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Radio observations of early-type galaxies

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Summary. A complete sample of 34 nearby early-type galaxies, based on the Arecibo survey by Dressel & Condon (1978) of objects from the Uppsala General Catalogue, has now been mapped at radio frequencies. New data are presented for 23 galaxies in the sample, and references are given to published maps of the remainder. The majority of the sources show strong jet-like structures, but others remain unresolved. These latter occur primarily in galaxies classed as S0 in the UGC. A strong correlation between radio luminosity and size has been found in the range $23.0 < \log P(2.7\,\mathrm{GHz}) < 25.0$ (P in $\mathrm{W\,Hz^{-1}}$; $H_0 = 50\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$). This correlation is in the sense that weak sources are confined within the optical extent of their parent galaxies, whereas strong sources generally attain large sizes (~ 200 kpc). A tentative explanation of this tendency is offered in terms of the flow instabilities in beams of energetic particles passing through dense media.

The radio luminosity function has been determined; although for a sample selected at 2.3 GHz, it agrees well with that found at lower frequencies.

1 Introduction

A study of nearby radio galaxies is interesting for at least three reasons: (i) they are the galaxies for which the most detailed optical information can be obtained; (ii) they are examples of the most common forms of active galaxy; (iii) because the radio structures are often of small angular size and low surface brightness, relatively little is yet known about their morphology.

This paper considers a sample of 34 early-type galaxies, based on the Uppsala General Catalogue (Nilson 1973) and the 2.3-GHz survey of galaxies in this catalogue by Dressel & Condon (1978). The sample is complete to well-defined optical and radio limits. Dressel & Condon (1978) believe their measured flux densities to be reliable above 15 mJy, and the UGC is complete down to m(pg) = 14.5 (see Section 8). The sample was chosen as follows:

(i) $0° < \delta < 37°$,
(ii) $\mathrm{m(pg)} < 14.0$ for $11^{\mathrm{h}}\,30^{\mathrm{m}} < \alpha < 13^{\mathrm{h}}\,00^{\mathrm{m}}$, < 14.5 elsewhere,
(iii) UGC Hubble type is E or S0,
(iv) Sources are unconfused and have $S(2.3\,\mathrm{GHz}) > 35$ mJy.

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(The first two conditions are set by the limits of Dressel & Condon's survey.) There are 34 sources satisfying these criteria, in a total solid angle of 3.8 sr.

Several previous surveys (e.g. Heeschen 1970; Ekers & Ekers 1973; Colla *et al.* 1975) have established the basic properties of early-type galaxies of low radio luminosity, as are found in the present sample. From these surveys it was apparent that a large fraction of nearby galaxies are weak radio emitters, and the radio power appears to be correlated with optical luminosity. Ellipticals with flat radio spectra are found to have compact nuclear radio components and show optical emission lines more frequently than those without nuclear components. It was also found that the radio power appeared to be correlated with optical luminosity.

Recent work has refined these data. Colla *et al.* (1975) and Auriemma *et al.* (1977) determined the radio luminosity function of early-type radio galaxies at 408 MHz and 1.4 GHz. They showed that about one-third of all early-type galaxies have $\log P(408\,\mathrm{MHz}) > 21.0$, although this fraction is ill-determined because the weakest sources are only detectable if they lie within a comparatively small distance, so not many are known. It was also shown (Auriemma *et al.* 1977) that the correlation between radio and optical luminosity is only strongly apparent for $M(\mathrm{pg}) < -22$. Fanti *et al.* (1977) have presented maps of 40 galaxies in the sample of Colla *et al.* (1975). At a best resolution of 6 arcsec, these maps reveal the gross characteristics of the emission in low-luminosity radio galaxies, namely a central component coincident with the galaxy's nucleus and two lobes extending to either side; often these were not resolved from the central component. Condon & Dressel (1978), using the Green Bank interferometer, discovered that galaxies classified as S0 in the UGC have a much greater proportion of their radio flux density in small-scale components than do those classified as E. O'Connell & Dressel (1978) obtained a homogeneous body of spectroscopic data for galaxies detected in the survey by Dressel & Condon (1978) and verified that galaxies with strong central radio components are more likely to show the emission line [O II] λ3727 than those without such components.

The purpose of the present paper is to provide data on the morphology and flux densities of a sample similar to that analysed by Colla *et al.* (1975); their survey covered 1.2 sr, mostly within the present survey area. The sample differs in being selected at a higher frequency (2.3 GHz rather than 408 MHz) and also has differing limiting flux densities (35 mJy, not 200 mJy) and apparent magnitudes (14.5, not 15.3). The radio maps given here also have angular resolution two or three times better than those of Fanti *et al.* (1977). Because this new study has been based on a high-frequency survey, it is particularly useful for discovering the properties of the flat-spectrum radio sources in galactic nuclei. Other matters of interest include the nature of the E–S0 distinction discovered by Condon & Dressel (1978), especially when better angular resolution is available; and the possible effect of the interstellar medium on radio sources which are small enough to be wholly contained within their associated galaxy.

After a description of the observational material, I shall deal with the morphology; the E–S0 distinction; correlation of luminosity with size of radio structures; the properties of central components; the incidence of optical emission lines; and the radio luminosity function in the range $20.0 < \log P(2.7\,\mathrm{GHz}) < 25.0$.

2 The data

In observing the sample described in Section 1, the objective was to obtain maps and flux densities at as many frequencies as possible. This ensures that the physical sizes and radio luminosities are well-determined. In practice, this meant that the 5-km telescope (Ryle 1972) was used to observe every source for which there were no adequate maps in the literature. Once the structure was known, subsequent observations were made at different frequencies, either to measure the spectral index of the central component or indeed to resolve it from the extended structure; these would also be 5-km observations. In the case of apparently unresolved sources or those with faint extended structure, maps were made with the One-Mile telescope (Elsmore, Kenderdine & Ryle 1966) to search for steep-spectrum emission of low surface brightness.

Both the 5-km and the One-Mile telescope are operated as earth-rotation synthesis instruments. Most of the 5-km maps were made from observations for 12 hr at a frequency of 2.7 or 5.0 GHz. With 16 simultaneous interferometer baselines, the aperture plane was usually sufficiently finely sampled, but for the more extended source NGC 3121, observations were made at 32 baselines to remove grating responses. For extended sources, flux densities were measured from the maximum amplitude due to the source on the smallest interferometer baseline, while for unresolved sources the flux density was also determined from the peak height on the map. This procedure provided a check on the presence of low-brightness extended structure.

Sources were observed with the One-Mile telescope at frequencies of 408 MHz and 1.4 GHz for a total of 48 hr each. Many of the resulting maps are confused by grating responses since only eight interferometer baselines were available. These maps were either CLEANed (Högbom 1974) or, in simple cases, interfering sources were removed from the maps by the method of Neville, Windram & Kenderdine (1969). Flux densities of unresolved sources could be read directly from the CLEANed map; in the case of resolved sources, the CLEAN map was convolved to a low resolution and then the flux densities could again be read directly. For unconfused sources, the flux density could also be measured from the amplitude on the lowest spacing.

Flux densities and spectral indices are presented in Table 1, and various intrinsic properties in Table 2. The maps are given in Fig. 1 and the captions describe any unusual processing.

Several points should be made about these data. (i) The composition of the sample. Tables 1 and 2 exclude some galaxies that satisfy the criteria of the complete sample given in Section 1. Most of these were labelled as confused detections by Dressel & Condon (1978), and in the early stages of the present observations it was generally found that such sources were illusory. Hence no confused detections are included in the sample. Also, several sources appear to be misidentifications, or could not be found using the 5-km telescope; these are NGC 3910 (undetectable), NGC 5444 (wrong identification – see Colla *et al.* 1975), NGC 7318 (undetectable – see Gillespie 1977) and UGC 12515 (wrong identification). In total, 15 galaxies were excluded from the sample, mostly those near strong sources like 3C 31 or M87. Data on four galaxies which are not in the sample are also included, since they are good examples of their morphological type.

(ii) Sources of data, polarizations, and errors. One of the objectives of this paper is to derive reliable total luminosities at a standard frequency, and spectral indices. To obtain flux densities, data were gathered from many authors at as many frequencies as possible in order to guard against wrong flux densities resulting from confusion, or from over-resolving sources, especially those which have extensive steep-spectrum radio structure. The compilation by Haynes *et al.* (1975) is particularly useful and contains measurements from many instruments. This publication also shows that it is difficult to measure reliable flux densities, especially for faint sources, as the values from different authors can be wildly discordant and errors are frequently underestimated. Finally, the quoted values are often based on inadequate polarization data, although the errors consequent on ignoring polarization are likely to be < 10 per cent (Moffet 1975).

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Table 1: Flux densities of the 38 galaxies

Name (NGC)	Flux density (mJy) 0.4 GHz	1.4 GHz	2.3 GHz	2.7 GHz	5.0 GHz	α	S(2.7 GHz)	Comments
315		420 (2)	1500 (1)	510 (1)	620 (2)	0.5	1500 (a) 510	See (1). For nucleus, $\alpha = -0.3$ to 5.0 GHz, then flat to 8.1 GHz.
383	9900 (3)	5000 (3)	1520	3270 (3) 120 (4)	2100 (3) 120 (4)	0.6 0.0	3160 (a) 120	3C 31 (see (4))
741*	2000 (3)	1000 (3)	440	550 20	220 (3)	0.9	450 (b) 20	
984	<40±20	45	50	36	40	0.0	45 (a)	Spectrum flat or declining below 1.4 GHz.
1167	2650	1880	1400	1200		0.4	1350 (a)	See (25) who find $\alpha = 0.54$
2749	120	55	46	40	25	0.6	40 (a)	
2892**				200 21	130 30	0.7 -0.5	200 (a)	(3) gives same 5 GHz flux density.
3121*	2200 (3)	1120	255	580	250	0.7	560 (b)	Resolved at low spacing at 5 GHz.
		150		80	36	1.0		Resolution problems for nucleus.
3332	190	70	51	45	35	0.6	45 (a)	0.4 GHz flux density confused by nearby source.
3569	<40±20	40	43	50	70	-0.4	50 (a)	
3593*	80	60	64	50		0.25	55 (a)	Faint extended object; invisible at 5 GHz.
3665**		122 (23)		100 10	70 9	0.5 0.0	100 (a)	(23) gives same 5 GHz flux.
3801*	1840	960	800	700	500	0.5	730 (a)	
3826**	<40±20	20	53	55	35		55 (a)	Inverted spectrum or turnover; or variable at 5 GHz?
3862*		5500 (5)	3077	2600 (6) 400	1600 (6) 400 (7)	0.95	2940 (a) 400	3C 264. See (5), (6) and (7). Central source has flat spectrum; see (6).
4261	35300 (8)	17800 (3)	10900	13100 (3)	8300 (3)	0.6	12400 (a)	3C 270. No central component at 15 GHz (9). See (10).
4278	580 (3)	550 (3)	434	450	400 (3)	0.2	450 (a)	

