RADIO FREQUENCY OBSERVATIONS OF THE NUCLEI OF GALAXIES

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Abstract. For spiral galaxies the nuclear radio emission is usually dominated by a complex distribution of emission with median diameter of 200 pc and median power of 10^{19} W Hz^{-1} sr^{-1} at 1400 MHz. There is a large range in both power and diameter. The power is independent of morphological type for the normal spirals but is correlated with the absolute optical magnitude and with the infrared emission. For Seyfert galaxies the emission is generally stronger, in some cases by several orders of magnitude (e.g. NGC 1275, 3C 120).

Elliptical galaxies have been found with very compact radio sources, some less than a parsec in diameter. These are as powerful as the strongest spirals ($\sim 10^{21}$ W Hz^{-1} sr^{-1}). Even stronger compact nuclear sources are now being found in the nuclei of those elliptical galaxies which also have extended radio sources (the radio galaxies). The presence of nuclear sources of this strength is so highly correlated with the presence of extended sources that this suggests a continuing involvement of the nucleus.

1. Introduction

The properties of strong radio sources have been reviewed by Kellermann and Pauliny-Toth (1968) and Kellermann (1971, 1972). They discuss the angular sizes, radio spectra, temporal variations and the physical conditions required to explain these observations. In this report I will concentrate more on the radio nuclei of normal spiral and elliptical galaxies.

2. Spiral Galaxies

This is the most common type of galaxy and consequently the closest systems are mainly of this type. Even so, our knowledge of the radio properties of the nuclei of these galaxies is still very fragmentary except, of course, for our own Galactic centre.

2.1. The Galaxy

The radio frequency emission from the centre of our Galaxy has three components: an extended source about $1\overset{\circ}{.}0 \times 0\overset{\circ}{.}4$ (180×70 pc) elongated along the galactic plane, a complex of giant H II regions in a similar area, and a non-thermal source, Sgr A, about $3\overset{'}{.}0 \times 2\overset{'}{.}4$ (9×7 pc) very close to the centre of the Galaxy. All these components can be seen in the 408 MHz map from Little (1974) reproduced in Figure 1. The extended component is of interest since it is such a component as would dominate our observations of extragalactic systems. It used to be thought that this component had a fairly flat flux density spectrum and could thus be an optically thin thermal source (Downes and Maxwell, 1966), but more recent observations (e.g. see Gordon, 1974) indicate that it is mainly non-thermal. Detailed reviews of the centre of our Galaxy have been prepared by Oort (1974) and by Gordon (1974).

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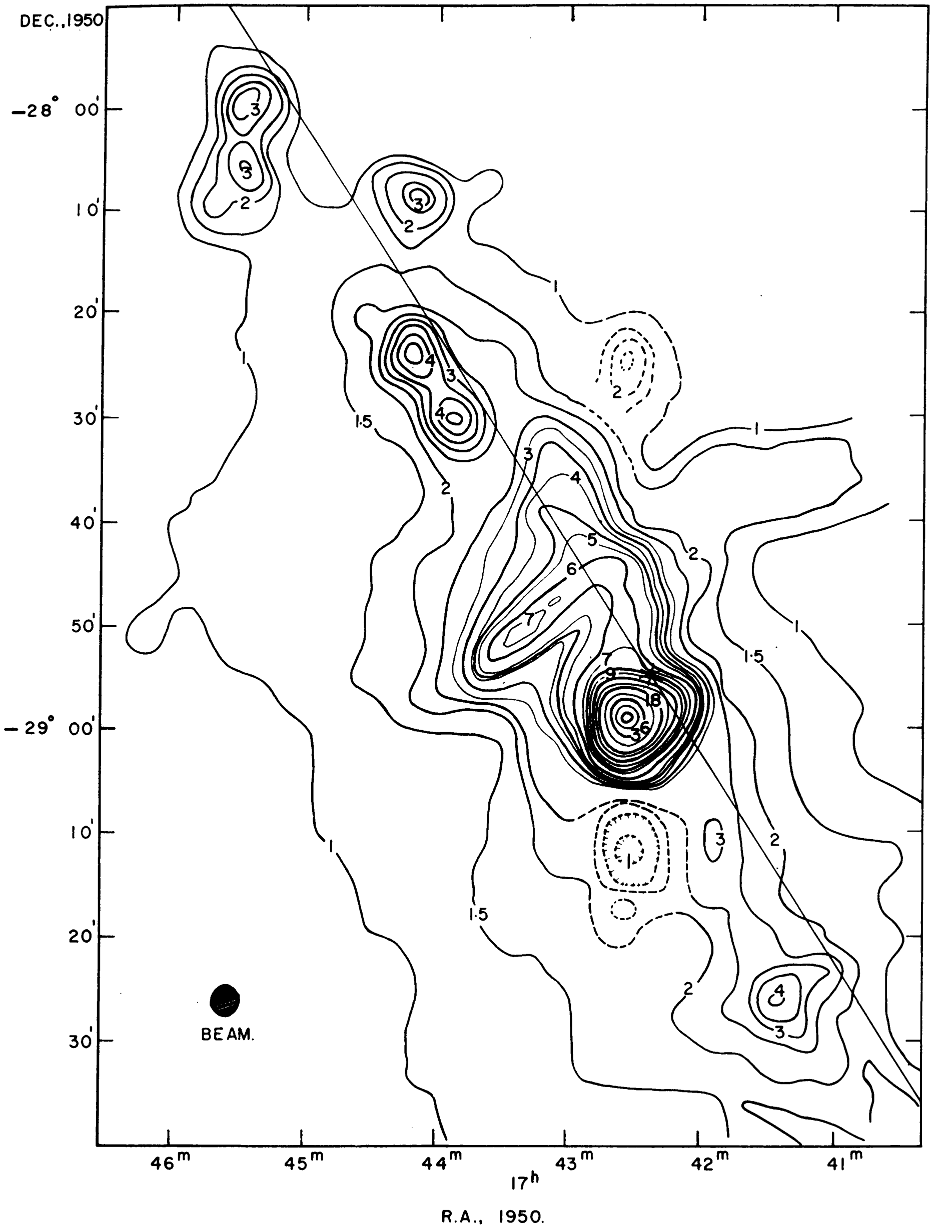

Fig. 1. Galactic Centre at 408 MHz. The contour interval is 680 K and the unit contour is at 1075 K. The dashed contours are sidelobe effects from Sgr A. This map obtained with the University of Sydney's Mills Cross radio telescope has been kindly supplied by Mr A. G. Little.

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2.2. M31

The nuclear emission from M31 was observed by Pooley (1969a) at 408 and 1407 MHz and, with higher sensitivity, by van der Kruit (1972) at 1415 MHz with 23″ resolution. A contour map based on the latter data is shown in Figure 2. The nuclear source has a similar scale to, but is an order of magnitude weaker than, the extended component in our galactic centre. It also is resolved into a complex of sources, although these do not appear to lie in the plane of the galaxy. Observations at 2695 MHz with 8″ resolution (Spencer, 1973) failed to detect any of these components, indicating that they have steep non-thermal spectra and that they are resolved.

2.3. M51

The nuclear source in M51 is clearly seen in the map by Mathewson *et al.* (1972). It is 16″ (700 pc) in extent and 10 times stronger than our galactic centre. The higher resolution observations by Spencer (1973) and de Bruyn (private communication) show that this source also breaks up into at least two components.

