THE KINEMATICS OF STARS AND GAS IN RADIO GALAXIES

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ABSTRACT

We present new data on the stellar kinematics of twelve elliptical galaxies associated with powerful ($\log P_{178\text{ MHz}} \geq 24.0 \text{ W Hz}^{-1}$) double radio sources. We combine these data with similar published data on nine other such galaxies. This sample of radio galaxies is then compared with a large sample of normal elliptical galaxies. We find that the stellar kinematics of radio galaxies do not differ strongly in a systematic way from those of normal elliptical galaxies of comparable optical luminosity. In particular, we do not confirm earlier reports that radio galaxies are generically rapidly rotating, dynamically peculiar systems, nor do we find evidence for a general alignment between the *stellar* rotation axis and the radio ejection axis (even for large or powerful radio sources).

We also present and summarize data on the kinematics of spatially extended emission-line gas in radio galaxies. Large velocity gradients along galaxy minor axes are sometimes observed, although well-aligned gas rotation and galaxy minor axes are found in other objects. The data do, however, indicate that good alignment exists between the *gas* rotation and radio ejection axes in large ($\geq 100 \text{ kpc}$) sources.

While the stellar kinematics of radio galaxies as a class are not peculiar, several interesting objects bear further study. Of these, 3C 305 exhibits the most unusual stellar kinematics (rapid rotation, low velocity dispersion, high optical luminosity). Its disturbed optical morphology and isolated location mark it as a good candidate for a recent merger. We note that several other radio galaxies in our sample or in the literature are similar to 3C 305 in exhibiting rapid rotation, low velocity dispersion, and a disturbed optical morphology.

We summarize the implications of our principal conclusions. First, it appears that the mechanism by which elliptical galaxies create powerful radio sources may not generally rely on detectable peculiarities in the large-scale stellar dynamics of the parent galaxy. Second, the data favor an extrinsic origin for the emission-line gas in radio galaxies. Galaxy mergers may be implicated in some cases. Third, the gas dynamics are apparently more important than the stellar dynamics in influencing the formation and/or propagation of radio jets. Fourth, the good alignment between the radio ejection and gas (or dust) rotation axes—even when these are skewed relative to the projected galaxy major/minor axes—may imply that many radio galaxies are triaxial in shape.

Subject headings: galaxies: internal motions — galaxies: structure — radio sources: galaxies

1. INTRODUCTION

In recent years there has been a growing recognition that nuclear activity is related to the properties of the surrounding, extranuclear environment (see review by Balick and Heckman 1982, and references therein). A particularly fascinating result has been the claim that the large-scale stellar dynamics of radio galaxies are peculiar compared with the dynamics of radio-quiet elliptical galaxies.

Simkin (1979) measured the stellar dynamics of the parent galaxies of three powerful radio sources and reported that (1) these galaxies rotated far more rapidly than normal ellipticals (e.g., Illingworth 1977) and (2) the stellar rotation and radio

ejection axes were well aligned. These were potentially important results, since they might explain why only certain elliptical galaxies produce radio sources, and why the radio ejection axis can remain constant in direction over very long periods of time (e.g., Miley 1980). However, further work by Jenkins and Scheuer (1980), Jenkins (1981), and Ekers and Simkin (1983) indicated that the situation was more complex: not all radio galaxies exhibited rapid stellar rotation, and fewer still showed any alignment between the radio and stellar rotation axes. Even so, reviewing the available data, Jenkins (1984) concluded that radio galaxies on average were indeed dynamically peculiar, showing both rapid rotation and misaligned stellar rotation and minor axes. Ekers and Simkin (1983) also reviewed the data and concluded that only galaxies associated with powerful radio sources showed a good alignment of radio and stellar rotation axes.

To help clarify this seemingly complex situation, we therefore embarked on a program to obtain data on the stellar dynamics of a significant number of radio galaxies. We concentrated on powerful radio sources and on strongly flattened radio galaxies with known rapidly rotating emission-line disks. These new data suggest that the stellar dynamics of radio galaxies are not peculiar in general, and that there is no strong, general relationship between the radio ejection and stellar rotation axes, even in powerful or large radio sources.

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TABLE 1
GALAXY OBSERVATIONS

Object (1)	P.A. (degrees) (2)	Slit (arcsec) (3)	Dector (4)	Integration (s) (5)
3C 33	19	2.5	Cryocam	1800
	110	2.5	Cryocam	3500
	114	2.5	Cryocam	2000
NGC 1275 (3C 84)	80	2.5	HGVS(V)	3100
	110	2.5	Cryocam	2000 ^a
	170	2.5	HGVS(V)	3100
3C 218 (Hydra A, A0915-11)	120	3.2	Cryocam	2000
	144	3.2	Cryocam	2000 ^a
NGC 3801 ^b	26	2.5	HGVS(V)	1550
	124	2.5	HGVS(V)	1550
M84 (NGC 4374, 3C 272.1)	80	2.2	HGVS(B)	1550
	168	2.5	HGVS(V)	2600 ^a
3C 293 (UGC 8782)	65	2.5	HGVS(V)	3100
3C 305 (IC 1065)	90	2.2	HGVS(B)	3100
	165	2.5	HGVS(V)	3100
3C 310	63	2.2	HGVS(B)	4700
	153	2.2	HGVS(B)	4700
NGC 6251	27	2.2	HGVS(B)	2350
	124	2.2	HGVS(B)	2350
3C 388	44	2.2	HGVS(B)	5500
	156	2.2	HGVS(B)	4700

NOTE.—Position angle (P.A.) of the slit is given in degrees east of north. The slit width is in arcseconds. (V) or (B) following the HGVS signifies the 5200 Å region or the 4200 Å spectral region, respectively (see Table 2).

^a Cloudy during some or all of the integration.

^b Data from Heckman *et al.* 1985a.

We have also obtained data on the kinematics of the emission-line gas in several radio galaxies, in order to investigate further the reported tendency for the radio ejection and gaseous rotation axes to be aligned (Simkin 1979; Kotanyi and Ekers 1979).

II. OBSERVATIONS AND DATA REDUCTION

The data in the present paper were all acquired on the 4 m Mayall Telescope of the Kitt Peak National Observatory (KPNO) during the period from 1981 April to 1982 October using two different long-slit spectroscopic systems: the High-

Gain Video Spectrometer (HGVS) and the Cryogenic Camera (Cryocam). These observations are summarized in Table 1 for the radio galaxies observed. The salient properties of the HGVS and Cryocam as configured for these observations are listed in Table 2.

The procedures followed in the acquisition, calibration, and reduction of the data were all standard and have been described in detail elsewhere (e.g., Kormendy and Illingworth 1982).

Following the flat-fielding, geometrical rectification, and sky subtraction procedures, the data were analyzed using a Fourier

TABLE 2
INSTRUMENTAL PARAMETERS

Parameter (1)	HGVS (2)	Cryogenic Camera (3)
Format	512 × 128	800 × 304 ^a
Slit length	2.9	4.2
Slit width	2".2-3".2	2".5-3".2
Spatial scale (arcsec pixel ⁻¹)	1".4	0".82
Spatial resolution (seeing dependent)	≥(2".0-2".5)	≥2".5
Wavelength range	3850-4550 Å ^b	4400-5900 Å ^c
Instrumental resolution (FWHM; Å)	4.7 ^{d,e}	11 ^e
Instrumental dispersion σ_i (km s ⁻¹) ^f	140 ^{d,e}	270 ^e

^a 512 × 300 processed to give V and σ .

^b Rest frame typical. The wavelength range was 4800-5500 Å for the NGC 1275 data at P.A. 80° and 170°; NGC 3801 at P.A. 26° and 124°; M84 at P.A. 168°; 3C 293; and 3C 305 at P.A. 165°.

^c Rest frame typical; shifted by 200-300 Å depending upon redshift.

^d For the data in the region 4800-5500 Å, FWHM = 4.5 Å and σ_i = 110 km s⁻¹.

^e Typical values of FWHM and σ ; dependent upon slit width used.

^f For a Gaussian response function where σ_i = FWHM/2.35.

quotient technique (e.g., Sargent *et al.* 1977). This involves the division (on a row-by-row basis) of the Fourier transform of the galaxy spectrum by the Fourier transform of the spectrum of a "template" star whose spectral type is a good match to the galaxy spectrum in the wavelength domain of interest. In our analysis, at least two template stars were used for each position angle covered. This served as one check on the reliability of the analysis procedure.

The Fourier quotient program generates velocities (V), velocity dispersions (σ), and associated error estimates for each row of galaxy data. Extensive testing of this procedure affirms its accuracy, but indicates that the calculated errors generally overestimate the true uncertainty by a small factor ~ 1 – 1.5 (e.g., Schechter and Gunn 1979; Efsthathiou, Ellis, and Carter 1980; Kormendy and Illingworth 1982; Davies *et al.* 1983, hereafter DEFIS; Davies and Illingworth 1983). The error estimates quoted in § III are those calculated by the program.

The low signal-to-noise (S/N) data from these distant, faint galaxies and the large instrumental dispersion (particularly for the Cryocam) resulted in significantly larger uncertainties for V and σ , compared with previous studies of normal elliptical galaxies. The data are, however, of adequate quality to establish dispersions, rotational velocities, and dynamical axis position angles (ϕ_{dyn}), except for the slowly rotating objects ($V \lesssim$

40 – 70 km s^{-1}), for which the stochastic and systematic errors can lead to very large uncertainties in ϕ_{dyn} .

