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A PREFERRED ORIENTATION FOR LARGE RADIO SOURCES RELATIVE TO THEIR ELLIPTICAL GALAXIES

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ABSTRACT

The relative orientations of 78 carefully selected radio sources and their parent elliptical galaxies have been determined. The radio structures are preferentially, but not exclusively, aligned toward the projected minor axes of the core (10–20 kpc) light distributions of the galaxies as seen on the red-sensitive print of the Palomar Sky Atlas. Furthermore, the trend toward this minor-axis alignment appears strongest among radio galaxies with linear extents >250 kpc. We suggest that alignment of the radio source collimator with the core minor axis favors the development of radio lobes at large distances from the galaxies; this is most easily understood if most of the galaxies studied are oblate rotators at their cores.

Subject headings: galaxies: general — radio sources: extended

I. INTRODUCTION

The relative alignments of powerful radio sources and their parent elliptical galaxies have often been discussed as a test for models of collimation processes and energy transfer in radio galaxies (Mackay 1971; Bridle and Brandie 1973; Gibson 1975; Schilizzi and McAdam 1975; Sullivan and Sinn 1975; Guthrie 1979). From the outset (Mackay 1971; Bridle and Brandie 1973) it was unclear whether radio galaxies should be treated as oblate or prolate rotators. Recently Illingworth (1977) showed that 12 of 13 giant (but not "radio") ellipticals rotate around their minor axes much more slowly than expected on conventional oblate models; Williams and Schwarzschild (1979) found departures from axial symmetry in two ellipticals; and Binney (1976, 1978) proposed that the forms of elliptical galaxies reflect initial anisotropies in the pregalactic condensations rather than centrifugal flattening.

The relation between light distributions and rotation for *radio emitting* ellipticals may be even more complex if their light is perturbed by strong line or nonthermal continuum emission, or (e.g., Saslaw and De Young 1972) by star formation along the radio source axis. Furthermore, the more distant features of some radio galaxies in rich clusters appear to have been realigned after leaving their parent object. Given these complications, prospects for constraining radio source models by optical-radio orientation studies now appear less attractive than they did in the early 1970s.

We report in this *Letter* what is therefore a surprisingly good correlation between the radio and optical orientations of a *carefully selected* sample of elliptical radio galaxies. Our results imply that orientational studies *interpreted with much greater circumspection than before* may still be useful in evaluating theories of radio galaxies.

II. OBSERVATIONS

In 1973 we compiled a list of over 1100 radio sources purportedly identified with elliptical galaxies, and searched the fields of these sources on the Palomar Sky Atlas prints for elliptical galaxies whose optical orientations might be measurable from these prints; 641 candidate fields were then studied at 2.7 and 8.1 GHz with the NRAO 91 m telescope and four-element interferometer as described by Bridle and Fomalont (1978). These observations provided maps of ~140 radio galaxies with (*a*) well-collimated radio structures, and (*b*) secure optical identifications according to the precepts of Bridle and Fomalont (1978). The optical orientations of these galaxies were measured from the Sky Atlas prints by techniques described fully elsewhere (Palimaka 1978; Palimaka, Bridle, and Fomalont, in preparation).

For simple radio structures, the radio position angles and their errors were obtained from the parameters of Gaussian models fitted to our observed interferometric visibilities. For complex radio structures which could not be represented well by small numbers of Gaussian components, the position angles were measured directly from the best available map, and their errors were assigned by subjective judgment of the uncertainties inherent in this process. Where possible, the radio posi-

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tion angles of noncollinear ("bent") structures were determined from the emission closest to the parent galaxy, to minimize any effects of realignment of the radio components by external factors. Sources bent by more than 45° from collinearity were discarded unless a "jet" or ridge of emission defined an "inner" position angle near the galaxy. No sources normally classified as "head-tails" were included.

