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Compact Radio Cores and the Relation between the Radio and Optical Axes of Elliptical Galaxies

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Abstract. We have reinvestigated the reported tendency for the extended radio structures associated with bright elliptical galaxies to be oriented preferentially along the optical minor axes. It is found that such a tendency exists only for those galaxies in which the compact radio cores coincident with their nuclei are quite prominent. If the galaxies are divided into two groups according to whether their cores account for less than or greater than 10 per cent of the total flux density at 2·7 GHz, the angle ϕ (between the radio axis and the optical minor axis) appears to be uniformly distributed between 0° and 90° for the former, but is nearly always < 30° for the latter group. One possible explanation is that the radio emission from compact cores suffers thermal absorption by ionized gas that is distributed differently in the two groups.

Key words: radio galaxies—elliptical galaxies—extended radio sources

1. Introduction

The relative orientation of the radio axes of extended radio sources and their associated elliptical galaxies can in principle be used as a test for models of formation of radio galaxies. Although there are many practical problems in applying such a test (see *e.g.* Palimaka *et al.* 1979), it has been found that in carefully selected samples of well-collimated radio structures the radio axes appear to be oriented preferentially but not exclusively towards the minor axes of the parent elliptical galaxies (Guthrie 1979; Palimaka *et al.* 1979, henceforth referred to as PBFB). The interpretation of this trend is however not straight-forward, mainly because the relation between the distribution of light and rotation of elliptical galaxies is unclear (*e.g.* Binney 1978; Jenkins and Scheuer 1980).

From the sample of 78 galaxies used by them, it was also noted by PBFB that the trend towards minor-axis alignment of radio orientations was stronger for the larger radio sources (with a projected size > 250 kpc). More recently, however, Guthrie (1980) has examined several other large sources in addition to those in the PBFB sample and found that the minor-axis trend is not significantly stronger for the large radio sources. A similar result has been reported also by Wilkerson and Romanishin (1981) who find that the radio axes of several large sources from the southern hemisphere are not aligned with their optical minor axes.

Noticing that some of the aligned large sources are known to have prominent compact radio components coincident with their optical nuclei (*e.g.* NGC 315 and 6251) we have investigated the relation between the strength of the nuclear radio component and the optical—radio orientation. We find, somewhat to our surprise, that the minor-axis trend noted earlier arises primarily due to galaxies with prominent radio cores (cores that account for > 10 per cent of the total flux density at 2·7 GHz). In galaxies that have only a weak or no detected core component, there is no evidence for the radio axis to show a preferred orientation.

In Section 2, we describe the sample of galaxies used by us and in Section 3 the results obtained. A brief discussion of the results is given in Section 4.

2. The sample

Although the orientation of the radio axis can usually be measured quite reliably, it is often difficult to determine the position angle (PA) of the optical image of the galaxy. Guthrie (1980) has independently attempted to measure on the glass plates of the Palomar Sky Survey (PSS), the optical orientations of all the 78 galaxies used by PBFB. He found that the optical PA of 31 galaxies could not be measured reliably because the galaxies either have very small ellipticities, or they appear too faint or asymmetric, or their images are confused with those of nearby objects. To ensure that the PAs of the galaxies are reliable, the basic sample used by us consists of the 47 PBFB galaxies measured also by Guthrie and the 14 additional well-collimated radio galaxies measured by him (listed in Table 5 of Guthrie 1980). We do not include the 18 galaxies measured by Wilkerson and Romanishin (1981) because few of them have been mapped in the radio with high angular resolution.

A careful examination of the available optical and radio data for the basic sample of 61 sources has led us to discard 7 of these for the following reasons. The optical PAs for four galaxies (*viz.* 0124 + 189, 1250 – 102, 1940 + 504 and 2354 + 471) measured from the red copies of the PSS by PBFB and by Guthrie differ by large amounts (in the range of 22° to 58°; the root-mean-square (rms) difference of the two sets of measurements for the other 43 galaxies is only about 7°). The source 1452 + 165 was excluded because its optical identification is uncertain (Bridle and Fomalont 1978). Two other sources *viz.* 1514 + 072 and 0034 + 254 were excluded because their radio axes cannot be determined reliably; the former is very poorly collimated (Fomalont, Palimaka and Bridle 1980) and the latter appears to have a wide-angle tailed structure with an opening angle of ~ 90° (Ekers *et al.* 1981). Our final sample therefore consists of the 54 sources listed in Table 1.