4374			3655	3900 (11) 150 (28)		0.6 (11) -0.3 (28)	3900 (a) 150	3C 272.1. See (7) and (11).
4472		225 (12) 125 (12)	132	140	95 (12) 60 (12)	0.7 0.6	135 (a) 85	See (12).
4486						0.8 0.3	110 Jy 5 Jy	3C 274. Data from (13). See also (14)
4552		60 (29)	92	120	100	∿ 0	120 (a)	
4789*	110 (3)		52	30	60 (3)	∿0.2	∿ 30 (c)	Uncertain α.
4827**	< 50	45	42		30 (3)	0.3	35 (b)	See (15).
4839*	210 (15)	80 (3)	43	45	20 (15)	0.9	40 (a)	cD galaxy.
4874*	450 (3)	220 (16)	132		120 (16)	0.5	160 (b)	See (16).
5127*	10.9 Jy	2.5 Jy	301	500 10		1.2	1100 (b)	2.7 GHz flux density is probably under-estimate (large source).
5141	1710 (15)	860 (15)	585		320 (15) 180 (15)	0.7	520 (a)	See (15)
5318	220	90	104	80	60	0.3	75 (a)	0.4 and 2.3 GHz flux densities include nearby source
5352*			101	130			130 (a)	
5490*	1400 (17)		390	650 50	500 (3) 35	0.4 0.6	650 (a) <50	Confusing nearby source - see (17). Core not well resolved at 2.7 GHz.
5532						0.6 0.5	2300 (a) 70	3C 296. See (18) and (19)
7052*	140	180	160	100 55	110 60	? 0.0	120 (c)	
7385	7300 (3)	2300 (3)	1129	1400 (3)	850 (3) 120 (21)	0.8	1460 (a)	See (20) and (21). Core, only at 5 GHz.
7485	400	70	108	140	90		140	Strange spectrum; variable at 2.7, 5.0 GHz?
7626*	2000 (3)	830 (3)	165	380 (3,5 km) 25	230 (3)	0.9	420 (b) 25	May be low-brightness structure and 2.7 GHz flux density may be an underestimate.
UGC 12591	120	115	115	100	65	0	100	Flat spectrum to 2.7 GHz, then turnover, α ≃ 0.3.

Table 1 cont'd

Name (NGC)	Flux density (mJy) 0.4 GHz	1.4 GHz	2.3 GHz	2.7 GHz	5.0 GHz	α	S(2.7 GHz)	Comments
7720		7900 (22)	1941		2500 (22)	0.8	4000	3C 465. See (22) for map, α's. Also (26).
					290 (22)	0.0	300	
7728*	>600	290	386	600	400	0.7	450	Much disagreement on fluxes - see (27), for 2.7 GHz flux density and α. Much very low brightness emission.
		220?		104	130	-0.4		

Notes: An asterisk next to a galaxy number indicates that a Cambridge map is given in this paper. A double asterisk indicates that the source is not a member of the complete sample. Unacknowledged flux densities at 0.4 and 1.4 GHz are from the One-Mile telescope and are of Stokes' parameters $I+Q$, and at 2.7 and 5.0 GHz are from the 5-km telescope and are $I-Q$. 2.3-GHz flux densities are from Dressel & Condon (1978) except where otherwise indicated. There are two entries for sources where a central component was observed. The error on flux densities of central components at 2.7 or 5.0 GHz is ± 3 mJy. Spectral indices are derived from the given flux densities or are as quoted by the authors referenced in the Comments column; α is defined by $S \propto \nu^{-\alpha}$. The adopted flux densities at 2.7 GHz, given in the column S(2.7 GHz), have been derived from a fit of a power law in frequency to the flux densities given in the preceding columns, as described in the text. An error class is given for each source, depending on how well the flux densities fit a power law; the classes are (a) flux density accurate to within 10 per cent and α to within ± 0.05, (b) 20 per cent and ± 0.1, (c) within 30 per cent and α not usefully known. These categories are only approximate for sources where measurements are available at few frequencies.

References

(1) Bridle *et al.* 1976. (2) Bridle *et al.* 1979. (3) Haynes *et al.* 1975. (4) Burch 1977. (5) Högbom & Carlsson 1974. (6) Northover 1976. (7) Jenkins, Pooley & Riley 1977. (8) Cameron 1971. (9) Baker, Green & Landecker 1975. (10) Kronberg 1972. (11) Riley 1972. (12) Ekers & Kotanyi 1978. (13) Turland 1975. (14) Kotanyi 1980. (15) Fanti *et al.* 1977. (16) Jaffe & Perola 1974. (17) Schilizzi & MacAdam 1975. (18) Fomalont, Palimaka & Bridle 1980. (19) Birkinshaw, Laing & Peacock 1981. (20) Robertson 1981. (21) Hardee, Eilek & Owen 1980. (22) van Breugel 1980. (23) Kotanyi 1979. (24) Gillespie 1977. (25) Bridle & Fomalont 1978. (26) Riley & Branson 1973. (27) Wielebinski *et al.* 1978. (28) R. A. Laing (private communication). (29) Hummel 1980.

In view of these difficulties, it was decided to gather flux densities at a set of standard frequencies (0.4, 1.4, 2.3, 2.7 and 5.0 GHz) and then fit a power law in frequency to the measurements, unless this was obviously an inappropriate approximation. From this fit the flux density at 2.7 GHz was deduced, this frequency being chosen as standard since it is close to the selection frequency of the sample, and observations are often available at 2.7 GHz. Errors have been calculated from the goodness of fit of the power law model, and since these are fairly crude estimates, sources have only been grouped into 'confidence classes' as regards their flux densities; see Table 1. Note finally that occasionally one flux density does not fit the power law curve whereas all the others do; such a measurement would be excluded from the fit since it is probably systematically wrong because of, for example, confusion.

(iii) Hubble types. Doubts have frequently been expressed about the classifications of early-type galaxies, particularly of faint objects on the Palomar Sky Survey prints. Ekers & Ekers (1973) found a tendency for radio-emitting S0s to be anomalously round, and concluded that some fraction of these galaxies were misclassified and were possibly the D systems originally defined by Mathews, Morgan & Schmidt (1964). In principle, ellipticals and S0s can be distinguished from one another by optical surface photometry, as they have different luminosity profiles away from the nucleus. S0s show a disc where the brightness falls off exponentially with radius, whereas in ellipticals the variation is a power law (see e.g. Freeman 1975). In practice, for this survey it was necessary to accept the classifications given in catalogues and to judge their accuracy *a posteriori* by the results obtained in so doing. Therefore, in this paper the UGC classifications will be adopted and the terms 'S0' and 'elliptical' will refer to this catalogue's Hubble types. For 18 galaxies in the sample which are independently classified in the *Second Reference Catalogue of Bright Galaxies* (de Vaucouleurs, de Vaucouleurs & Corwin 1976), the two catalogues agree on the Hubble type in 12 cases, but there is disagreement on the classification of three out of four S0s. It is therefore not clear how the class 'UGC S0' relates to other observers' classifications, and a full discussion of this issue is deferred to Section 4.

(iv) Optical magnitudes. The Second Reference Catalogue tabulates a quantity $B(T)$ which is the total blue apparent magnitude of a galaxy. A test showed that, for early-type galaxies, there is a good linear correlation between UGC photographic magnitudes and $B(T)$; since the latter quantity is based on photoelectric photometry, this gives confidence in the UGC magnitudes, which on average only differ from $B(T)$ by a shift in zero point.

(v) Sizes. The size of a radio source without prominent features (such as hotspots) would normally be defined as the dimensions down to a given level of surface brightness at a given frequency. Since the present paper utilizes maps from many instruments, at different frequencies, resolutions and sensitivities, such an approach is not feasible. Instead, the sizes given in Table 2 are the largest known dimensions; this imprecise measure suffices to show whether the sources are bigger or smaller than their associated galaxy, which is the only distinction that I wish to draw.

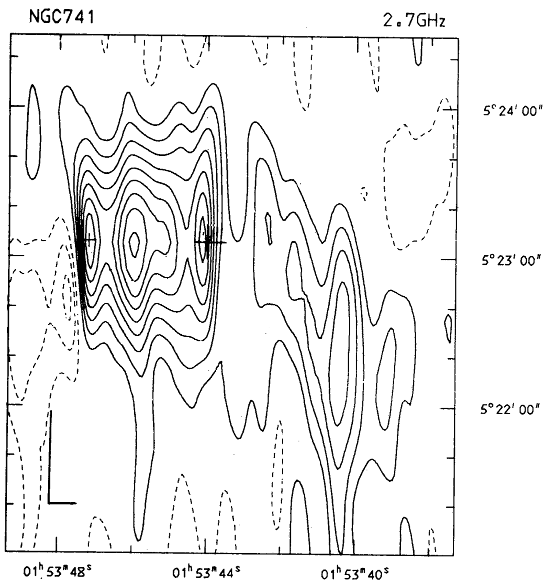
Several checks were made with maps from Cambridge telescopes to ensure that sizes were not being underestimated. For nine extended sources mapped with the 5-km telescope, the maps were convolved to half their original resolution. Also available were One-Mile maps of 15 sources in the complete sample, as well as maps of NGC 2892, 3665, 3826 and 5322, which are sources of similar morphology to those in the sample. It was clear from these data that, in most cases, the full-resolution 5-km map gave an adequate measure of the source size. In fact, only NGC 5127 and 7728 appeared substantially larger on convolution of the 5-km maps, and for these it was already apparent that only a small fraction of the total flux density showing at small interferometer baselines was visible on a full-resolution map.