III. RESULTS

a) General

The relevant optical and radio properties of the galaxies studied in the present paper are listed in Table 3, the contents of which are described in the accompanying notes. The results extracted from the Fourier quotient program are summarized in Table 4, along with other optical and radio data. In Figure 1 we display the variation of velocity (V) and velocity dispersion (σ) along the position angles covered for the various radio galaxies (also tabulated in Table 7 in the Appendix). Finally, in Table 5 we summarize the rotational properties of the program galaxies parameterized in the standard way to account for the galaxy ellipticity (ϵ) and the mean stellar velocity dispersion ($\bar{\sigma}$) within $r_e/2$, where r_e is the effective radius. The parameterization procedure is described in the notes to Table 5, and in more detail in DEFIS and Illingworth (1981). Note that in Tables 3 and 5 we have incorporated results from the literature on nine other galaxies associated with powerful ($\log P_{178 \text{ MHz}} \gtrsim 24.0 \text{ W Hz}^{-1}$ for $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$) radio sources: NGC 1316 = Fornax A (Jenkins and Scheuer 1980;

TABLE 3
RADIO GALAXY PARAMETERS

Object (1)	z (2)	B_T (3)	M_B^{UH} (4)	r_e (arcsec) (5)	$\log P_{178}$ (W Hz $^{-1}$) (6)	Scale ^a (kpc arcsec $^{-1}$) (7)
3C 33	0.0595	16.3 ^b	−21.8	4	27.0	1.68
NGC 1275 (3C 84)	0.0172	12.35	−23.3 ^c	29	25.8	0.50
3C 218 (A0915–11)	0.0546	14.7	−23.3	9	27.4	1.54
NGC 3801	0.0115	13.0	−21.3	16	24.4	0.33
M84 (NGC 4374)	0.0031	10.31	−21.0	53 ^d	24.0	0.10
3C 293 (UGC 8782)	0.0452	15.2 ^b	−22.1	6	26.2	1.28
3C 305 (IC 1065)	0.0410	14.3	−22.9 ^c	10	26.1	1.17
3C 310	0.0540	16.4 ^b	−21.4	4	26.8	1.53
NGC 6166 (3C 338)	0.0303	13.05	−23.5	18	26.2	0.87
NGC 6251	0.0245	14.0 ^c	−21.9	10	25.4	0.67
3C 388	0.0908	16.6 ^b	−22.7	4	27.0	2.52
NGC 7720 (3C 465)	0.0293	13.65	−22.8	13	26.2	0.84
NGC 315	0.0171	12.2	−23.1	32	24.8	0.49
NGC 1316 (Fornax A)	0.0063	9.67	−23.0	95 ^d	25.8	0.18
IC 2082	0.0395	13.9	−23.3	19 ^d	25.7	1.13
M87 (NGC 4486)	0.0034	9.56	−22.0	95 ^d	26.1	0.10
NGC 4839	0.0232	12.7	−23.2	42	24.0	0.67
IC 4296	0.0121	11.58	−22.9	48 ^d	25.6	0.35
NGC 5128	0.0016 ^f	(6.7) ^f	(−21.0) ^f	300 ^f	24.6	0.02
A2029 (IC 1101)	0.0777	15.0	−23.4	15 ^d	26.0	2.10
NGC 7626	0.0127	12.25	−22.3	34	24.7	0.37

NOTES.—Redshifts z (col. [2]) are taken from Burbidge and Crowne 1979 or DEFIS, Table 3. Integrated blue magnitudes, B_T (col. [3]), are taken from the RC2 (de Vaucouleurs, de Vaucouleurs, and Corwin 1976), except as noted below. Absolute blue magnitudes (col. [4]) are derived from B_T and z as described in the text, assuming a uniform Hubble flow with $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$ for consistency with DEFIS. The effective radius r_e (col. [5]) is determined from the relation between r_e and M_B^{UH} given by DEFIS (eq. [3] and Fig. 8), except as noted. The value of $\log P_{178}$ given in col. (6) is the total radio power in W Hz^{-1} at 178 MHz.

^a Based on $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

^b B -magnitudes from Sandage 1972. These are B_{25} and probably underestimate B_T .

^c These luminosities probably overestimate the luminosity of the evolved stellar population. NGC 1275 and 3C 305 show strong Balmer absorption lines in the ultraviolet, indicative of recent star formation. NGC 1275 also has a nonthermal optical nuclear source.

^d Values of r_e are taken from DEFIS (Table 3) or the RC2.

^e B -magnitudes from the UGC (Nilson 1973). Again B_T will probably be underestimated.

^f For NGC 5128 the distance is taken to be 3 Mpc (Davies *et al.* 1984); B_T , M_B^{UH} , and r_e for the old stellar population are taken from Dufour 1979. P_{178} is from Cooper, Price, and Cole 1965.

TABLE 4
ROTATION AND DISPERSION RESULTS

Object (1)	P.A. (degrees) (2)	V_m (km s ⁻¹) (3)	Sense (4)	$\bar{\sigma}$ (km s ⁻¹) (5)	σ_{fit} (km s ⁻¹) (6)	P.A. Major Axis (degrees) (7)	P.A. Radio (degrees) (8)
3C 33	20	47 ± 22	W	227 ± 14 ^a	230	155 ^b	20
	112	35 ± 18	W				
NGC 1275	80	23 ± 12 ^c	(W)	246 ± 10 ^d	309	110	160
	110	18 ± 10	(E)				
	170	48 ± 12 ^c	W				
3C 218	132 ^e	13 ± 18	...	322 ± 20	309	130 ^f	3
NGC 3801	26	14 ± 8	(W)	168 ± 6	208	118 ^b	123
	124	130 ± 7	E				
M 84	80	11 ± 11	(E)	278 ± 4	196	134 ^f	176
	130 ^g	7 ± 24 ^g	...				
	168	2 ± 6	...				
3C 293	65	154 ± 15	E	185 ± 17 ^c	244	62 ^b	93/123 ^h
3C 305	90	143 ± 17	W	178 ± 9	285	77 ^b	43
	165	55 ± 23	W				
3C 310	63	19 ± 18 ⁱ	(W)	191 ± 14 ^a	212	79 ^b	159
	153	17 ± 25	(E)				
NGC 6166	35	11 ± 11	...	290 ± 10 ^j	321	35	90
NGC 6251	27	40 ± 16	E	293 ± 10	234	19 ^b	117
	124	29 ± 16	W				
3C 388	44	89 ± 28	W	365 ± 23 ^a	274	(20 ^b)	65
	156	58 ± 40	(E)	346 ± 8 ^j	280	25	125
NGC 7720	25	9 ± 7	...				

NOTES.—Col. (2) gives the position angle (P.A.) in degrees (defined east from north) for the spectrograph slit. The maximum rotational velocity is given in col. (3). This is a weighted average as described in the text of the V data of Table 7 for $0.5r_e \leq r \leq (1-1.5)r_e$. The sense of the rotation, defined as the receding (redshifted) side, is given in col. (4). Values are given in parentheses unless the V_m values are significant at the 2σ or greater level. No rotational sense is given for V_m values of $\leq 1\sigma$. The mean velocity dispersion (see text) within $r_e/2$ (except as noted below) from all position angles is given in col. (5). Col. (6) tabulates the velocity dispersion expected from the $L \propto \sigma^{-n}$ relation from the DEFIS data as discussed in the text. The P.A. of the optical major axis is given in col. (7), from the UGC unless noted. Uncertain values are enclosed in parentheses. The P.A. of the radio source axis is given in col. (8), taken from unpublished VLA maps for 3C 33, 3C 218, 3C 310; from Pedlar, Booler, and Davies 1983 for NGC 1275; from Jenkins 1982 for NGC 3801; from Bridle, Fomalont, and Cornwell 1981 for 3C 293; from Heckman *et al.* 1982 for 3C 305; from Burns, Schwendeman, and White 1983 for 3C 338 = NGC 6166; from Perley, Bridle, and Willis 1984 for NGC 6251; from Burns and Christiansen 1980 for 3C 388; and from Eilek *et al.* (1984) for 3C 465 = NGC 7720.

^a Value of $\bar{\sigma}$ determined for $0 \leq r \leq \frac{1}{2}r_e \rightarrow r_e$, since $r_e \leq 5''$ in these galaxies. Any bias should be small, since no strong gradients were apparent.

^b Values derived from KPNO video camera and CCD frames. For 3C 33, the P.A. changes from $80^\circ \pm 10^\circ$ in the inner $4''$ to $155^\circ \pm 10^\circ$ in the outer region (see text).

^c There is very large scatter in these data. Values of V_m approaching 80 km s^{-1} could not be excluded for NGC 1275.

^d Average of dispersions from the HGVs and the Cryogenic Camera. The latter data are 20% larger in the mean (due to lower resolution?).

^e Mean of data in P.A. 120° and 144° . No significant difference in $V(r)$ could be seen.

^f Values from Birkinshaw and Davies 1985.

^g Data from Davies 1981; $\bar{\sigma} = 291 \pm 9$ from his data.

^h Values for radio position angles are for the very bright inner radio source (93°) and the faint outer source (123°) as given by Bridle, Fomalont, and Cornwell 1981.

ⁱ V_m average for $r \geq 3''$. Averaging data for $r \geq 5'' (=r_e)$ results in $V_m = 78 \pm 32$, but this much larger V_m mainly arises from one value at $r \sim 10''$ or $\sim 2r_e$. Giving such high weight to this value is unwise.

