A CORRELATION BETWEEN ELLIPTICITY AND CORE-STRENGTH IN EXTENDED RADIO GALAXIES

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Abstract. We show that in the case extended radio sources a correlation exists between the fraction of the radio flux retained in the core component and the ellipticity of the underlying galaxy. The correlation is in the sense that stronger cores occur in flatter galaxies. It would seem that there exists a class of intrinsically rounder, redder, massive ellipticals with larger velocity dispersions and metallicities, that can form extended radio sources more efficiently. Thus the occurrence of a radio source appears to be related to the dynamical and chemical evolution of the Galaxy.

1. Introduction

Recent observations of elliptical galaxies have cast doubts on the long-standing belief that they form a one-parameter family, with their properties determined only by the total mass. Terlevich *et al.* (1981) find that flatter ellipticals have smaller velocity dispersions and metallicities than the rounder ones; van den Bergh (1979) had already noted that flatter ellipticals are bluer. We show in this paper that in the case of extended radio sources, the fraction of radio flux retained in the core component depends on the intrinsic ellipticity of the underlying galaxy, with stronger cores occurring preferentially in flatter galaxies. Seen in conjunction with the recent results (Kapahi and Saikia, 1982) that an alignment of radio and minor axes is a privilege of the strong-core galaxies, our result suggests that the intrinsic axial ratio plays a far more important role in determining the properties of elliptical galaxies than hitherto envisaged.

Our sample described in the next section has been compiled from different sources and is incomplete and inhomogeneous. While the correlation seen in such a sample is presented in Section 3, the selection and projection effects are discussed in the following two sections to elucidate the fact that a correction for such effects can only augment the correlation. Obviously, more observations are necessary to confirm this idea, and we hope that this paper will incite an interest towards obtaining them.

2. The Sample

Our sample listed in Table I consists of 91 extended radio sources for which information is available both on the fraction f_c of radio flux contained in the core component at 2.7 GHz and on the ellipticity of the underlying galaxy. Most of the galaxies were observed either at 2.7 and 8.1 GHz with the NRAO interferometer or at 4.9 GHz with the VLA (Bridle and Fomalont, 1978; Fomalont and Bridle, 1978;

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TABLE I

Ellipticity and core-strengths of the sample galaxies

Name	E	Ref.	f_c	Ref.*
0220+427 3C 66B	E0	RC2	0.043	BF
0632+263 4C 26.23	0	BNG	0.04	FB
0802+243 3C 192	ED0	BNG	< 0.002	FPB
0928+67 N 2892	0	RC2	0.105	J
1228+126 M 87	E0	RC2	0.05	J
1707+344 4C 34.45	DE0	BNG	< 0.006	FPB
0108−142 PKS	1	BNG	< 0.1	FPB
0109+492 3C 35	1	BNG	0.018	BF
0124+189 PKS	1	BNG	< 0.1	FPB
0206+355 4C 35.03	E1	RC2	0.065	BF
0331+391 4C 39.12	1	BNG	0.34	BF, F77
0712+534 4C 53.16	1	BNG	0.059	BF
0844+319 4C 31.32, I 2402	D1	BNG	0.05	BF
0844+540 4C 54.17	D1	BNG	< 0.1	FPB
0915+320	1	BNG	< 0.1	FB
0924+302 B2 I 2476	DE1	BNG	< 0.02	E81
1005+007 PKS	1	BNG	0.188	FPB
1142+198 3C 264, N 3867	ED1	BNG	0.09	BF
1222+131 3C 272.1, N 4374	E1	BNG	0.09	JPR
1250−102 PKS, N 4760	1	BNG	0.188	BF
1333−337 I 4296	1	BNG	0.01	G77
1414+110 3C296, N 5532	D1	BNG	0.02	FPB
1602+178 4C17.66	DE1	BNG	< 0.1	FPB
1834+196		BNG	0.165	BF
1940+504 3C 402		BNG	0.03	BF
2058−135 IC 1347	1	BNG	< 0.1	FB
2247+113 4C 11.71, N 7385	E1	BNG	0.086	J
2318+07 N 7626	E1	RC2	0.06	J
2354+471 4C 47.63	1	BNG	< 0.1	FPB
0043+201 4C 20.04A	DE2	BNG	0.06	ORP, BF
0104+321 3C31, N 383	E2	BNG	0.02	BF
0136+397 4C39.04	2	BNG	< 0.1	FB
0153+053 4C05.10, N 741	2	BNG	< 0.05	FPB
0300+162 3C76.1	E2	BNG	< 0.01	JPR, MKN
0305+039 3C78, N 1218	2	BNG	0.033	FPB
0356+102 3C98	E2	BNG	< 0.1	JPR, FB
0652+426 4C42.22	2	BNG	0.33	BF
0744+559 DA240	ED2	BNG	< 0.1	WSW, SBW
1004+143 N 3121	E2	UGC	0.14	J
1033+003 4C0037	2	BNG	< 0.1	FPB
1102+304 B2	D2	BNG	< 0.1	F77
1113+295 4C29.41B	ED2	BNG	0.024	R75, BF
1122+390 N 3665	ED2	BNG	0.16	K79
1123+203 4C20.25	DE2	BNG	0.44	BF
1137+123 PKS	2	BNG	< 0.1	FPB
1154−038 PKS	2	BNG	0.193	FPB
1227+81 N 4472	E2	RC2	0.63	J
1249+035 PKS	2	BNG	< 0.1	FPB
1313+079 4C07.32	E2	BNG	< 0.1	FB