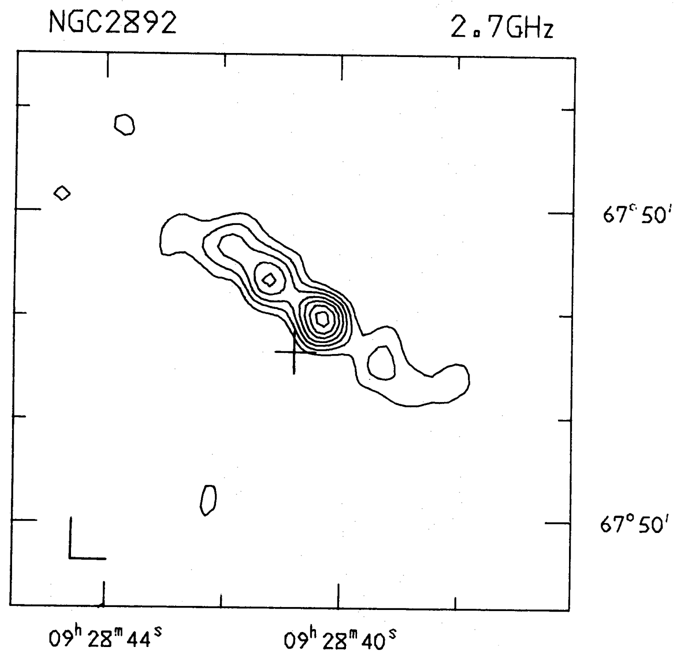
Table 2: Intrinsic properties of the galaxies

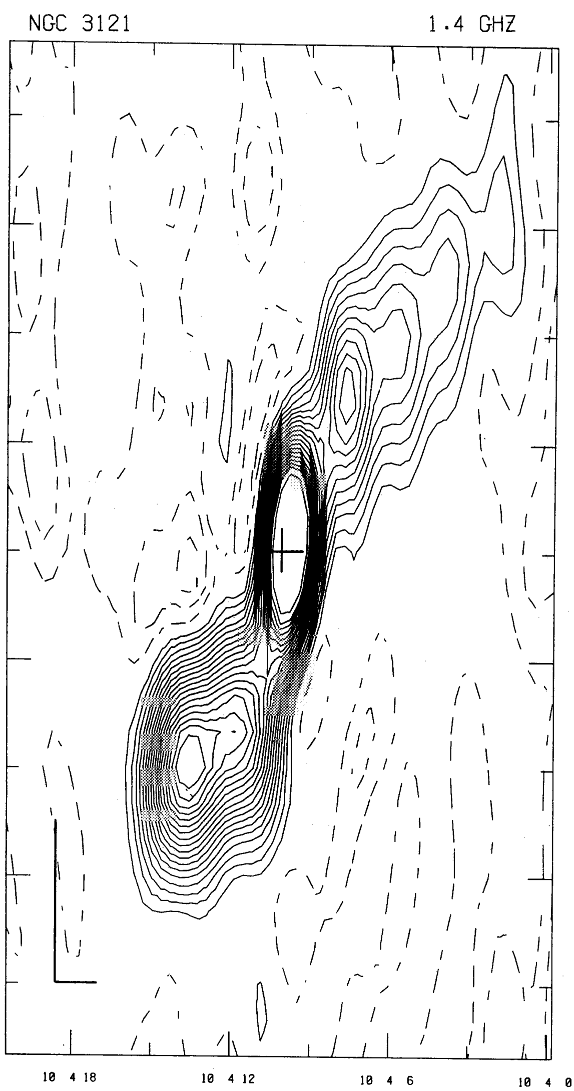
Name (NGC)	Type (UGC)	v (km s^{-1})	log P(2.7 GHz)/(W Hz^{-1})	Absolute Magnitude (UGC)	Size (kpc)	Size Ratio	Emission Lines
315	E	5218	24.2 23.8	-22.9	1500 (2)	+1	No
383	SO	5095	24.6 23.1	-21.9	>1.1 Mpc	+1	No
741	E	5645	23.8 22.5	-22.3	90	+1	No
984	SO	-	-	(14.2)	-	-1	-
1167	SO	4859	24.2	-21.3	2 (25)	-1	No
2749	E	4118	22.5	-21.5	-	-1	Yes
2892**	E	-	-	(14.1)	60 arcsec	-1	-
3121	E	-	-	(14.0)	400 arcsec	+1	-
3332	SO	5882*	22.8	-21.8	-	-1	-
3569	SO	7447*	23.1	-21.5	-	-1	-
3593	SO	543	20.7	-18.6	2	-1	Yes
3665**	E/SO	2012	22.2 21.2	-21.6	10	-1	No
3801	SO	3174	23.5	-20.9	15	-1	No
3826**	E	-	-	(14.2)	-	-1	-
3862	E	6159	24.6 23.8	-21.6	100 (6)	+1	No
4261	E	2090	24.4	-21.3	110 (10)	+1	No
4278	E	651	21.9	-19.6	-	-1	Yes
4374	SO	854	23.1 21.7	-20.5	12 (11)	-1	No
4472	E	817	21.6 21.4	-21.0	12 (12)	-1	No
4486	E	1200	24.8 23.5	-21.7	50 (14)	+1	Yes

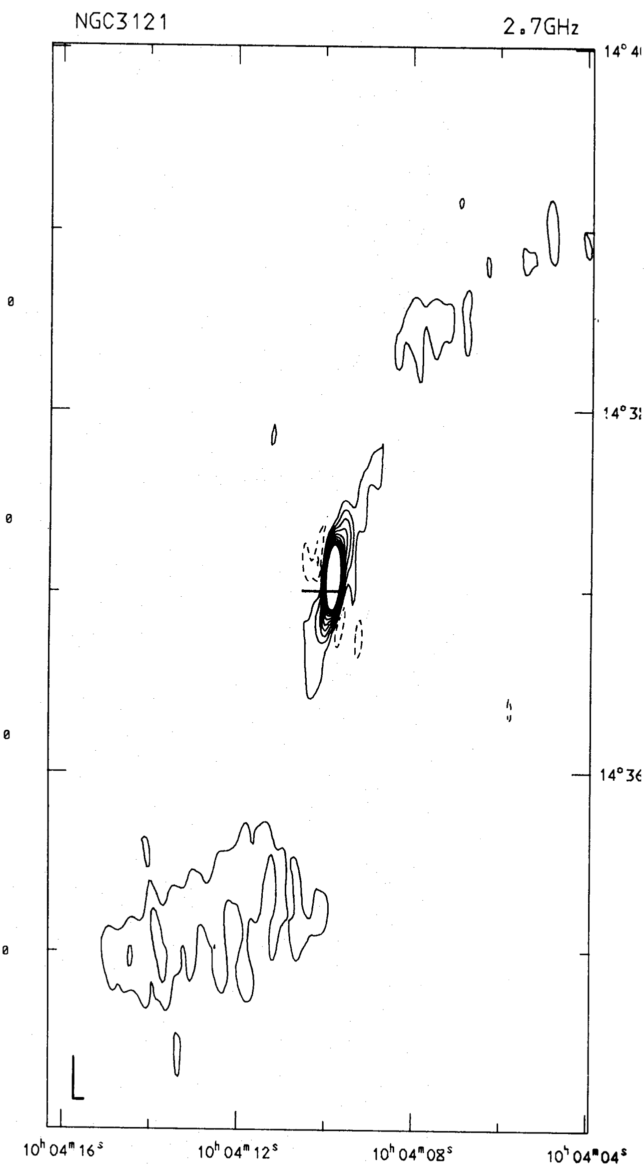
4552	E	165	20.2	-16.7	-	-1	No
4789	E/SO	8373	23.0	-23.0	20	-1	No
4827**	SO	7653	23.3	-22.0	30 (OMT)	-1	No
4839	E	7451	23.0	-22.5	30	-1	No
4874	SO	7176	23.6	-22.3	30 (5 GHz)	-1	
5127	E	4869	24.1 22.0	-21.2	280 (OMT)	+1	No
5141	SO	5283	23.8	-21.4	20 (15)	-1	No
5318	SO?	4179*	22.8	-21.3	-	-1	-
5352	E/SO	-	-	(14.2)	75 arcsec	-1	-
5490	E	4889*	23.8 <22.7	-21.7	40	-1	-
5532	SO	7106	24.7 23.2	-22.7	250 (19)	+1	No
7052	E	5198	23.4 22.8	-21.8	40	-1	No
7385	E	8051	24.6	-21.9	1200 (20)	+1	No
7485	SO	-	-	(13.8)	-	-1	-
7626	E	3638	23.4 22.2	-21.8	35	-1	No
UGC 12591	SO-a	-	-	(13.7)	-	-1	-
7720	E	9238	25.2 24.1	-22.7	350 (26)	+1	Yes
7728	E	9470	24.3 23.6	-22.4	>160 (OMT)	+1	No

Notes: Hubble types and apparent magnitudes, as well as approximate sizes of the galaxies on the Palomar Sky Survey prints, are taken from the UGC (Nilson 1973). Absolute photographic magnitudes have been calculated using the redshifts and corrections for galactic absorption given in the Second Reference Catalogue (de Vaucouleurs *et al.* 1976); recession velocities marked with an asterisk are from J. Huchra (private communication). The 2.7-GHz flux densities used are from Table 1. Sizes of the radio structures are as defined in Section 2 and are, unless otherwise noted, from 5-km maps. The size ratio is given as +1 if the source is larger than the optical extent of the galaxy, and as −1 otherwise. Data on the existence of emission lines are taken from Gisler & Friel (1979). Double asterisks indicate that the galaxy is not in the complete sample.


NGC741
2.7GHz
5°24′00″
5°23′00″
5°22′00″
01h53m48s
01h53m44s
01h53m40s


NGC2892
2.7GHz
67°50′
67°50′
09h28m44s
09h28m40s


NGC 3121
1.4 GHZ
14 40 0
14 38 0
14 36 0
14 34 0
10 4 18
10 4 12
10 4 6
10 4 0


NGC3121
2.7GHz
14°36
10h04m16s
10h04m12s
10h04m08s
10h04m04s

Because of this check, and because flux densities are known at many frequencies from instruments with a wide range of angular resolutions, it seems unlikely that large sources of low surface brightness would have escaped notice. To reiterate, therefore, no more is claimed for the dimensions given in Table 2 than that they are those within which most of the radio emission originates.

The optical diameters have been taken from the UGC.

(iv) Distances. These have been taken as (velocity of recession/H_0) with $H_0 = 50$ km s^{-1} Mpc^{-1}.