High - (few arcsec) resolution radio structures and information on the flux densities of core components for most of the sources in Table 1 are available in the literature from observations made either at 2·7 and 8·1 GHz, with the NRAQ interferometer, or at 4·9 GHz with the Very Large Array (Bridle and Fomalont 1978; Fomalont and Bridle 1978; Fomalont, Palimaka and Bridle 1980). A few sources have been mapped at 5 GHz with the Cambridge 5-km telescope or the Westerbork synthesis telescope. In a couple of cases maps with poorer resolution are available only at 1·4 GHz but the flux densities of their core components have been determined at higher frequencies using either the VLA or the NRAO interferometer.

For each source, where information on core flux density is available, we have evaluated the ratio, f_c, of the core flux density to the total source flux density at 2·7 GHz. The frequency of 2·7 GHz was chosen because measurements are available for a majority of the sources at this frequency. Where measurements do not exist at 2·7 GHz we have estimated f_c from measurements at a higher frequency using the spectral indices for the core and extended emission if known, or otherwise assuming values of $\alpha_{core} = 0$ and $\alpha_{ext} = 0{\cdot}8$, (spectral index defined as $S \propto \nu^{-\alpha}$), the typical values for well-observed sources. Since nearly all the galaxies in the sample have a redshift < 0·1 no attempt was made to transform f_e to the frame of reference of each galaxy.

For most of the sources without detected core components, upper limits of a few per cent can be placed on the values of f_c from the published maps. We have adopted a generally conservative upper limit of 0·1 in such cases.For 9 sources, however, the measurements are not of adequate resolution or sensitivity to place a reliable upper limit at $f_c = 0{\cdot}1$. These sources are considered separately.

The observed and estimated parameters are given in Table 1. The source name in coordinate designation and an alternative name or catalogue by which the source is generally known are listed in Columns 1 and 2 respectively. The redshift (generally taken from the compilation by Burbidge and Crowne 1979) is entered in Column 3. The PA of the optical minor axis is given in Column 4. If the PA has been measured both by PBFB and Guthrie, the average value from their measurements on the red copies of the PSS is entered. Column 5 gives the PA of the radio axis determined from the best available maps, references to which are given in Column 8 with the code given at the end of the Table. The magnitude of the difference between the optical and radio PAs is listed in Column 6 and an estimate of the largest linear size of the radio structure (for H_0 = 50 km s^{-1} Mpc^{-1}) is given in Column 7. Column 9 gives an estimate of f_c. A blank in Column 9 implies that the source has not been adequately mapped to determine f_c reliably. The total source luminosity at 2·7 GHz in W Hz^{-1} sr^{-1} is given in Column 10. The linear size and luminosity for sources without measured redshift have been computed by estimating the redshift from the apparent magnitudes as in PBFB. An indication of additional notes on some sources is given by an asterisk in Column 9.

3. The relation between f_c and ϕ

There are 45 galaxies in Table 1 for which fairly reliable values of (or upper limits to) the fractional flux density in the core component at 2·7 GHz, f_c, could be determined from observations reported in the literature. The values of f_c are plotted in Fig. 1 against the angle, ϕ , between the radio axis and the optical minor axis. A clear tendency can be seen for galaxies with relatively strong radio cores to have their

Table 1. The sample of radio galaxies.