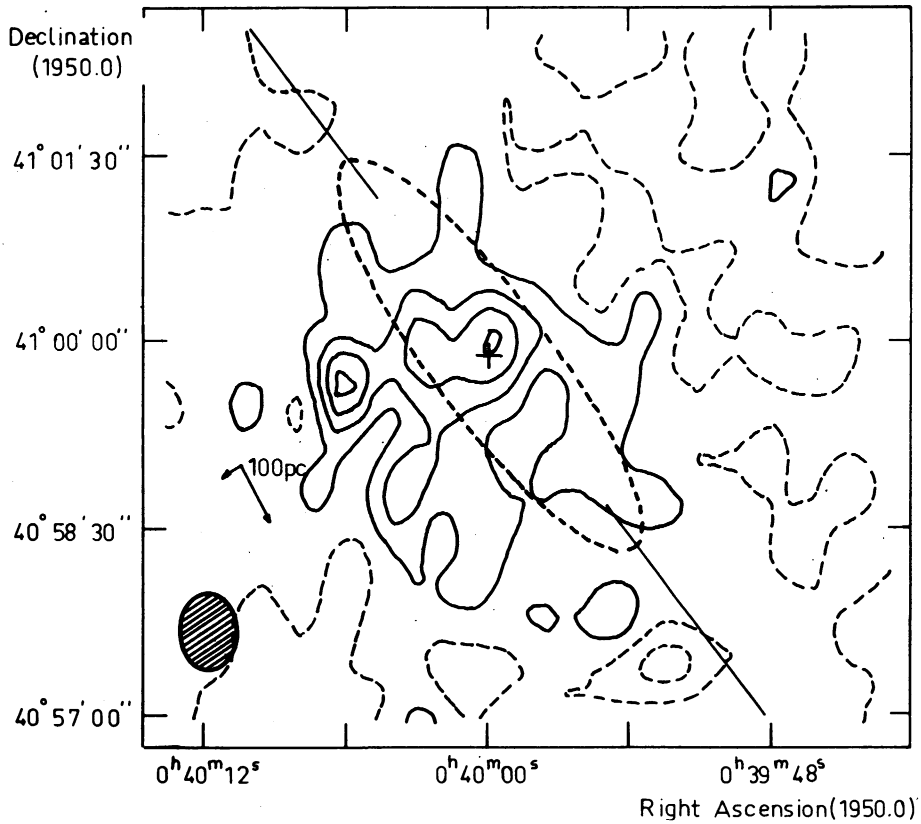

Fig. 2. 1.4 GHz continuum map of the nucleus of M31 from the data of van der Kruit (1972). The contour interval is 1.6 K and the zero and negative contours are dashed. The arrows indicate the directions of the major and minor axes and the apparent length of 100 pc in the plane of M31.

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2.4. Other spiral galaxies

In order to separate clearly the nuclear radio sources from the sometimes complex emission of the galactic disks, I have used only high resolution observations with good spatial coverage. Van der Kruit (1973c) discusses the properties of a sample of 45 galaxies observed in detail with the Westerbork array. I have enlarged this sample of galaxies by adding observations from the Cambridge and Greenbank arrays and some more recent observations from Westerbork. The resulting sample is not complete to a given optical magnitude since different selection criteria have been used in the various programmes, and in such a heterogeneous sample it is especially important to avoid erroneous correlations arising because of differing sensitivities and differing distances for various types of galaxies. For each galaxy I have used its distance and the sensitivity of the observation to calculate the absolute radio power level at which its nucleus would still be detectable. All the galaxies for which a nuclear source could be detected if it were stronger than the median for the final sample are listed in Table I. Hence, for galaxies in this table, there will be no bias with radio power above the median value of 8×10^{18} W Hz^{-1} sr^{-1} at 1410 MHz. There may still be bias in the sample with respect to other properties, e.g. the numbers of each optical type, but these have less serious consequences. Nuclei have only been included if they are known to be less than 1 kpc in extent. Most galactic nuclei for which we have linear dimensions are considerably smaller than this, but the resolution of many of the observations is such that the sample would be too much reduced by use of a smaller size criterion.

Galaxies which have distinct nuclear radio sources but which do not form part of the complete sample are listed in Table II. In all cases the most recent distance determinations available and a Hubble constant of 55 km s^{-1} Mpc^{-1} (Sandage, 1972) have been used.

2.5. Seyfert galaxies

Wade (1968) and van der Kruit (1971) have shown that the radio emission from the nuclei is stronger for Seyfert galaxies. In some cases, e.g. NGC 1275 (3C 84), it is more than a thousand times stronger than the normal spiral nuclei, while other Seyfert galaxies have radio powers in the upper range of the distribution of power from normal spirals.

For NGC 1275 there are two recent results of considerable interest. Detailed interferometer observations between Algonquin Park and Chilbolton by Legg *et al.* (1973) at 2.8 cm wavelength indicate a structure for the smallest nuclear component which is elongated by 3×10^{-3} arc sec (2 pc) in position angle $-6°$ and consists of at least four components less than or about 10^{-3} arc sec (0.5 pc) in diameter. A similar distribution is required to fit the 2 cm observations between Greenbank, Owens Valley and Fort Davis (Kellermann, private communication). The second result is the detection by De Young *et al.* (1973) of the 21-cm neutral hydrogen line in absorption at a redshift corresponding to $+2820$ km s^{-1} with respect to the systemic velocity for NGC 1275. This line is only 6 km s^{-1} wide.

TABLE I

Spiral galaxies – selected sample

Name NGC	Other	Type	Dist. Mpc	Total $(M_0)_p$[a]	Total S_{1415}[b]	Nucleus S_{1415}[b]	Nucleus $\log(P_{1415}$[c]$)$	Ref.[d]
224	M31	Sb	0.65	−23.1	8.0	0.10	17.6	1, 15
253		Sc	4.3	−21.6	5.0	2.2	20.6	2
598	M33	Sc	0.72	−20.0	3.1	<0.003	<16.3	3
628	M74	Sc	14	−21.4	0.1	<0.004	<18.9	4
891		Sb	7	−20.7	0.7	0.025	19.1	5, 17
1003		Sc	13	−19.9		<0.005	<18.9	6
1058		Sc	4	−19.2		<0.005	<18.9	6
2403		SABcd	3.5	−20.5	0.3	<0.003	<17.6	3
2681		Sa	14	−19.8		<0.003	<18.8	7
2685		S0	17	−19.8		<0.003	<18.9	7
2841		Sb	11	−21.1	<0.2	<0.005	<18.7	6
2903		SABbc	13	−21.9	0.4	0.07	20.1	3
3031	M81	Sab	3.5	−21.6	0.5	0.08	19.0	3, 8
3034	M82	I0	3.5	−21.0	8.0	8.0	21.0	9, 10
3077		Ir?-Sef	6	−18.8	<0.3	0.021	18.9	7
3184		Sc	8	−19.5	<0.2	<0.005	<18.5	6
3359		SBc	18	−20.9	<0.2	<0.003	<19.0	7
3432		SBm	8	−19.2	0.11	<0.01	<18.8	4
3953		Sc	19	−21.2	<0.2	<0.003	<19.0	7
4051		Sb-Sef	12	−20.1	0.05	0.021	19.5	7, 8
4156		SBb	12	−18.5		<0.004	<18.8	7
4258	M106	Sbc	8	−21.2	0.9	<0.025	<19.1	11
4425		Sa	20	−19.5		<0.003	<19.1	12
4438		Sap	20	−21.4	0.12	0.090	20.6	12
4485			8			<0.005	<18.5	13
4490		SBdp	8	−21.1	0.8	0.02	19.1	13
4631		SBd	8	−20.9	1.3	0.025	19.2	3, 14
4736	M94	Sab	8	−20.8	0.3	0.013	18.9	7
4826	M64	Sab	7	−20.4	0.09	<0.052	<19.4	3
5055	M63	Sbc	8	−21.0	0.6	0.020	19.1	3
5194	M51	Sbc	9.5	−21.5	1.5	0.080	19.9	16, 19
5457	M101	Sc	7	−21.7	0.5	0.004	18.3	17
5907		Sc	8	−19.9		<0.005	<18.5	6
6946		Sc	10	−21.2	1.3	0.088	19.9	18
7331		Sbc	14	−22.0	0.6	<0.005	<19.0	4
7640		SBc	14	−21.1		<0.005	<19.0	4
-	IC342	SABcd	6		2.0	0.13	19.6	4
–	our Galaxy	–	0.01			4600.	18.7	

[a] Absolute photographic magnitude corrected for inclination and galactic absorption according to Holmberg (1958).
[b] 10^{-26} W m^{-2} Hz^{-1}.
[c] W Hz^{-1} sr^{-1},
[d] 1. van der Kruit (1972)
2. Becklin *et al.* (1973)
3. van der Kruit (1973a)
4. van der Kruit (1973b)
5. Baldwin and Pooley (1973)
6. de Bruyn, private communication
7. van der Kruit (1971)
8. Wade (1968)
9. Macdonald *et al.* (1968)
10. Kronberg *et al.* (1972)
11. van der Kruit *et al.* (1972)
12. Ekers, in preparation
13. Allen *et al.* (1973)
14. Pooley (1969b)
15. Pooley (1969a)
16. Mathewson *et al.* (1972)
17. Allen, private communication
18. Rots, private communication
19. Spencer and Burke (1972), Spencer (1973).