3 Morphology

From an inspection of the maps in Fig. 1 and those referenced in Table 1, it is first clear that even weak radio galaxies have structures which suggest that they are powered by beams in the same manner as more powerful sources. A large fraction of the sample consists of sources similar to 3C 31 (NGC 383) which has a central component and two strong radio jets. Examples are NGC 315, 383, 3121, 3593, 3801, 4374, 4472(?), 4486, 4789(?), 5127, 5141, 5352, 5490, 5532, 7052, 7385, 7626, 7720 and 7728: a total of 19 sources including the two doubtful candidates for which adequate maps are not available. NGC 4472 is at low declination and NGC 4789 is small and faint. The classification of NGC 3801 is based primarily on a VLA map at 1.4 GHz (Jenkins & Laing, in preparation). Secondly, there are the sources which seem to consist only of a central component, whether observed at high frequency and resolution with the 5-km telescope, or lower frequency and resolution with the One-Mile telescope. There are 10 such sources in the sample: NGC 984, 1167, 2749, 3332, 3569, 4278, 4552, 5318, 7485(?) and UGC 12591. The uncertain classification for

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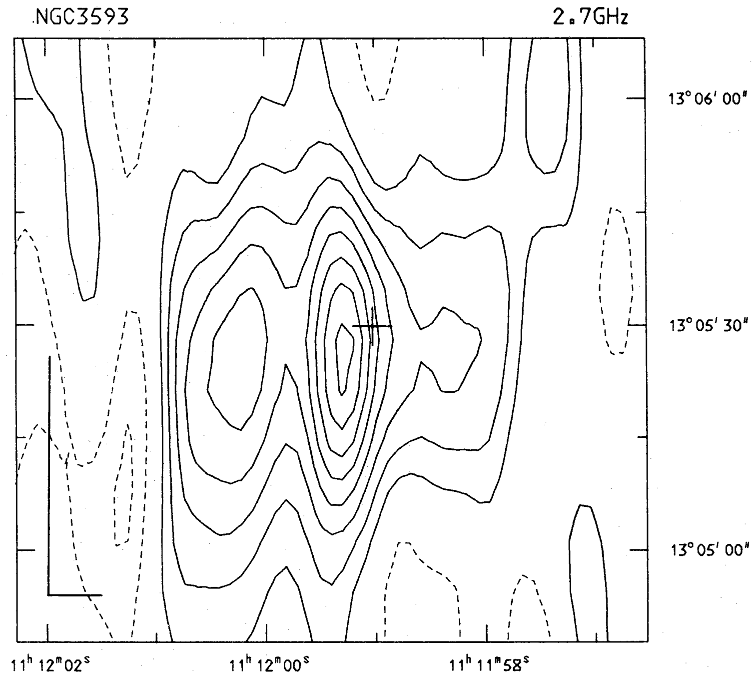
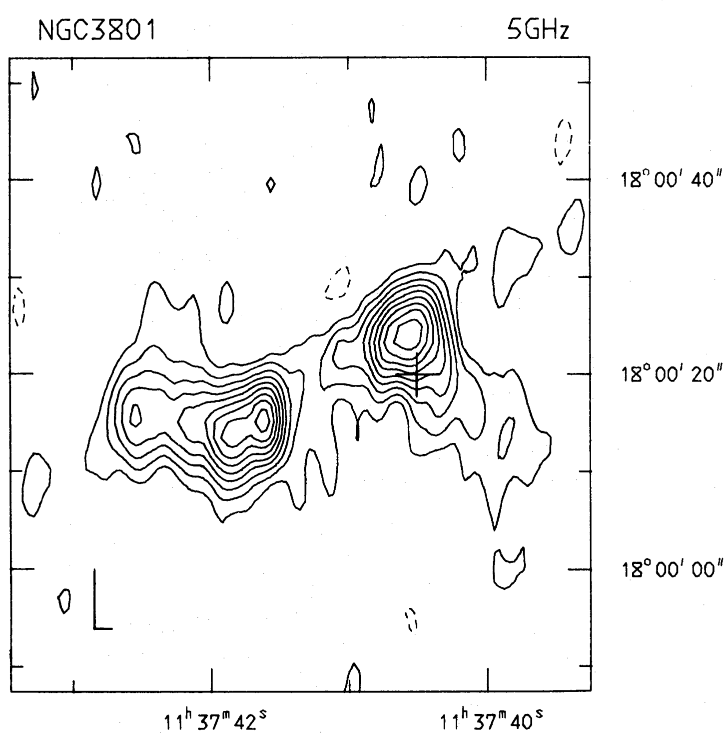
Figure 1. Brightness distributions of 15 nearby radio galaxies at 1.4, 2.7 or 5.0 GHz. For each source, details of the map are given. Maps at 1.4 GHz are from the One-Mile telescope and are of Stoke's parameters $I+Q$; those at 2.7 and 5.0 GHz are from the 5-km telescope and are of $I-Q$. The zero contour level is suppressed on the maps and negative contours are dashed. Unless otherwise noted, the contour interval is 3 mJy/beam area for 5-km maps and 5 mJy for One-Mile maps. Details are given of any unusual map processing. A cross marks the position of the associated galaxy's nucleus, as given by Dressel & Condon (1976). The formal accuracy of these positions is ± 4 arcsec. Map coordinates are for epoch 1950.0. The L-shape in the map corner gives the FWHM of the beam in right ascension and declination. The FWHM in right ascension of the beam is: 23 arcsec at 1.4 GHz, 3.6 arcsec at 2.7 GHz 2.0 arcsec at 5.0 GHz at full resolution, and is larger in declination by a factor cosec δ. NGC 741. The map has been convolved to a beam three times wider in right ascension than usual, and consequently the flux density scale is uncertain. The unresolved source to the east, marked with the cross, is NGC 742. NGC 3593. The contour interval is 2 mJy/beam area and the map is at half resolution. NGC 3801. The contour interval is 4 mJy/beam area. From the position of an unresolved nuclear source visible on a VLA map at 1.4 GHz (Jenkins & Laing, in preparation), it seems likely that Dressel & Condon's (1976) position is too far west by 1 s in right ascension. NGC 3862 (= 3C 264). The contour interval is 6 mJy/beam area. NGC 4789. A grating response crossing the source has been removed. Note that Dressel & Condon's (1976) position for the galaxy is not significantly offset from the radio source. NGC 4839. The contour interval is 2 mJy/beam area. The associated object is a very elliptical cD galaxy (Oemler 1976). NGC 4874. The contour interval is 6 mJy/beam area and the map has been convolved to the 2.7-GHz resolution. NGC 5127. The contour interval is 2 mJy/beam area on both 5-km maps; it is 3 mJy on the One-Mile map. The smaller-scale 5-km map is at half-resolution, to show the extended structure. (A source of this size is not properly sampled in a single 12-hr run with the 5-km telescope.) NGC 5352. The map is at half-resolution. NGC 7052. The contour interval at 2.7 Ghz is 2 mJy/beam area and the map has been phase-referenced with respect to the central source. NGC 7728. Several interfering sources (including 3C 465) have been removed from the 1.4-GHz map, but there is still some residual north–south structure at a low level which represents the remaining grating responses. The contour interval is 5 mJy/beam area and then (at the peak) 20 mJy. The 5.0-GHz map has been phase referenced and the contour interval is 4 mJy. (Note that the right ascension scale is 1 s per division.)





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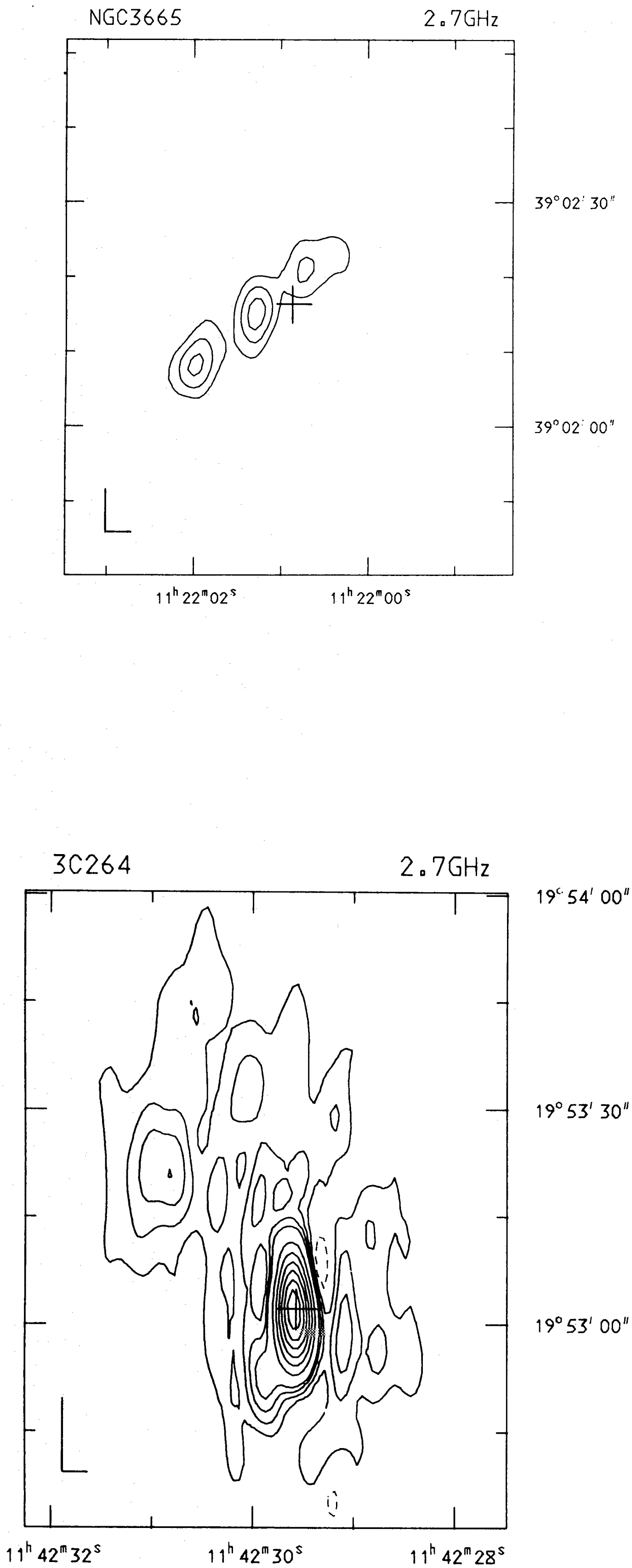

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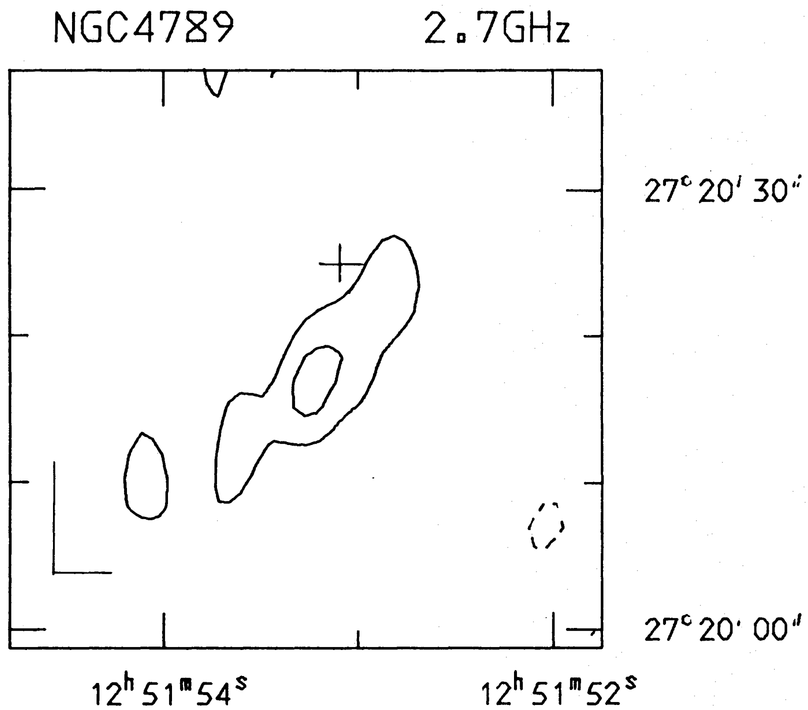