(continued)

Table I (continued)

Name	E	Ref.	f_c	Ref.*
1316+299 4C29.47	DE2	BNG	0.03	BF
1317+258 4C25.42	2	BNG	< 0.05	BO
1318−434 N 5090	E2	BNG	0.2	SM, S76
1319+428 3C285	DE2	BNG	0.005	FB
1321+319 N 5127	DE2	BNG	0.008	E81
1323+370 4C37.38	2	BNG	< 0.1	RA
1346+268 4C26.42	CD2	BNG	0.185	BF
1407+177 4C17.57, N 5490	E2	BNG	< 0.1	FPB
1422+268 B2	ED2	BNG	< 0.02	FPB, F77
1557+708 4C70.19, N 6048	E2	RC2	0.029	BF
1640+826 N 6251	DE2	BNG	0.35	BF
1744+557 4C55.33.1, N 6454	DE2	BNG	0.35	BF
1759+211 4C21.51	2	BNG	0.07	BF
1833+326 3C382	2	BNG	0.06	RB, BF
2103+124 PKS	2	BNG	0.133	FPB
2117+605 3C430	2	BNG	0.01	RP
2229+391 3C449	2	BNG	0.016	BF, F77
2335+267 3C465, N 7720	CD2	BNG	0.066	BF
2337+265 N 7728	E2	UGC	0.2	J
0055+300 B2, N 315	D3	BNG	0.34	B79, BF
0325+039 3C88	DE3	BNG	0.047	FPB
0518−458 PictorA	3	BNG	0.02	C77
0714+286 4C28.18	3	BNG	< 0.046	BF
0938+399 3C223.1	DE3	BNG	< 0.01	RP, FB
1003+351 3C236	DE3	BNG	0.60	WSW, BF
1127+012 PKS	3	BNG	< 0.1	FPB
1216+061 3C270, N 4261	ED3	BNG	0.02	FPB
1254+277 B2, N 4839	D3	BNG	< 0.1	F77
1322+366 4C36.24, N 5141	ED3	BNG	0.097	BF
1430+251 4C25.46	DE3	BNG	0.1	FB
1452+166 3C306	CD3	BNG	0.208	BF
1514+004 4C00.56	ED3	BNG	0.294	FPB
1514+072 3C317	CD3	BNG	0.203	FPB
1553+245 4C24.35	DE3	BNG	0.35	BF, F77
1559+021 3C227	D3	BNG	< 0.02	FPB
1615+324 3C332	D3	BNG	0.041	FPB
1626+39 3C338, N 6166	CD3	BNG	0.129	BF
0755+379 4C37.21, N 2484	E4	BNG	0.101	BF
1710+156 MLO	4	BNG	0.11	FPB
1350+316 3C293	D5	BNG	0.83	BF
2116+262 N 7052	5	BNG	0.41	F77, CD

* J: Jenkins (1982); other references: as in Kapahi and Saikia (1982).

Fomalont *et al.*, 1978). Some additional sources were taken from Jenkins (1982) and from the compilation of Kapahi and Saikia (1982).