The optical orientations were measured on the E (red-sensitive) and O (blue-sensitive) Sky Atlas prints. Measurements on the O prints proved more susceptible to error than those from the E prints, due to the generally smaller and fainter O print images. The small O print images are also more susceptible to distortion by tracking errors, which we find not to be negligible on all prints (from the evidence of measured ellipticities of stellar images near those of the galaxies). As the O print images also might not indicate the overall distribution of the stars in a radio elliptical (due to nonthermal emission or enhanced star formation along the path of the radio source), we adopt the E print position angles as our primary data. We exclude all measurements which we judge to have been influenced by instrumental or print distortions (whatever their cause), and all galaxies whose images on the Sky Atlas show significant asymmetries. We also defer discussion of galaxies with noticeable concentrations of dust or with multiple nuclei, and those classified by us as S0, to a later paper.

Each optical position angle was measured independently by several observers. Where both a diffuse "envelope" and a more compact (often burned-out) "core" were distinguishable, both position angles were recorded but the core position angles form our primary data. These "cores" are typically 10–20 kpc in diameter.

The standard deviation of all otherwise acceptable E print measurements is 7°; that of all acceptable radio position angles is 4°. Any galaxy for which the combined optical and radio position-angle errors are $>20°$ was rejected. Only 70 "clean" elliptical galaxies with well-collimated radio sources met these and all preceding criteria. Because of this severe attrition from our original sample, we supplemented our data with radio maps published since 1973, adding a further eight well-identified radio galaxies which meet all of our criteria.

III. THE OVERALL DISTRIBUTION OF RELATIVE ORIENTATIONS

Table 1 lists our data for the 78 radio galaxies which survived our selection process. The largest linear size (LLS) of each radio source (estimated from the 20% peak brightness contours of its extended structure) and the 2.7 GHz monochromatic luminosity ($P_{2.7}$) were computed for $H_0 = 50$ km s^{-1} Mpc^{-1} and $q_0 = 0.5$; if the redshift of a galaxy was unknown it was estimated from the apparent magnitude, as in Bridle and Fomalont (1978).

Figure 1 shows the overall distribution of the 78 position-angle differences (optical major axis minus radio collimation axis). The shaded distribution is derived from 40 "well-ordered" galaxies whose O print images do not show blue subsystems which are significantly misaligned with the measured red images, and whose "core" and "envelope" position angles agree on the E print.

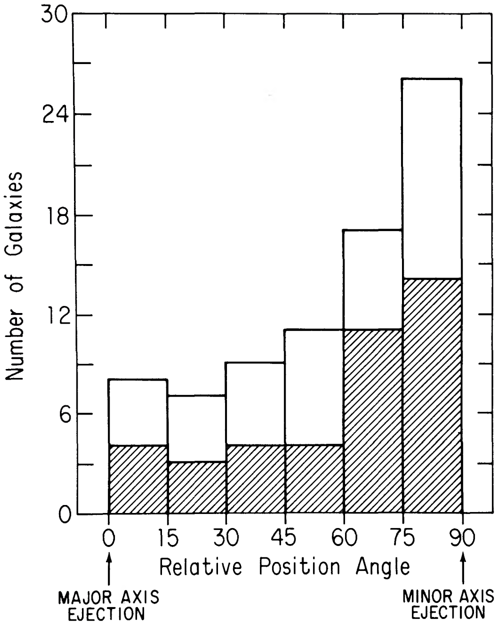

FIG. 1.—The distribution of relative position angle |radio-optical| for the sample of 78 radio galaxies. The shading indicates the distribution of the well-ordered sample.

Both distributions in Figure 1 are nonrandom at the 99% confidence level, based on χ^2 tests against random distributions. We conclude that the radio collimation axes are preferentially, but not exclusively, aligned within ~30° of the projected minor axes of the inner ~15 kpc of the galaxies on the E prints. Somewhat surprisingly, this holds equally for the 38 galaxies which show evidence for internal misalignments and for the 40 "well-ordered" systems.