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TABLE II

Other spiral galaxies with nuclear radio emission

NGC 936	2655	3504	4151	4945	7469
1068	2782	3516	4321	5005	7552
1097	2798	3521	4569	5035	
1275	3079	3623	4579	5383	
1569	3227	3627	4594	5548	
1808	3310	3628	4670	5866	
2445	3351	3888	4676A	6052	

2.6. Statistics for the spiral galaxies

Figure 3 shows the distribution of linear diameters for those spiral galaxies in which the nucleus is resolved or for which the upper limit is less than 400 pc. The median diameter for the sample is 200 pc, which is similar to the diameter of the most extended component of the Galactic centre. Some radio nuclei are very much smaller than this and the resolved nuclei may also contain components of smaller diameter.

The distribution of radio spectral indices between 1400 and 5000 MHz is shown in Figure 4. There is a broad spread around $\alpha = -0.7$ containing all the resolved nuclei, but a few galaxies have inverted spectral indices, including the Seyfert galaxy NGC 1275 which contains the very compact variable radio source 3C84 discussed in the

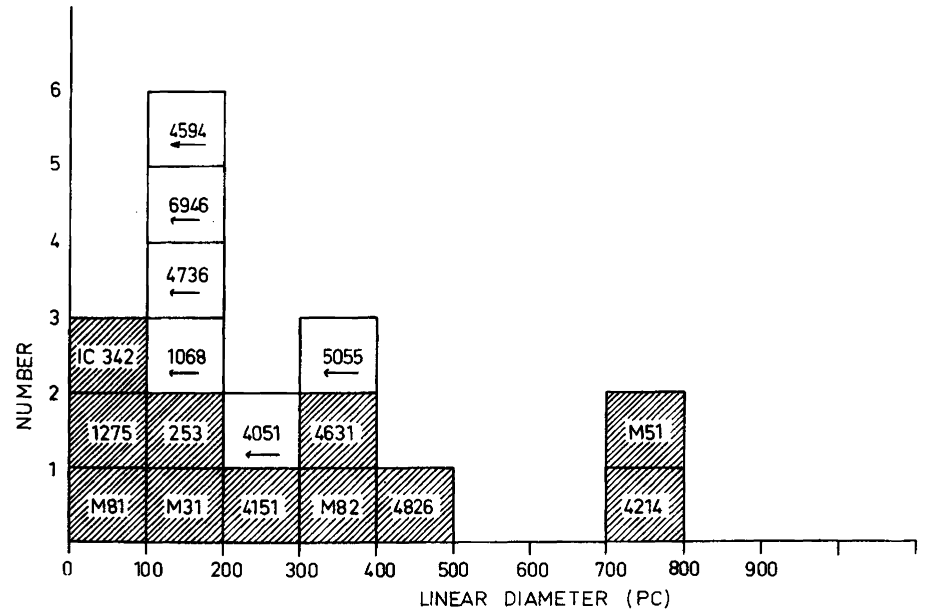

Fig. 3. Distribution of the major axis diameters of the nuclear radio sources in spiral galaxies. All limits for diameters are included if they are < 500 pc.

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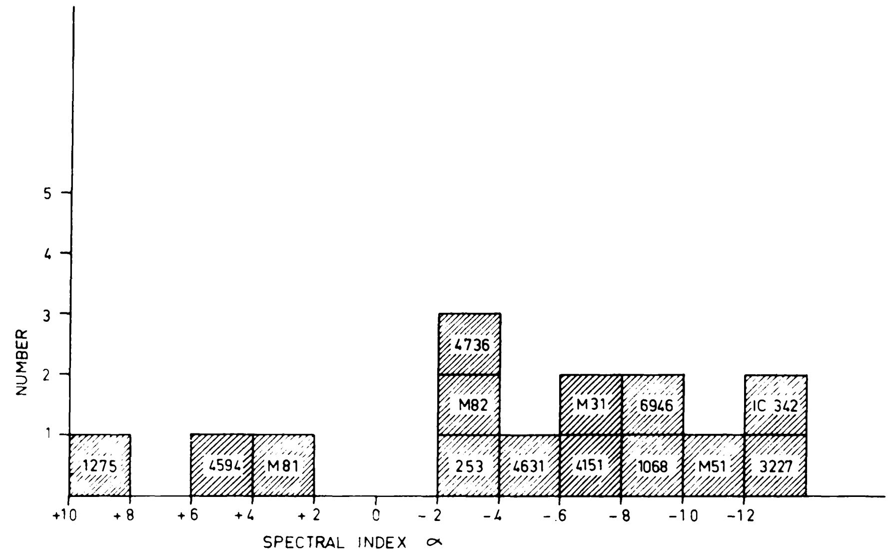

Fig. 4. Distribution of the radio spectral index, α, for the nuclei of spiral galaxies, α is defined by $S \propto \nu^{\alpha}$.

last section, and M81 which has diameter $<2''$ (<35 pc) and is the smallest of the normal spiral nuclei known (Wade 1968). From a sample of observations obtained with somewhat lower resolution, Le Squéren and Crovisier (1974) have found a mean spectral index of -0.7 for the nuclei and -1.1 for the disk emission from spiral galaxies.

Figure 5 shows that there is correlation between the radio power of the nucleus and the absolute optical magnitude. Since only the sample of Table I is included, this cannot result from the selection effects. There is a weak correlation between the strength of the nuclear source and the strength of the disk radio emission, and the disk radio emission is also correlated with the absolute optical magnitude, so it is not clear which pairs of parameters are causally related. Van der Kruit (1973c) also compares the nuclear power with the brightness of the disk and finds an absence of galaxies with bright disks and nuclear power below 10^{19} W Hz^{-1} sr^{-1}. Although this may still be correct for this sample of galaxies, it is weakened by the presence of two galaxies, NGC 7331 and NGC 4490, which have brighter disks but no distinct nuclear sources. Hence, at present we cannot make a strong case for the nucleus providing a significant supply of radiating electrons for the disk emission.

Essentially no correlation is seen between the radio power of the nucleus and the optical type for the normal spirals plotted in Figure 6. This and other correlation diagrams are discussed by van der Kruit (1973c). He also concludes that for normal spirals neither the radio power of the nucleus nor its ratio to the total power is dependent on optical type or the presence of a bar. There is a weak correlation of radio power with Byurakan type but this is only statistically significant for the Seyferts.

2.7. Correlation with infrared emission

Van der Kruit (1971) showed that there was a correlation between the 10μ emission and the nuclear radio emission. Although this correlation is maintained in the larger sample of galaxies in van der Kruit (1973c), he comments that for the normal spirals the sample is very incomplete and that the correlation could arise from the selection

