rms noise in the map is 0.15 mJy beam^{-1} and the dynamic range is about 400. The core itself has a deconvolved size of 21 $\times$ 17 mas in PA 62° which is close to the overall PA of the source. The flux densities in the two jet components are very similar; 1.7$\pm$0.15 mJy each. We determine a jet counter-jet flux ratio of 1.0$\pm$0.2.

3.2. 1331$-$099

This radio galaxy of linear size 2 Mpc is rather symmetric and is not known to have a large-scale jet. The core was detected at a relatively bright level (86 mJy) in the pilot observations by Graham et al. (1981). The present observations with a resolution of 25 mas show an asymmetric jet structure in the central region (Fig. 1 right). The core itself is extended in the direction of the jet indicating structure on smaller scales. The core has an elongation in PA 107° which is close to the direction of the large-scale structure of the source (PA 106°). The total flux density in the core is 55$\pm$5 mJy, with a peak of 36$\pm$2 mJy. The flux density of the jet is 7 mJy and the rms noise in the map is 0.11 mJy beam^{-1}.

The jet is seen on the side of the source which has the fainter hotspot. This finding is very significant in view of the strong trend for any one-sided jet or the brighter jet to point to the stronger and more compact of the hotspots. The jet extends for 180 mas amounting to a linear extent of 280 pc. A large

Table 1. Properties of the large radio galaxies observed in our sample. The source positions given are those used in the correlator. Col.9 refers to the correlated flux density of the source and the errors quoted are the 3σ noise estimates from the maps. The derived parameters have been calculated for $H_0 = 50\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$.
References: 1. Hine 1979, Bondi et al. 1993; 2. van Breugel and Jaegers 1982; 3. Willis et al. 1974, Tsien 1982; 4. Mayer 1979, Jaegers 1986; 5. Masson 1979; 6. NFRA Newsletter, 1991 issue nr.4; 7. A.K. Singal pvt. comm., Graham et al. 1981; 8. Willis and Strom 1978, Rawlings et al. 1990.

Source	RA(J2000)	Dec(J2000)	z	FR type	Linear size in Mpc	Log P at 1.4GHz in W/Hz	Ref.	S(1.67GHz) in mJy
4C39.04	01 39 30.447	+39 57 03.26	0.211	II	2.0	26.23	1	20±5
3C130	04 52 52.788	+52 04 47.62	0.109	I	1.5	26.20	2	14±2
DA 240	07 48 36.666	+55 48 58.90	0.036	II	2.0	25.41	3	105±10
4C73.08	09 49 46.157	+73 14 23.82	0.058	II	1.7	25.74	4	11±2
HB13	10 32 58.954	+56 44 53.09	0.034	I	2.0	24.50	5	17±2
1245+673	12 47 33.361	+67 23 16.46	0.106	II	2.1	26.06	6	249±10
1331-099	13 34 18.573	-10 09 28.70	0.081	II	1.6	25.83	7	60±5
3C 326 A	15 52 09.181	+20 05 23.41	0.089	II	2.7	26.10	8	10±2
3C 326 B	15 52 09.104	+20 05 48.31						no detection

emission gap of 470 pc separates the jet from the core. The position angle of the jet (PA 99°) is significantly different from the large scale position angle. The jet is slightly resolved in the transverse direction. The deconvolved jet width is 30 mas at its widest.

We calculate a lower limit for the ratio of the flux densities of the jet and the (undetected) counter-jet to be about 20 (taking the ratio of jet flux to three times the rms noise).

4. Discussion

The discussion mainly centres on the results of the longer observations carried out on DA 240 and 1331−099. Our observations of the eight Mpc-size radio galaxies have revealed that compact cores exist in these largest sources as well, indicating continuing activity. Given these sizes and the likely large orientation angles, the cores are not expected to be Doppler boosted. In fact, the radio core strengths we determine for the giants are similar (within a factor of 2) to core strengths in radio galaxies with an order of magnitude smaller sizes (in the same total power range and redshift; we considered the B2 sample in Giovannini et al., 1988).