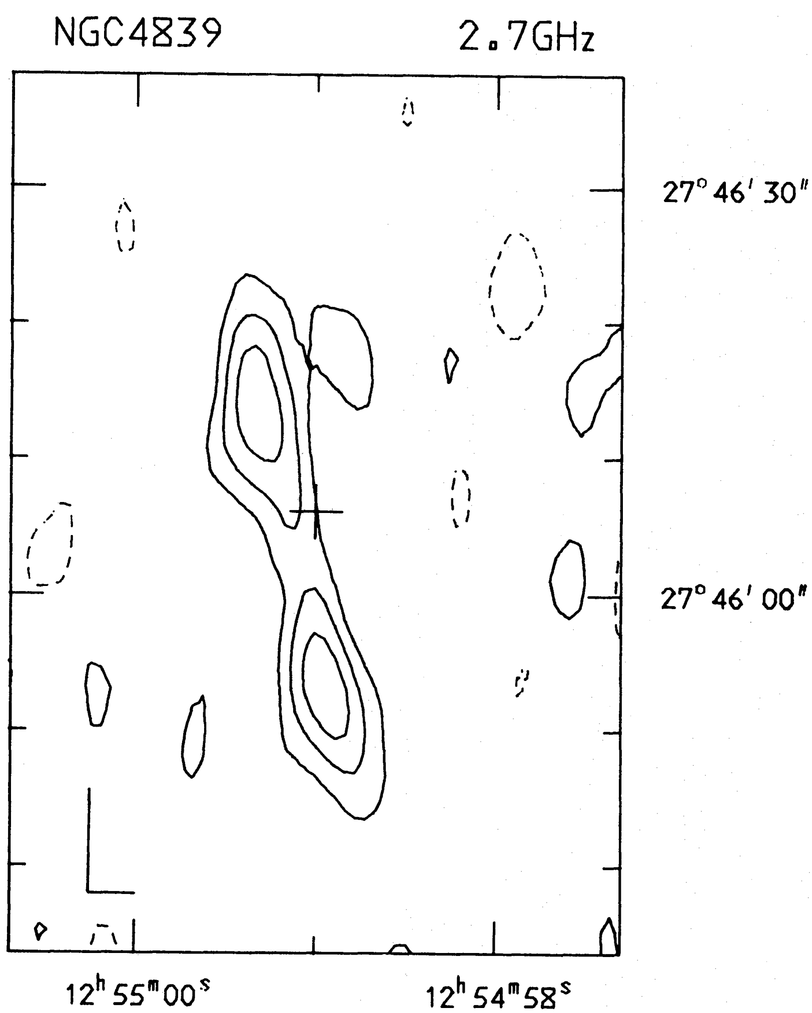

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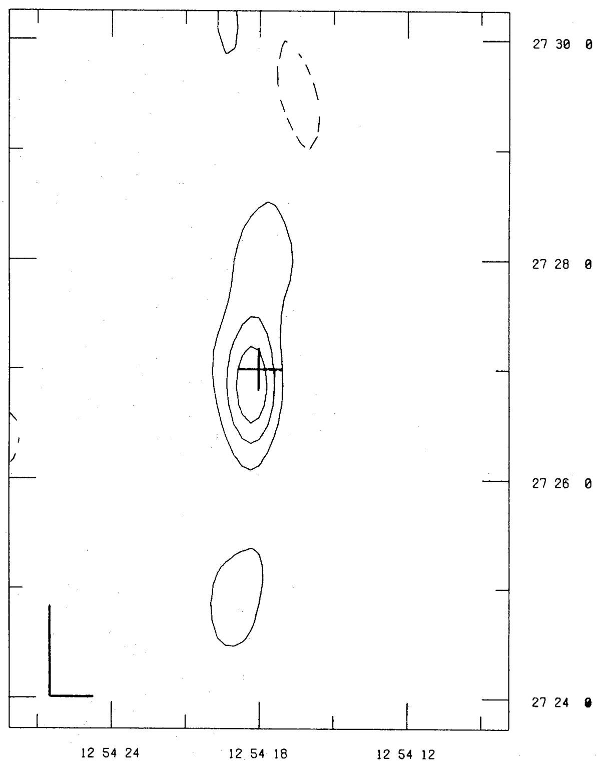

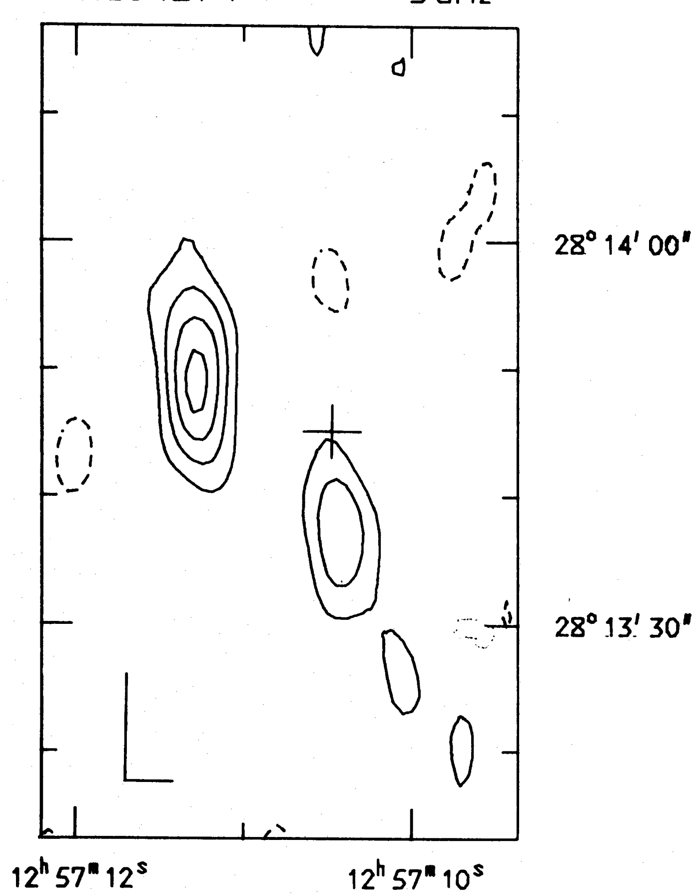

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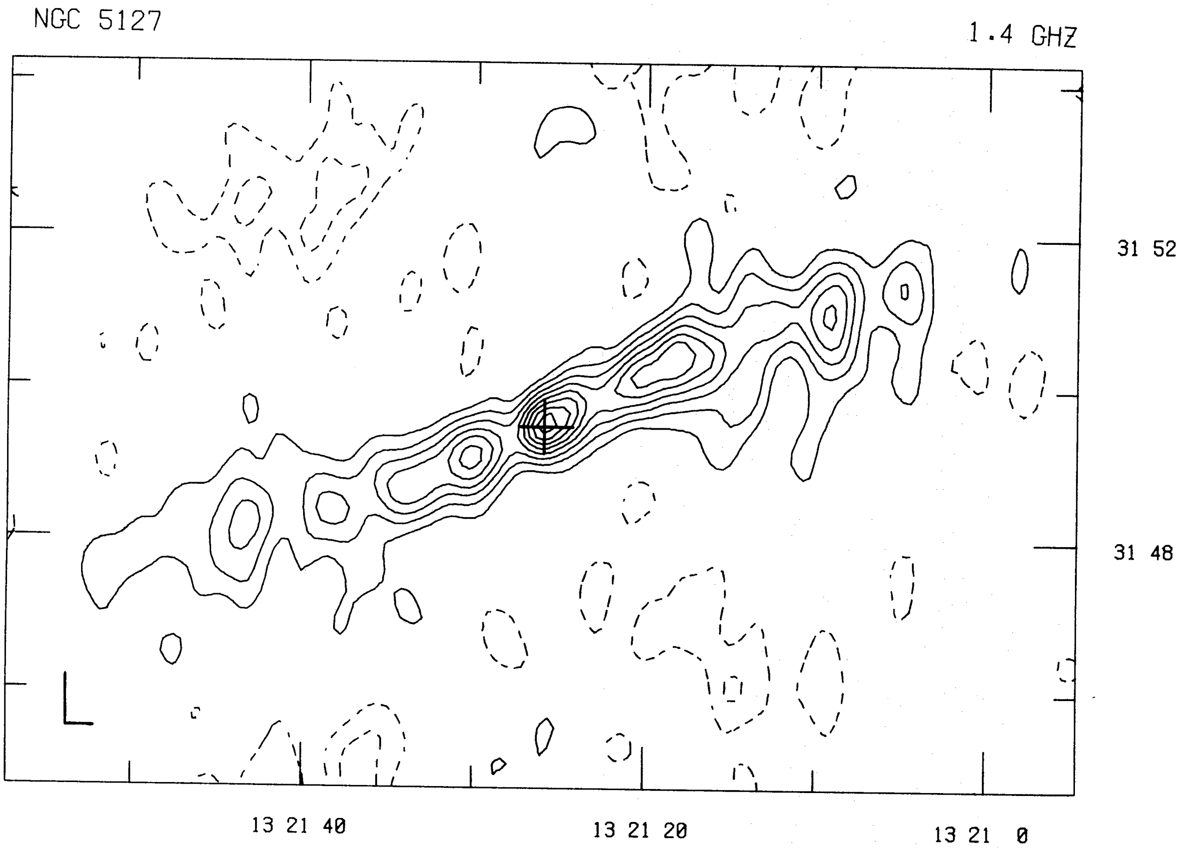

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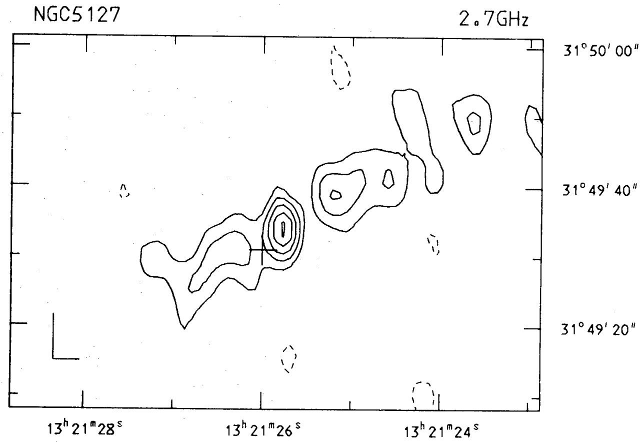
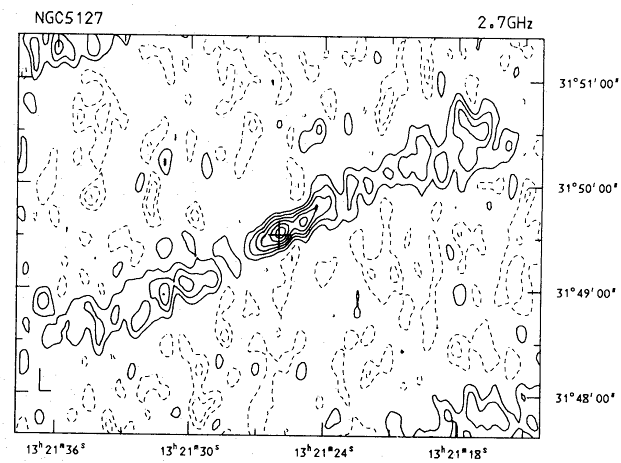
NGC 7485 is because it shows some evidence of a low-frequency halo – see Table 1. Lastly, there are two double sources, apparently without jets or central components (NGC 4261 and 4839), two unclassifiable sources (NGC 3862 = 3C 264 and NGC 4874) and NGC 741, which is probably a 'bent double' (Simon 1978), although at its low declination the resolution is too poor to be sure of this.