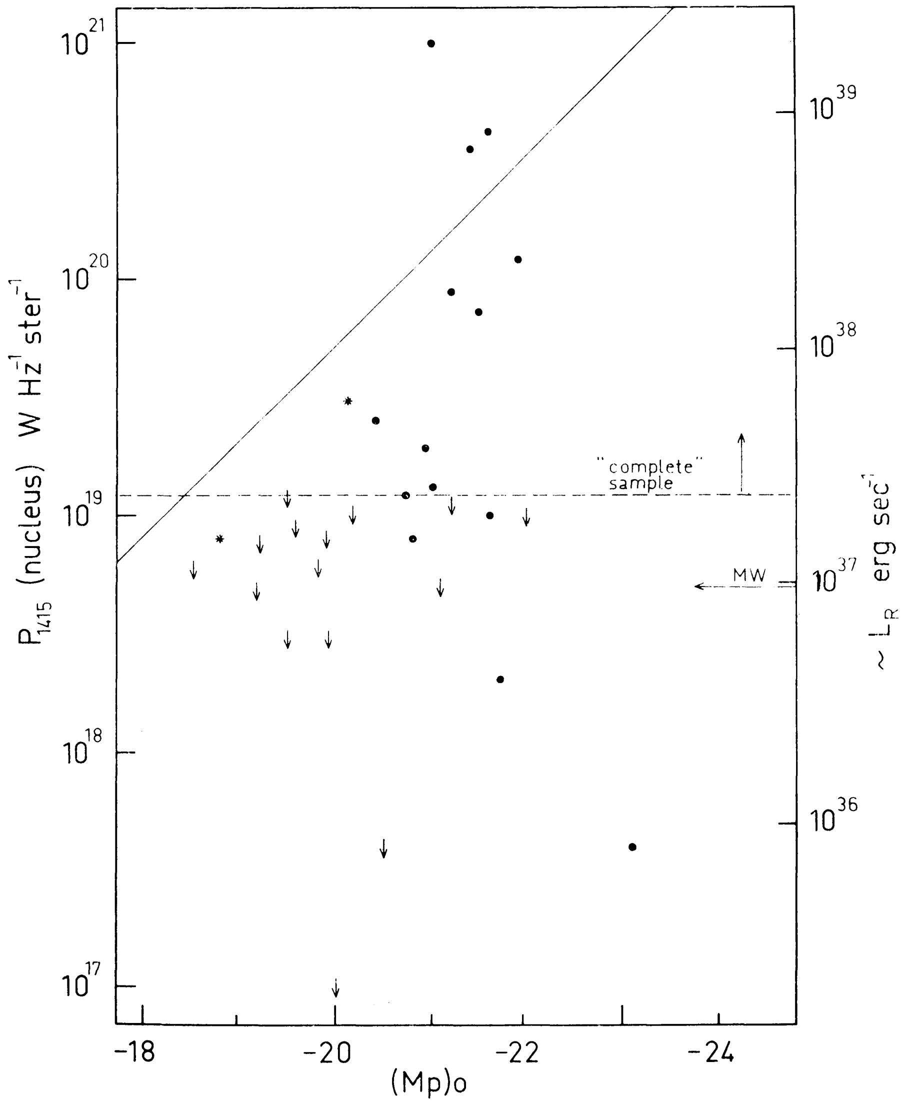

Fig. 5. Plot showing the correlation between the monochromatic radio power at 1.4 GHz and the absolute optical luminosity of spiral galaxies. The two Seyfert galaxies in the selected sample are indicated by *. A radio luminosity scale, L_R, is shown for a power law spectrum of index −0.7 integrated from 10^7 to 10^{11} Hz.

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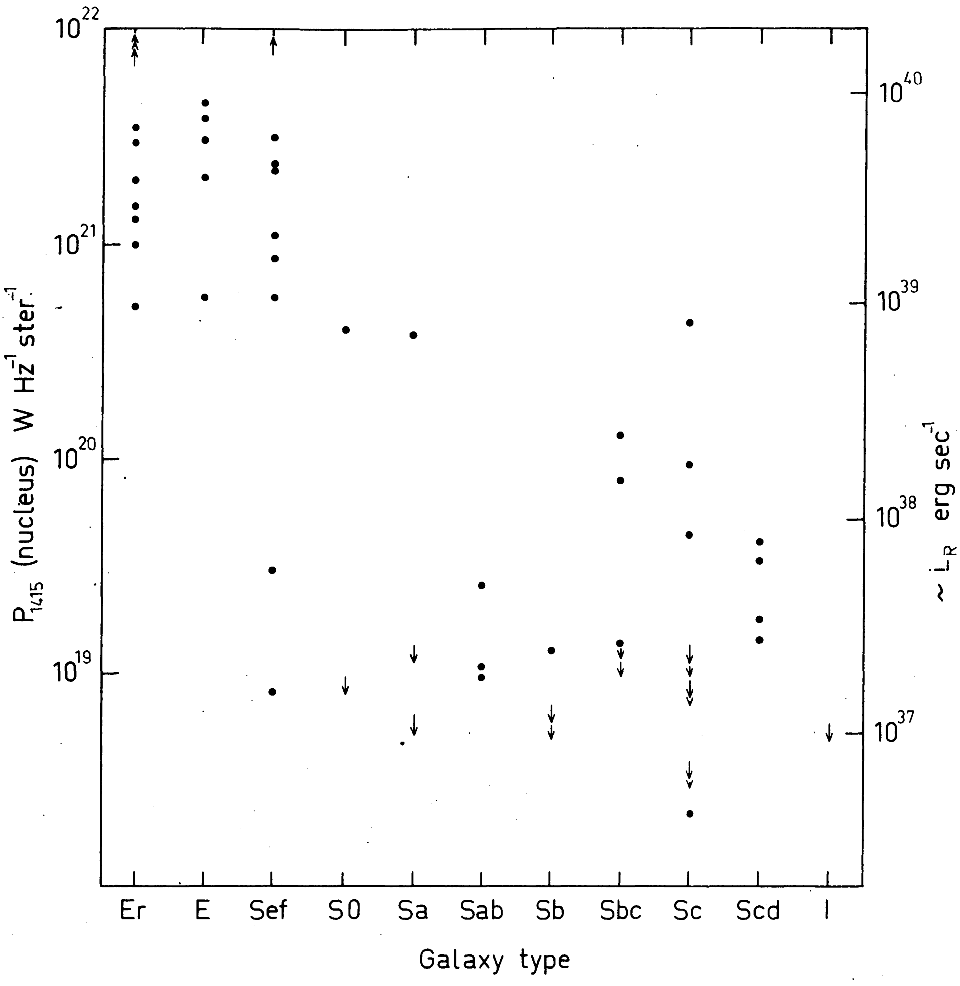

Fig. 6 Plot of the monochromatic radio power at 1.4 GHz for different Hubble types and for the Seyfert galaxies, Sef, and the radio galaxies, E_R. The radio luminosity scale, L_R, is defined in Figure 5.

effects. The Seyfert galaxies do constitute a complete sample and for these there is also a clear correlation.

For M82 (Klienmann and Low, 1970) and NGC 253 (Becklin *et al.*, 1973), both the radio and infrared nuclei are extended and have comparable dimensions. In M82 the radio and the infrared structure have been resolved into bright knots (Kronberg *et al.*, 1972) but there is no detailed correlation between the positions of the infrared and radio knots.

2.8. Other radio emission possibly associated with nuclear activity

In a few spirals there is evidence for radio emission which, although outside the nuclear region, could be interpreted as resulting directly from nuclear activity.

In NGC 4258 van der Kruit *et al.* (1972) observed a pair of radio arms and proposed