^j Mean of data from Tonry 1984 and Illingworth 1986.

Bosma, Smith, and Wellington 1984) and (from DEFIS) NGC 315, NGC 4839, NGC 7626, IC 2082, IC 4296, M87, and the radio-loud cD galaxy IC 1101, in Abell 2029.

i) Stellar Velocity Dispersion

We have compared the dynamical properties of these powerful radio galaxies to those of normal ellipticals (from DEFIS) in several ways. First in Figure 2 we have plotted the mean stellar velocity dispersion $\bar{\sigma}$ (see notes to Table 4) against the integrated absolute blue magnitude of the galaxy (M_B^{UH}), using distances derived from a uniform Hubble flow model with $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$. In this figure the radio and normal galaxies do not show any significant differences in the mean. However, we can not rule out small (0.1 dex) average differ-

ences in $\bar{\sigma}$ between the radio-loud and -quiet ellipticals, such as those inferred by Heckman (1983) from a much larger sample of galaxies. Several of the radio galaxies in our sample are individually peculiar, and will be discussed in § IIIb below. The tendency seen in Figure 2 for radio galaxies to be optically luminous is well known (e.g., Auriemma *et al.* 1977).

ii) Stellar Rotational Velocity

Another comparison of the radio and normal elliptical galaxies is made in Figure 3. Here the rotational velocity normalized by the mean velocity dispersion, $V_m/\bar{\sigma}$, is plotted as a function of galaxy ellipticity ϵ and compared with models of oblate, rotationally supported ellipticals. It is clear from this figure that there are no significant dynamical differences in the

FIG. 1.—Rotational velocities V referenced to the systemic velocity and velocity dispersions σ plotted against radius in arcseconds along the position angle indicated. All the data are folded about the nucleus, with opposite sides being represented by filled circles or filled squares. Scales in kpc arcsec^{-1} based on $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$ are given in Table 3.

FIG. 1.—Continued

FIG. 1.—Continued

TABLE 5
ROTATIONAL PROPERTIES

Object (1)	M_B^{UH} (2)	ϵ^a (3)	V_m (km s ⁻¹) (4)	$\bar{\sigma}^b$ km s ⁻¹ (5)	$(V_m/\bar{\sigma})$ (6)	$(V/\bar{\sigma})^*$ (7)
3C 33	-21.8	0.11	47 ± 22 ^c	227 ± 20	0.21 ± 0.10	0.59 ± 0.28
NGC 1275	(-23.3)	0.29	48 ± 12 ^c	246 ± 18	0.20 ± 0.05	0.31 ± 0.08
3C 218	-23.3	0.11	13 ± 18	322 ± 28	0.04 ± 0.06 ^d	0.12 ± 0.18 ^d
NGC 3801	-21.3	0.45	130 ± 7 ^e	168 ± 12	0.77 ± 0.07	0.85 ± 0.08
M84	-21.0	0.10	11 ± 11 ^f	280 ± 17 ^g	0.04 ± 0.04 ^f	0.12 ± 0.12 ^d
3C 293	-22.1	0.49	154 ± 15	185 ± 20	0.83 ± 0.12	0.85 ± 0.12
3C 305	(-22.9)	0.36	143 ± 17 ^h	178 ± 14	0.80 ± 0.11	1.07 ± 0.15
3C 310	-21.4	0.16	19 ± 18 ⁱ	191 ± 18	0.10 ± 0.10 ^d	0.23 ± 0.23 ^d
NGC 6166	-23.5	0.22	11 ± 11	290 ± 20	0.04 ± 0.04 ^d	0.08 ± 0.08 ^d
NGC 6251	-21.9	0.13	40 ± 16 ^h	293 ± 20	0.14 ± 0.06	0.36 ± 0.16
3C 388	-22.7	(0.15)	89 ± 28 ^h	365 ± 32	0.24 ± 0.08	0.57 ± 0.19
NGC 7720	-22.8	0.29	9 ± 7	346 ± 22	0.03 ± 0.02 ^d	0.05 ± 0.04 ^d
NGC 315	-23.1	0.31	11 ± 23	311 ± 22	0.04 ± 0.08	0.06 ± 0.12
NGC 1316	-23.0	0.32	132 ± 7	209 ± 6	0.63 ± 0.04	0.94 ± 0.06
IC 2082	-23.3	0.33	35 ± 15	230 ± 21	0.15 ± 0.07	0.21 ± 0.10
M87	-22.0	0.14	3 ± 11 ^j	303 ± 21	0.01 ± 0.04 ^d	0.03 ± 0.12 ^d
NGC 4839	-23.2	0.51	23 ± 10	255 ± 9	0.09 ± 0.04	0.09 ± 0.04
IC 4296	-22.9	0.10	64 ± 12	291 ± 21	0.22 ± 0.04	0.66 ± 0.12
NGC 5128	(-21)	(0.15)	90	150	0.6 ± 0.1	(1.4 ± 0.3)
A2029	-23.4	0.33	<20	369 ± 5	≤0.05	≤0.08
NGC 7626	-22.3	0.17	20 ± 20	290 ± 32	0.07 ± 0.07	0.16 ± 0.16

NOTES.—Integrated absolute blue magnitudes based on a uniform Hubble flow model with $H_0 = 50$ km s⁻¹ Mpc⁻¹ and the B_T of Table 3 are given in col. (2). Ellipticities $\epsilon = (1 - b/a)$ are given in col. (3) from sources noted below. Mean rotational velocities for $r \geq (0.2-0.5)r_e$ are given in col. (4), followed by the velocity dispersion averaged over $r \leq r_e/2$ as in Table 4. The dimensionless rotation is tabulated in col. (6), and this value normalized by that expected for an oblate isotropic rotator is given in col. (7) (Illingworth 1981; DEFIS).

^a Ellipticities were taken from DEFIS for M84, IC 2082, M87, and IC 4296; from our own CCD or video camera frames for 3C 33, 3C 218, NGC 3801, 3C 293, 3C 305, 3C 310, 3C 388; from Young *et al.* 1979 for NGC 6251; from Schweizer 1980 for NGC 1316; from Birkinshaw and Davies 1985 for 3C 218; and from the UGC for the remainder. Very uncertain values are given in parentheses.

^b Values of $\bar{\sigma}$ from DEFIS (Table 3) and Table 4 of this paper. Value for NGC 1316 is from the data of Bosma, Smith, and Wellington 1984. Since some of the error estimates are unrealistically small, an additional factor of 0.06 has been added in quadrature with the errors given in the tables to indicate more accurately the level of systematic uncertainty in these values (see, e.g., Terlevitch *et al.* 1981).

^c The largest rotational velocity found is tabulated. No corrections have been applied (see text).

^d These values are all consistent with zero rotation at the ~ 1 σ level or less.

^e Value for ellipsoidal component. Hint of a stellar disk at large radii (see Heckman *et al.* 1985a).

^f The largest V_m seen is tabulated, although all three position angles give mean velocities consistent with zero rotation.

^g Weighted average of data of Davies 1981 and our data (see notes to Table 4).

^h Any corrections to the major axis are uncertain, and in any case are small compared with the errors and have not been applied.

ⁱ As for the other galaxies, V_m is the weighted mean of velocities for $r \geq r_e/2$ or less (here $r_e/2 \sim 2''$). Averaging only the velocities for $r \geq 5''$ gives $V_m \sim 78 \pm 32$ km s⁻¹, but these data are very uncertain, being measurements at $r_e \leq r \leq 2r_e$ and are strongly dependent on one large velocity at $r \sim 2r_e$. Accordingly, this latter average is not used.

^j Values from Bosma, Smith, and Wellington 1984 for NGC 1316; for $\bar{\sigma}$ a weighted average of all σ values for $a_e \leq 60''$ (P.A. 60°) and $b_e \leq 40''$ (P.A. 142°) is taken, and a weighted average $\langle V \rangle$ is used for $V(r \geq 40'')$ in P.A. 60° for V_m . For M87 V_m is a weighted average of the data of Sargent *et al.* 1978 for $r \geq 10''$.

mean between the radio galaxies and normal elliptical galaxies. As is the case for normal luminous ellipticals, radio galaxies are not rotationally supported oblate spheroids.

In Figure 4 we have plotted the log of the normalized rotational velocity $(V/\sigma)^*$ against M_B^{UH} , again for both powerful radio galaxies and the normal ellipticals from DEFIS. The parameter $(V/\sigma)^*$ is the rotational velocity in units of the velocity dispersion normalized by the value of (V/σ) expected for a rotationally supported oblate spheroid having the observed ellipticity ϵ (see DEFIS and our Fig. 3). We have determined the median value of $\log (V/\sigma)^*$ for the normal ellipticals in bins of M_B^{UH} which were 1 mag wide. We then find that seven radio galaxies fall above these medians, 11 lie below, and two have upper limits to $\log (V/\sigma)^*$ which are above the median. Thus, while a number of individual radio galaxies exhibit rapid rota-

tion (discussed in §§ IIIb and IV), the sample as a whole does not appear peculiar compared with the normal ellipticals.