It therefore appears that low-luminosity radio sources in early-type galaxies have the following properties: (i) about two-thirds are linear sources with prominent radio jets and central components; (ii) about one-third are entirely confined to the nucleus of the galaxy, i.e. the innermost kiloparsec or less; (iii) only a small fraction of sources do not fall into these two categories; (iv) as usual, the extended sources have spectral indices in the range 0.5–1.0, whereas the unresolved sources have flatter or even inverted spectra.

4 Comparison with optical types

On the basis of the UGC Hubble types, it is found that ellipticals account for 15 extended and three unresolved sources, whereas there are seven extended and seven unresolved sources in S0s. This result is significant at the 5 per cent level (using the Fisher exact probability test – see Siegel 1956) and bears out the conclusion of Condon & Dressel (1978) noted earlier, that S0s produce sources of small angular size more frequently than ellipticals. Although the present result is not as significant statistically as that obtained by Condon & Dressel (1978), it is based on more detailed information on the radio morphologies. Note that the mean distances for the ellipticals and S0s are very similar, so that the deficiency of resolved S0s is not due to their being further away on average. There is an indication that the





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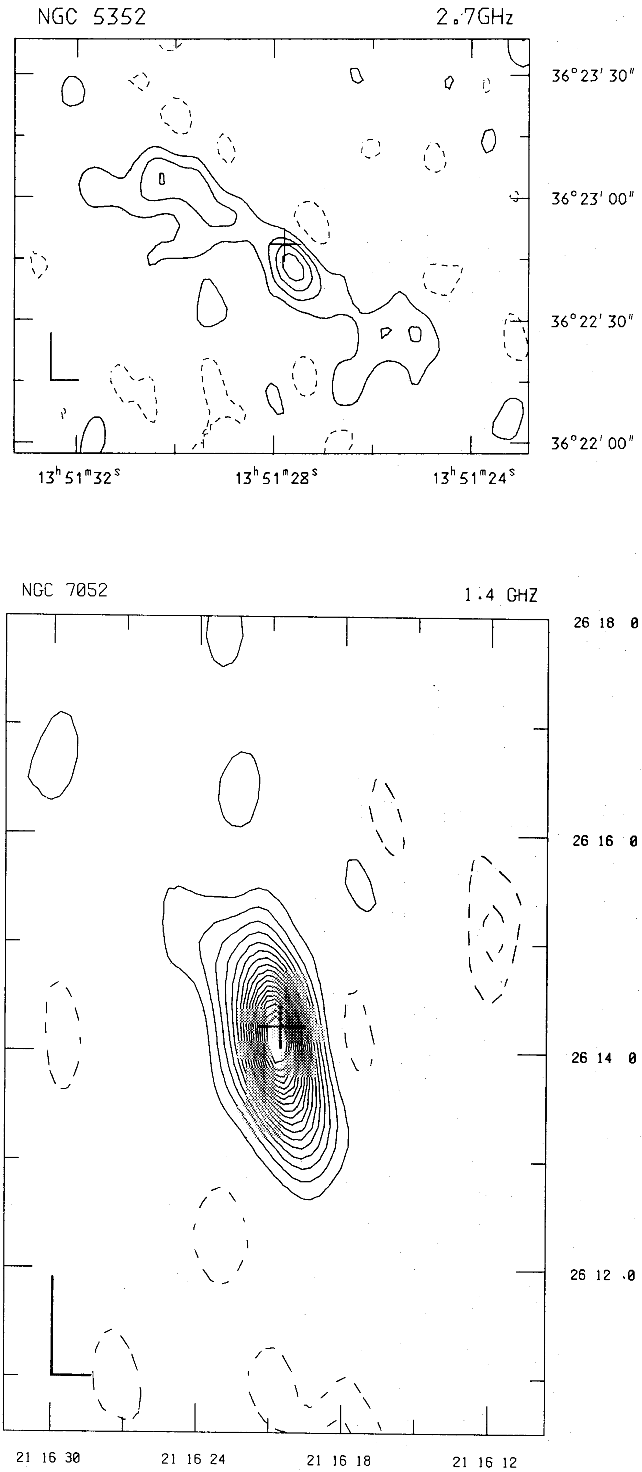
unresolved sources in ellipticals are less luminous than those in S0s; the three in ellipticals (NGC 2749, 4278 and 4552) are considerably less powerful than the four in S0s with known distances, namely NGC 1167, 3332, 3569 and 5318.

This information suggests that conditions in S0s are less favourable for the formation of large radio sources; also, S0s are capable of containing luminous sources within small regions, whereas in ellipticals only the most feeble sources remain confined. This result deserves closer examination, because the classification of radio galaxies as S0 has been called into question by Ekers & Ekers (1973). In the present sample, the Hubble types are taken from the UGC, and, as already noted, there is scant agreement with classification given independently in the Second Reference Catalogue. However, it is not true that these S0s are simply misclassified ellipticals, as can be seen by comparison with the definitive axial ratio distributions of various Hubble types, given by Sandage, Freeman & Stokes (1970). The 'Radio S0s' are flatter than SFS ellipticals but rounder than SFS S0s. This is probably due to the presence of D galaxies (Mathews *et al.* 1964) among the radio S0s. This hypothesis is confirmed by the existence of a strong correlation between the axial ratio and intrinsic optical size for the 11 radio S0s of known redshift. The Spearman rank test (Siegel 1956) gives a significance level of at least 5 per cent, which is improved by omitting NGC 4374. The photometry of King (1978) shows that this galaxy is not an S0.



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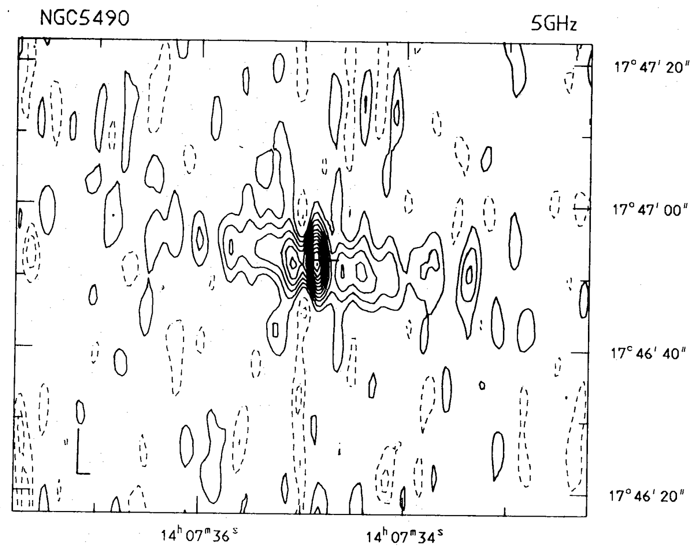
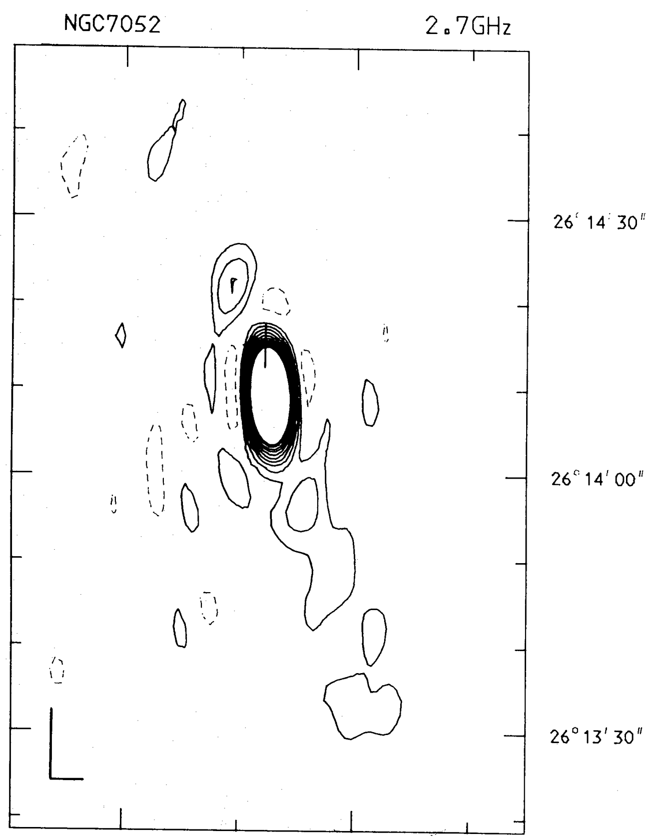
The sense of the correlation is that round galaxies tend to be substantially larger than flat ones. This is not consistent with all 11 galaxies having the same physical shape, and suggests that Nilson is classifying some giant ellipticals with extended spherical haloes as S0. Such haloes, seen on the Palomar Sky Survey, might mimic an exponential disc seen face-on and lead to such misclassification. If one excluded large galaxies (like NGC 383, 1167, 4874 and 5532) from the S0 sample, the difference in the radio morphology between ellipticals and S0s