IV. ORIENTATION STATISTICS AND LINEAR SIZES OF SOURCES

The fact that individual "giant" (>1 Mpc, $H_0 = 50$ km s^{-1} Mpc^{-1}) radio sources lie very near the projected minor axes of their parent elliptical galaxies has frequently been noted; e.g., 3C 236 (Fomalont and Miley 1975), NGC 315 (Bridle *et al* 1976), and NGC 6251 (Waggett, Warner, and Baldwin 1977). Table 2A shows the distributions of the optical-radio position-angle differences for three groups, each of 26 galaxies, separated according to their largest linear sizes. Below each group of 26 is the χ^2 probability that it samples a random distribution. Also given are data for the 13 largest and the 13 smallest; these have lower statistical significance but assist in checking trends. The sources <250 kpc in size are randomly oriented relative to their galaxies, whereas both groups of sources >250 kpc in size show a strong preference for minor-axis ejection;

TABLE 1

Optical and Radio Position-Angle Data

Field Name	Optical P.A. (E print)	Radio P.A.	Relative P.A.	LLS (kpc)	log $P_{2.7}$ (W Hz^{-1})
0018−194	17°	111°	86°	1100	25.86
0034+254*	163	83	80	110	23.21
0043+201	69	172	77	330	25.20
0055+300*	42	129	87	1400	24.23
0055+265*	152	109	43	230	25.02
0104+321*	135	147	12	170	24.64
0106+130	131	20	69	430	26.05
0108−142	53	100	47	120	25.08
0109+492	101	9	88	950	25.39
0124+189*	76	13	63	71	24.89
0153+053	73	84	11	45	23.90
0220+427*	33	50	17	210	25.02
0300+162*	134	110	24	95	24.93
0305+039*	144	56	88	48	25.25
0325+023	153	63	90	200	25.07
0326+396	128	82	46	220	24.24
0331+391	101	180	79	14	24.10
0356+102	72	25	47	230	25.34
0632+263*	16	115	81	110	24.57
0652+426*	124	50	74	69	24.89
0712+534*	120	114	6	39	24.84
0714+286	73	133	60	110	25.24
0734+806	49	150	79	540	26.10
0745+521*	37	92	55	200	24.72
0802+243	13	118	75	310	25.69
0818+472*	103	4	81	51	25.88
0819+061	98	38	60	570	25.44
0836+299*	59	27	32	78	24.91
0844+540	45	113	68	58	25.00
0844+319	123	170	47	540	25.15
0915+320	46	31	15	470	24.57
0936+361	118	164	46	980	26.23
0938+399	45	15	30	230	25.80
1000+201*	112	8	76	150	25.91
1003+351*	45	123	78	5800	26.19
1005+007	38	71	33	26	24.90
1033+003	131	8	57	300	24.81
1102+304	147	70	77	260	24.74
1113+295*	138	71	67	110	25.13
1122+390*	35	118	83	6	22.28
1127+012	100	12	88	140	25.51
1137+123*	139	12	53	140	25.08
1154−038*	45	109	64	400	24.43
1216+061*	150	83	67	100	24.39
1222+131*	116	167	51	12	23.17
1249+035*	27	146	61	150	25.15
1250−102	65	162	83	35	23.72
1251+278	30	169	41	97	25.79
1254+277*	51	11	40	23	23.00
1313+072*	40	71	31	200	25.21
1318−434*	100	24	76	550	24.87
1322+366*	75	7	68	23	23.92
1333−337*	47	125	78	780	24.65
1358−113*	41	125	84	260	24.56
1407+177*	6	73	67	250	24.13
1411+094*	84	178	86	260	26.11
1414+110*	146	85	61	200	24.77
1422+268	118	96	22	120	24.49
1433+553	110	143	33	230	25.36
1449−129	135	89	46	720	25.81
1514+004*	53	132	79	390	25.27
1514+072	21	16	5	43	25.05
1547+309	136	120	16	46	25.54
1553+245	19	129	70	23	24.11
1602+178*	117	171	54	74	24.52
1640+826*	27°	124°	83°	2800	24.91
1710+156	5	169	16	19	25.14
1759+211	60	50	10	200	25.21
1833+326*	73	48	25	420	25.73
1833+653	97	19	78	38	26.15
1834+197*	22	142	60	210	24.12
1940+504*	34	28	6	37	24.48
2058−135	29	101	72	340	24.49
2103+124	59	138	79	260	25.49
2116+262	65	22	43	23	23.15
2117+605*	106	35	71	140	25.80
2229+391*	7	9	2	170	24.30
2354+471	52	64	12	180	24.64

* Members of the well-ordered sample.

the distributions for the 26 largest and 26 smallest are different at the 99% level of confidence. It therefore appears that *largest linear size is an active filter for the minor-axis concentration*, and that among "clean" radio galaxies (as defined in § II) the trend toward minor-axis alignment is a property of all well-collimated sources larger than 250 kpc, and so is not restricted to the giant systems.