This conclusion differs strongly from that drawn by Jenkins (1984). He tested a similar sample of galaxies with the same tool [the $(V/\sigma)^*$ versus M_B^{UH} relation], and concluded that the radio galaxies were more rapidly rotating on average. It is therefore important to understand why we differ. First, our sample includes such slowly rotating objects as NGC 1275, NGC 6166, NGC 6251, NGC 7720, 3C 310, and IC 1101, which were not in Jenkins's smaller sample. Second, Jenkins's sample included 3C 33, 3C 98, and 3C 218, which were reported by Simkin (1979) to exhibit very rapid rotation. As discussed below, we were not able to confirm Simkin's results for 3C 33 and 3C 218, and so they are moved from the rapid rotation to the slow rotation category. Third, neither the data of Schechter

FIG. 2—The log of the mean velocity dispersion ($\bar{\sigma}$) is plotted against the absolute blue magnitude (M_B^{UH}). The most powerful radio sources ($\log P_{178 \text{ MHz}} > 25.3$ W Hz^{-1} for $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$) are indicated by plus signs (error bars on $\bar{\sigma}$ indicated); the less powerful radio sources ($24.0 \leq \log P_{178 \text{ MHz}} < 25.3$) are indicated by crosses (with error bars on $\bar{\sigma}$); and normal elliptical galaxies (from DEFIS) are indicated by filled circles.

and Gunn (1979) regarding NGC 7626 nor those of R. Davies and M. Birkenshaw (1985, private communication) regarding NGC 741 and NGC 4261 support Jenkins's report that they are rapid rotators.

iii) Alignment between Rotation and Radio Axes

Our new results also indicate that there is no longer any basis for claiming that there is a good general alignment

between stellar rotation and radio axes, even considering only the most powerful radio sources (Ekers and Simkin 1983). For the radio galaxies with the most rapid rotation (and hence the most well-defined rotation axes), the radio and stellar rotation axes⁹ are offset by $89^\circ \pm 5^\circ$ (NGC 3801), $\sim 60^\circ$ (3C 293), $36^\circ \pm 10^\circ$ (3C 305), $45^\circ \pm 20^\circ$ (NGC 1316), and $20^\circ \pm 20^\circ$ (IC 4296). For the slow rotators the results are more ambiguous: $52^\circ \pm 22^\circ$ (3C 33), $65^\circ \pm 39^\circ$ (NGC 1275), $32^\circ \pm 28^\circ$ (NGC 6251), and $52^\circ \pm 36^\circ$ (3C 388). Palimaka *et al.* (1979) found that only very large ($\geq 250 \text{ kpc}$ for $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$) radio sources show a good alignment between the galaxy minor axis and the radio ejection axis. Can a similar distinction be drawn on the basis of the stellar kinematical data? Unfortunately, there are only four large sources for which the offset between the radio ejection and stellar rotation axes has been even roughly determined (IC 4296, $20^\circ \pm 20^\circ$; 3C 33, $52^\circ \pm 22^\circ$; NGC 1316, $45^\circ \pm 20^\circ$; NGC 6251, $32^\circ \pm 28^\circ$). NGC 5128 = Cen A shows a significant stellar velocity gradient *along* the axis of the associated large radio source Cen A (Davies *et al.* 1984), so it must have significantly misaligned radio and stellar rotation axes (see Table 5 and Figs. 3 and 4). Thus, the available data do not support the idea of generally well-aligned stellar rotation and radio ejection axes, even in large sources. A significantly larger sample will be needed to investigate whether a weaker statistical trend exists for roughly aligned axes (as seems to be the case for the radio ejection and galaxy minor axes; cf. Birkinshaw and Davies 1985 and references therein).

The question of alignment can also be addressed using the kinematics of the emission-line gas in radio galaxies. Simkin (1979) claimed that the radio ejection axis is aligned with the

FIG. 3— $V_m/\bar{\sigma}$ from Table 5 plotted against ellipticity ϵ . Elliptical galaxy data (from DEFIS, Table 3) are compared with data for radio galaxies from our Table 5. The solid line labeled *oblate* is the model relation for rotationally flattened oblate galaxies with isotropic dispersions (Binney 1978). The line labeled *prolate* defines the median relation for like-structured prolate galaxies. The meanings of the various symbols are the same as in Fig. 2.

⁹ Assuming an inclined disk model. While this could be a poor model for the stellar velocity field in an elliptical galaxy, insufficient data are available to establish what is the appropriate form.

FIG. 4.—The log of the dimensionless rotational velocity scaled relative to its expected value in a rotationally supported oblate spheroid [$\log (V/\bar{\sigma})^*$; see text] is plotted against the galaxy blue absolute magnitude M_B^{UH} ($H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$). The meanings of the various symbols are the same as in Fig. 2.

TABLE 6
RADIO EJECTION AND GAS ROTATION AXES

Object (1)	Radio Size (kpc) (2)	$\Delta\theta$ (degrees) (3)	References (4)
NGC 612 (PKS 0131 – 36)	400	12	1
3C 33	380	1	2, 3
NGC 1052	4	40 ^a	4
NGC 1316 (Fornax A)	570	55	5
3C 98	250	14	2
3C 184.1	600	5	2
3C 218 (Hydra A)	525	5	2, 3, 6
NGC 3801	9	5 ^b	3, 7
NGC 4278	1	47 ^c	8
NGC 5128 (Cen A)	570	13	9
3C 293	2	59	10
3C 305	9	56	11
3C 405 (Cygnus A)	210	5	2
IC 5063 (PKS 2048 – 57)	8	63	12
PKS 2158 – 380	120	22	13

NOTES.—Radio size (col. [2]) is the total extent in kpc. $\Delta\theta$ (col. [3]) is the difference between the radio axis and the gas rotation axis.
^a $\Delta\theta \sim 72^\circ$ if the VLBI radio jet position angle is used (Jones, Wrobel, and Shaffer 1983).
^b NGC 3801 has two dust/gas disks whose projected rotation axes are orthogonal. The value quoted is for the minor axis gaseous disk at small radii ($r \lesssim 15''$). At larger radii $\Delta\theta \approx 85^\circ$ (see Heckman *et al.* 1985a).
^c $\Delta\theta \sim 22^\circ$ if the VLBI radio jet position angle is used (Jones, Wrobel, and Shaffer 1983).
REFERENCES.—(1) Goss *et al.* 1980; Ekers *et al.* 1978. (2) Simkin 1979. (3) This paper. (4) Wrobel 1984; Davies and Illingworth 1985. (5) Schweizer 1980; Cameron 1971. (6) Ekers and Simkin 1983. (7) Heckman *et al.* 1985a; Jenkins 1982. (8) Wrobel and Heeschen 1984; Demoulin-Ulrich, Butcher, and Boksenberg 1984. (9) Taylor and Atherton 1983; Schreier, Burns, and Feigelson 1981. (10) van Breugel *et al.* 1984. (11) Heckman *et al.* 1982. (12) Danziger, Goss, and Wellington 1981. (13) Fosbury *et al.* 1982.

gas rotation axis, while Kotanyi and Ekers (1979) also reached a similar conclusion for the radio axis and the gas rotation axis inferred from the dust-lane morphology. In Table 6 we have summarized the available emission-line data (from the present paper and from published sources). These data are displayed in histogram form in Figure 5, from which it is evident that moderately large radio sources (≥ 100 kpc for $H_0 = 50$) are generally aligned (mean alignment $15^\circ \pm 6^\circ$) with the emission-line gas rotation axis, while small (≤ 10 kpc) sources apparently are not.

iv) *Misaligned Gas Rotation/Galaxy Minor Axes*

Several clear-cut cases of strong velocity gradients along the galaxy minor axis in the emission-line gas are known in radio galaxies. In NGC 1316 = Fornax A (Schweizer 1980), NGC 5128 = Cen A (e.g., Taylor and Atherton 1983), NGC 3801 (this paper and Heckman *et al.* 1985a) and probably 3C 405 = Cyg A,¹⁰ the gas is apparently arrayed in a disk whose rotation axis is along the galaxy's projected *major* axis (as is the case inferred for many examples of minor axis—"polar"—dust lanes cataloged by Hawarden *et al.* 1981). In 3C 33 (Simkin 1979; this paper [see details below]) and 3C 405 = Cyg A (Simkin 1979; Mathews, Morgan, and Schmidt 1964) the gas rotation axis may be skewed relative to the major/minor axes. NGC 708, M84, and 3C 305 all have dust lanes which are skewed relative to the galaxy major/minor axes, but in each case the radio source is aligned with the inferred dust rotation axis (Kotanyi and Ekers 1979). Examples of dust lanes (Hawarden *et al.* 1981), emission-line disks (Demoulin-Ulrich, Butcher, and Boksenberg, 1984), and H I disks (Knapp 1983) which are skewed relative to the major/minor axes are known in normal (relatively radio-quiet) elliptical galaxies as well. We will discuss the significance of these results in § IV below.