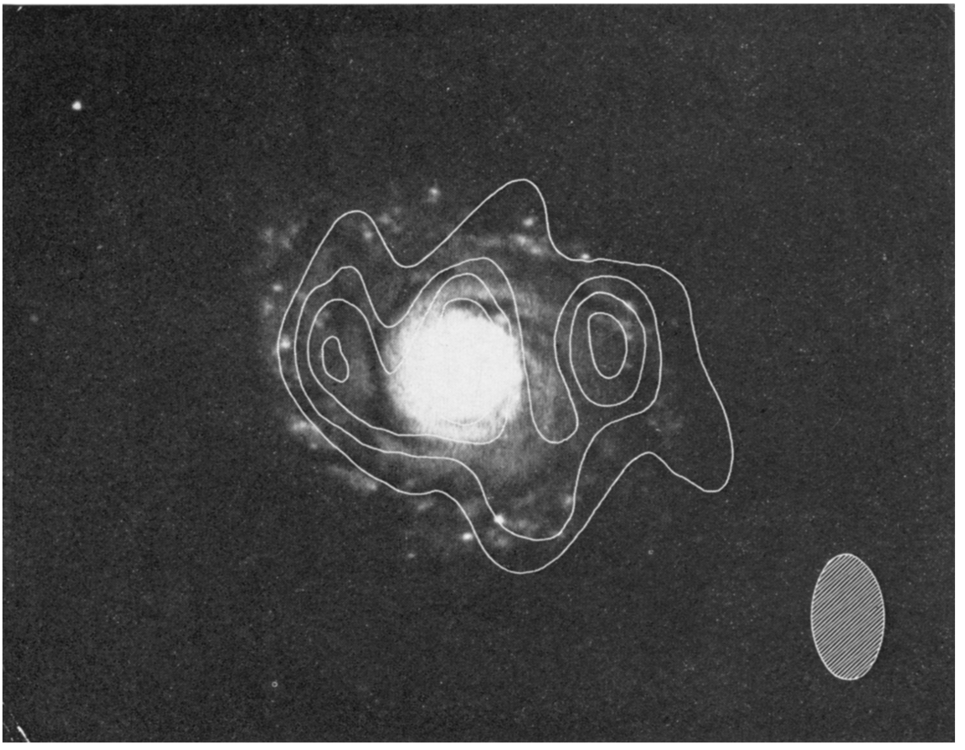

Fig. 7. 1.4 GHz continuum observations of NGC 4736 from van der Kruit (1971) superimposed on an optical photograph from the Mt. Wilson 100-inch telescope. Contour values are 2, 4, 6, 8 and 12 K. This composite was kindly supplied by Prof. J. H. Oort.

a model involving the violent expulsion of material from the nucleus of this galaxy. There is no striking optical or radio activity present in the nucleus now, although the radio arms do continue smoothly into the nuclear region. Further discussions of this galaxy are given by Oort (p. 375) and by van der Kruit (p. 431) in this symposium.

NGC 4736* and NGC 4631 (Figures 7 and 8) are spiral galaxies with double radio sources which, by their symmetry with respect to the nucleus, are suggestive of direct nuclear involvement. Since NGC 4631 is an edge-on galaxy, it is possible that in this case we are seeing the normal spiral arm emission, as is suggested by Pooley (1969b). NGC 3726 (Figure 9) was thought to be a similar case (van der Kruit, 1971), but the more accurate radio position determined by de Bruyn (private communication) shows that these radio components are not symmetrical about the nucleus. More sensitive observations are required to see whether these components are discrete sources or are two peaks in a complex distribution of emission. At present the sample of sources in spiral galaxies is too small to say whether there is a class of spiral galaxies with the same kind of double radio emission as found in the radio galaxies. However, the

* Note added in proof: Additional observations now indicate that at least part of the western source may be associated with H II regions (A. Bosma, private communication).

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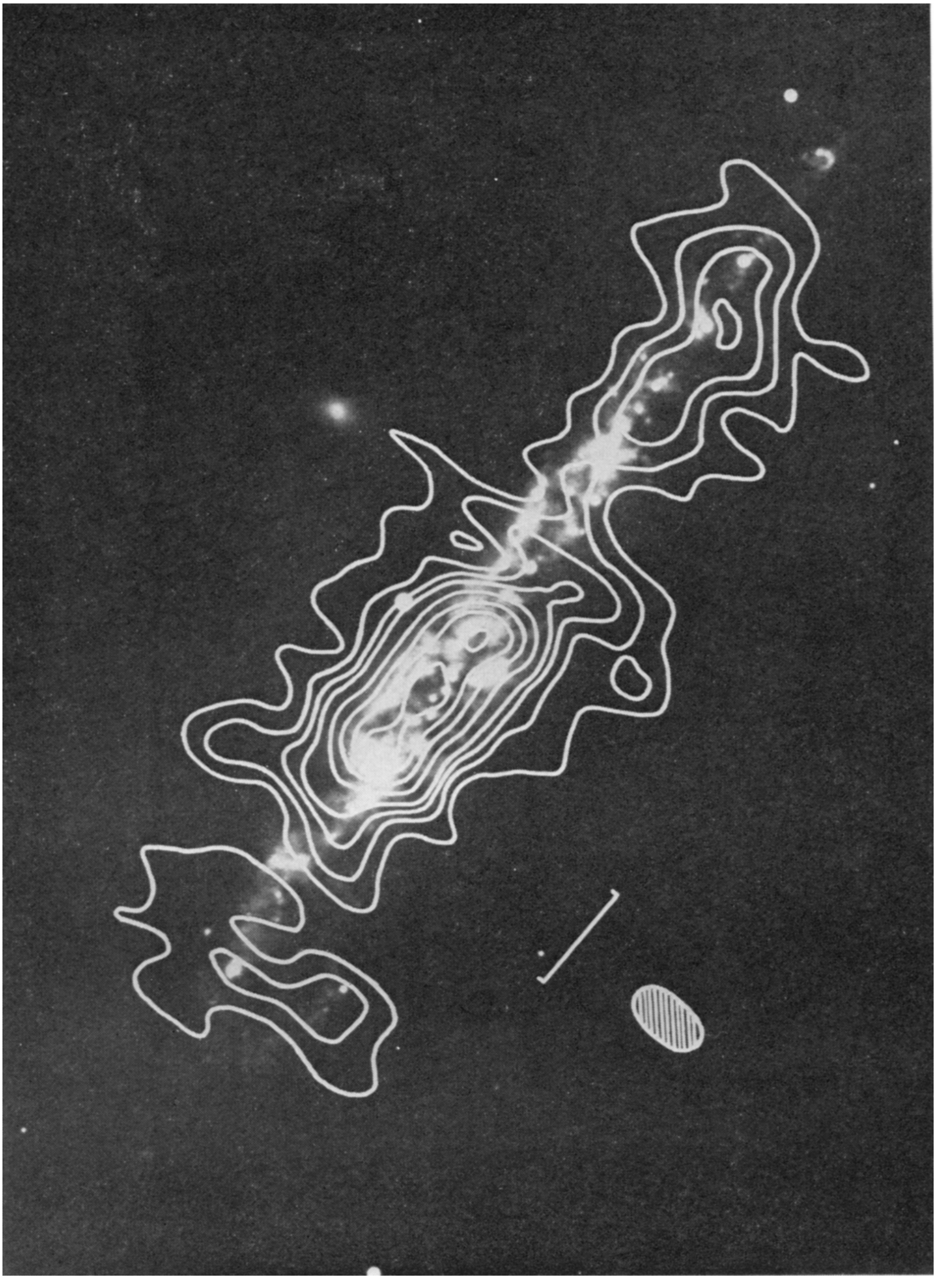

Fig. 8. 1.4 GHz continuum map of NGC 4631 from Pooley (1969). The contour interval is 3 K, and alternate contours above the fourth have been omitted. The line is of length 1′.

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Fig. 9. 1.4 GHz continuum map of NGC 3726 based on the observations of van der Kruit (1971) and superimposed on a print from the Palomar Sky Survey by de Bruyn (private communication) using an improved determination of the position.

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range of radio power for the radio galaxies is now known to extend down to values comparable to these spiral galaxies (Ekers, 1974), e.g. the giant elliptical NGC 4472 is an example of a double radio galaxy with a radio power at 1.4 GHz of only 10^{20} W Hz^{-1} sr^{-1} and a separation of 7 Kpc, quite comparable to NGC 4736.

3. Elliptical Galaxies

The radio properties of the elliptical galaxies differ from those of the spiral galaxies in just as marked a way as do the optical properties. The elliptical galaxies are often associated with powerful extended radio sources – the radio galaxies – a phenomena which is rare, if present at all, in the spiral galaxies. The compact radio sources in the nuclei of the elliptical galaxies are also quite different from those of most of the spirals. The nuclear sources in the elliptical galaxies have been found by two different procedures and since these have quite different selection effects I will discuss them separately.

