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THE OPTICAL POLARIZATION PROPERTIES OF QUASARS

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ABSTRACT

Optical polarimetry is presented for 163 radio-selected quasars, including a complete sample of 90 sources stronger than 2 Jy at 5 GHz. Including new and published data, the polarimetry is over 90% complete. Synchrotron components are detected in over 30% of these flat spectrum quasars, with an optical polarization threshold of $p > 3\%$. The fraction of polarized quasars is a strong function of the compactness of the radio emission, as measured on VLBI scales. Including the duty cycle correction, essentially every quasar with $S_{\rm core} > S_{\rm ext}$ at radio wavelengths has a prominent blazar component at optical wavelengths. Virtually all of the radio sources with weak emission lines (or BL Lac objects) are highly polarized.

Optical and radio polarization are not correlated, and there is no difference in the $\alpha_{\rm ro}$ distributions of high- and low-polarization quasars, or sources with strong and weak emission lines. Redshift information is incomplete, but BL Lac objects appear to have lower redshifts than strong-lined quasars. The distribution of $V/V_{\rm max}$ for radio BL Lac objects indicates much stronger evolution than is found for X-ray–selected BL Lac objects. Overall, there is a strong statistical link between compact radio structure, apparent superluminal motion, strong optical polarization, and weak emission lines. This can be understood if both the optical and the compact radio emission are relativistically beamed. However, the Lorentz factors of the material emitting the optical and radio radiation must be different.

Subject headings: BL Lacertae objects — polarization — quasars — radio sources: general
radio sources: variability

I. INTRODUCTION

Much of our understanding of the energetic phenomena occurring in quasi-stellar objects or quasars has come from studies of the small fraction that have radio emission. Quasars with compact radio emission have a number of properties that indicate the dominance of incoherent synchrotron emission. These include variability and linear polarization at radio and optical wavelengths (Saikia and Salter 1988) and smooth energy distribution from millimeter to optical wavelengths (Landau *et al.* 1986). By contrast, the emission mechanisms operating in the vast majority of optically selected quasars are mysterious (Condon *et al.* 1981; Sanders *et al.* 1989).

There is also much indirect evidence that relativistic bulk motion of the emitting material is modifying the observed properties of some quasars. Observations of apparent superluminal motion at milliarcsecond scales and one-sided radio jets at arcsecond scales are particularly persuasive (Pearson and Readhead 1988; Bridle and Perley 1984). Model-dependent evidence includes intrinsic radio variability that violates the brightness temperature limits of the synchrotron process, a lower X-ray flux than would be expected if the synchrotron–self-Compton mechanism is operating (Marscher *et al.* 1979), and infrared luminosities that exceed the Eddington limit for an isotropic, gravitational power source (Impey *et al.* 1982). It is often assumed that relativistic motion is a *general* property of radio sources. In this case, the observational distinctions between radio galaxies and quasars and between flat and steep spectrum radio sources may be caused by Doppler boosting and projection effects. A number of "unified schemes" have been proposed to amalgamate radio sources, with varying degrees of scope and success (Blandford and Rees 1978; Orr and Browne 1982; Barthel 1989).

Compact radio emission is associated with specific optical properties: rapid variability, a high degree of linear polarization, and a smooth nonthermal continuum. The term "blazar" has been coined for such radio sources (Angel and Stockman 1980). This definition includes the highly polarized and violently variable quasars (Moore and Stockman 1981), as well as the BL Lac objects with weak emission lines. Compact radio emission appears to be fundamental to the blazar phenomenon, because searches for radio-quiet examples have been unsuccessful (Impey and Brand 1982; Borra and Corriveau 1984; Jannuzi and Green 1989). Even X-ray–selected blazars can be detected, albeit weakly, at radio wavelengths (Stocke *et al.* 1985, 1989).