The ellipticity class $n = 10(1-b/a)$ for 78 galaxies is taken from Guthrie (1980, 1981), who has measured a large number of galaxies on a homogeneous set of plates. Another seven ellipticity classes are taken from de Vaucouleurs *et al.* (1976; hereafter referred to as RC2), who also provide axial ratios for four galaxies classified as *L*, from which *n* has been estimated. Finally, the ellipticity class for two galaxies has been estimated from the dimensions taken from Nilson (1973; hereafter referred to as UGC). A comparison of RC2 data on axial ratios and Guthrie's estimate of ellipticity class shows a general agreement between the two except for the galaxies for which RC2 axial ratio corresponds to $n = 0$. In the latter case, Guthrie's estimates are very much flatter than the RC2 estimates, and hence the solitary galaxy (N 2892) in our sample with RC2 axial ratio corresponding to $n = 0$ has been rejected leaving us with a sample of 90 galaxies.

There are 12 galaxies in our sample which have been classified as *L* in RC2. For seven of these, Guthrie gives morphological type: they are CD, C, DE, or ED. Ekers and Ekers (1973) have suggested that extended source radio SO galaxies may really be ellipticals, misclassified because of the extensive envelopes that mimic a disk. Such misclassifications would never be labelled LB (Dressel, 1981). Since none of the *L* galaxies in our sample is classified LB, we assume that all these 12 galaxies are misclassified ellipticals, and not genuine lenticulars.

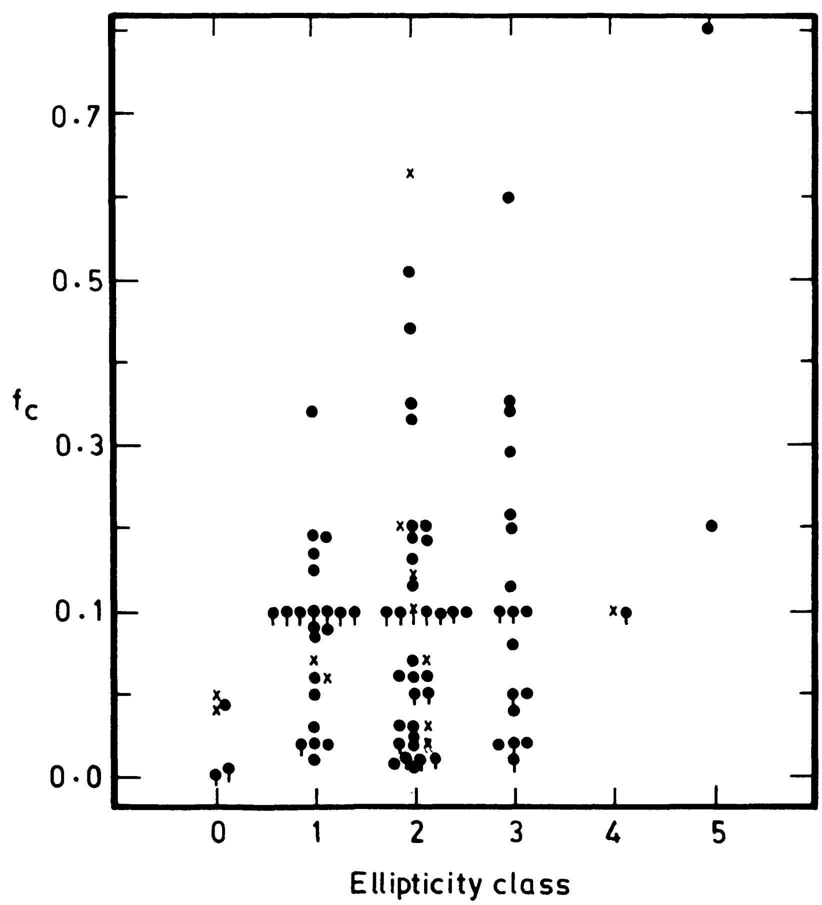

Fig. 1. The distribution of fractional core-strength (f_c) against the ellipticity class of the underlying galaxy. The crosses denote the galaxies for which Guthrie's estimate of ellipticity class are not available. Formal upper limits to f_c are marked.