3.1. Surveys of Nearby Elliptical Galaxies

Heeschen (1968) found that two elliptical galaxies NGC 1052 and NGC 4278 contained small diameter sources with radio spectra typical of the spectra of the optically thick variable radio sources found especially in the QSO's. One of these, NGC 1052, was strong enough to be detected subsequently in a very-long-baseline interferometer experiment and was found to have a diameter $<0''.001$, corresponding to a linear diameter of <0.1 pc (Cohen *et al.*, 1971). Further surveys of elliptical galaxies (Heeschen, 1970a; Ekers and Ekers, 1973) yielded the additional sources given in Table III. Because of their greater average distance and the lower sensitivity of the surveys we cannot construct a sample of elliptical galaxies complete to the same luminosity level as used for the spirals. Thus we cannot easily make a direct comparison between the frequency of nuclear radio emission in spiral and elliptical galaxies but it is clear from the data in Table III, plotted in Figure 6, that many elliptical galaxies have more powerful radio nuclei than are found in any of the normal spirals. The lowest absolute monochromatic luminosity for which we have some elliptical galaxies left in the sample is $P_{1415} = 6 \times 10^{20}$ W Hz^{-1} sr^{-1}. At this luminosity Ekers and Ekers estimate a space density of 2.4×10^{-4} Mpc^{-3}, only a few times less than the density of spiral galaxies with this luminosity.

The nuclei of elliptical galaxies generally have complex spectra and show a low frequency cut-off (Heeschen, 1970b). The distribution of radio spectral index for these galaxies (Figure 10) is quite different from that of the spiral galaxies (Figure 4).

Most of the nuclear sources in Table III are known to be less than a few arc sec in extent but only one, Cen A, has probably been resolved. It was not detected in the VLB observation of Broderick *et al.* (1972), implying an angular size $>0''.004$ (0.14 pc), but this was near the sensitivity limit. Wade *et al.* (1971) obtained a limit of $<0''.5$ (<17 pc). Two other galaxies, NGC 1052 (Cohen *et al.*, 1971) and Virgo A (Cohen *et al.*, 1969), are still unresolved with very-long-baseline interferometers,

TABLE III

Radio emission from the nuclei of nearby elliptical galaxies

Name NGC	Other	Type	Dist. Mpc	Total M_p	Total S_{1415}[a]	Nucleus S_{1415}[a]	Nucleus $\log(P_{1415}$[b]$)$	Nucleus $\alpha_{1415-5000}$	Ref.[e]
1052		E3	25	−20.4	0.35	0.35	21.3	+0.6	1
–	VV6-8-34 4C 39.12	E0	110	−21	1.05	0.45	22.7	−0.5	2
1587		E1	69	−21.3	0.10	0.10	21.7	−0.3	1
2911		S0p	54	−20.2	0.11	0.11	21.5	+0.1	1
3078		E2	40	−21.2	0.25	0.15	21.4	−0.1	1, 2
3998		S0	22	−20.5	0.08	0.08	20.6	+0.3	1
4278	B1217+29	E1	18	−20.1	0.51	0.51	21.2	−0.2	1
4472		E1	20	−21.8	0.18	0.13	20.7	−0.7	2
4486	Vir A	E0	20	−22.0	214	0.85[c]	21.5		3
4552		E0	20	−20.6	0.14	0.14	20.7	+0.6	1
5077		E3	45	−20.8	0.19	0.19	21.6	+0.1	1
5128	Cen A	Ep	7	−22.1	1330	2.40[d]	21.0	+0.2	4

[a] 10^{-26} W m^{-2} Hz^{-1}.
[b] W Hz^{-1} sr^{-1}.
[c] Flux density at 13 cm.
[d] Flux density at 11 cm.
[e] 1. Ekers and Ekers (1973)
2. Ekers, in preparation
3. Cohen *et al.* (1969)
4. Wade *et al.* (1971).

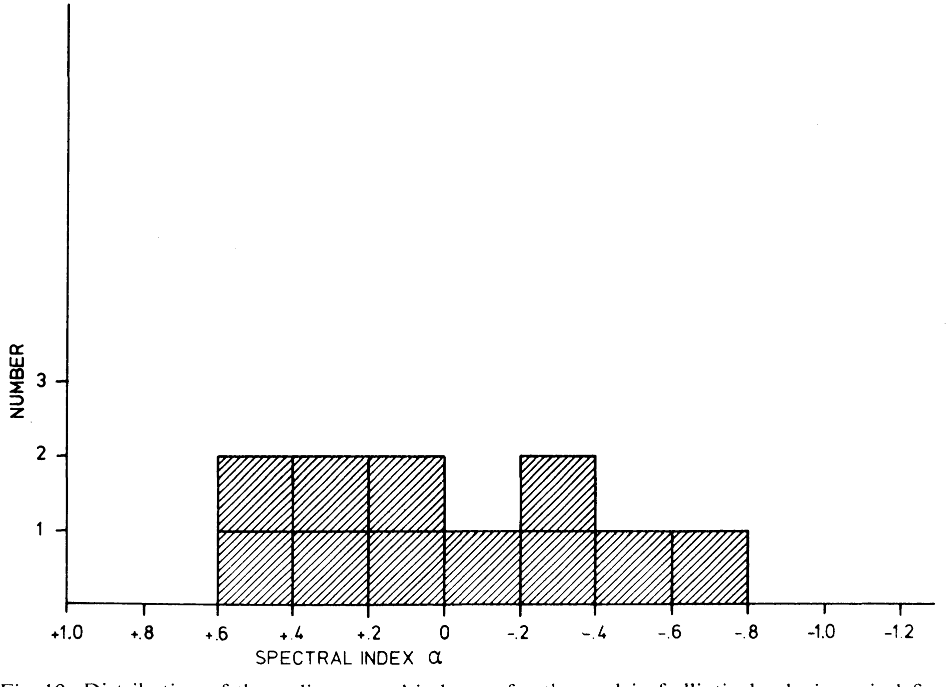

Fig. 10. Distribution of the radio spectral index, α, for the nuclei of elliptical galaxies. α is defined $S_{1.4}/S_{5.0} = (1.4\text{ GHz}/5.0\text{ GHz})^{\alpha}$ but note that in general these sources do not have power law spectra.

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indicating components less than 0.2 pc in diameter. If the low frequency cut-off seen in the spectra of other nuclei is due to synchrotron self-absorption then those sources are also likely to have comparably small linear dimensions.

3.2. Compact sources in the nuclei of radio galaxies

Two of the galaxies in Table III, Virgo and Centaurus A, also have powerful extended radio components and are well-known members of the class of radio galaxies. Many of the other galaxies in Table III also have extended components, e.g. NGC 4472, and although these are much weaker than the well-known radio galaxies they are presumably the same class of object. This high correlation between the presence of compact and extended components was noted by Ekers (1972). High resolution, high frequency radio observations now show that the presence of a compact radio nucleus is indeed a very common phenomena in the radio galaxies. A list of radio galaxies

TABLE IV

Radio galaxies with nuclear radio emission

Name		Dist.	Total		Nucleus		Ref.[e]
Radio	NGC	[z]	Optical[a]	S_{5000}[b]	S_{5000}[b]	$\log(P_{5000}{}^{c})$	
P0036+03	193	0.0145	14.3 E2	0.57	0.05	21.5	3
3C66		0.0215	12.6 ED2	3.7	0.23	22.5	13
3C83.1 B	1265	0.0181[d]	14. ED3-4	3.5	0.015	21.1	1, 2
3C109		0.306	15.7 N	1.6	0.38	24.9	4
3C129			(17) E, Obsc	2.2	0.07		2, 5
3C264	3862	0.0206	12.7 DE1	2.0			6
3C274 Vir A	4486	0.0037[d]	8.7 E2	72.1	(0.85)	21.6	7
3C277.3		0.0857	15.9 E2	1.2			6
Cen A	5128	0.0016	7.0 DE3	126	(2.7)	20.8	8
3C310		0.0543	15.2 DE2, 3	1.3	0.35	23.5	14
3C315		0.1086	16.8 DE2, 3	1.3			6
3C338	6166	0.0303	12.5 cD4	0.49	0.11	22.5	10
3C382		0.0586	14.7 D3	2.2	0.23	23.4	12
3C390.3		0.0569	15.4 N	4.5	0.35	23.5	11
3C402			14 D3	0.9	0.15		9
			15		0.15		
3C405 Cyg A		0.0570	15.1 cD3	371	1.1	24.0	6
3C452		0.0820	16.0 ED	3.3	0.13	22.4	12
3C465	7720	0.0301	13.2 D4	2.8	0.28	22.3	12, 14