The connection between compact radio emission and blazar optical properties is strong. About 70% of the known superluminal sources are confirmed blazars, and the VLBI structure axis and the preferred position angle of optical polarization are often aligned (Rusk and Seaquist 1985; Impey 1987). Occasionally, radio and optical flux variations are correlated (Jones *et al.* 1981). A single synchrotron component can usually fit the energy distribution from millimeter to ultraviolet wavelengths. At low redshifts, such as those found for the BL Lac objects, the signatures of nonthermal optical emission can be masked by dust and starlight in the surrounding galaxy. High linear polarization is an important characteristic of blazars, because it directly indicates optically thin synchrotron emission in a highly anisotropic (or ordered) magnetic field.

No large and complete radio-selected sample of blazars has been published. Part of the reason for this is observational bias. Historically, many of the radio sources targeted for polarimetry were those with weak emission lines in the optical spectrum, leading to highly polarized quasars being missed. Also, polarimetry of optically faint counterparts to strong radio sources is difficult, though infrared photometry shows

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that such sources may have blazar characteristics (Rieke, Lebofsky, and Kinman 1979). Finally, the BL Lac objects that have received the most attention are those with absorption-line redshifts from the host galaxy. At higher luminosities, the galaxy component is not as noticeable, and at lower luminosities, the nonthermal core is swamped by starlight from the elliptical galaxy.

In this paper, we use the optical property of strong linear polarization ($p > 3\%$) to detect the blazar population in a complete sample of radio-selected quasars. These radio sources are all stronger than 2 Jy at 5 GHz and identified with stellar objects, although the conclusions apply to other samples of quasars. In particular, we have avoided selection according to optical brightness or emission line strength. Recent surveys have shown a high proportion of blazars in samples of core-dominated quasars (Biermann *et al.* 1981; Impey and Tapia 1988; Fugmann and Meisenheimer 1989; Kühr and Schmidt 1989; Wills 1989). The sample is defined in § II, and the polarization measurements are described in § III (see also Impey and Tapia 1988). In § IV, statistical properties of the complete radio sample are summarized, and in § V the results are interpreted in terms of relativistic beaming and unified models of quasars. The conclusions from this work follow in § VI.

II. SELECTION OF THE SAMPLE

The basis for this study is the catalog of strong radio sources compiled by Kühr *et al.* (1981), using the NRAO-MPI surveys in the north and the Parkes surveys in the south. The catalog is over 99% complete for sources stronger than 1 Jy at 5 GHz; this is the highest frequency for which all-sky complete samples are available. The high frequency of selection results a majority of flat spectrum sources ($\alpha > -0.5$, where $S_\nu \propto \nu^\alpha$ from 2.7 GHz to 5 GHz). About 80% of the core-dominated sources are identified with quasars, and the distribution of the optical counterparts peaks above 19 mag (Bolton 1977). With a combination of optical and infrared techniques, about 95% of flat spectrum quasars can be identified (Condon, Jauncey, and Wright 1978; Rieke, Lebofsky, and Kinman 1979). Spectroscopic and polarimetric information have been obtained for a high fraction of these sources. The luminosity function is almost complete. By contrast, samples selected at a low radio frequency (such as the 3CR at 178 MHz) contain mostly steep spectrum sources with extended radio emission. The optical counterparts are usually faint galaxies, and it has taken great efforts with optical and infrared techniques to complete the identifications and redshifts (Lilly and Longair 1984; Spinrad 1986).

a) *Complete Quasar Samples*

We define two statistically complete subsets of the 518 sources in the Kühr *et al.* catalog. The first consists of 165 sources stronger than 2 Jy at 5 GHz (the "2 Jy" sample). The second consists of 220 sources with 5 GHz flux densities between 1.5 and 2 Jy (the "1.5 Jy" sample). Polarimetry is presented here for the 90 quasars in the 2 Jy sample and the 50 quasars with flat radio spectra in the 1.5 Jy sample. The lower flux density boundary of these two groups of radio sources is unavoidably fuzzy, since core-dominated radio sources are variable (Jones *et al.* 1981; Bennett, Lawrence, and Burke 1984). For inclusion in these samples, all published 5 GHz flux densities were averaged, including data obtained after the Kühr *et al.* catalog was published. Our conclusions are not sensitive to the exact choice of the weakest sources, since the luminosity function of 5 GHz radio sources is very broad (Peacock 1986).