TABLE II

The ellipticity distributions of the sample galaxies and of different comparison samples

n	Present sample			RSA	Arecibo		Heck-man	Hummel Kotanyi Ekers	Jenkins
	$f_c < 0.1$	$f_c \geqslant 0.1$	Total		Total	Strong			
0	5	0	5	23	12	4	11	6	3
1	19	5	24	24	12	3	9	6	3
2	25	14	39	26	9	3	8	5	4
3	10	8	18	32	9	3	8	5	2
4	1	1	2	23	4	1	2	1	0
5	0	2	2	20	3	1	1	0	0
6	0	0	0	11	1	0	0	1	0
7	0	0	0	8	1	1	0	0	
Total	60	30	90	167	51	16	39	24	12

3. The Correlation

The core-strengths of all the sample galaxies are plotted in Figure 1 against the ellipticity class. Following Kapahi and Saikia (1982) we divide our sample into two groups, $f_c < 0.1$ (weak core) and $f_c \geqslant 0.1$ (strong core). Table II shows the distribution of the sample galaxies of different ellipticity classes between the two core-strength groups. The cumulative frequency distributions (CFDs) of the two core-strength groups is shown in Figure 2a. It is clear that the distribution of weak-core galaxies is shifted towards rounder galaxies. A Kolmogorov-Smirnov test based on the maximum deviation of 0.233 at $n = 1$ shows that there is a 23 % chance that the two distributions are identical. Though this formal value is not insignificant, the fact that the two CFDs differ systematically increases our confidence in the result. Furthermore, the selection and projection effects discussed in the following sections can only smear out such a correlation and hence the statistical tests can only set a lower limit to our confidence.

There are too few galaxies in the bins $n = 0$, 4, and 5, to be statistically meaningful. We will hence group the ellipticity classes into three bins: $n = 0$–1 (round), $n = 2$, and $n = 3$–5 (flat). A χ^2-test shows that the core-strength of the sample galaxies is related to the ellipticity class at a confidence level of 96 % (85 % for the Guthrie sample). The stronger cores thus occur preferentially in flatter galaxies.

It is important to test whether this correlation holds for the entire sample, or only for a particular morphological subset (E or D) of the sample. For 45 galaxies in our sample, morphological types are available from Guthrie. The χ^2-significance for the above correlation for this reduced sample is better than 99 %. The correlation holds good for the morphological subsets of this sample, E+ED (90 %),