Source	Other name	Redshift	PA_{opt}	PA_{rad}	ϕ $\lvert PA_{opt} - PA_{rad} \rvert$	Linear size	Reference to radio structure	f_c	Log P_t 2·7 GHz
			deg	deg	deg	kpc			
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
0018 − 194	PKS		104	111	7	1100	SM		24·8
0043 − 424	PKS	0·0526	69	136	67	150	E69		24·7
0043 + 201	3C 21	0·1028	165	172	7	900	ORP, BF	0·06	24·1
0055 + 300	B2, N 315	0·0167	131	129	2	1400	B79, BF	0·34	23·1
0153 + 053	4C 05·10, N 741	0·0185	170	84	86	45	FPB	<0·05	22·8
0300 + 162	3C 76·1	0·0324	54	110	56	40	JPR, MKN	<0·01	23·8
0305 + 039	3C 78	0·0288	53	56	3	78	FPB	0·19	24·1
0325 + 023	3C 88	0·0302	64	63	1	200	FPB	0·05	24·0
0331 + 391	4C 39·12	0·0209	10	0	10	15	BF, F77	0·34	23·0
0356 + 102	3C 98	0·0306	164	25	41	249	JPR, FB	<0·01	24·2
0518 − 458	PKS, Pictor A	0·0350	2	102	80	414	C77	0·02	25·1
0652 + 426	4C 42·22		33	50	17	69	BF	0·33	23·8
0714 + 286	4C 28·18	0·083	158	133	25	105	BF	<0·05	24·1
0744 + 559	DA 240	0·0350	160	63	83	1955	WSW, SBW	0·06	24·1
0924 + 302	B2	0·0266	139	55	84	488	E81	<0·02	22·5
0938 + 399	3C 223·1	0·1075	136	15	59	199	RP, FB	<0·01	24·7
1003 + 351	3C 236	0·0989	137	123	14	5700	WSW, BF	0·60	25·1
1005 + 282	B2	0·1476	95	150	55	587	F78	*	23·5
1033 + 003	4C 00·37		46	8	38	300	FPB	<0·1*	23·7
1102 + 304	B2	0·072	57	70	13	260	F77	0·10	23·6
1113 + 295	4C 29·41	0·0481	50	71	21	105	R75, BF	0·02	24·0
1122 + 390	B2, N 3665	0·0067	124	118	6	60	K79	0·16*	21·2
1127 + 012	PKS		11	12	1	140	FPB	<0·1	24·4
1137 + 123	PKS		46	12	34	140	FPB	<0·1	24·0
1154 − 038	PKS		134	122	12	400	FPB	0·18	23·3
1216 + 061	3C 270, N 4261	0·0073	63	83	20	104	FPB	0·02	23·3
1222 + 131	3C 272·1, N 4374	0·0031	27	167	40	11	JPR	0·09	22·1
1249 + 035	PKS		118	146	28	150	FPB	<0·1	24·0
1254 + 277	B2, N 4839	0·0249	150	11	41	23	F77		21·9
1317 + 258	4C 25·42		165	54	69	65	BO	<0·05	24·1
1318 − 434	PKS, N 5090	0·011	6	24	18	550	SM, S76	0·20*	23·8
1321 + 318	B2, N 5127	0·0161	159	111	48	320	E 81		22·9
1322 + 366	4C 36·24, N 5141	0·0174	166	7	21	23	BF	0·10	22·8
1323 + 370	4C 37·38		2	154	28	25	RA	<0·1	23·7
1333 − 337	PKS, IC 4296	0·0129	141	125	16	780	G77	0·01	23·5

1358 − 113	PKS	0·025	135	125	10	205	SM		23·3
1407 + 177	4C 17·57		94	73	21	250	FPB	<0·1	23·0
1414 + 110	3C 296	0·0237	55	65	10	200	FPB	0·02	23·7
1422 + 268	B2	0·037	30	96	66	121	FPB, F77	<0·02	23·4
1514 + 004	4C 00·56	0·053	147	135	12	500	FPB	0·26	24·2
1553 + 245	4C 24·35	0·0426	107	129	22	23	BF, F77	0·35	23·0
1559 + 021	3C 327	0·1039	48	99	51	762	FPB	<0·02	25·3
1610 + 296	B2, N 6068	0·0313	91	66	25	55	F77		22·4
1637 − 771	PKS	0·0431	179	165	14	182	E 69		24·4
1640 + 826	N 6251	0·0234	114	124	10	2800	WWB	0·51	23·4
1710 + 156	MLO		96	169	73	19	FPB	<0·11	24·0
1744 + 557	4CT 55·33·1	0·0304	100	77	23	223	BF	0·35	23·3
1759 + 211	4C 21·51		145	50	85	179	BF	0·07	24·1
1833 + 326	3C 382	0·0578	166	48	62	416	RB, BF	0·06	24·6
2103 + 124	PKS		155	138	17	260	FPB	0·13	24·4
2116 + 262	B2, N 7052	0·0164	154	22	48	23	F77, CD	0·41	22·1
2117 + 605	3C 430	0·0549	18	35	17	140	RP	<0·01	24·7
2229 + 391	3C 449	0·0171	98	9	89	168	BF, F77	0·02	23·2
2356 − 611	PKS	0·0963	93	134	41	900	C77		25·5