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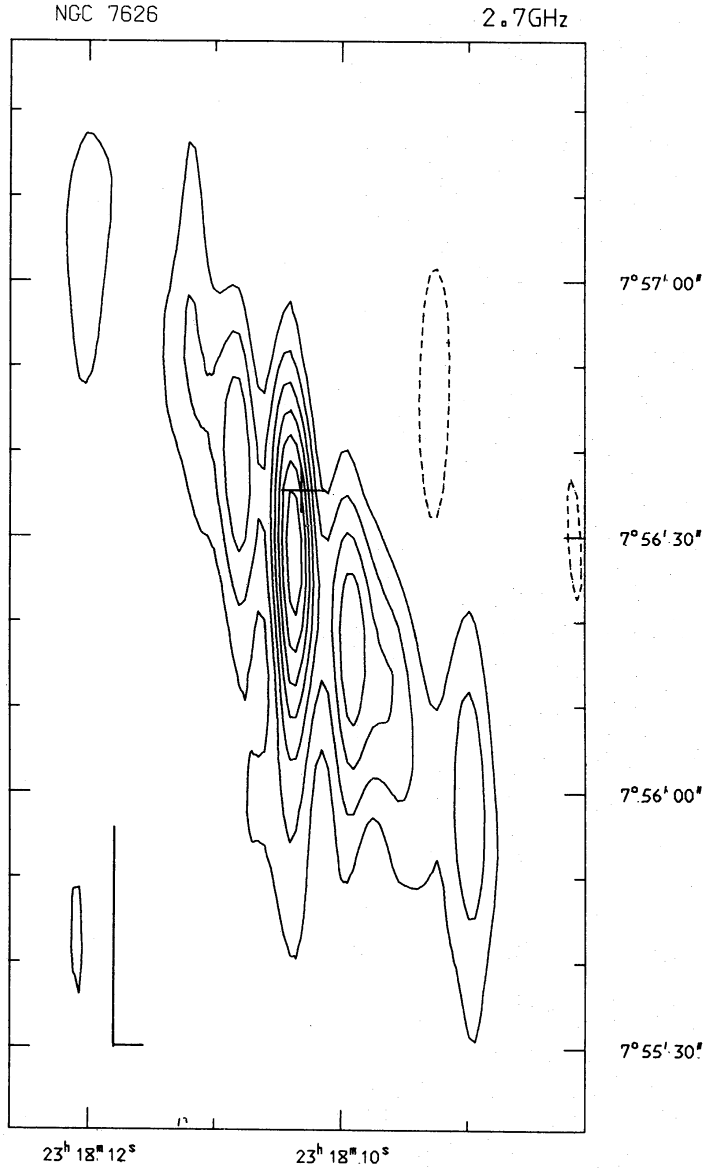
would be enhanced. For example, three of the six S0s with extended radio structure have optical diameters greater than 60 kpc, whereas this is true of only one of four unresolved S0s. In summary, therefore, despite the problem of misclassification, there seems to be good evidence for a difference in radio morphology between ellipticals and S0s. This is apparent if one takes Hubble types at their face value, and becomes more pronounced if account is taken of the cD galaxies which can mimic pole-on S0s. The reason for this difference in



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radio morphology may be linked to the fact that S0s are detected more frequently in the 21-cm H I lines than are ellipticals (see e.g. Biermann, Clarke & Fricke 1979). In Section 5 it is argued that the presence of a dense interstellar medium may mean that only powerful beams can penetrate beyond the confines of the parent galaxies.

5 Relation to optical size

The distribution of linear sizes for sources in the sample is given in Table 3. It is apparent that 30 kpc is the important scale in the distribution, since sources are usually either smaller than this, or else very much larger. The typical diameter of an early-type galaxy on the Palomar Sky Survey prints is also about 30 kpc. Not only do sources tend to be either rather large, or small, but there is also a strong correlation between luminosity and size, in the following sense. For the present sample, there are 11 'weak' sources ($23.0 < \log P(2.7\,\text{GHz}) < 24.0$) and 10 of these (the 'small' ones) have radio structure smaller than the optical extent

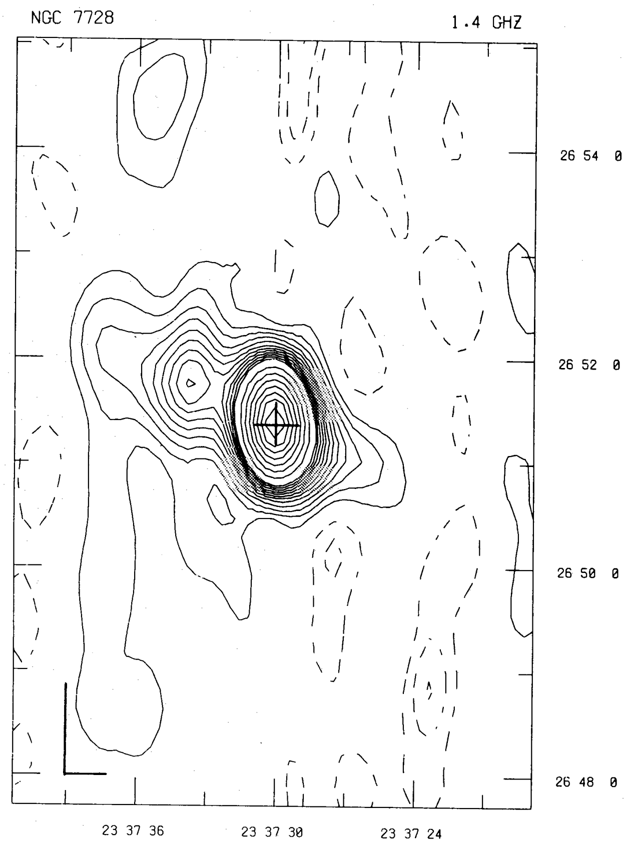

Figure 1 – *continued.*

of the associated galaxy; of the 10 'strong' sources ($24.0 < \log P(2.7\,\mathrm{GHz}) < 25.0$), nine are larger than the galaxy. The correlation can be made more precise, although less dramatic, by consideration of the radio luminosity function (see Section 8). Over the range $23.0 < \log P$ $(2.7\,\mathrm{GHz}) < 25.0$, the space density (per interval of $\log P$) of the small sources falls by a factor of 10, whereas that of the large sources rises by a factor of 3. There is no similar trend if the space density is considered as a function of optical absolute magnitude, indicating that the correlation of size is primarily with radio luminosity. (Although there is a correlation between absolute magnitude and radio luminosity, the size–radio luminosity correlation will, if it is fundamental, be diluted by the scatter on the optical–radio luminosity correlation, and thus a size–absolute magnitude correlation would not necessarily be detectable. Note also that the correlation between absolute magnitude and radio luminosity is not particularly strong for the present sample; see Section 8.)

An important question is whether the original survey by Dressel & Condon (1978) would have been able to detect weak but large sources. One can easily show that, at the resolution of their survey, sources of size ~100 kpc and luminosity $\log P(2.7\,\mathrm{GHz}) > 23$ should not have been missed. On the other hand, very large sources, or sources consisting of two widely separated weak components, might well have escaped detection; but we have no evidence from any other survey that such sources exist – see the note on Table 3.

A qualitative explanation as to why the more luminous sources extend well outside their parent galaxies can be given in terms of the stability of beams in radio sources. It is known that these beams are subject to Kelvin–Helmholtz instabilities at the interface between the beam and the surrounding medium. A low-density beam in a high-density environment becomes more stable as its energy flux increases – that is, as its velocity or density increase.

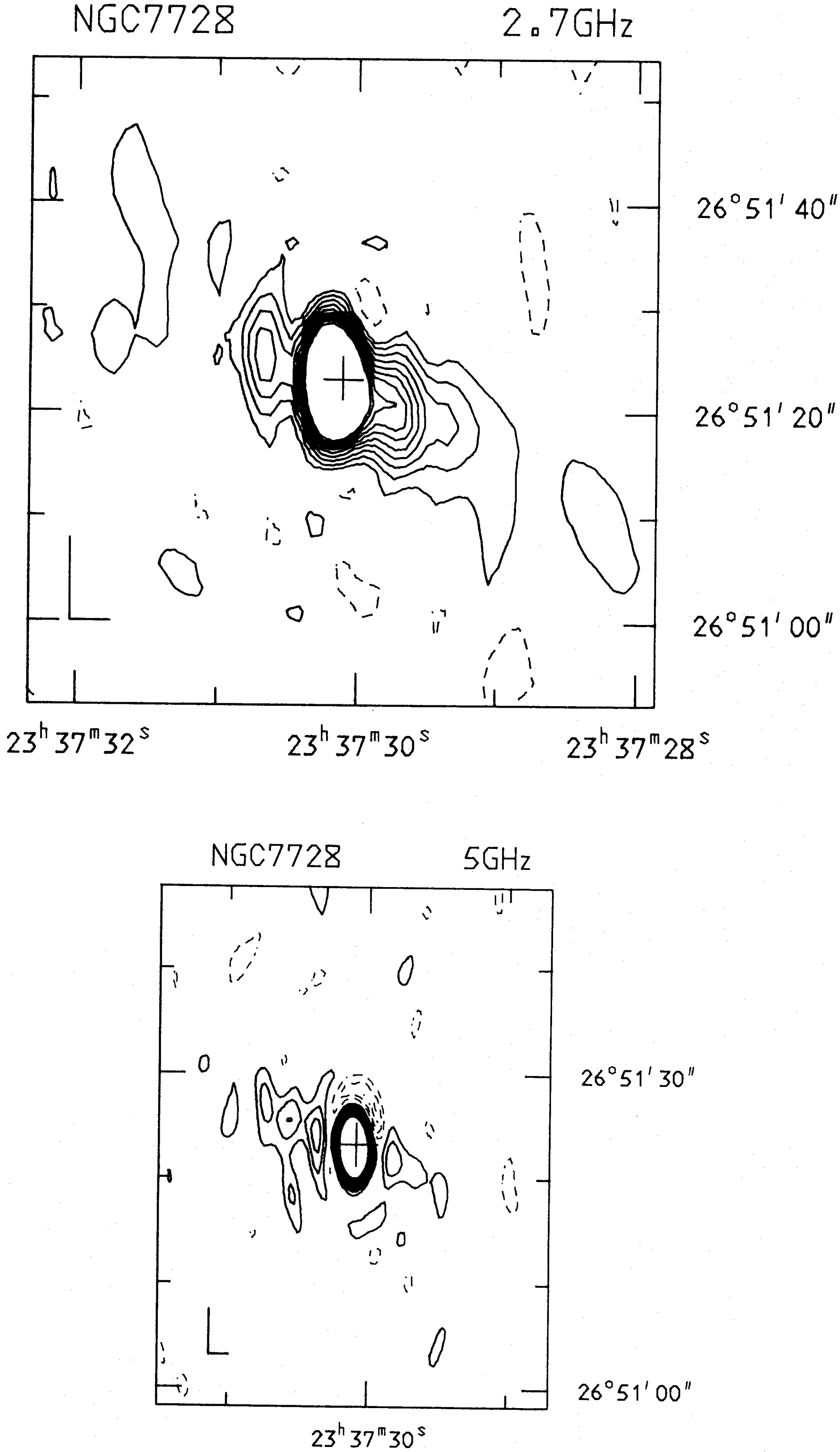

Figure 1 – *continued.*

Moreover, as instabilities develop at the beam's circumference, they are convected along at roughly the beam velocity (see Hardee 1979 for quantitative details). Based on these ideas, I explain the size–luminosity correlation as follows. A 'growth length' for a beam would be given by (beam velocity × growth time for destructive instabilities). Hardee's equation (15)

Table 3. The distribution of physical sizes in the present sample, and in the sample of Colla *et al.* (1975).

