

VLBI OBSERVATIONS OF A COMPLETE SAMPLE OF RADIO GALAXIES. I. SNAPSHOT DATA

G. GIOVANNINI,^{1,2} L. FERETTI,^{1,2} AND G. COMORETTO³

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ABSTRACT

A complete sample of 26 radio galaxies has been selected from the B2 and 3CR catalogs, in order to study the properties of radio galaxies on the milliarcsecond scale.

As a first step, we obtained VLBI snapshot observations for 16 galaxies, in order to have an indication of the size and flux density of the milliarcsecond component. We present here the results of these observations. All but one galaxy were detected. In most cases, the total flux density detected in the VLBI data is comparable (>80%) to the flux density present in the arcsecond core. More than half the sources show indication of the presence of extended structure.

Subject headings: galaxies: structure — interferometry — radio sources: galaxies

I. INTRODUCTION

In recent years, great attention has been devoted to the study of small-scale structures in quasars and powerful radio galaxies. Very high resolution observations have proved the existence in the nuclei of these objects of compact ($\lesssim 1$ mas) radio sources (cores) and of small-scale features (jets) which seem often to be related with the larger radio structures. Current models favor the idea that a central engine supplies the energy to the extended radio lobes and that the compact radio nucleus reflects the characteristics of the central engine.

VLBI mapping has been performed up to now mainly for strong radio sources identified with quasars, BL Lac objects, and powerful radio galaxies (Fanaroff-Riley Type II). For low-power radio galaxies (Fanaroff-Riley Type I, hereafter FR-I), instead, VLBI observations are very scarce so far, due to the present limited availability of the VLBI technique in its high sensitivity form (Mark III). A few systematic studies (Schilizzi 1976; Wehrle *et al.* 1984) have been made for faint radio galaxies at VLBI resolution, with a single baseline only and at one position angle.

It is well known that quasars and powerful radio galaxies show at the arcsecond resolution different morphology with respect to the low-power radio galaxies (one-sidedness, hot spots, bends, wiggles). It is interesting to find out if these differences are present also at mas resolution: this is expected to be the case if the small- and large-scale structures are strictly connected in the low-power radio sources, as they are in the high-power ones (Hough and Readhead 1989, and references therein).

The knowledge of the radio properties of FR-I radio galaxies on the milliarcsecond scale is of great importance to understand the physical mechanism responsible for the nuclear activity and the evolution of radio sources in the nuclear environment.

In order to get new insight in the study of radio galaxies at the VLBI scale, we undertook a project of observations of a complete sample of radio galaxies selected from the B2 and 3CR samples. We adopted a two-stage observing strategy. As a

first step, we took snapshot observations of 16 galaxies, for which no VLBI data were available. We give in this paper the results, obtained by these observations, and the “observing status” of all the galaxies of the sample. The present results give us the necessary information to pursue the second step, which consists of the mapping of all the detected sources with better sensitivity and u - v coverage.

A Hubble constant $H_0 = 100 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $q_0 = 0$ is used in this paper for the computation of intrinsic parameters.

II. SELECTION OF THE SAMPLE

Taking also into account the present performances of the VLBI observations, we have selected from the B2 and 3CR samples of galaxies (Feretti *et al.* 1984; Giovannini *et al.* 1988, and references therein) the sources that satisfy the following conditions:

- 1) Declination $\delta > 10^\circ$;
- 2) Galactic latitude $b > 15^\circ$;
- 3) Arcsecond-core flux density at 5 GHz $S_c \geq 100 \text{ mJy}$;
- 4) Apparent visual magnitude of the associated galaxy $m_v \leq 20$ for the 3CR sources.

We remind the reader that the B2 radio galaxies derive from two samples, which are complete down to the limiting magnitude of $15.7 m_{pg}$ (“bright” sample) and $16.5 m_v$ (“faint” sample), the second sample covering only a fraction of the sky area where the first sample is defined (Colla *et al.* 1975; Fanti *et al.* 1978). The term *arcsecond core* is used in this paper to indicate any structure unresolved in a map taken with the Very Large Array (VLA) or the Westerbork Synthesis Radio Telescope (WSRT) at 5 GHz.

The total sample consists of 27 radio galaxies. The sample is complete and therefore suitable to perform statistical studies. The list of radio galaxies and their characteristics are given in Table 1, which is organized as follows:

Column (1): Radio galaxy name.

Column (2): Redshift.

Column (3): Absolute optical magnitude.