To include more extended sources, we added quasars from the 3CR catalog (Spinrad *et al.* 1985). Of these 51 sources which are stronger than 9 Jy at 178 MHz, 11 are common to the 2 Jy sample and four to the 1.5 Jy sample. Polarimetry has been published for 33 of the 3CR quasars (Angel and Stockman 1980; Moore and Stockman 1981, 1984; Wills *et al.* 1980; Stockman, Moore, and Angel 1984). Unfortunately, the subset with polarimetry is biased toward the optically brightest sources. Almost 75% of the quasars with polarimetry are brighter than 18 mag, whereas all but one of the quasars without polarimetry are fainter than 18 mag. This bias will be taken into account in our analysis. The 2 Jy quasars suffer no such bias, because the polarimetry is over 90% complete. This paper concentrates on the 90 quasars in the 2 Jy sample. However, some statistical tests include the 1.5 Jy and 3CR quasars to make a larger sample of 176.

b) *Quasars versus Radio Galaxies*

All radio sources discussed in this paper are quasars, i.e., they have stellar counterparts on sky survey plates. The identification process may introduce a bias which affects the interpretation of the results. Optical counterparts of radio sources are either quasars or radio galaxies. Quasars have nonthermal optical emission, whereas the optical emission of radio is dominated by the photospheres of late-type giants, although some nonstellar continuum may be present. Distinguishing stellar and nonstellar identifications depends on: (1) the depth and angular resolution of the photograph or CCD frame, (2) the distance of the source, (3) the nature of the host galaxy, and (4) the contrast between the stellar and nonstellar continua. It may also depend on the orientation of the radio structure and the orientation of obscuring material in the host galaxy.

In the 2 Jy sample, BL Lac is a source which lies at the boundary of confusion between stellar and resolved sources (Kinman 1975). The host galaxy of BL Lac is very compact, and deep optical images are required to clearly resolve it. However, it has a redshift of 0.069, and a lower luminosity than most of the 2 Jy quasars. Radio properties can be used to make a clear distinction between quasars and radio galaxies. On average, quasars have stronger cores, stronger and more one-sided jets, and smaller linear dimensions than radio galaxies (Owen 1986; Miley 1980). Figure 1 plots the compactness (or ratio of core to extended flux density on arcsecond scales) against α_r for quasars (*circles*) and radio galaxies (*crosses*) gathered from the literature (Kühr *et al.* 1981; Perley 1982; Ulrich and Meier 1984; Feretti *et al.* 1984; Browne and Perley 1986). The ratio $S_{\rm core}/S_{\rm ext}$ measured with instruments like the VLA is often referred to as the parameter R by radio astronomers. Virtually every source with $\alpha > -0.3$ or $S_{\rm core} > S_{\rm ext}$ is a quasar.

There are 90 quasars, 62 radio galaxies, and 13 unidentified sources in the 2 Jy sample. The quasar identifications peak at magnitudes substantially brighter than the limit of sky survey plates, whereas the galaxies extend to very faint levels. The distribution of radio spectral index measured between 2.7 and 5 GHz is also relevant. The familiar peak around $\alpha_r = -0.7$ is seen for radio galaxies, while quasars have a very broad range of α_r. The conventional definition of flat spectrum is $\alpha_r > -0.5$, and 80% of these radio sources are quasars. If a sufficiently flat spectrum sample is chosen, essentially all of the optical counterparts will be quasars. The few unidentified sources