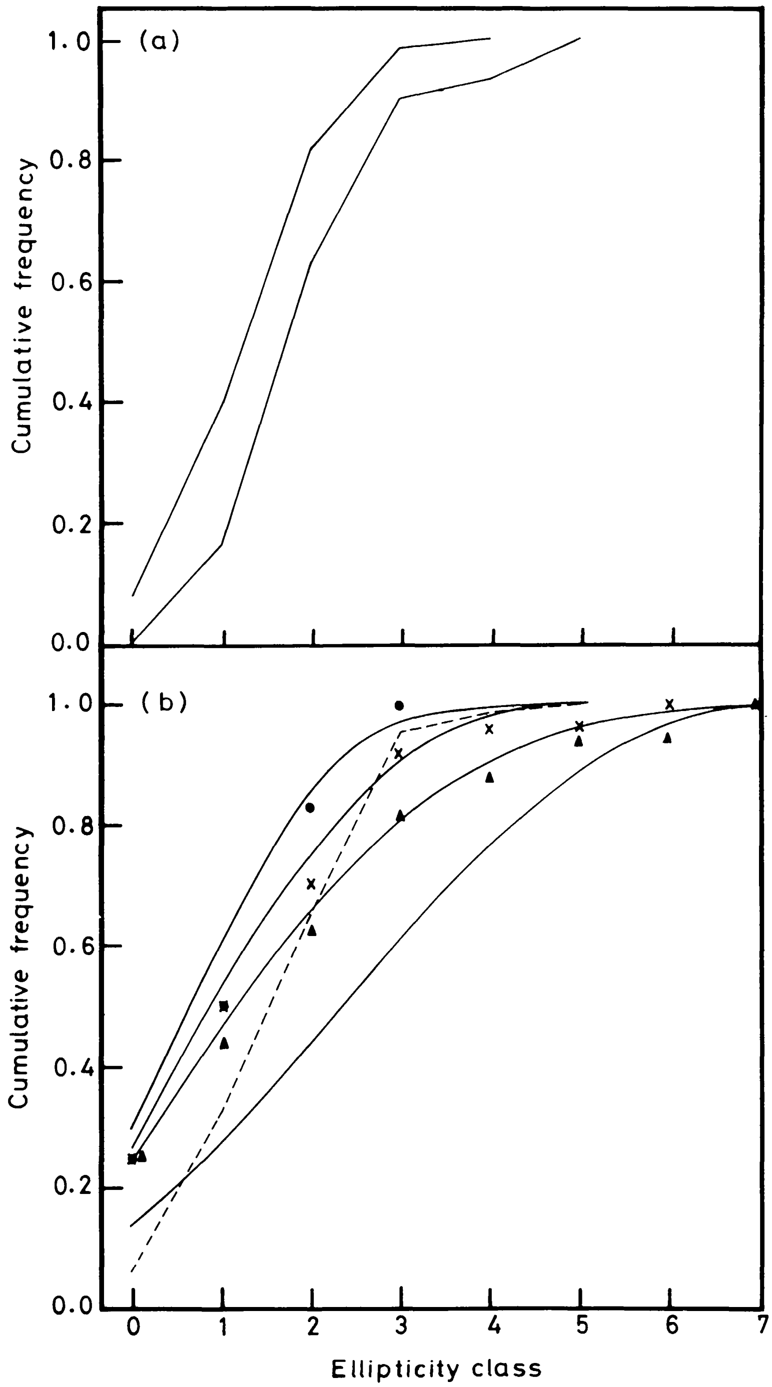

Fig. 2. (a) Cumulative frequency distribution of weak-core ($f_c < 0.1$) and strong-core ($f_c \geqslant 0.1$) galaxies. (b) Smoothed cumulative frequency distributions of various samples. The continuous curves from right to left represent the RSA sample, the Arecibo sample, the Heckman sample and the present sample corrected for its incompleteness in round galaxies. The dashed line represents the present sample before correction. Other symbols are: filled triangles, the strong Arecibo sources; crosses, the HKE sample; filled circles, the Jenkins sample.

DE + D + CD (95%). Clearly, the flatter galaxies have higher fractional core-strength irrespective of whether the galaxy is E or D.

Having shown that the correlation holds good for all the different subsets of our sample, we shall henceforth consider only the total sample of 90 galaxies.

4. The Selection Effects

A major part of the sample is an incomplete subset of a larger sample of galaxies with well-defined optical and radio flux limits (Bridle and Fomalont, 1978; Jenkins, 1982). Since Fomalont and his co-workers were primarily interested in a correlation between the radio and optical minor axes, the sample is deficient in circular-looking galaxies. But there are no discriminations based on the strength of the core. In particular, the ellipticity-based selection effects do not act differently on the two core-strength groups so as to contrive the correlation deduced in the last section. We believe that, apart from its incompleteness in the rounder galaxies, the sample represents the distribution of extended-source radio galaxies well, as the following comparisons with other samples show.

We have compared the ellipticity distribution and CFD of our sample with those of different samples listed below:

(1) The RSA sample: 167 unambiguous, normal ellipticals from the Revised Shapley-Ames Catalogue (RSA; Sandage and Tammann, 1981). The ellipticity class was also taken from RSA.

(2) The Arecibo sample: 51 galaxies detected above 3σ limit by the Arecibo survey (Dressel and Condon, 1978), and classified as E by UGC. The ellipticity class was estimated from the dimensions listed in UGC as measured on Palomar red plates.

(3) The strong Arecibo sample: A subset of sample 2, consisting of 16 sources with flux density $S_{2380} \geqslant 100$ mJy.

(4) The Heckman sample: 39 sources from the list of Heckman (1983) with the radio power at 1.4 or 2.4 GHz $> 10^{21}$ W Hz^{-1}. The ellipticity class was taken from RC2 when available, or derived from the UGC data.

(5) The HKE sample: 24 radio-detected sources from the complete sample of Hummel *et al.* (1983); the ellipticity classes were also taken from the same source.

(6) The Jenkins sample: 12 extended radio sources from the complete list of Jenkins (1982), the ellipticities being taken either from RC2, or estimated from UGC data.