[a] Photometry mostly from Sandage (1973).
[b] 10^{-26} W m^{-2} Hz^{-1}.
[c] W Hz^{-1} sr^{-1} assuming $q = -1$, $\alpha = 0$.
[d] Mean z for cluster.
[e]
1. Miley *et al.*, this symposium, p. 109
2. Riley (1973)
3. Ekers, in preparation
4. Branson *et al.* (1972)
5. Hill and Longair (1971)
6. Longair, private communication
7. Cohen *et al.* (1969)
8. Wade *et al.* (1971)
9. Miley, private communication
10. Jaffe, private communication
11. Harris (1972)
12. Riley and Branson (1973).
13. Northover (1973)
14. Miley and van der Laan (1973)

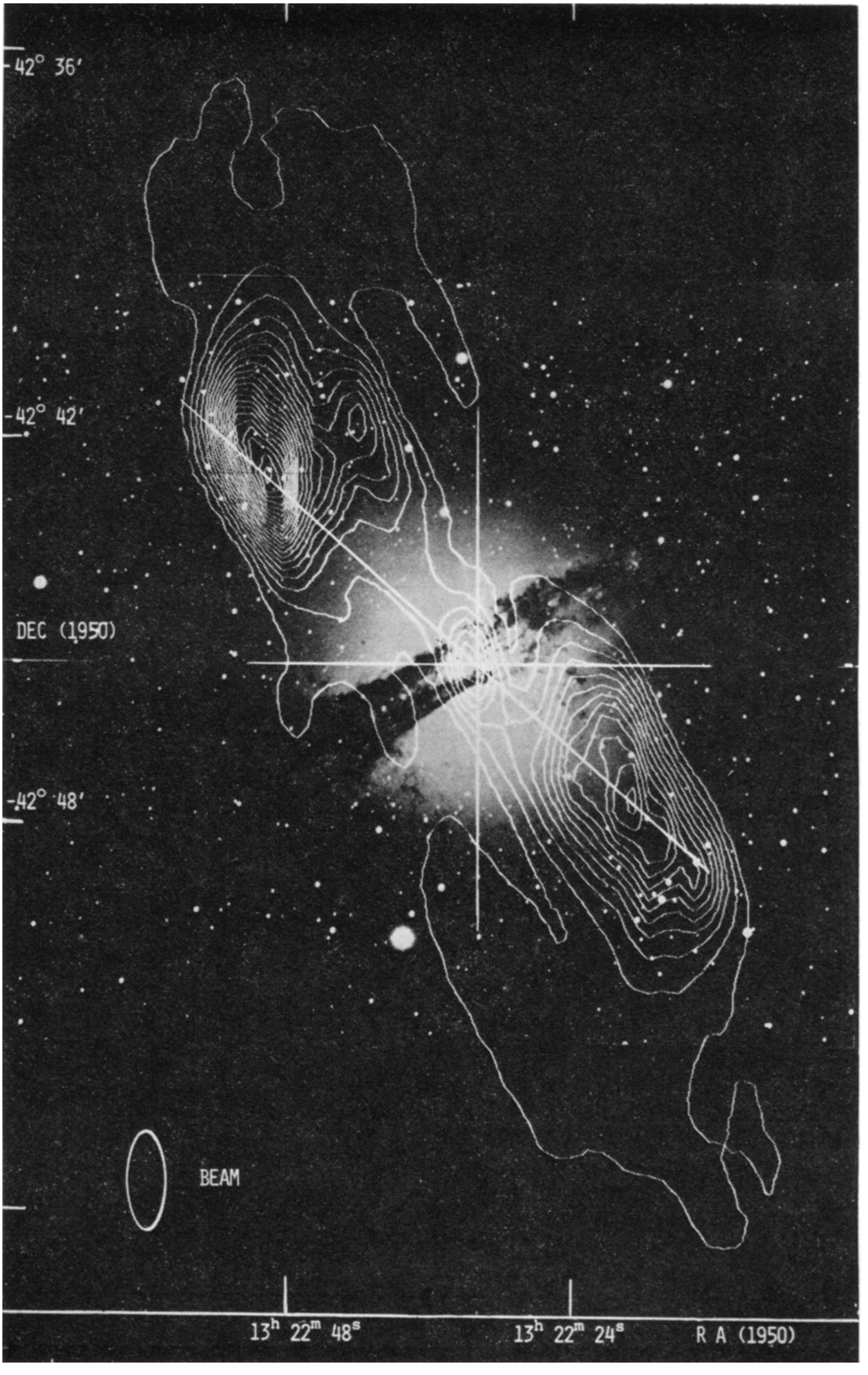

Fig. 11. 1.4 GHz continuum map of the central components of Cen A superimposed on an optical photograph from the Hubble atlas. This map has been obtained with the Fleurs Synthesis Radio-telescope and has been kindly supplied by Dr R. Frater.

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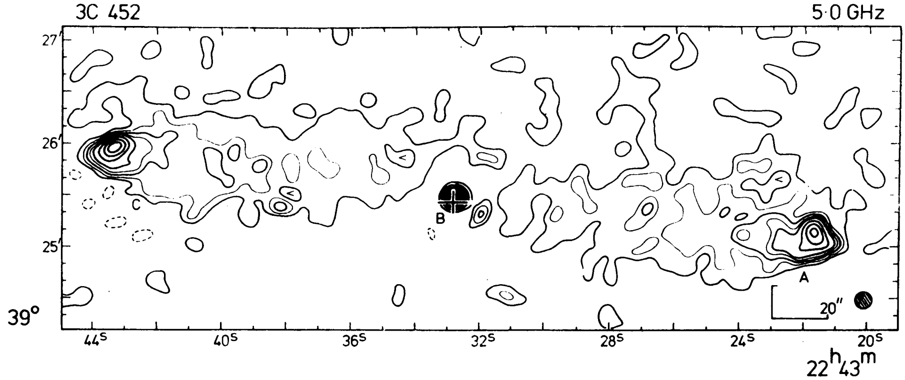

Fig. 12. 5 GHz map of 3C 452 obtained with the One-Mile Radiotelescope at Cambridge (Riley and Branson, 1973).

with nuclear components is given in Table IV and two examples are shown in Figures 11 and 12. These components have eluded detection until now, since their flat spectra and weakness relative to the extended sources have made them inconspicuous in previous lower frequency maps.

Most of the galaxies in Table IV are optically bright, indicating that these are relatively nearby objects and in most cases the compact nuclear sources are near the radio detection limit. This suggests that in the more distant radio galaxies there may be many nuclear sources which are below the present detection limit.

Compact nuclear sources have been detected in 15 out of 25 extended 3C sources identified with galaxies brighter than $m_p = 16$ which have been observed with either the Cambridge or Westerbork synthesis telescopes at 5 GHz. In comparison, out of a sample of 114 E galaxies brighter than $m_p = 16$ *without* extended radio sources, Ekers and Ekers (1973) found no nuclear components as strong as any of those in Table IV. The presence of compact nuclear sources in such a large fraction of the radio galaxies, and only in the radio galaxies, is of considerable interest since it implies that it is usual for the compact and extended components to be present concurrently. This could happen if (i) both types of radio emission are continuous for most of the lifetime of a unique type of elliptical galaxy, or (ii) both types of radio emission are transient but switch on and off together. Both these cases argue that the extended component is maintained by a continuous injection of energy – in (i) because the present energy in relativistic particles in the extended sources is insufficient to enable it to continue radiating for the life of the galaxy and in (ii) because the information about whether the nucleus is on or off has to be transmitted to the extended component and the only plausible way to do this is to switch on or off the energy supply.

4. Quasi-Stellar Objects

Although there is still some disagreement on whether QSO's should be included in a discussion of nuclei of galaxies, I will do so and also make the simplest consistent

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assumption about the nature of the redshifts, namely that they are cosmological.