References to radio structure:

B79 Bridle *et al.* (1979)
BF Bridle and Fomalont (1978)
BO Burns and Owen (1979)
C77 Christiansen *et al.* (1977)
CD Condon and Dressel (1978)
E69 Ekers (1969)
E81 Ekers *et al.* (1981)
F77 Fanti *et al.* (1977)
F78 Fanti *et al.* (1978)
FB Fomalont and Bridle (1978)
FPB Fomalont, Palimaka and Bridle (1980)
G77 Goss *et al.* (1977)
JPR Jenkins, Pooley and Riley (1977)
K79 Kotanyi (1979)
MKN Macdonald, Kenderdine and Neville (1968)
ORP Owen, Rudnick and Peterson (1977)
R75 Riley (1975)
RA Rudnick and Adams (1979)
RB Riley and Branson (1973)
RP Riley and Pooley (1975)
S76 Schilizzi (1976)
SBW Strom, Baker and Willis (1981)
SM Schilizzi and McAdam (1975)
WSW Willis, Strom and Wilson (1974)
WWB Waggett, Warner and Baldwin (1977)

Additional notes:

1005 + 282: Map at 1415 MHz (Fanti *et al.* 1978) shows a possible central component. But as the total measured flux density is only ∼ 60 mJy, it is not possible to estimate f_c (2·7 GHz) reliably.

1033 + 003: Fomalont, Palimaka and Bridle (1980) note that the central component ($\alpha_c \sim 0{\cdot}45$) has a size of ∼ 5 arcsec at 2·7 GHz and is probably an equal double at 8·1 GHz. The core could therefore be of the 'extended' type. If one of the two components coincides with the nucleus the value of f_c is likely to be $< 0{\cdot}1$.

1122 + 390: The value of $f_c = 0{\cdot}16$ is based on the measured flux density of 15 mJy at 5 GHz (Kotanyi 1979). In a VLBI experiment at this frequency, van Breugel *et al.* (1981), however, find a correlated flux density of 30 ± 7 mJy.

1318 − 434: Schilizzi (1976) reports a correlated flux density of 630 mJy at 8·1 GHz in a VLBI experiment. The value of f_c (2·7 GHz) $= 0{\cdot}20$ assuming $\alpha = 0$ for the VLBI component.

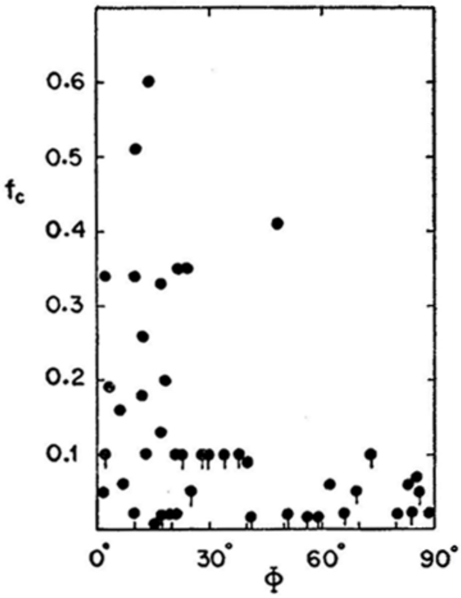

Figure 1. Relation between the fractional flux density in the core (f_c) , and the angle between the radio axis and the optical minor axis (ϕ). Points with short vertical lines are upper limits to f_c.

radio axes aligned preferentially towards their optical minor axes. Of the 16 galaxies in which the core component accounts for at least 10 per cent of the total flux density, only one is seen to have its radio axis misaligned by more than 30° with respect to the optical minor axis. Even in the case of this single exception (2116 + 262), the radio contours (Fanti *et al.* 1977) show a considerable bending of the radio axis away from the nucleus. The radio PA listed in Table 1 for this galaxy is based on the shape of the outermost contours, whereas contours close to the nucleus suggest an orientation within 30° of the optical minor axis. Fig. 1 also suggests that the range of φ-values may increase fairly abruptly for $f_c \lesssim 0{\cdot}1$. A larger sample of galaxies and better estimates of f_c for those with upper limits are needed to assess the significance of any such trend.