The frequencies listed in Table II and the CFDs shown in Figure 2b indicate that the samples 2 and 3 are quite similar to each other, and so are the samples 4 and 5. However, as we move from the samples 1 to 6, the distributions become more and more deficient in flatter galaxies. This fact agrees with the idea that the rounder ellipticals are more likely to be radio emitters (Heeschen, 1970; Ekers and Ekers, 1973; Hummel *et al.*, 1983).

Our purpose here is to find a suitable comparison sample for the sample in

Table I so that we may recognize the selection effects based on ellipticity. Obviously, Jenkins's extended-source sample is the right choice, since our sample is also drawn from lists of extended sources. We find from Figure 2b that there is a general agreement between the two samples at the flatter end, but our sample appears deficient in the roundest galaxies. The extremely small size of Jenkins's sample discourages us from employing it directly in an estimation of the correction for this deficiency. On the other hand, the five radio samples listed above have all a relatively flat distribution of galaxies between $n = 0$ and 2, with a weighted average value of $(N_0 + N_1)/N_2 = 2.38 \pm 0.37$. We have excluded here the RSA sample since it may not represent a sample of radio galaxies well. We will also assume that the $n = 2$ class in our sample is complete, since it consists of galaxies which are elongated enough to enable an accurate measurement of the major axis. We thus expect 93 ± 14 galaxies in $n = 0$–1 class against the observed value of 29 showing that this class is only 31% complete: Distributing these equally in $n = 0$ and 1 bins, we get the CFD shown in Figure 2b.

If the 64 new galaxies added to the roundest bins are distributed between the strong- and weak-core groups in the same ratio as observed, the correlation discussed in the previous section would obviously be improved. However, we refrain from quoting the statistical results in view of the small number of actually observed galaxies.

5. The Projection Effects

The random inclination of galaxies to the line of sight makes several intrinsically flatter galaxies appear rounder, and smears out any correlation that may exist between the intrinsic axial ratio and other galaxian properties. The number of galaxies with an intrinsic axial ratio q that appear with the projected axial ratio between (b_1, b_2) is given by

$$N(q; b_1, b_2) = (1 - q^2)^{-1/2} \left[(b_2^2 - q^2)^{1/2} - (b_1^2 - q^2)^{1/2} \right]. \quad (1)$$

The distribution $\psi(q)$ of intrinsic axial ratio can be obtained by the best-fit method, comparing the observed distribution of apparent axial ratios with the expected one given by

$$N(b_1, b_2) = \int \psi(q) N(q; b_1, b_2)\, \mathrm{d}q \quad (2)$$

(see Sandage *et al.*, 1970).

Considering the small number of galaxies in the observed sample, and a large correction factor estimated for the selection effects, we will not attempt to model the distribution of intrinsic axial ratios. We only make a crude estimate of intrinsically round ($q = 0.95$), intermediate ($q = 0.8$) and flat ($q = 0.6$) galaxies assuming that q can take only these three discrete values. Also, we will bin the apparent axial ratios into apparently round, intermediate and flat bins as discussed in Section 3. Equation (1) shows that out of the galaxies with $q = 0.6$, 25% will appear with $n = 0$–1, 19 % with $n = 2$ and the rest with $n = 3$–4, out of the galaxies with $q = 0.8$, 52 % will appear with $n = 0$–1 and the rest with $n = 2$.

The distribution of intrinsic axial ratios obtained using these numbers is listed in Table III. It is apparent from the table that the distribution of the weak-core

TABLE III

The distributions of apparent and intrinsic axial ratios

n	Apparent axial ratios			q	Intrinsic axial ratios (normalized frequency)		Total	Fraction of strong-core galaxies
	$f_c<0.1$	$f_c \geqslant 0.1$	Total		$f_c<0.1$	$f_c \geqslant 0.1$		
0–1	77	16	93	0.95	51.5(0.46)	2.4(0.06)	53.9(0.35)	0.04
2	25	14	39	0.80	41.9(0.37)	19.0(0.46)	60.9(0.40)	0.31
3–5	11	11	22	0.60	19.6(0.17)	19.6(0.48)	39.2(0.25)	0.50
Total	113	41	154		113.0(1.00)	41.0(1.00)	154.0(1.00)	0.27