Column (4): Arcsecond core flux density at 5 GHz, in mJy; the epoch of this measurement is often not available in the literature.

Column (5): Spectral index of the arcsecond core in the range 1.4–5 GHz, when available, $[S(\nu) \propto \nu^{-\alpha}]$.

¹ Istituto di Radioastronomia del CNR.

² National Radio Astronomy Observatory.

³ Osservatorio Astrofisico di Arcetri.

TABLE 1
THE COMPLETE SAMPLE

Name (1)	z (2)	M_V (3)	S_c (mJy) (4)	α (5)	$\log P_t$ (W Hz ⁻¹) (6)	Type ^a (7)
0055 + 30 (NGC 315)	0.0167	-22.4	546	-0.2	23.95	D
0104 + 32 (3C 31)	0.0169	-21.3	140	0.4	24.50	D
0116 + 31 (4C 31.04)	0.0592	-22.0	≤ 1460	0.5	25.10	P
0206 + 35 (4C 35.03)	0.0375	-21.9	106	0.2	24.28	HC
0220 + 43 (3C 66B)	0.0215	-21.7	182	0.0	24.98	D
0222 + 36	0.0327	-21.5	140	0.2	23.59	HC
0258 + 35 (NGC 1167)	0.0160	-21.0	≤ 243	1.5	24.05	T
0331 + 39 (4C 39.12)	0.0202	-21.7	149	0.3	23.88	HC
0410 + 11 (3C 109.0)	0.3056	-22.9	263	...	27.12	D
0648 + 27	0.0409	-22.5	213	-0.3	23.70	P
0755 + 37 (NGC 2484)	0.0413	-21.9	195	0.1	25.04	D
0836 + 29 (4C 29.30)	0.0790	-22.4	131	-0.1	25.08	T
1101 + 38 (Mk 421)	0.0300	-21.6	640	-0.2	24.05	D
1142 + 20 (3C 264)	0.0206	-21.3	200	...	24.85	T
1144 + 35	0.0630	-21.9	250	...	24.15	CJ
1217 + 29 (NGC 4278)	0.0021	-19.5	350	0.2	21.44	P
1222 + 13 (3C 272.1)	0.0037	-21.4	180	...	23.27	D
1228 + 12 (3C 274)	0.0037	-21.7	4000	0.2	25.07	D
1322 + 36 (NGC 5141)	0.0175	-20.8	150	-0.6	23.75	D
1441 + 52 (3C 303)	0.1410	-21.4	150	...	26.11	CJ
1626 + 39 (3C 338)	0.0303	-22.3	105	0.3	25.25	D
1641 + 17 (3C 346)	0.1620	-22.4	220	...	26.33	HC
1652 + 39 (Mk 501)	0.0337	-22.6	1250	0.1	24.35	HC
1833 + 32 (3C 382)	0.0586	-22.2	188	0.0	25.70	D
1845 + 79 (3C 390.3)	0.0569	-21.6	330	...	25.97	D
2249 + 39 (3C 452.0)	0.0811	-21.4	130	...	26.30	D
2335 + 26 (3C 465)	0.0301	-22.2	270	...	25.30	T

^a Type keys: CJ = core jet, D = double, HC = halo core, P = pointlike, T = tailed.

Column (6): Logarithm of the arcsecond core radio power at 5 GHz, in W Hz⁻¹.

Column (7): Logarithm of the total radio power at 408 MHz, in W Hz⁻¹.

Column (8): Morphology of the large-scale radio structure.

The galaxies of this sample are mostly of low-intermediate luminosity, with $\log P_t$ at 408 MHz ranging from 23.5–27.0 W Hz⁻¹. The structure of all these sources is well known on the arcsecond/arcminute scale, thanks to good dynamic range VLA and/or WSRT maps. A large variety of structures is present in the sample, from classical doubles to tail sources (see Table 1).

Nine of the selected radio galaxies, having strong cores, were observed in the past with VLBI; therefore we concentrated on the remaining 18 galaxies. We obtained observations for 16 of them. The remaining two (0206 + 35 and 0648 + 27) were not observed for technical reasons, but the source 0206 + 35 has been observed by P. Parma (private communication).

III. OBSERVATIONS AND DATA REDUCTION

According to the first step of the adopted observing strategy, we conducted a pilot experiment, observing the 16 selected sources with the snapshot technique.