We cannot rule out the possibility that radio luminosity is also an active filter for the minor-axis preference (see Table 2B), as $P_{2.7}$ and LLS are falsely correlated in our sample (its range in redshift is greater than its range in flux density); but the distributions in Table 2B imply that any trend with luminosity is weaker than that with linear size.

V. COMPARISON WITH EARLIER RESULTS

The results shown in Table 2 partially explain why the "minor-axis" trend was not found by Mackay

TABLE 2

Distributions of Relative Position Angle within Selected Ranges of Linear Size and Monochromatic Luminosity

A.

Relative P.A.	LLS (kpc)				
	≤40	≤102	102–250	≥250	≥450
0°–30°	3	7	6	2	1
30°–60°	4	7	9	4	3
60°–90°	6	12	11	20	9
$P(>\chi^2)$ ...	...	38%	48%	0.001%	...

B.

Relative P.A.	$P_{2.7}$(10^{25} W Hz^{-1})				
	≤0.17	≤0.44	0.44–1.62	≥1.62	≥6.00
0°–30°	1	7	6	2	0
30°–60°	3	5	8	7	4
60°–90°	9	14	12	17	9
$P(>\chi^2)$ ...	...	7.6%	34%	0.12%	...

(1971), Bridle and Brandie (1973), Gibson (1975), or Sullivan and Sinn (1975). Their samples contained few radio sources with linear sizes >250 kpc, and so were drawn from a population with only a weak minor-axis preference. In addition, we rejected many galaxies studied by these authors on grounds of optical asymmetries, jets, or faintness. The samples used by Schilizzi and McAdam (1975) and Guthrie (1979) contain a higher proportion of large sources, and the minor-axis trend did indeed begin to appear in these authors' results.

VI. DISCUSSION

Recent high-resolution studies of radio galaxies (Northover 1973; Burch 1977; van Breugel and Miley 1977; Waggett, Warner, and Baldwin 1977; Bridle *et al.* 1979) show that bright collimated jets of emission connect the active nuclei of some radio galaxies to their distant radio lobes. These observations favor source models in which relativistic particles and magnetic fields are supplied to the lobes by relativistic beams (Blandford and Rees 1974; Benford 1978) or plasmon streams (Christiansen, Pacholczyk, and Scott 1977) that suffer radiative losses at radio frequencies. Our results have a consistent (if not unique) interpretation in terms of such models.

If the proposed relativistic beams or plasmon streams are collimated by flattened mass distributions in galactic nuclei (as in the model of Blandford and Rees 1974), our results imply that the shortest dimensions of these collimating masses are preferentially within ~30° of the minor axes of the stellar distributions in the inner ~15 kpc of their galaxies. This would be dynamically plausible if most *radio* galaxy cores rotate as oblate or nearly oblate systems so that the minor axis of their light is near the axis of their net angular momentum.

The relation between size and orientation could be explained on these models if a misalignment of the source collimator with the surrounding mass distribution leads to precession of the collimator around the core minor axis. The supply of particles and fields to the radio lobes would then continually change direction relative to the galaxy; this could inhibit the formation of very distant radio lobes by continually changing the location of the "working surface" at which particle deposition occurs and of the channel through a circumgalactic medium along which energy is transferred to the lobes. Such a mechanism should lead to correlations among source morphology, orientation, and size, which we will test elsewhere.