The radio properties of the QSO's are similar to those of the elliptical galaxies in that they have both compact and extended components. The extended radio components associated with QSO's are indistinguishable from those associated with elliptical galaxies. The compact radio sources identified with QSO's have very similar radio spectra but are $\sim 10^5$ times brighter than the elliptical galaxy nuclei and 100 times brighter than the brightest Seyfert nuclei. This class of compact radio source has been studied intensively and observations of the radio spectra, intensity variations, angular structure and variations in structure have been reviewed by Kellermann (1972) and others. The observational situation regarding the spectral and intensity variations has not changed significantly since then, but detailed observations with very-long-baseline interferometers show increasingly complex structures involving two or more spatially separated components (Broderick *et al.*, 1972; Clark *et al.*, 1973), some of which exhibit temporal changes. Initially these changes were interpreted as components separating with apparent velocities in excess of the speed of light (Whitney *et al.*, 1971; Cohen *et al.*, 1971), whereas further analysis indicates that the changes may be equally well explained by components of variable intensity (Dent, 1971; Kellermann *et al.*, 1973). An apparent contraction has been observed for the N galaxy P1934–63 by Robertson *et al.* (1973).

5. Summary

Figure 13 shows the positions of the extragalactic radio sources, both compact and extended, on a linear size-luminosity plot. For clarity, many of the upper limits on radio galaxy diameter are not included in the diagram but the centroid of the linear size distribution for all radio galaxies is within the distribution of the galaxies shown. There may be a few objects straddling the gap between the extended and compact sources but a definite separation in the distribution of linear size will remain.

Spiral galaxies clearly produce a different kind of radio nuclei than those observed in elliptical galaxies. They generally have weaker, larger radio nuclei with much steeper spectra than do the elliptical galaxies. Some of the unresolved, flat spectrum, spiral nuclei, such as in M81, could be of the same type as the elliptical galaxy nuclei, but this would be a rare, perhaps intermittent, phenomena. It is also possible that subcomponents of the spiral nuclei will be similar to the elliptical galaxy nuclei in linear size, but they will be many orders of magnitude weaker.

Two of the elliptical galaxies, M87 and NGC 1052, contain the smallest extragalactic radio sources known. Unfortunately, the angular sizes of most of the elliptical galaxy nuclei are not known and they do not appear in Figure 13. If they are just as compact, they would form a continous distribution running all the way up in power to the two Seyfert galaxies 3C120 and NGC 1275. These two Seyfert galaxies have nuclei quite different from the rest of the Seyfert galaxies which lie much closer in radio properties to the ordinary spiral galaxies. It appears that there is a real gap in power between the compact QSO's and the strongest galaxy nuclei, but statistically

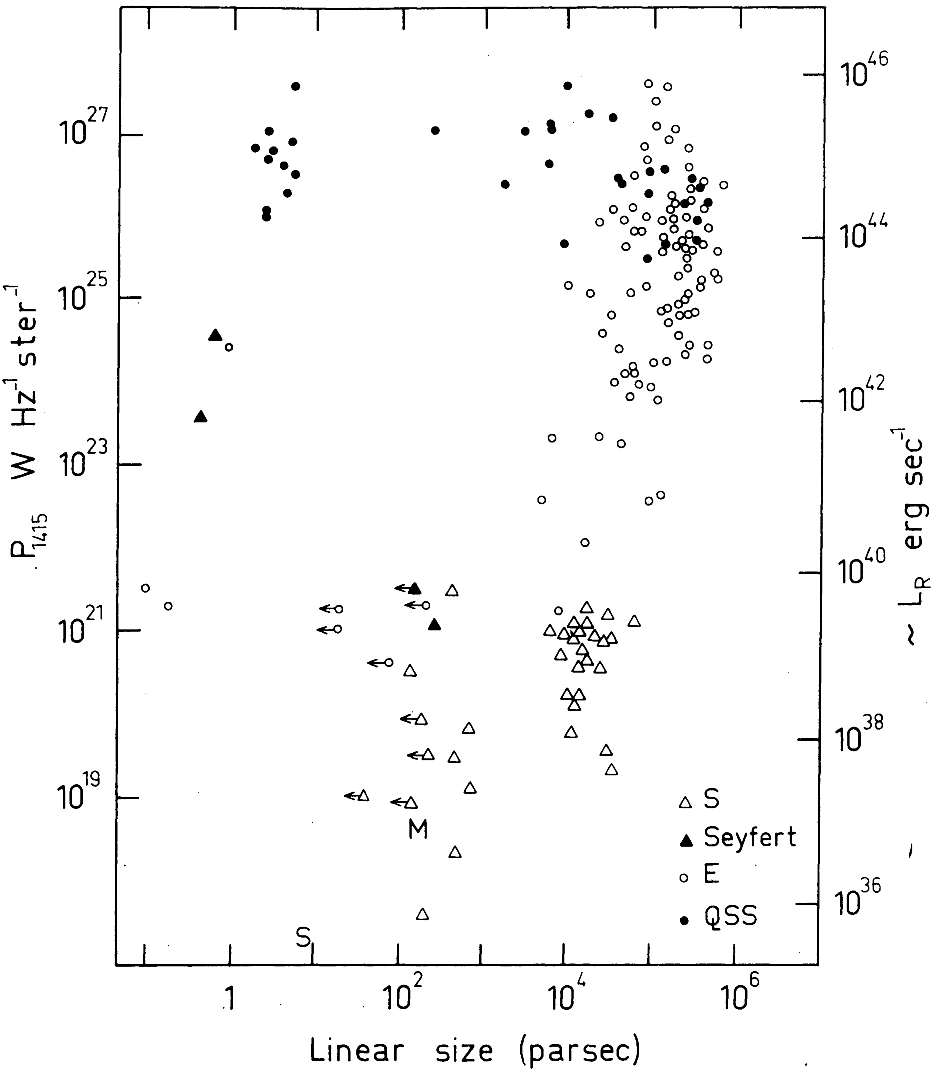

Fig. 13. Plot of the monochromatic radio power at 1.4 GHz against linear diameter for all known classes of extragalactic radio source. For clarity, objects with upper limits to the diameter are not plotted except for the weak radio nuclei. The radio luminosity scale, L_R, is defined in Figure 5. The extended source in our galactic centre is indicated by *M* and the Sgr A source by *S*.

complete observations with very-long-baseline interferometers would be necessary to check this further.

The high correlation between the presence of compact and extended sources in elliptical galaxies implies that the nucleus has a continuing involvement in the production of a radio galaxy, but perhaps the much more powerful optical and radio events called QSO's are a transient phase in the life of a galaxy.

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DISCUSSION

Toomre: How many components are there in Kellermann's models of 3C 273 and 3C 279?

Kellermann: Three.

Bracewell: The source at the centre of NGC 5128 has been observed at 2.8 cm at Stanford with an 18 arc sec beam. The flux density of 1.5×10^{-26} W m^{-2} Hz^{-1}, taken in conjunction with the values at 3.8 and 21 cm, will help to indicate the spectrum. Do you think that it could represent a new pair of ejecta being cooked up?

Ekers: The energy content of the compact component is too small by many orders of magnitude for it to be able to expand adiabatically to the size of the double source.

Seielstad: You have pointed out that the radio properties of the quasars are continuous with those of the bright radio galaxies. But if you bring them 1000 times closer, so that their radio powers are 10^6 times less, then they are continuous with other types of source.

Ekers: They become continuous with the disks of spiral galaxies, which they look nothing like.

Seielstad: There are ellipticals like NGC 1052.

Ekers: Right, you can try to scale the compact radio components in quasars, but for the QSOs with double radio components I am less sure that a local interpretation would give a class of objects like any other known radio source.

Longair: I can comment on the statistics of nuclear radio components. We have detected central components in about 12 out of 50 sources. In the complex, nearby radio sources associated with Abell's clusters, Julia Riley informs me that all have now been found to contain compact components. For double sources, the statistics are less complete but at least 10% of all doubles have central components. This is a very conservative lower limit and it is quite conceivable that all double sources contain such components.

Miley: We find a compact nuclear component in 3C 310. This is a large relaxed double radio galaxy with a very steep radio spectrum. Since it is presumably old, the detection of a nuclear component reinforces your point that continuous injection may be occurring.

Ekers: All 17 of these are identified with galaxies of magnitude < 16.2. Maybe the fact that they are in clusters is relevant, but the main point is that they are all close, low-luminosity objects and we have detected practically a complete sample out to a certain distance.

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