The present observations show that the two edge-brightened giants 1331−099 and DA 240 have one-sided and two-sided pc-scale jets, respectively. From these observations of DA 240 and 1331-099 we can estimate the orientation of the radio source to the plane of the sky. If we assume that the FR II radio galaxies and quasars have the same bulk Lorentz factors of 10 (UP95) then for a ratio of jet to counter-jet flux density of 20, we estimate that 1331-099 must be oriented to the line of sight by $\leq 57°$ and DA 240 to be almost in the sky plane for a jet to counterjet flux ratio of unity.

On parsec scales the jet counter-jet asymmetries are largely expected to represent the asymmetric Doppler beaming effects. While with better sensitivities the largely one-sided kpc jets in powerful edge-brightened radio galaxies have begun giving way to several cases of continuous or quasi- continuous counter-jets (e.g. Carilli 1989; Saripalli et al., 1994; Leahy and Perley 1995), on parsec scales however, the (presumably) larger bulk Lorentz factors and Doppler decrement combine to make it difficult to detect counter-jets. Recently, milliarcsecond counter-jets have been detected in 3C 84 and Cyg A (Vermeulen et al. 1994; Walker et al. 1994; Krichbaum et al. 1995). The jet counter-jet flux density ratios for the two sources are respectively 9 and 10, much larger than the value we find for DA 240 (on an order of magnitude larger scales although still over parsec scales). This is, therefore, the first instance of a parsec scale jet and counter-jet having nearly equal strengths. Such a result is what is expected for radio galaxies of such large sizes and is a strong support for the unification scheme. A similar detection has been reported for the largest radio galaxy, 3C 236 (Schilizzi et al. 1988). Further observations are needed to obtain a clear estimate of the flux ratio of the two jets .

Considering the VLBI observations of all the GRGs, NGC 315 , NGC 6251, 3C 236, DA 240 and 1331−099, the jet counter-jet ratios in all require them to lie at angles to the line of sight between 40° to 90°.

Within Barthel's unification scheme the radio galaxies and quasars share the same average bulk Lorentz factor, $\gamma = 10$ (UP 95), for which the angle at which the Doppler factor is unity is 25°. Beyond this angle de-amplification occurs and the jets are very diminished in brightness which would render their detection very difficult. The Doppler factors for 1331−099 and DA 240 respectively are 0.22 and 0.11 for a Lorentz factor of 10 and for orientations obtained from their jet to counter-jet flux ratios. The flux densities of the approaching jets should presumably have been reduced by $\frac{5}{2}^{\mathrm{th}}$ power of the above factors (see UP95; assuming a smooth and continuous jet).

Given the large angle inferred for DA 240, the fact that we see the two jets despite de-amplification by a factor $\delta^{2.5} = 0.004$ (where the Doppler factor is taken as 0.11), suggests that either the intrinsic jet power is very large (250 times