The observations were made with telescopes at Onsala, Effelsberg, Westerbork (full array), Jodrell Bank, Medicina, and Haystack at 4.99 GHz, in left circular polarization. The observations were made in two observing runs, in 1985 October and 1986 June. For each source, we obtained from 1–8 scans of 13 minutes each. The signals were recorded with the Mark III VLBI system in mode B, with a 28 MHz bandwidth. The synthesized beam reaches ~2 mas in the E-W direction,

thanks to the transatlantic baselines, while in the N-S direction it ranges from 4–8 mas.

The correlation was done at the Max-Planck-Institut für Radioastronomie in Bonn. An integration time of 3 minutes was used. The correlated flux scale was calibrated using 1404 + 286 (OQ208), 2201 + 315 and 0552 + 398 (DA193), which are believed to be essentially unresolved at these spacings and whose flux densities were measured at Effelsberg during the observations.

Simple models of Gaussian sources were fitted to the visibility amplitudes, in order to have indication of the source structure. We classified as extended sources those which are best fit by an extended single source or a multiple-component model.

We attempted also to produce hybrid maps of the sources using the CORTEL program (Cornwell and Wilkinson 1981) as the first step of the procedure. Due to the limited u - v coverage, however, the results are often ambiguous.

We give in Table 2 the observing details of each source of the complete sample, included those previously observed by other authors. The table is organized as follows:

Column (1): Radio galaxy name.

Column (2): Recorder used in VLBI observations.

Column (3): Stations involved in the observations.

Column (4): Observing time ("?" means that this information is missing in the quoted paper).

Column (5): Date of the VLBI experiment (year and month).

Column (6): FWHM of the beam of the observation in mas and, between parentheses, the position angle of the major axis in degrees.

Column (7): Corresponding linear resolution in pc, in the same position angle given in column (6).

Column (8): Reference to VLBI observations.

TABLE 2
OBSERVATIONAL DATA

Name (1)	Recorder (2)	Stations ^a (3)	Time ^b (4)	Date (5)	Beam ^c (mas) (6)	Beam (pc) (7)	Reference (8)
0055+30.....	Mk IIIb	B, W, L, S, J, K	6 × 13 minutes	1985 Oct	6 × 2 (0)	1.4 × 0.5	1
0104+32.....	Mk IIIb	B, W, L, S, J, K	6 × 13 minutes	1985 Oct	6 × 2 (0)	1.4 × 0.5	1
0116+31 ^d	Mk II	K, N, G, F, Y ₁ , O, H	~ 12 hr	1983 Dec	64 × 41 (0)	49.7 × 31.8	2
0206+35 ^e	Mk IIIb	K, W, L, S, J	2 hr	1989 Jun	...	...	3
0220+43.....	Mk IIIb	B, W, L, S, J, K	2 × 13 minutes	1985 Oct	5 × 2 (60)	1.5 × 0.6	1
0222+36.....	Mk IIIb	B, W, L, S, J, K	2 × 13 minutes	1985 Oct	6 × 2 (20)	2.7 × 0.9	1
0258+35.....	Mk IIIb	B, W, L, S, J, K	2 × 13 minutes	1985 Oct	5 × 2 (25)	1.1 × 0.5	1
0331+39.....	Mk IIIb	B, W, L, S, K	1 × 13 minutes	1985 Oct	6 × 2 (30)	1.7 × 0.6	1
0410+11.....	Mk II	B, G	?	1975 Apr	~ 1	~ 2.6	4
0648+27 ^f	...	...	...	...	...	...	...
0755+37.....	Mk IIIb	B, W, L, S, J, K	8 × 13 minutes	1986 Jun	4 × 2 (0)	2.2 × 1.1	1
0836+38.....	Mk IIIb	B, W, L, S, J, K	6 × 13 minutes	1986 Jun	4 × 2 (-15)	4.0 × 2.0	1
1101+29.....	Mk II	O, W, B, S, V	6 hr	1979 Mar	~ 1	~ 0.4	5
1142+20.....	Mk IIIb	B, W, L, S, J, K	4 × 13 minutes	1986 Jun	8 × 2 (0)	2.3 × 0.6	1
1144+35.....	Mk IIIb	B, W, L, S, J, K	2 × 13 minutes	1986 Jun	6 × 2 (15)	4.9 × 1.6	1
1217+29.....	Mk II	O, B, W, J	6 hr	1981 Apr	10 × 10	0.3 × 0.3	6, 7
1222+13 ^e	Mk II	G, O, H, A, F, Q	?	1979 Apr	6 × 3 (45)	0.3 × 0.2	8
1228+12 ^e	Mk II	World array	12 hr	1984 Apr	4 × 4	0.2 × 0.2	9
1322+36.....	Mk IIIb	B, W, L, S, J, K	2 × 13 minutes	1986 Jun	4 × 2 (30)	1.0 × 0.5	1
1441+52.....	Mk IIIb	B, W, L, S, J, K	3 × 13 minutes	1985 Oct	6 × 2 (-45)	9.6 × 3.2	1
1626+39.....	Mk IIIb	B, W, L, S, J, K	5 × 13 minutes	1985 Oct	7 × 2 (-15)	2.9 × 0.8	1
1641+17.....	Mk IIIb	B, W, L, S, J	2 × 13 minutes	1986 Jun	12 × 6 (-45)	21.2 × 10.6	1
1652+39.....	Mk II	J, B, S, W, G	14 hr	1982 Dec	11 × 8 (-69)	5.1 × 3.7	10
1833+32.....	Mk IIIb	B, W, L, S, J, K	1 × 13 minutes	1985 Oct	8 × 3 (0)	6.2 × 2.3	1
1845+79.....	Mk II	L, S, B, W, K, G, Y ₁ , O	?	1985 Apr	1 × 1	0.8 × 0.8	11
2249+39.....	Mk IIIb	B, W, L, S, J, K	2 × 13 minutes	1985 Oct	3 × 2 (0)	3.1 × 2.0	1
2335+26.....	Mk II	B, G	?	1975 Apr	~ 1	~ 0.4	4