¹⁰ The isophotes of Cyg A undergo a rapid rotation in orientation, with a major axis in P.A. $\sim 110^\circ$ interior to radii of $\sim 3''$ – $4''$, and a major axis in P.A. $\sim 160^\circ$ farther out (Kronberg, van den Bergh, and Button 1977). Simkin (1979) found the rotation axis in P.A. $\sim 116^\circ$ for gas interior to $r \sim 5''$.

b) *Individual Galaxies*

i) 3C 33

We do not confirm the very rapid rotation of the stellar component reported for this galaxy by Simkin (1979). She found rotation with a peak velocity $V_m \sim 280$ km s⁻¹ and a rotation axis in position angle $24^\circ \pm 9^\circ$. Our data indicate $V_m \sim 35 \pm 18$ km s⁻¹ along the corresponding dynamical major axis (P.A. = 114°) and $V_m \sim 47 \pm 22$ km s⁻¹ close to the reported dynamical minor axis (P.A. = 20°). Our data thus imply a rotation axis of the stellar component at $148^\circ \pm 22^\circ$. We have analyzed a Gunn *r* band CCD image of 3C 33 (kindly provided by R. Green) using the GASP program at KPNO. The structure of the galaxy changes significantly at a radius $\sim 4''$. Interior to this, the ellipticity is $\sim 0.10 \pm 0.02$ and the major axis is in P.A. $\sim 80^\circ \pm 10^\circ$. Exterior to this, the ellipticity rises rapidly to $\sim 0.25 \pm 0.05$ with the major axis in P.A. $\sim 155^\circ \pm 5^\circ$. Since our stellar kinematic data refer to the region interior to $r \sim 5''$, the misalignment between the rotation and minor axes in this region ($22^\circ \pm 23^\circ$) is not significant. However, the measured position angle of the major axis in the interior may be misleading in terms of the stellar component in 3C 33. The region of emission-line gas seen in Figure 6 has a major axis in P.A. $\sim 60^\circ$ and an axial ratio $\sim 2:1$, and is found only interior to $r \sim 4''$ (H. Butcher 1984, private communication). The H α + [N II] $\lambda\lambda 6548, 6584$ lines will produce $\sim 4\%$ – 8% of the light in the Gunn *r* band image within this region, and could slightly distort the isophotes.

Our data do not reveal good alignment between the stellar rotation axis and radio axis (see above), but alignment cannot be conclusively ruled out in view of the relatively large uncertainty. The measured velocity dispersion (227 km s⁻¹) is very close to that expected for a galaxy of this luminosity (230 km s⁻¹). We conclude that the stellar dynamics of 3C 33 are not unusual for a galaxy of its type (see Figs. 2, 3, and 4).

While our data conflict with Simkin's regarding the stellar dynamics, we do confirm her results regarding the emission-line gas. Our results are displayed in Figure 6 and show that $V_m \sim 250 \pm 50$ km s⁻¹ in P.A. 114° and $V_m \sim 50 \pm 50$ km s⁻¹ in P.A. 20° . The gas rotation axis is then aligned with the radio

FIG. 5.—Histogram of the degree of alignment between the observed emission-line gas rotation axis and the radio ejection axis ($\Delta\theta$ in degrees). Large (≥ 100 kpc for $H_0 = 50$ km s⁻¹ Mpc⁻¹) sources are indicated by crosshatching, and small (< 10 kpc) by unhatched boxes. There are no sources in the 10–100 kpc range in our sample (see Table 6).

FIG. 6.—Velocity indicated by the $[\text{O III}] \lambda 5007$ emission line in 3C 33 is plotted as function of position along the slit in position angles 20° and 114° . The large velocity change in the gas in P.A. 114° is not seen in the stars along the same P.A. (see Fig. 1).

axis, but is misaligned by $\sim 30^\circ$ (45°) relative to the minor axes in the inner (outer) parts of the galaxy (see above).

ii) NGC 1275 = 3C 84

NGC 1275 proved to be a most difficult object to investigate kinematically. First, it has a strong featureless optical continuum in the nucleus which washes out the stellar absorption lines. Second, it has very strong, broad, and spatially extended emission lines which must be excised from the data before running the Fourier quotient program. Third, there is a significant young stellar component which is not well matched by typical template stars. However, this last effect should be minimal in the wavelength range we used (around the Mg b lines at 5165–5180 Å).

Taken at face value, our data indicate slow but detectable rotation ($\sim 50 \text{ km s}^{-1}$) about a rotation axis in P.A. $\sim 85^\circ \pm 39^\circ$. This result is rather surprising, if correct, since the minor axis is in P.A. $\sim 20^\circ$. The difference is, however, only $\sim 1.6\sigma_{\text{P.A.}}$. In view of the above difficulties with the data and the relatively large uncertainties, this rotation needs to be confirmed. We note further that the radio axis (e.g., Pedlar, Booler, and Davies 1983) is in P.A. $\sim 170^\circ$, aligned with neither the galaxy minor axis nor the (very uncertain) stellar rotation axis.

While the velocity dispersion we measure is $\sim 20\%$ below the value expected for a typical elliptical of the same M_B^{UH} , this could be due in part to the additional luminosity supplied by both the nonthermal nuclear source and the young stellar component in NGC 1275. Also, we have not been able to determine a value for the velocity dispersion in the inner $\sim 5''$ (2.5 kpc). If the dispersion rises significantly in the core of this galaxy, we will have significantly underestimated $\bar{\sigma}$.

iii) 3C 218 = Hydra A

As in the case of 3C 33, our results do not confirm Simkin's (1979) report of rapid rotation of the stellar component. We find $V_m \sim 13 \pm 18 \text{ km s}^{-1}$ along the reported dynamical major axis, as opposed to her value of $V_m \sim 175 \text{ km s}^{-1}$. Since we did not observe at any other position angles, we cannot comment on the degree to which the stellar rotation axis might be aligned with the radio source axis or galaxy minor axis. The velocity dispersion we measure ($\bar{\sigma} = 322 \pm 20 \text{ km s}^{-1}$) is close to that expected for such a luminous elliptical. The stellar dynamics of 3C 218 then appear quite normal.

Our data on the kinematics of the emission-line gas (from the $[\text{O III}] \lambda 5007$ and $\text{H}\beta$ lines) agree with Simkin's data along a similar position angle (Fig. 7). We find a rotational velocity of $\pm 150 \text{ km s}^{-1}$ in P.A. 132° . The gas rotation axis and galaxy minor axis appear to be reasonably well aligned in 3C 218 (P.A. 29° versus P.A. 40° ; Ekers and Simkin 1983).

The radio galaxy 3C 218 is surrounded by smaller galaxies, one of which is projected upon the galaxy itself. Velocities relative to 3C 218 of several of these are given in Appendix B.

iv) NGC 3801

NGC 3801 is a fascinating object characterized by complex and roughly orthogonal dust features, broad 21 cm H I emission and absorption lines (Heckman *et al.* 1983), and a Z-

FIG. 7.—Mean velocity indicated by the $[\text{O III}] \lambda 5007$ and $\text{H}\beta$ emission lines in 3C 218 is plotted as a function of position along the slit in position angles 144° and 120° . The large velocity change in the gas is not seen in the stars (see Fig. 1).

shaped radio source wholly embedded within the galaxy (Jenkins 1982). We will discuss our various optical and radio data in detail in a separate paper (Heckman *et al.* 1985a). Here we emphasize those aspects of the data bearing on the question of possible peculiarities in the stellar dynamics of radio galaxies.

The stellar rotation is rapid along the major axis of the galaxy, rapid enough for NGC 3801 to be a rotationally supported oblate object (e.g., Illingworth, 1981). The stellar rotation curve rises steeply and then flattens out at a radius of $\sim 6'' = 2$ kpc. Given NGC 3801's modest absolute magnitude ($M_B^{\text{UH}} = -21.1$), neither this rapid rotation nor the rather small velocity dispersion ($\bar{\sigma} = 168 \pm 6 \text{ km s}^{-1}$) is particularly unusual (see Figs. 2, 3, and 4).

The radio source axis is almost exactly orthogonal to the rotation axis of the stellar component, and is hence orthogonal to the dust lane lying along the galaxy's minor axis.

v) M84 = 3C 272.1

Owing to its brightness and relative proximity, this galaxy can be studied in more detail than the other radio galaxies. Our data indicate that M84 can be rotating by no more than $\sim (10/\sin i) \text{ km s}^{-1}$. Such slow rotation is common in moderately luminous elliptical galaxies such as M84 (see Fig. 4).

Inasmuch as we have not detected rotation, nothing can be said concerning any alignment between the radio and stellar rotation axes. However, the central dust lane (e.g., Kotanyi and Ekers 1979) is orthogonal to the radio axis, but is skewed relative to both the major and minor axes. The only peculiarity in the stellar dynamics of M84 is the rather high velocity dispersion ($\bar{\sigma} = 278 \pm 4 \text{ km s}^{-1}$, compared with an expected value of 196 km s^{-1} based on M_B^{UH}). However, use of a Virgo-centric flow model distance would lessen this discrepancy. While the dispersion falls slowly as a function of radius, there is no rise in σ in the core, as is the case for M87 (Sargent *et al.* 1978). Whatever its cause, the $\sigma(r)$ nuclear cusp in M87 is not ubiquitous in radio galaxies (see also Davies and Illingworth 1985).

vi) 3C 293

This galaxy and its associated radio source have been the subject of several recent radio and optical investigations (van Breugel *et al.* 1984; Bridle, Fomalont, and Cornwell 1981). Optically, the galaxy is interesting for indications of recent interaction (see Fig. 8 [Pl. 1] and discussion later) and is peculiar among elliptical galaxies in terms of both its high ellipticity ($\epsilon \sim 0.5$), and its dust-riddled morphology (see van Breugel *et al.* 1984). Since these authors showed that 3C 293 possesses a rapidly rotating disk of emission-line gas, we have included it in our survey.

The stellar component also shows a strong velocity gradient ($V_m \sim 154 \text{ km s}^{-1}$) along the galaxy major axis. The velocity curve seems to be linear out to a radius of 6 kpc and then to flatten out. This rotation is in fact rapid enough that 3C 293 could be a rotationally flattened oblate object.