The distributions of ϕ in the two subsamples comprising of 29 galaxies with $f_c < 0{\cdot}1$ and 16 galaxies with $f_c \geqslant 0{\cdot}1$ are shown as histograms in Fig. 2 which also shows separately the distributions of ϕ for the 9 galaxies for which f_c is unknown and for all the 54 galaxies taken together. It may be seen that the radio axes of galaxies with weak cores ($f_c < 0{\cdot}1$) seem to bear no relation with their optical appearance A χ^2 test for this sample shows no significant departure from a uniform distribution of f between 0° and 90°. But the ϕ - distribution for galaxies with prominent cores ($f_c \geqslant 0{\cdot}1$) appears to depart strongly from a uniform distribution, with 12 of the 16 galaxies having $\phi < 20°$. The χ^2 test in this case rejects the uniform distribution with a confidence level of 99·9 per cent. It is also interesting to note that the distribution of ϕ for the 9 galaxies with unknown values of f_c lies closer to that for galaxies with $f_c < 0{\cdot}1$, which is consistent with the above trend since most galaxies in Table 1 have weak cores.

When all the galaxies in Table 1 are considered together there is a significant tendency towards minor axis alignment as noted earlier by Palimaka *et al.* (1979) and

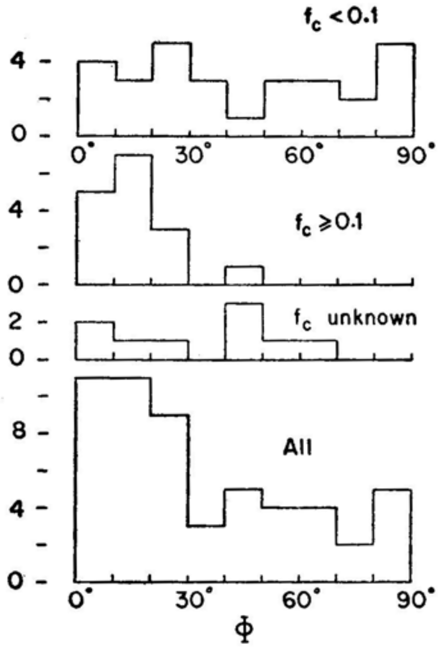

Figure 2. Distributions of the alignment-angle ϕ

Guthrie (1980). But it now seems clear from Fig. 2 that this tendency arises almost entirely from the galaxies with prominent cores. The reported alignment between the radio and optical axes appears to be true only for this class of galaxies.

Given that the strength of the radio core is somehow related to the relative radio-optical orientation of radio galaxies it is worth enquiring if this relation depends on the nature of the core component. It has been shown by Bridle and Fomalont (1978) that the core components in galaxies can be of two kinds depending on their size and radio spectrum. Most cores are of the 'compact' kind with sizes much smaller than 1 kpc (VLBI observations often indicate sizes of $\lesssim 1$ pc) and flat or inverted radio spectra characteristic of regions showing synchrotron self0-absorption. A significant minority of cores are however of the 'extended' kind with steep spectra ($\alpha > 0{\cdot}5$) and sizes up to few kpc. In the present sample of galaxies with $f_c \geqslant 0{\cdot}1$, only one source (*viz.* 1003 + 351 ≡ 3C 236) appears to have an extended steep-spectrum core, all others having $\alpha_{core} < 0{\cdot}5$ at high frequencies. Galaxies in the $f_c < 0{\cdot}1$ group for which spectral information is available, also appear to have $\alpha_{core} < 0{\cdot}5$. The relation between f_c and ϕ therefore appears to apply to the compact cores. Little can however be said about such a relation for the extended cores alone from the present sample.

Apart from the correlation with f_c, we have also attempted to see if the angle ϕ correlates with other known properties of the radio galaxies. In Figs 3 and 4 we show plots of ϕ against the total radio luminosity, P_t (2·7 GHz), and the core luminosity, P_c (2·7 GHz), respectively. Within the range of luminosities covered by the sample, ϕ shows no significant correlation with P_t . Although there appears to be a possible weak anticorrelation between ϕ and P_c , such a relation is only to be expected in view of the f_c–ϕ relationship.