^a Station keys: (A) Arecibo; (B) Bonn; (F) Fort Davis; (G) Green Bank; (H) Hat Creek; (J) Jodrell Bank; (K) Haystack; (L) Medicina; (N) NRL; (O) OVRO; (Q) VRO; (S) Onsala; (Y₁) VLA (one antenna); (V) Helsinki; (W) Westerbork.

^b "6 × 13 minutes," for example, means six scans of 13 minutes each.

^c Number in parentheses is the position angle of the major axis in degrees.

^d VLBI data at 327 MHz.

^e VLBI data at 1.6 GHz.

^f No VLBI data.

REFERENCES.—(1) This paper; (2) Wrobel and Simon 1986; (3) Parma *et al.* 1990; (4) Preuss *et al.* 1977; (5) Bååth *et al.* 1981; (6) Schilizzi *et al.* 1983; (7) Jones, Wrobel, and Shaffer 1984; (8) Jones, Sramek and Terzian 1981; (9) Reid *et al.* 1989; (10) van Breugel and Schilizzi 1986; (11) Alef *et al.* 1988.

IV. DISCUSSION OF THE RESULTS

The new data presented here improve the statistical knowledge of the mas structure of radio galaxies. They provide information on linear scales ranging from 1–30 pc. We detected 15 out of the 16 observed radio galaxies. Therefore, among the 27 radio galaxies having an arcsecond core flux density $S_c \geq 100$ mJy, 24 have a detected milliarcsecond structure, two have not been observed, and only the source 0258+35 was not detected. This source is characterized by a very steep spectrum arcsecond core (Table 1) and is likely to present a radio structure on the subarcsecond scale.

The results of the present observations and of the information available from the literature for the other objects of the sample are given in Table 3 as follows:

Column (1): Radio galaxy name.

Column (2): Integral flux density at 5 GHz (unless differently specified in the note) of the milliarcsecond structure in mJy.

Column (3): Ratio of flux density in milliarcsecond core to that in arcsecond core.

Column (4): The milliarcsecond structure (P = pointlike, E = extended, according to § III).

Column (5): Notes.

The flux densities given in Table 3 obtained from the present data, refer to the shortest baselines and have uncertainties of about 10%.

Most sources (17) exhibit some extended structure on the VLBI scale, generally from the transatlantic baselines. Among the sources classified as extended, 0055+30 and 2249+39 show a flux density decrease in the transatlantic baselines of about 40%, and the others show a flux decrease of between 10% and 20%. This indicates that in general, the resolved VLBI structure is a small fraction of the unresolved component.

We give in Figure 1 the number of galaxies with pointlike and extended VLBI structure as a function of the total radio power at 408 MHz. There is no statistically significant tendency for the most compact structures to occur in any particular range of total radio power.

The sources 1101+38, 1144+35, and 1217+29 are known to be variable; in particular the B2 radio galaxy 1144+35 shows a constant increase of the flux density from 1974 to now, as shown in Figure 2.