Both the rapid rotation and the low velocity dispersion ($\bar{\sigma} = 185 \text{ km s}^{-1}$) are unusual (but not unprecedented) for an elliptical galaxy with $M_B^{\text{UH}} \sim -22$ (see Figs. 2 and 4). The apparent rotation axis of the stellar component (P.A. $\sim 155^\circ$) is badly misaligned with the axes of both the bright inner and the faint outer radio emission (P.A. 93° and 123° , respectively). Despite its rapid rotation, and rather low central velocity dispersion, we believe that 3C 293 is a bona fide (though peculiar) elliptical galaxy. We see no sign of a *stellar* disk in 3C 293 in

our kinematic data. That is, the stellar velocity dispersion remains high, and the stellar rotational velocities remain significantly less than those of the emission-line gas ($V_{\text{abs}} \sim 154 \text{ km s}^{-1}$ versus $V_{\text{ems}} \sim 260 \text{ km s}^{-1}$), well out (~ 15 kpc) from the center of the galaxy (cf. Kormendy and Illingworth 1982).

vii) 3C 305

This intriguing object (Heckman *et al.* 1982) is similar to, but more extreme than, 3C 293 in its stellar kinematics. Like 3C 293, 3C 305 is flattened ($\epsilon \sim 0.4$), possesses a disk of emission-line gas rotating rapidly about the galaxy minor axis, has a dusty and peculiar optical morphology, and is associated with a radio source only a few kpc in size. This radio source is oriented approximately perpendicular to a faint dust lane in the inner part of the galaxy (Kotanyi and Ekers 1979).

The stellar kinematics of 3C 305 also closely resemble those of 3C 293. The stars are rotating rapidly about P.A. $7^\circ \pm 10^\circ$ (close to the minor axis) with $V_m = 143 \pm 17 \text{ km s}^{-1}$, exhibiting solid-body rotation out to a radius of ~ 5 kpc and a flat rotation curve farther out. The emission-line gas rotation curve turns over at a similar radius. As in 3C 293, there is no kinematic signature of a substantial stellar disk: the stellar rotation represents $\sim 55\%$ of the rotation velocity in the emission-line gas (Heckman *et al.* 1982), and the stellar velocity dispersion remains high even ~ 15 kpc out from the nucleus. Thus, 3C 305 may be classified as a peculiar E galaxy. Since 3C 305 is a highly luminous galaxy ($M_B^{\text{UH}} = -22.9$) the rapid stellar rotation makes it quite unusual, as does the low stellar velocity dispersion ($\bar{\sigma} = 178 \pm 9 \text{ km s}^{-1}$), which is $\sim 40\%$ below what would be expected for a typical elliptical galaxy of this luminosity. While 3C 305 is unquestionably an atypical object in terms of its stellar dynamics, this may arise partly from the fact that the blue luminosity of its evolved stellar population may be significantly overestimated by M_B^{UH} , since young stars can be detected spectroscopically (see Heckman *et al.* 1982).

Heckman *et al.* (1982) speculated (on both morphological and spectroscopic grounds) that 3C 305 represents a recent galaxy merger. This is further substantiated by new CCD imaging data showing faint plumes extending out ~ 90 kpc on either side from the elliptical main body of 3C 305 (see Fig. 8 and Fig. 9 [Pl. 2]). Since 3C 305 resides in a region of very low galaxy density, these plumes (if of gravitational tidal origin) could be the result of a merger (Toomre 1977). It is then interesting that numerical simulations of mergers of disk galaxies do yield central velocity dispersions in the elliptical-like merger products that are below those in normal elliptical galaxies (White 1983; Veeraraghavan and White 1984). Moreover, Bosma, Smith, and Wellington (1984) found that NGC 1316 = Fornax A (which Schweizer 1980 has argued is a merger remnant) is very similar to 3C 305 in its stellar dynamics (fast rotation, low velocity dispersion). We will discuss these issues below (§ IV) and in more detail elsewhere (Heckman *et al.* 1985, in preparation).

viii) 3C 310

The parent galaxy of 3C 310 is relatively faint and distant, making a study of its kinematics difficult. However, 3C 310 is a powerful radio source which would have been expected to have well-aligned radio and rotation axes (Ekers and Simkin 1983). For this reason we included it in our sample.

Our measurements are consistent with zero rotation for 3C 310 ($19 \pm 18 \text{ km s}^{-1}$). This galaxy appears dynamically normal in this sense, as well as in terms of its velocity disper-

sion. Higher quality data will be needed to investigate the question of aligned radio, rotation, and minor axes in this object.

ix) NGC 6166 = 3C 338

NGC 6166 is the dominant galaxy in the rich cluster Abell 2199. A separate paper (Illingworth 1986) will deal with its dynamics in more detail. In summary, it exhibits no detectable rotation and has a normal velocity dispersion for its blue luminosity (see also Tonry 1984).

x) NGC 6251

This galaxy is associated with one of the longest, straightest, and most beautiful radio jets known (e.g., Perley, Bridle, and Willis 1984). Young *et al.* (1979) have studied its photometric properties in detail, and have pointed out a similarity to M87 in its nonisothermal core.

Our data indicate that NGC 6251 is slowly rotating ($V_m \sim 47 \pm 16 \text{ km s}^{-1}$) about an axis in P.A. $\sim 85^\circ \pm 28^\circ$. In view of the large uncertainties, the data are consistent with a rotation axis aligned with the minor axis in P.A. 109° (the radio axis is also roughly along the minor axis at P.A. 117°).

The velocity dispersion is high compared with the value expected for an average elliptical galaxy with $M_B^{\text{UH}} = -21.9$ ($\sigma = 293 \text{ km s}^{-1}$ observed versus 234 km s^{-1} expected). However, normal elliptical galaxies show a similar scatter about the mean, so the stellar dynamics of NGC 6251 do not appear extraordinary.

xi) 3C 388

This is the most distant galaxy in our sample ($z = 0.0908$) and is to our knowledge the most distant galaxy whose stellar kinematics have yet been measured. It is identified with a powerful radio source of somewhat unusual morphology (Burns and Christiansen 1980).

Despite 3C 388's distance and faintness, we have detected possible slow rotation at $V_m \sim 93 \pm 40 \text{ km s}^{-1}$ about an axis in P.A. $\sim 117^\circ \pm 36^\circ$. This is consistent with the galaxy minor axis (P.A. $\sim 110^\circ$) but is misaligned with the radio axis in P.A. 65° . The velocity dispersion we measure is large ($\bar{\sigma} = 365 \pm 23 \text{ km s}^{-1}$). The blue luminosity of 3C 388 ($M_B^{\text{UH}} = -22.7$) would predict $\sigma \sim 274 \text{ km s}^{-1}$ ($\sim 30\%$ lower than observed). 3C 388 can be described as a slowly rotating (normal) elliptical.

xiii) NGC 7720 = 3C 465

This cluster-dominant galaxy will be discussed by Illingworth (1986). It is a very slow rotator ($V_m = 9 \pm 7 \text{ km s}^{-1}$), and the velocity dispersion is somewhat higher than average ($336 \pm 8 \text{ km s}^{-1}$ measured versus 280 km s^{-1} predicted from $M_B^{\text{UH}} = -22.8$; see also Tonry 1984).

IV. SUMMARY AND IMPLICATIONS

The principal conclusions to be drawn from the data presented above are as follows:

1. The parent galaxies of radio sources (even very powerful sources) do not as a class, or even on average, exhibit rapidly rotating stellar components when compared with normal elliptical galaxies. The large dispersion in $(V/\bar{\sigma})^*$ characteristic of luminous ellipticals ($M_B^{\text{UH}} \lesssim -21$) is also found for these radio ellipticals.

2. There are indications that high rotation speeds may be related to galaxy interactions or mergers. The five most rapidly rotating objects in Table 5, 3C 293 (Fig. 8), 3C 305 (Fig. 8), NGC 3801 (Heckman *et al.* 1985a), NGC 1316/Fornax A (e.g.,

Schweizer 1980) and NGC 5128/Cen A (e.g., Malin, Quinn, and Graham 1983) all have either asymmetric tails and plumes and/or inclined gaseous disks, suggestive of recent interaction. It is also interesting that in the (σ, M_B) -plane, these objects lie close to the locus of theoretical models for the production of an elliptical galaxy from a merger of two disk galaxies (Veeraraghavan and White 1984). This is in contrast to most luminous ellipticals, which are observed to have higher σ at a given M_B than predicted by the models.

3. We find no strong evidence for good alignment between the radio ejection and stellar rotation axes, even for the large and/or powerful radio sources where such an alignment has been previously suggested. However, the presently available data are inadequate to rule out firmly a weak statistical tendency for the radio ejection and stellar rotation axes to align. Available data do demonstrate that large ($\gtrsim 100 \text{ kpc}$ for $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$) radio sources are usually well aligned with the rotation axis of the emission-line gas, while small ($\lesssim 10 \text{ kpc}$) sources apparently are not.

4. Several clear cases of large velocity gradients in the emission-line gas along the galaxy minor axis are known. Hence, the gas rotation axis may align with the galaxy major or minor axes, or may be skewed relative to both. Similar situations can be inferred for the dust disks seen in radio galaxies, and for the gas/dust disks in radio-quiet ellipticals.