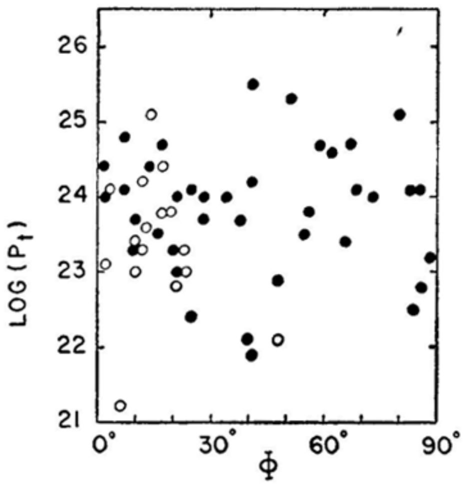

Figure 3. The total radio luminosity, P_t (2·7 GHz), plotted against the alignment angle ϕ . Unfilled circles here and in subsequent figures refer to galaxies with $f_c \geqslant 0{\cdot}1$.

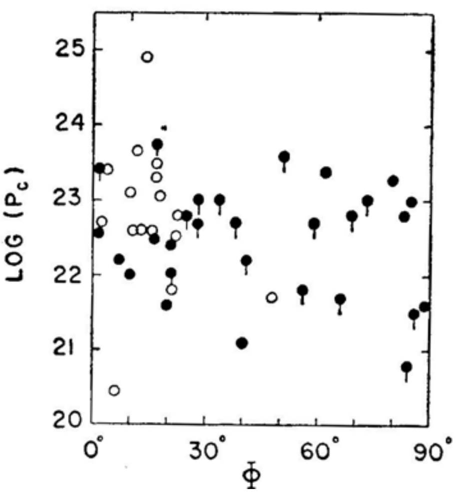

Figure 4. The core luminosity, P_c (2·7 GHz), versus the alignment angle ϕ.

A plot of the total linear extent of the radio galaxies versus ϕ , shown in Fig. 5, does not indicate any significant correlation, contrary to such a suggestion in the data of PBFB.

4. Discussion

Although the galaxies used in the present investigation do not form a complete sample in any well-defined way, we can think of no observational or selection bias that could have led to the distributions shown in Fig. 2. If elliptical galaxies are generally oblate spheroids, the fact that the radio axes appear to lie preferentially towards the minor axes of their light distribution appears to be consistent with the beam model of radio sources (*e.g.* Blandford and Rees 1974) in which the beams are collimated

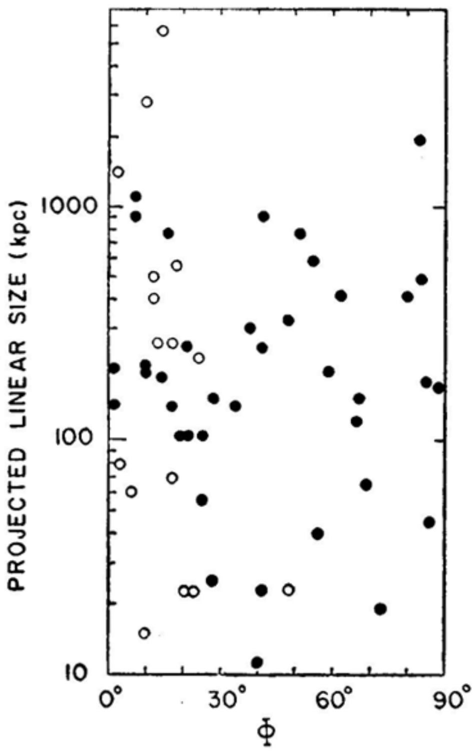

Figure 5. Plot of the maximum projected linear size of radio emission versus the alignment angle ϕ.

by a flattened mass distribution in the galactic nucleus and emerge along the rotation axis of the nuclear engine. An alignment that is not perfect and universal can be caused by one or both of the two main possibilities: the apparent ellipticity of galaxies not being due to rotation and a misalignment of the nuclear collimator with respect to the stellar distribution.

If the present finding that the relative strength of the radio core component is a good filter for the minor-axis trend is indeed true and not just the result of an extreme statistical fluctuation, then it must tell us something important about the processes taking place in the nuclei of extended radio sources.