In some cases, the flux density in the milliarcsecond core is higher than that in the arcsecond core, suggesting a possible

TABLE 3
VLBI DATA

Name (1)	S_{mas} (mJy) (2)	$S_{\text{mas}}/S_{\text{as}}$ (%) (3)	Type (4)	Notes (5)
0055 + 30.....	560	102	E	
0104 + 32.....	115	115	P	
0116 + 31.....	3330	...	E	VLBI data at 327 MHz, two components
0220 + 43.....	200	109	P	Variable
0222 + 36.....	90	64	E?	
0258 + 35.....	<15	...	...	
0331 + 39.....	125	83	P	
0410 + 11.....	220	84	P	
0755 + 37.....	190	97	E	
0836 + 29.....	120	91	E	
1101 + 38.....	680	106	E	BL Lac object, variable
1142 + 20.....	180	90	E	
1144 + 35.....	680	...	E	Variable
1217 + 29.....	350	100	E	Variable, complex structure
1222 + 13.....	180	...	P	VLBI data at 1.6 GHz
1228 + 12.....	364	...	E	Virgo A, VLBI data at 1.6 GHz, one-sided
1322 + 36.....	75	50	P	
1441 + 52.....	170	113	E?	
1626 + 39.....	100	95	E	
1641 + 17.....	165	75	P	
1652 + 39.....	1220	97	E	
1833 + 32.....	190	101	E?	
1845 + 79.....	350	106	E	Superluminal motion
2249 + 39.....	120	92	E	
2335 + 26.....	230	85	E?	

time variation of the core flux density. Values lower than 110, however, could as well be due to calibration uncertainties. Figure 3 shows a histogram of the ratio of flux density in the milliarcsecond core to that in the arcsecond core. In a few cases, only a fraction of the arcsecond flux density is detected, indicating that a subarcsecond structure is likely to be present. In most radio galaxies (19/22), the flux density of the mas structure is greater than 80% of the flux density of the arcsecond core. This result is different from that obtained by Wehrle *et al.* (1984), who found that for most galaxies the flux in the VLBI component is only a fraction of the flux detected in the arcsecond core. However, those authors selected their sample without any consideration of the flux density of the arcsecond scale structure of the sources. Therefore their sample is quite different from ours. Only two sources are present in both samples, and for these sources the observational results are consistent.

A recent VLBI survey of galaxies and quasars, is presented by Pearson and Readhead (1988). Their sample consists of 65 sources with a total flux at 5 GHz greater than 1.3 Jy. They

detected 71% of the observed sources, and the fraction of flux density present in the milliarcsecond core is almost uniformly distributed from 10%–100%. Also in this case, however, a comparison with our sample is not straightforward. The selection of the Pearson and Readhead sample was made on the basis of single-dish data and therefore still includes a large fraction of flux density from extended lobes, while our selection is based essentially on the flux density of the arcsecond core. Moreover, our Mk III snapshots have a higher sensitivity than their observations, in fact, they failed to detect 0220 + 43 (3C 66B). The comparison between our results and theirs provides evidence that the arcsecond core flux density is strictly related to the milliarcsecond structure flux density.

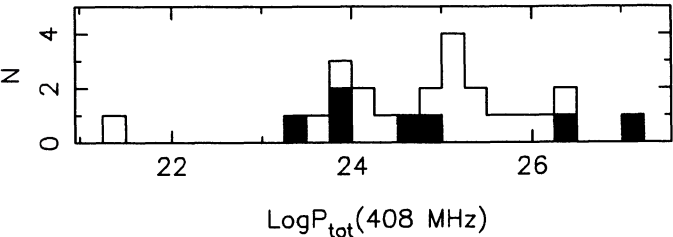


FIG. 1.—Number of galaxies with pointlike milliarcsecond structure (black squares) and extended milliarcsecond structure (white squares) vs. the total radio power at 408 MHz.