galaxies is peaked at intrinsically roundest galaxies whereas most of the strong-core galaxies are distributed between the intermediate and flat bins. Also, the fraction of strong-core galaxies increases steadily from a mere 4 % among the round galaxies to 50 % in the flat ones. It is also evident from the table that we expect 14 strong-core and 25 weak-core galaxies with intermediate or flat intrinsic axial ratios to appear rounder. While the observed number of weak-core galaxies is consistent with this restriction, the strong-core galaxies are deficient by a factor of three. Since it is difficult to conceive of a selection effect that discriminates only against the strong-core round galaxies, we are justified in correcting both the groups by the same factor. In order to avoid negative frequency in strong-core, intrinsically round galaxies, we need to have at least 79.1 galaxies in the apparently round bin, of which 65.4 would be in the weak-core and 13.6 in the strong-core groups.

6. Discussion

We have shown in this paper that there is a correlation between the apparent ellipticity of a radio elliptical galaxy and the fraction of radio flux retained within the core. Flatter galaxies are more likely to retain a substantial fraction of their radio power within the confines of their optical size. Considering the effects of the random inclination of the galaxies to the line of sight, it appears that the distribution of weak-core radio galaxies is peaked towards intrinsically round galaxies, while that of the strong-core galaxies peaks towards flatter ones.

The distribution of intrinsic axial ratios of the weak-core galaxies appears to be very much different from that of a local sample of normal ellipticals. The weak-core extended-source radio galaxies are peaked close to the intrinsic axial ratio $q = 1.0$, whereas the normal ellipticals are peaked at $q = 0.6$ (Sandage *et al.*, 1970).

On the other hand, within the uncertainties of the small-number statistics, it is possible that the strong-core radio ellipticals follow the same distribution as the normal ellipticals. We propose that the ellipticals that have their radio emission totally confined within the optical dimensions may be considered as $f_c = 1$ limit of the strong-core group. The 12*E* galaxies in the list of Jenkins (1982) which follow this criterion are distributed as 6, 3, and 3 in the round, intermediate and flat bins. This distribution leads us to 2.5, 4.1, and 5.4 galaxies in the similar bins corresponding to the intrinsic axial ratios. This distribution also agrees with the distribution of strong-core galaxies derived in the last section. In this context, it is also important to note that SO galaxies – which are flatter than ellipticals – do not normally show radio emission extending beyond their optical dimensions (Ekers and Ekers, 1973).

There are 12 extended radio sources and 12 compact radio ellipticals in Jenkins's (1982) sample. Among the 12 extended sources, 5 have $f_c \geqslant 0.1$. The corresponding ratios were 30/90 for the larger (but incomplete) sample used here, and 41/154 after correction for incompleteness in the rounder galaxies. Thus, between one-fourth to one-half of the extended radio sources have strong cores. Furthermore, the weaker radio galaxies are rarely extended (Jenkins, 1982). It would hence appear that the majority of radio ellipticals retain at least a significant fraction of their radio luminosity within the confines of the optical dimensions. Powerful double radio sources with weak cores are indeed a minority.

It has often been surmised that the radio emission occurs preferably in rounder systems (Heeschen, 1970; Ekers and Ekers, 1973; Jenkins, 1982). However, Dressel (1981) failed to find a similar relationship for a larger sample. The arguments presented in this paper show that the extended weak-core radio sources are indeed rounder. Considering the facts that the extended radio sources are generally stronger radio-emitters than the compact ones (Jenkins, 1982), and that weak-core galaxies form a major fraction of extended radio sources, it is easy to see how the relationship can persist in a sample of strong sources. However, as the radio detection threshold is improved, a large number of compact sources are added to the sample tending to obliterate such a correlation.

Heckman (1983) has recently shown that the radioloud ellipticals have larger masses, mass-to-light ratios, velocity dispersions and (perhaps) stellar metallicities than do radio-quiet ellipticals. In the light of the present work, it would appear that these properties are related directly to the fractional core-strength. We would thus identify a class of intrinsically rounder ellipticals with larger masses, mass-to-light ratios, velocity dispersions and stellar metallicities, which can form extended radio sources more efficiently. If this idea is proved, it would offer clues to relate the occurrence and mechanism of radio emission to the dynamical and chemical ecolution of the parent galaxy. A major uncertainty has been introduced in our arguments because of the incompleteness of the sample. Detailed high-resolution observations on the radio structure of a larger, complete sample of ellipticals would shed more light on this problem.

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