The above conclusions bear directly on a number of important, unanswered questions in the study of active galaxies. One such question is, "what is the origin of the gas in active elliptical galaxies?" Two pieces of evidence favor an external source. First, the gaseous and stellar angular-momentum axes are frequently quite dissimilar. Second, as discussed in detail by Heckman *et al.* (1985b), many radio galaxies with well-developed interstellar media show morphological and/or kinematic evidence for a recent merger or violent interaction.

The second question upon which our data bear is, "Why do only a small fraction of elliptical galaxies exhibit strong radio emission?" Our work suggests that the answer to this question may not directly involve the global stellar dynamics (although Heckman 1983 has concluded that galaxy mass is an important parameter regarding radio emission). Adequate fueling through accretion may be the critical factor that results in a radio elliptical.

Finally, the data are pertinent to the question, "By what mechanism is the radio ejection axis set?" We have noted the tendency for the radio ejection to occur along the rotation axis of gas/dust disks (e.g., see Fig. 5). The direction of the radio ejection axis is known to be set on very small scales near the nucleus (a few parsecs or less; see Bridle and Perley 1984) where dynamical relaxation times are short. Thus an ejection axis which is observed to align with a gas rotation axis and which is to remain stable for an appropriate duration ($\sim 10^8$ years?) must be determined by gas in stable orbits.

In an oblate potential, such orbits lie in the equatorial plane. Hence, the galaxy minor, radio ejection, stellar rotation, and gas/dust rotation axes should all align. This is not the case for the majority of radio galaxies.

In a tumbling prolate potential, the stable gas orbits in the interior of the galaxy lie in the plane perpendicular to the major axis, i.e., the gas rotation axis is aligned with the major axis (Tohline and Durisen 1982). When projection effects are accounted for, the apparent stellar rotation axis can be skewed relative to the galaxy minor, gas/dust rotation, and radio ejection axes. However, the radio ejection, gas/dust rotation, and

galaxy major axes should always align in this case. Such a model fits some radio galaxies (e.g., Cen A) but not others (Birkinshaw and Davies 1985 and Palimaka *et al.* 1979 find a tendency for *minor* axis alignment of radio sources, while misaligned gas/dust rotation and galaxy major axes are common).

The situation is considerably more complex in a triaxial galaxy, because the gas may circulate in stable orbits which lie in planes perpendicular to the longest or the shortest axes of the figure (e.g., van Albada, Kotanyi, and Schwarzschild 1982; Merritt and de Zeeuw 1983). Moreover, the projection of a triaxial figure on the sky may result in an *apparent* major axis whose orientation is skewed to that of the true long axis of the system (e.g., van Albada, Kotanyi, and Schwarzschild 1982). In this case, the gas (or dust) rotation axis can align with the apparent (projected) major or minor axis, or be skewed relative to both. This is then consistent with the results summarized above for radio galaxies. It is clearly important to enlarge the sample of radio (and normal elliptical) galaxies with well-determined photometric and kinematic properties to test more critically the possibility that many are triaxial in form.

In conclusion, while firm answers are not yet possible for any of the questions listed above, it does seem likely that further study of the stellar and gas dynamics of radio galaxies will offer unique insights into the nature of both extragalactic radio sources and elliptical galaxies.

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APPENDIX A

The data for the velocity V (referenced to the systemic velocity), the velocity dispersion σ , and the line strength γ are tabulated in Table 7. Errors $\epsilon(V)$, $\epsilon(\sigma)$, and $\epsilon(\gamma)$ are given. Radii r are in arcseconds, with *negative* radii for data *east* of the nucleus. V , $\epsilon(V)$, σ , and $\epsilon(\sigma)$ are in km s^{-1} . The data of Table 7 are folded about the nucleus and plotted in Figure 1.

Occasionally, small differences may be seen in Figure 1 in the radii for corresponding V , σ , and γ points. This results from the ϵ^{-2} weighting factor applied to the radii of data values that are being averaged. For tabulation purposes, we have used radii that are the mean of those for the V and σ data, except where the differences are large. In this case separate radii are given for the V data and for the σ and γ data. Mean radii are used only where the radius differences are $\leq 5\%$.

TABLE 7
ROTATION AND DISPERSION DATA

r	V	$\epsilon(V)$	σ	$\epsilon(\sigma)$	γ	$\epsilon(\gamma)$	r	V	$\epsilon(V)$	σ	$\epsilon(\sigma)$	γ	$\epsilon(\gamma)$
3C 33; P.A. 20°							-7.4.....	-34	44	197	58	0.41	0.10
5.8.....	46	46	308	66	0.83	0.11	-11.1.....	-120	64	264	82	0.61	0.21
3.6.....	15	39	218	60	0.57	0.07	-13.2.....	-17	50	203	66	0.66	0.18
2.0.....	-6	37	237	53	0.56	0.06	-17.0.....	103	50	275	60	0.99	0.23
0.4.....	41	33	239	50	0.59	0.06	-25.8.....	-55	92	303	108	1.17	0.45
-0.8.....	15	38	198	60	0.59	0.08	NGC 1275; P.A. 110°						
-2.0.....	30	29	182	49	0.57	0.06	30.5.....	127	74	365	98	0.54	0.11
-3.7.....	-50	50	177	88	0.45	0.08	16.6.....	36	70	420	89	0.52	0.09
-5.8.....	-90	47	188	83	0.57	0.09	11.9.....	-13	70	326	91	0.49	0.10
3C 33; P.A. 112°							10.2.....	-27	59	258	84	0.44	0.08
5.5.....	27	51	...	...	...	...	8.1.....	4	39	267	55	0.46	0.06
2.9.....	24	38	263	54	0.45	0.05	6.4.....	-84	48	312	64	0.48	0.07
1.1.....	54	22	229	41	0.48	0.04	4.2.....	-42	27	263	39	0.40	0.03
(0.0) ^a	-8	31	219	44	0.60	0.06	-4.1.....	51	27	263	39	0.40	0.03
-1.2.....	-4	18	225	34	0.58	0.04	-6.3.....	7	30	253	44	0.45	0.04
-2.9.....	-61	28	242	48	0.53	0.05	-7.8.....	18	33	264	48	0.49	0.05
-5.6.....	-4	37	...	...	...	...	-9.4.....	26	39	259	59	0.56	0.07
NGC 1275; P.A. 80°							-11.6.....	34	41	328	52	0.63	0.07
28.0.....	...	...	228	84	0.65	0.20	-15.1.....	14	37	279	54	0.65	0.08
25.1.....	-5	48	...	...	...	...	-20.4.....	-64	37	270	58	0.62	0.07
17.9.....	103	80	332	88	1.03	0.32	-29.7.....	36	56	263	82	0.69	0.12
13.1.....	187	33	216	45	0.89	0.17	NGC 1275; P.A. 170°						
10.6.....	87	29	224	36	0.92	0.14	38.4.....	38	62	123	124	1.43	0.72
7.7.....	-109	31	214	40	0.72	0.12	23.2.....	97	62	146	115	0.67	0.30
4.7.....	-72	38	269	51	0.57	0.13	18.2.....	95	54	196	88	0.77	0.26
-4.9.....	-20	43	259	50	0.53	0.11	12.1.....	-57	52	209	84	0.54	0.17