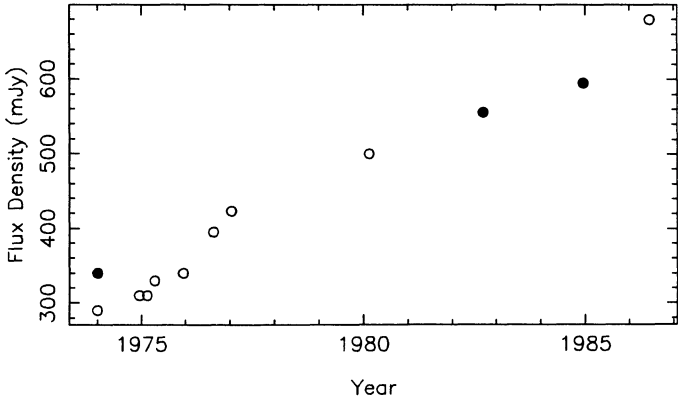


FIG. 2.—Plot of the flux density variation of the radio galaxy B2 1144 + 35. Empty dots are measurements at 5.0 GHz, while filled ones are at 1.4 GHz. References for flux densities are: 1974 = Colla *et al.* (1975); from 1975 to 1980 = Ekers, Fanti, and Miley (1983); 1982 = Parma *et al.* (1986); 1985 = Fanti *et al.* (1987); 1986 = This paper.

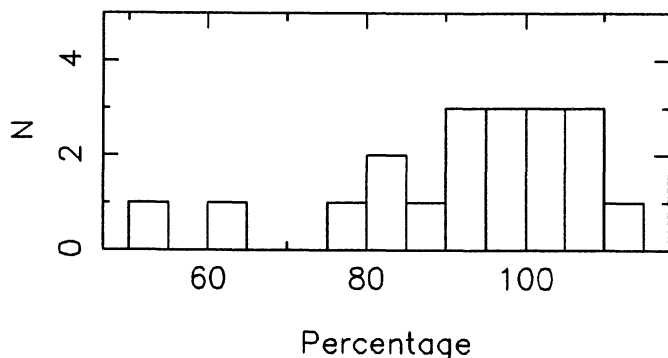


FIG. 3.—Number of galaxies vs. ratio of flux density in milliarcsecond core to that in arcsecond core, for the detected galaxies having VLBI data at 5 GHz. The variable radio galaxy B2 1144 + 35 is not used.

The results obtained in the present paper allow us to re-examine the correlation between the core power and total power in radio galaxies, investigated by Giovannini *et al.* (1988). In that paper, the power of the arcsecond core is used, while the present data provide the power of the milliarcsecond core. The fact that, in most radio galaxies, the flux density of the milliarcsecond core is a high percentage of the flux density of the arcsecond core implies that the correlation found by Giovannini *et al.* (1988) is confirmed. The plot in logarithmic scale of the core power at 5 GHz in W Hz^{-1} , P_c , versus the total power at 408 MHz in W Hz^{-1} , P_t , for the 20 radio galaxies having VLBI data at 5 GHz is given in Figure 4. The best-fit linear regression of these data is

$$\log P_c = 0.60 \log P_t + 8.64,$$

fully consistent with that given by Giovannini *et al.* (1988).

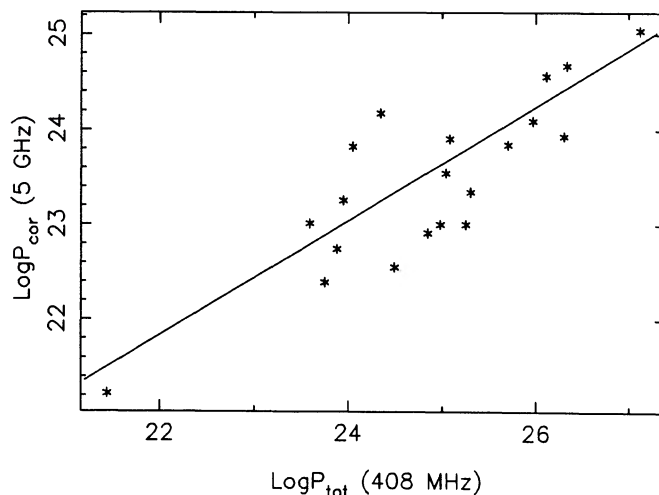


FIG. 4.—Plot of milliarcsecond core power at 5 GHz vs. total radio power at 408 MHz, for galaxies having VLBI data at 5 GHz. The variable radio galaxy B2 1144 + 35 is not used.

It seems, therefore, that the power of the arcsecond core is a good estimate of the power of the very compact radio nucleus and that the mechanism of energy transport between the central engine and the radio lobes is generally very efficient up to the arcsecond scale. This point will be better investigated when detailed maps of the milliarcsecond structure will be available.

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G. COMORETTO: Osservatorio Astrofisico di Arcetri, L.go E. Fermi 5, I-50126 Firenze, Italia

L. FERETTI and G. GIOVANNINI: Istituto di Radioastronomia, via Irnerio 46, I-40126 Bologna, Italia