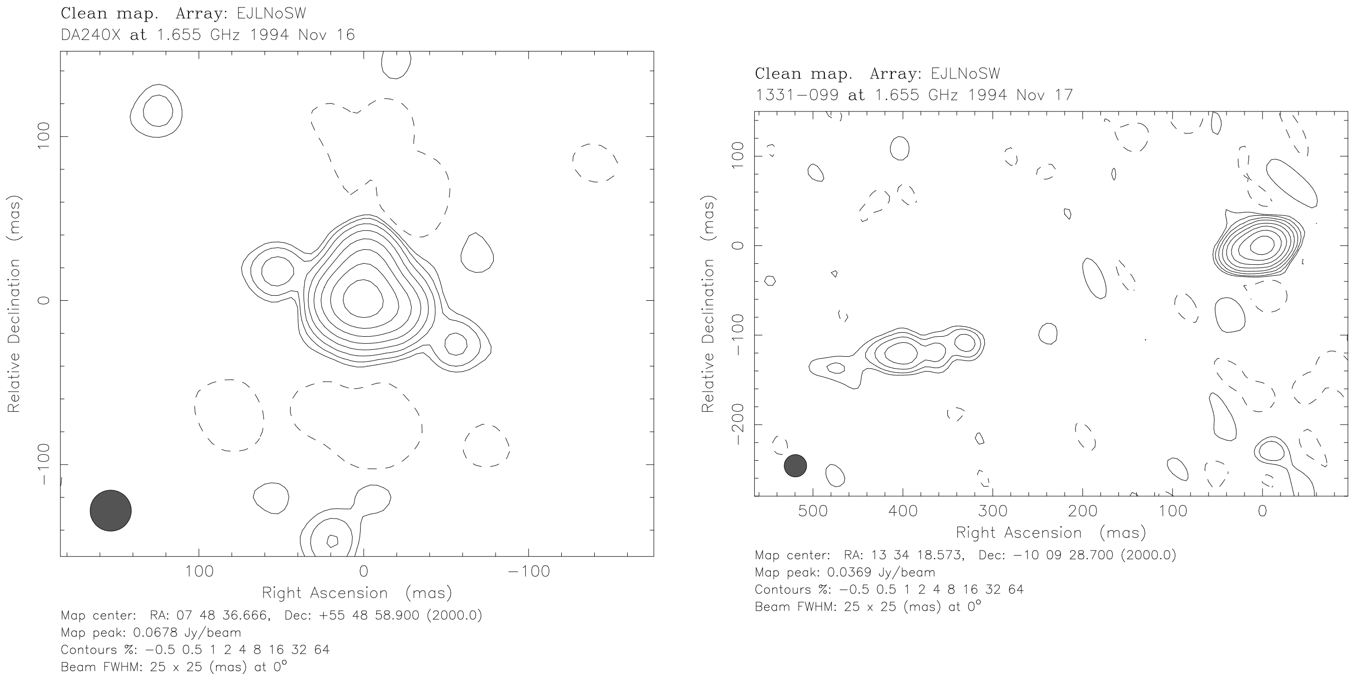

Fig. 1. EVN maps of DA 240 (left) and 1331−099 (right) at 18cm with a resolution of 25mas.

the observed power) or that there exist, as suggested by Pelletier & Roland (1989) and Laing (1992), perhaps two bulk velocity flows in the jets, one fast and the other slow, such that while the fast flow having a bulk Lorentz factor of 10 is not seen, we see only the emission from the slower flow. On the other hand, the intrinsic powers corrected for the large de-amplification are respectively 2×10^{24} W Hz^{-1} and 9×10^{24} W Hz^{-1} for DA 240 and 1331−099, which are in the same range as the kpc scale jet and counter-jet powers found in powerful radio galaxies and the powers estimated for counterjets in quasars (Bridle 1988).

Whether on kiloparsec scales or parsec scales, the counter-jets in quasars and radio galaxies have remained elusive, even more so on the parsec scales. Even among the few reported cases all of which are radio galaxies (3C 84 and Cyg. A; Bridle 1990) none has jet to counter-jet flux density ratio as low as unity. In this context the parsec scale jets in DA 240 having equal strengths contrast most sharply with the larger jet counter-jet ratios known for core dominated quasars.

The observations of Megaparsec size radio galaxies has shown that there is support for the unification scheme for radio galaxies and quasars, and that there is no compelling need to invoke intrinsic jet asymmetry or one-sidedness.

5. Conclusions

We observed a sample of radio galaxies selected on the basis of their Megaparsec linear sizes with a six station European VLBI Network. The aim was to determine nuclear properties in the giants that contrast maximally with those of core-dominated quasars, specifically, the higher frequency of jets and counter-jets and flux density ratios near unity expected within the unification scheme proposed for edge-brightened radio galaxies and quasars. Six out of eight objects were observed for the first time and our observations revealed compact nuclear cores in them. DA 240 and 1331−099 were observed for a longer period. We detect twin jets in DA 240 and an asymmetric core-jet structure in 1331−099. The detected parsec scale jet in 1331−099 is seen to point in the direction of the weaker of the two hotspots. The two parsec scale jets in DA 240 have a flux density ratio of unity, making it the clearest instance of parsec scale jets of equal strengths in FR II radio galaxies, and lends strong support to the unification scheme.

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