The assumptions needed to explain our results on the "gravitational slingshot" model of energy transfer (Saslaw, Valtonen, and Aarseth 1974) would be less conventional. This model requires the radio axis to lie near the orbital plane of an original multibody system in the galactic nucleus, unless the ejected spinars are gravitationally scattered as they leave the galaxy. Our results would imply that orbits of such spinars before ejection were preferentially inclined between 60° and 90° to the major axes of the stellar distributions of the cores. This would be implausible *unless the cores of radio galaxies are generally prolate rotators*. This model might explain the relation between orientation and linear size of the radio sources by invoking loss of bulk kinetic energy of the spinars in scattering events; but to account for the symmetry of most radio sources around their galaxies would require additional ad hoc assumptions about the symmetry of scattering of spinars leaving the galaxy in opposite directions.

To summarize, the presence in some radio galaxies of collimated radio jets, our sample's overall preference for minor-axis ejection, and the size-orientation relation are all consistent with energy supply to the radio lobes by relativistic beams or plasmon streams which are preferentially oriented toward the rotation axes of oblate cores of elliptical galaxies. We therefore exhort optical astronomers to determine spectra and velocity fields for the inner 10–20 kpc of galaxies in the 0°–15° and 75°–90° bins in Table 1. It would be particularly valuable to observe the rotation of the cores with radio emission near their *major* axes (0°–15° bin), and to distinguish whether these alignments are due to prolate stellar systems or to enhancement of the total light along the path of energy supply to the radio lobes, e.g., by nonthermal emission, by strong emission lines from shocked gas, or by stimulated star formation.

Since this *Letter* was completed, we learned of new observations of the rotations of five radio galaxies by Simkin (private communication). She finds their rotation axes to be directed near, but not exactly toward, the brighter features of their radio lobes. Her result is consistent with ours if the inner ~15 kpc regions of most large radio galaxies are indeed oblate rotators.

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REFERENCES

Benford, G. 1978, *M.N.R.A.S.*, **183**, 29.
Binney, J. 1976, *M.N.R.A.S.*, **177**, 19.
———. 1978, *M.N.R.A.S.*, **183**, 501.
Blandford, R. D., and Rees, M. J. 1974, *M.N.R.A.S.*, **169**, 395.
Bridle, A. H., and Brandie, G. W. 1973, *Ap. Letters*, **15**, 21.
Bridle, A. H., and Fomalont, E. B. 1978, *A.J.*, **83**, 704.
Bridle, A. H., Davis, M. M., Fomalont, E. B., Willis, A. G., and Strom, R. G. 1979, *Ap. J.* (*Letters*), **228**, L9.
Bridle, A. H., Davis, M. M., Meloy, D. A., Fomalont, E. B., Strom, R. G. and Willis, A. G. 1976, *Nature*, **262**, 179.
Burch, S. F. 1977, *M.N.R.A.S.*, **181**, 599.
Christiansen, W. A., Pacholczyk, A. G., and Scott, J. S. 1977, *Nature*, **266**, 593.
Fomalont, E. B., and Miley, G. K. 1975, *Nature*, **257**, 99.
Gibson, D. M. 1975, *Astr. Ap.*, **39**, 377.
Guthrie, B. N. G. 1979, *M.N.R.A.S.*, in press.

Illingworth, G. 1977, *Ap. J.* (*Letters*), **218**, L43.
Mackay, C. D. 1971, *M.N.R.A.S.*, **151**, 421.
Northover, K. J. E. 1973, *M.N.R.A.S.*, **165**, 369.
Palimaka, J. J. 1978, M. Sc. thesis, Queen's University at Kingston.
Saslaw, W. C., and De Young, D. S. 1972, *Ap. Letters*, **11**, 87.
Saslaw, W. C., Valtonen, M. J., and Aarseth, S. J. 1974, *Ap. J.*, **190**, 253.
Schilizzi, R. T., and McAdam, W. B. 1975, *Mem. R.A.S.*, **79**, 1.
Sullivan, W. T. and Sinn, L. A. 1975, *Ap. Letters*, **16**, 173.
van Breugel, W. J. M., and Miley, G. K. 1977, *Nature*, **265**, 315.
Waggett, P. C., Warner, P. J., and Baldwin, J. E. 1977, *M.N.R.A.S.*, **181**, 465.
Williams, T. B., and Schwarzschild, M. 1979, *Ap. J.*, **227**, 56.

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