The fact that the galaxies showing the best minor-axis alignment (those with prominent radio cores) have the same range of radio luminosities and projected linear sizes as the galaxies that show no preferential alignment, suggests that the difference in the relative core intensities of the two sets of galaxies is more likely to arise from different geometrical and/or absorption effects rather than from a difference in the strength of the nuclear activity itself.

If relativistic beaming effects are important in the cores of these radio galaxies, as suggested for the cores of the much more luminous quasars (Scheuer and Readhead 1979; Blandford and Konigl 1979), the relative core strength would be expected to be a function of the orientation of the radio axis with respect to the observer's line of sight. This does not however explain the alignment of the radio and optical axes. Furthermore, if the beams in strong-cored galaxies are oriented closer to our lines of sight, the image of such galaxies should appear more circular than those of the

Weak-cored ones. No significant difference in the apparent ellipticities of the two types of galaxies can, however, be noticed in the present sample. Another argument against strong relativistic beaming is that some of the largest known radio galaxies in the sample (*e.g.* NGC 6251 and NGC 315) have very prominent cores, so that their true sizes would then have to be even larger.

If absorption effects are invoked to explain the observations, the cut-off frequency (below which absorption is important) would have to be significantly higher in the misaligned galaxies (with weak cores at 2·7 GHz) than in the well-aligned galaxies (large f_c). There is marginal evidence in support of this in the data. The two-point spectral index of the core component between 2·7 and 8·1 GHz, $\alpha_{2.7}^{8.1}$, is known for 10 galaxies with $f_c < 0{\cdot}1$ and 10 with $f_c \gtrsim 0{\cdot}1$ (excluding 3C 236). Although all these have $\alpha_{2.7}^{8.1} < 0{\cdot}5$, four galaxies in the former group have an inverted spectrum with $\alpha_{2.7}^{8.1} < -0{\cdot}2$ while none in the latter group have $\alpha_{2.7}^{8.1} < -0{\cdot}2$. High resolution observations at a number of frequencies are clearly necessary to determine the spectra of the core components more accurately.

The absorption could be either synchrotron self-absorption within the core or free-free absorption in an ionized medium on the line of sight to the core. In the case of synchrotron self-absorption it is not clear why the cutoff frequency should be different in the two groups of galaxies. An interesting possibility that deserves further investigation can however be suggested to explain the f_c–ϕ relation in terms of thermal absorption of the core components if the absorbing material is distributed differently in the two groups. In the aligned galaxies, the rotation axes of the inner nuclear engine and of the rest of the galaxy presumably coincide, and if the ionized gas (possibly that responsible for the narrow emission lines) is distributed in a thin accretion disk, the radio emission from the core would traverse very little gas from most directions of view. In the case of the misaligned galaxies, on the other hand, the two rotation axes could be very different and the ionized gas distributed more or less spherically around the nucleus. Free-free absorption would then be important from all directions of view.

For an electron temperature $T_e \sim 10^4$ K, the cutoff frequency ν_c (in MHz) for thermal absorption is given approximately by the relation

$$\nu_c \sim \tfrac{1}{2}\, n_e\, l^{1/2}$$

where n_e is the electron density (cm^{-3}) and / the l pathlength (pc). Since the narrow-line regions of radio galaxies have generally been inferred to have electron densities of 10^2–10^5 cm^{-3} and sizes of ~ 10–10^3 pc, free-free absorption can indeed be important at frequencies near 2·7 GHz even for fairly small filling factors.

If absorption is indeed important, one might expect the cores of galaxies with low values of f_c to have on an average lower brightness temperatures than those with large values of f_c . It is, however, not yet possible to test this with the available data since there is little information on the angular sizes of the cores.

From a search of the literature, we find that the stellar rotation axes have been determined (Simkin 1979; Jenkins and Scheuer 1980; Jenkins 1981) for only 5 galaxies in the present sample. Four of these (*viz.* 3C 98, 3C 270, 0153 + 053 and 1330-337) have $f_c < 0{\cdot}1$ and show no tendency for their rotation axes to align either with their radio axes or with their isophotal minor axes. The other galaxy (NGC 3665) with $f_c > 0{\cdot}1$ has a rotation axis of 105° ± 5° (Jenkins 1981), within 20° of its optical minor axis and the radio axis. It would be extremely valuable to study the stellar kinematics of many more radio galaxies particularly those with relatively strong central components.

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