TABLE 7—Continued

<i>r</i>	<i>V</i>	$\epsilon(V)$	σ	$\epsilon(\sigma)$	γ	$\epsilon(\gamma)$	<i>r</i>	<i>V</i>	$\epsilon(V)$	σ	$\epsilon(\sigma)$	γ	$\epsilon(\gamma)$
NGC 1275; P.A. 170°							3C 305; P.A. 90°						
9.0.....	112	29	178	41	0.73	0.13	15.1.....	53	67	...	...	...	...
6.0.....	37	25	217	31	0.68	0.10	14.2.....	...	...	207	79	1.27	0.27
-5.9.....	-104	34	241	42	0.56	0.11	10.6.....	140	62	...	...	...	...
-9.3.....	38	53	259	71	0.36	0.12	6.6.....	51	97	182	140	0.48	0.17
-12.3.....	30	34	225	58	0.64	0.14	5.3.....	82	59	172	98	0.61	0.15
-17.5.....	-105	47	332	71	0.89	0.25	4.0.....	152	52	254	67	0.83	0.15
-27.3.....	-47	104	314	119	2.35	0.99	2.6.....	108	34	210	45	0.82	0.11
-30.7.....	8	48	70	122	1.46	0.54	1.3.....	37	32	225	40	0.72	0.08
3C 218; P.A. 120°/144°							(0.0) ^a	10	27	195	36	0.62	0.07
7.8.....	-7	92	339	133	1.02	0.19	-1.3.....	-41	26	177	35	0.65	0.07
6.1.....	-59	57	285	82	0.84	0.11	-2.6.....	-119	28	116	51	0.57	0.08
4.2.....	-56	49	383	61	0.85	0.08	-4.0.....	-152	33	101	67	0.53	0.09
2.0.....	-33	38	282	57	0.57	0.05	-5.3.....	-121	56	126	103	0.46	0.14
0.3.....	6	29	308	38	0.69	0.05	-7.3.....	-176	39	159	65	0.74	0.15
-0.8.....	72	47	309	62	0.63	0.07	-9.8.....	-184	63	92	145	0.81	0.27
-2.0.....	20	32	332	40	0.76	0.05	-16.8.....	-198	67	192	117	0.94	0.31
-4.1.....	-63	41	329	57	0.81	0.07	3C 305; P.A. 165°						
-5.7.....	-33	79	254	118	0.70	0.13	13.9.....	52	46	132	75	1.24	0.41
M84; P.A. 80°							7.7.....	22	41	150	76	0.75	0.22
28.8.....	-8	41	153	63	0.56	0.12	4.7.....	25	23	184	33	1.11	0.76
22.2.....	-27	47	292	52	0.72	0.11	1.9.....	10	17	193	22	0.97	0.10
15.5.....	-25	23	260	26	0.95	0.09	0.7.....	-11	19	194	25	1.00	0.12
8.8.....	-17	23	260	25	0.87	0.08	-2.0.....	-24	15	165	21	0.96	0.09
4.5.....	19	17	286	18	1.03	0.07	-4.6.....	2	17	91	39	0.75	0.10
(0.0) ^a	-25	16	303	15	1.14	0.07	-7.6.....	-72	40	203	54	1.17	0.28
-2.0.....	-16	16	314	16	1.12	0.07	-14.4.....	-98	62	...	...	...	...
-4.9.....	16	21	301	22	1.08	0.08	3C 310; P.A. 63°						
-10.1.....	-19	25	275	27	0.99	0.09	9.6.....	183	60	...	...	...	...
-16.8.....	26	32	295	34	0.89	0.10	8.8.....	...	...	248	71	0.95	0.22
-23.5.....	-5	32	220	38	0.89	0.12	5.9.....	19	87	...	...	...	...
-30.1.....	24	55	225	66	0.72	0.16	3.0.....	22	33	191	46	0.93	0.14
M84; P.A. 168°							1.3.....	0	19	114	37	0.88	0.10
40.9.....	49	30	202	39	0.36	0.06	(0.0) ^a	-30	23	166	36	0.89	0.11
31.5.....	-11	40	167	55	0.30	0.07	-1.3.....	-13	32	234	42	1.02	0.14
25.2.....	25	31	213	41	0.36	0.06	-2.9.....	36	30	202	47	0.84	0.13
16.2.....	12	18	246	21	0.69	0.06	-6.6.....	-46	77	...	...	...	...
10.1.....	-13	14	263	16	0.89	0.06	-9.9.....	...	...	172	73	0.96	0.22
6.2.....	-11	17	264	19	0.97	0.09	-10.5.....	-38	50	...	...	...	...
3.5.....	4	13	283	14	1.08	0.07	3C 310; P.A. 153°						
2.0.....	-14	19	292	19	1.08	0.08	6.6.....	49	45	144	79	1.29	0.31
0.8.....	2	13	265	15	0.99	0.07	3.1.....	-46	38	191	59	0.90	0.17
-1.4.....	6	21	324	23	1.20	0.13	1.3.....	30	39	257	48	1.15	0.18
-3.5.....	-22	15	316	16	1.18	0.09	(0.0) ^a	-20	31	188	44	0.87	0.13
-6.6.....	2	15	269	16	0.90	0.07	-1.3.....	-5	36	219	49	1.03	0.17
-10.4.....	25	20	265	23	0.90	0.09	-2.8.....	41	55	238	74	0.96	0.23
-14.3.....	2	17	224	21	0.66	0.06	-8.6.....	60	104	316	156	1.10	0.59
-21.2.....	-8	21	182	28	0.42	0.05	NGC 6251; P.A. 27°						
-30.3.....	-1	25	190	33	0.42	0.06	16.4.....	-57	54	275	76	1.15	0.29
-42.1.....	40	49	171	72	0.17	0.05	8.6.....	-36	68	232	79	0.64	0.20
3C 293; P.A. 65°							5.7.....	-24	30	207	38	0.91	0.12
17.2.....	-303	56	128	92	0.43	0.19	3.1.....	-54	22	266	26	1.00	0.09
12.6.....	-192	54	103	103	0.67	0.28	0.8.....	39	20	297	22	0.89	0.07
9.3.....	-198	42	141	86	0.50	0.16	-1.3.....	57	39	347	43	0.90	0.11
6.1.....	-107	31	202	42	1.03	0.20	-3.2.....	18	27	309	30	1.05	0.10
3.3.....	-66	21	128	35	0.76	0.12	-5.8.....	73	36	256	42	1.01	0.15
1.4.....	-41	23	147	38	1.06	0.17	-9.2.....	-16	41	264	66	0.69	0.14
-1.0.....	65	26	254	32	1.31	0.18	-16.1.....	59	30	139	58	1.10	0.18
-3.4.....	87	37	178	53	0.71	0.18	NGC 6251; P.A. 124°						
-5.6.....	172	68	183	96	0.83	0.35	12.9.....	-51	41	293	67	1.27	0.24
-9.6.....	55	43	158	74	0.63	0.23	7.9.....	1	35	193	57	0.84	0.14
-11.5.....	154	33	146	53	1.04	0.26							
-16.4.....	177	39	...	...	...	...							
-17.6.....	...	...	130	107	0.88	0.27							

TABLE 7—Continued

r	V	$\epsilon(V)$	σ	$\epsilon(\sigma)$	γ	$\epsilon(\gamma)$	r	V	$\epsilon(V)$	σ	$\epsilon(\sigma)$	γ	$\epsilon(\gamma)$
NGC 6251; P.A. 124°							3C 388; P.A. 44°						
4.7.....	65	37	372	47	1.37	0.17	-1.3.....	73	51	454	71	1.71	0.36
1.9.....	-18	22	266	27	0.92	0.08	-2.6.....	-47	54	434	74	2.12	0.46
(0.0) ^a	7	34	310	42	0.85	0.11	-4.0.....	-146	64	303	87	1.55	0.42
-1.8.....	-15	23	274	28	0.84	0.07	-6.0.....	-24	66	369	107	1.40	0.48
-4.2.....	-40	35	293	47	0.80	0.12	3C 388; P.A. 156°						
-8.0.....	-44	56	306	73	0.90	0.19	4.6.....	-49	112	391	153	0.73	0.47
-12.4.....	-87	44	272	63	1.13	0.22	2.6.....	-87	68	456	100	1.64	0.45
3C 388; P.A. 44°							1.3.....	-12	50	352	66	1.25	0.25
5.7.....	109	94	265	133	1.02	0.41	(0.0) ^a	-48	45	321	57	1.10	0.20
4.0.....	204	82	324	103	1.25	0.43	-1.3.....	49	52	404	71	1.43	0.29
2.6.....	70	68	369	92	1.40	0.38	-2.6.....	25	62	377	86	1.44	0.37
1.3.....	-16	46	250	60	0.95	0.18	-4.0.....	103	121	458	195	0.64	0.47
(0.0) ^a	24	50	359	67	1.09	0.22							

^a Bin centered on nucleus. Appropriate radius depends upon seeing, slit size, and surface brightness distribution. For a uniform distribution $r_{\text{app}} = 0.7$ for these data.

APPENDIX B

Spectra of several of the galaxies surrounding 3C 218 were obtained along with the data on 3C 218 itself. Separations, position angles, and velocities relative to 3C 218 are given in Table 8. The field is shown in Figure 10 (Plate 3). The compact galaxy projected into the envelope of 3C 218 (9° SE) appears to have a large central velocity dispersion. No emission lines ([O III] $\lambda 5007$ or H β) were seen in these other galaxies.

TABLE 8
NEARBY GALAXIES TO 3C 218

Object (1)	Spectrum P.A. (degrees) (2)	Separation (arcsec) (3)	ΔV (km s ⁻¹) (4)	σ (km s ⁻¹) (5)
A.....	120	9 (SE)	630	390 $\pm$ 47
B.....	120	74 (NW)	740	260 $\pm$ 55
C.....	144	35 (SE)	^a	^a
D.....	144	43 (NW)	470	(275 $\pm$ 115)

NOTES.—The velocity difference $\Delta V = V_{3C\ 218} - V_{\text{gal}}$. A, B, and probably D have later type stellar spectra similar to those of 3C 218 and standard stars.

^a No strong features that can be clearly identified with the Mg b lines can be seen in the data for object C. The Fourier quotient result indicated that this galaxy was redshifted 9055 km s⁻¹ with large uncertainty with respect to 3C 218.

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FIG. 8.—*Right-hand panel*: *R* band frame of 3C 293 from the RCA CCD on the No. 1 0.9 m telescope at KPNO. The integration time was 900 s. The field size is 275" north-south by 440" east-west, with 1' indicated by the horizontal line. Note both the companion galaxy to the southwest and the plume of material extending $\sim 90''$ (~ 120 kpc) to the southwest of the main galaxy. See van Breugel *et al.* (1984) for an image showing the dusty interior of the galaxy. *Left-hand panel*: *B* band frame of 3C 305 from RCA prime-focus CCD on the 4 m telescope at KPNO (kindly obtained by M. Aaronson). The integration time was 900 s. The field size is 186" east-west by 297" north-south, again with 1' indicated by the horizontal line. The data are displayed at high contrast to show the broad outer "arms" (~ 180 kpc in total projected extent).

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PLATE 2

FIG. 9.—The same 4 m frame of 3C 305 as in Fig. 8, but displayed at lower contrast to show the complex structure and faint dust lane in the interior of the galaxy. The displayed field is 148" square.

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FIG. 10.—3C 218 (Hya A) and the field surrounding it displayed at high and low contrast. The data are from a 900 s *R* band exposure with the RCA CCD on the No. 1 0.9 m telescope at KPNO. The field is 275" north-south by 440" east-west; the horizontal line is 1' in length.

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