Size (kpc)	Number of sources	
0–30	18	21
30–60	4	6
60–90	1	7
90–120	2	4
120–150	0	2
150–180	0	1
>180	7	8

Note that the sample from Colla *et al.* (1975), although not entirely independent, was selected by the Bologna Cross, of beamwidth 3 ×10 arcmin², whereas the Arecibo telescope (used by Dressel & Condon 1978) has a beam of diameter 2.7 arcmin. Colla *et al.* (1975) also estimated the angular sizes of the sources with an instrument (the Westerbork telescope) which is more sensitive to structure of low brightness than is the 5-km telescope.

shows that the growth length is proportional to the Mach number of the beam, its radius, and the square root of the ratio of its density to that of the external medium. Suppose that the instabilities result from the interaction between the beam and the galaxy's interstellar medium; as the beam carries more energy, a point will be reached where the growth length is greater than the scale height of the galaxy's atmosphere. Instead of being totally disrupted (and consequently radiating) inside the galaxy, the beam will then travel on until it radiates its energy in other processes, presumably associated with its interaction with the intergalactic medium. Therefore this simple model explains why low-luminosity radio sources are comparable in size to the galaxies that produce them. To understand the mechanisms better, one would need to know more about (a) the stabilities of beams in media of varying density, and (b) the pressures and densities in the atmospheres of galaxies. The nature of these atmospheres is at present an open question; Faber & Gallagher (1976) have suggested that the gas in ellipticals is heated to the virial temperature by supernovae and is in fact leaving the galaxies in a steady wind. In this case, the densities would be low. However, there may be regions where the galactic wind does not blow and the atmosphere is cooler and denser (Bailey 1980). It is intriguing in this context that galaxies with dominant nuclear radio sources tend to show optical emission lines, since the model suggested in this section would predict that the smaller sources would be found in galaxies with a relatively cool and dense interstellar medium, which could radiate in lines like [O II] 3727 – see Section 6 for a brief further discussion of this issue.

Simple calculations, using a model of galaxy atmospheres due to Lance Miller (private communication), suggest that the equipartition pressure in a representative jet (NGC 5490) can be laterally confined by gas at 10^7 K. The X-ray luminosity of such gas is well below current detection limits, and its mass is small, $< 10^9 M_\odot$.

6 Emission lines

Only five of the galaxies in the present sample are known to have emission lines, which is comparable with the general frequency of such emission in ellipticals (Humason, Mayall & Sandage 1956). Unfortunately the optical data are very inhomogeneous, but the present results are relevant to the correlation which is claimed to exist between the presence of emission lines and an unresolved nuclear radio component. This correlation has been most thoroughly examined by O'Connell & Dressel (1978). These authors consider a sample based on the Arecibo 2.3-GHz survey, and find emission lines in many of the 12 (out of 29) galaxies which show unresolved radio components. However, the data given in the present paper show that 31 (out of 34) galaxies have an unresolved nuclear component, a difference from O'Connell & Dressel's work which may result from their use of low-resolution interferometric data, with fringe spacings of approximately 6 arcsec. It is therefore not yet clear to which feature of the radio morphology the occurrence of emission lines is related.

7 Nuclear sources associated with extended emission

Nearly all of the galaxies have compact components in their nuclear regions, with the flat spectra characteristic of small sources (< 100 pc). A measure of caution is necessary, however. When extended emission is present, it is sometimes not clearly separable from that of the nuclear source. For example, the 5-km maps of NGC 3121 and 5490 give spectral indices of the nuclear sources (between 2.7 and 5.0 GHz) which are appreciably steeper than those of the extended structure; this probably indicates that the nuclei are confused with the surrounding emission regions, at least at 2.7 GHz.

With this caveat in mind, the two-point spectral indices (see Table 1) for the central components of NGC 383, 3121, 4374, 4472, 5490, 5532, 7720 and 7728 are 0.0, 1.0, −0.3, 0.6, 0.6, 0.5, 0.0 and −0.4. NGC 4486 (= M87) has a spectrum defined from 408 MHz to 8.1 GHz with $\alpha = 0.3$. For NGC 315 and 3862, the spectra rise at low frequencies and then flatten.

It follows therefore that the luminosities of the nuclear sources are somewhat ill-determined; first, because of the resolution problem and secondly, because the spectra are likely to have complicated shapes and the monochromatic luminosity is not necessarily a good measure of the total luminosity. Nevertheless, taking the luminosities of Table 2, one finds that a plot of $\log P(\text{nucleus})/P(\text{total})$ against $\log P(\text{total})$ is a scatter diagram. If this is not a result of the problems referred to above, it suggests that the mechanism which produces radio emission in the nucleus is either unrelated to, or does not significantly affect, the transport of energy from the nucleus to the jets. The nuclear sources do not, for example, seem to correspond to some constant fraction of beam energy being radiated in the nucleus in consequence of flow instabilities there. For more powerful radio galaxies ($\log P$ (2.7 GHz) > 24) the fractional contribution of the central component shows a slight tendency to decrease with total radio luminosity (Riley & Jenkins 1977).

8 The radio luminosity function

The radio flux limit is well above the detection limit of Dressel & Condon's (1978) survey. Also, the $\langle V/V(\max)\rangle$ test shows that the UGC is complete (for ellipticals and S0s considered separately) down to m(pg) = 14.5. Since the radio and optical flux limits of the sample are well-defined, the radio luminosity function can be estimated by the method of maximum volume (Schmidt 1968). There are 30 galaxies in the sample with known redshifts, the maximum being only $z \sim 0.03$; the distribution of $V/V(\max)$ is not significantly

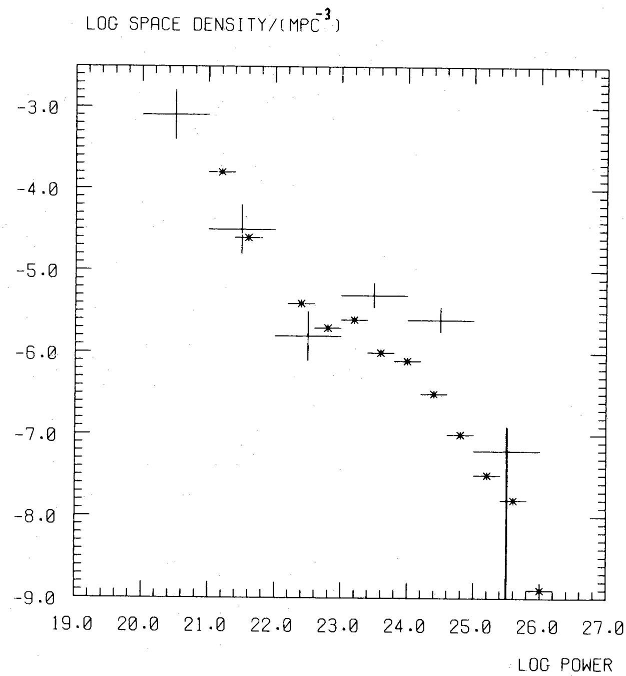

Figure 2. The radio luminosity function at 2.7 GHz is plotted as a function of log luminosity (in W Hz^{-1}). Horizontal bars give the widths of the bins, and the vertical bars are estimates of the error due to the statistical fluctuations of the number of sources in each bin. The luminosity function determined by Colla *et al.* (1975) at 408 MHz is also given; these points are marked with stars. The vertical errors are much smaller than the 2.7-GHz sample, since a larger sample was used; also, the bins are only 0.4 wide in the logarithm, rather than 1.0.

non-uniform and $\langle V/V(\max)\rangle = 0.43 \pm 0.05$, so that these objects apparently form an unbiased sample with respect to distance.

The radio luminosity function is given in Fig. 2. After correction for the different values of H_0 used, and allowing for the shift in $\log P$ resulting from the different frequencies, it is in agreement with that determined by Colla *et al.* (1975) from their sample selected at 408 MHz. The luminosity function has five features of interest: (i) The agreement with the determination of Colla *et al.* (1975) shows that there is not a large population of flat-spectrum sources in nearby galaxies. (ii) The space density of radio galaxies rises rapidly at low powers and, at $\log P(2.7\,\mathrm{GHz}) < 20$, about one-third of all early-type galaxies would be radio emitters. These sources make a negligible contribution to the background flux, unless they were more powerful in the past. In an Einstein–de Sitter universe, the weak sources ($\log P(2.7\,\mathrm{GHz}) < 22$) only produce a background brightness of 10^{-2} mJy arcmin^{-2}, at 2.7 GHz. (iii) There is a plateau in the luminosity function around $22 < \log P(2.7\,\mathrm{GHz}) < 24$, which is associated with the transition to sources which extend outside the optical galaxy. (iv) The number of galaxies in the sample is determined almost entirely by the optical cut-off, even at the low radio flux limit of 35 mJy. This means that radio galaxies of small apparent optical magnitude are rare; there can only be ~ 50 with $m(\mathrm{pg}) < 13.5$ and $S(2.3\,\mathrm{GHz}) > 35$ mJy in the whole sky. (v) Colla *et al.* (1975) give the optical luminosity function for early-type galaxies. This allows one to discover if there is a correlation between optical absolute magnitude and radio power. No strong correlation is found in the range $-21 > M(\mathrm{pg}) > -23$, which contains most of the galaxies in the sample. This result is not necessarily in disagreement with previous work. Auriemma *et al.* (1977) found that the correlation only becomes strong for $M(\mathrm{pg}) < -22$, and both these authors and Colla *et al.* (1975) used much larger samples than the present one, augmenting them with 3C radio galaxies to ensure that high-luminosity objects were adequately represented.

9 Conclusions

The morphology of weak radio sources in early-type radio galaxies suggests that they are powered by beams, as is thought to be the case for powerful radio galaxies. The frequent occurrence of jets is remarkable, although there are sources where no sign of any extended structure can be found, and in these sources the radio emission is confined to a region < 1 kpc in size in the galactic nuclei.

Galaxies classed as S0 by Nilson contain only unresolved nuclear components much more frequently than do those classed as ellipticals. The compact components in S0s also seem to be more luminous.

The luminosity of a radio source is related to whether or not its beams penetrate beyond the confines of the parent galaxy. It is suggested that this is because beams are unstable in galaxy atmospheres, unless they are carrying a sufficiently large energy flux to convect instabilities at their circumference out of the galaxy before these instabilities grow to destructive proportions.

The radio luminosity function for this sample, which is selected at 2.3 GHz, agrees with that of Colla *et al.* (1975), which was selected at 408 MHz, implying that there are not many flat-spectrum sources amongst nearby galaxies. It is interesting that the size of the present sample is largely limited by its optical cut-off, a result which shows that increasing the radio sensitivity will not much increase the total number of optically bright ($m(pg) < 13.5$) radio galaxies known.

Acknowledgments

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