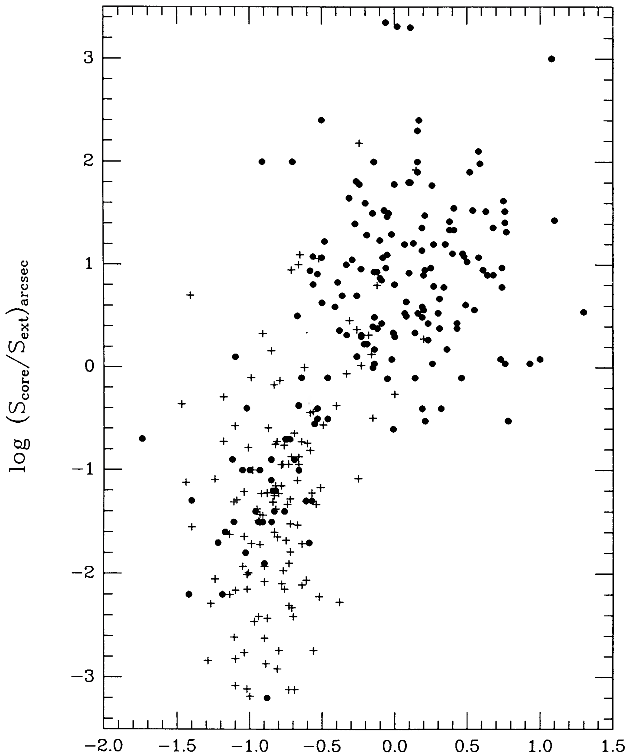

FIG. 1.—Ratio of core to extended radio flux density at 5 GHz plotted against radio spectral index between 2.7 and 5 GHz. Compactness on arcsecond scales is derived from VLA observations in the literature. Symbols correspond to quasars (*circles*) and radio galaxies (*crosses*).

(10%) have a distribution of α_r which is similar to that of the radio galaxies. Therefore, we estimate that no more than two or three quasars have been missed due to the magnitude limit for identifications.

III. POLARIMETRIC DATA

Optical polarimetry for strong radio sources has been compiled from published data, and new data obtained in Chile. The highly polarized sources from the southern survey have been presented by Impey and Tapia (1988); in this paper we include all the measurements of low polarization. The observations presented here were made using the MINIPOL polarimeter at Las Campanas Observatory in Chile. All observations were obtained on the Du Pont 100 inch (2.54 m) telescope during the period 1984 March 29 to 1986 June 4. Full details of the calibration and accuracy of the instrument are presented by Dolan and Tapia (1986) and Impey, Malkan, and Tapia (1989), and the level of interstellar polarization as a function of galactic latitude is given by Impey and Tapia (1988).

The polarimetry is presented in Tables 1, 2, and 3, which all have the same format. Columns (1) and (2) list the source designation and name. The redshift, average 5 GHz flux density, V magnitude, and Galactic latitude are in columns (3)–(6). Optical magnitudes and redshifts were taken from the Kühr catalog, with several redshifts added from Hewitt and Burbidge (1987). Compact radio sources often have variable optical emission, so the V magnitude undoubtedly depends on the epoch of observation. The degree of polarization in percent, polarization position angle, and U.T. date of observation are in columns (7)–(9). The observations were made unfiltered, and the spectral band defined by the sensitivity of the GaAs phototubes lies between 3200 and 8800 Å (FWHM). For a typical radio source energy distribution, the effective wavelength of the polarization measurement is ~ 5500 Å. MINIPOL uses a superachromatic half-wave plate that rotates through a full modulation cycle in 12 ms. The observing sequence consisted of M seconds of object itegration followed by N seconds of integration on a blank sky patch 30″ away. To reduce the statistical error of the sky observation, the ratio of N to M was less than the square root of the ratio of sky counts to object counts. We confirmed that the polarization error reduces according to photon statistics. In other words, the fit to the modulated signal agrees with the predicted polarization error, $100(2/N)^{1/2}$, where N is the number of counts. A discussion of the precision and repeatability of MINIPOL observations is given by Impey, Malkan, and Tapia (1989).

A number of radio sources have polarimetry published by other investigators. Where multiple observations exist, every attempt was made to use the *first* published measurement in column (7). This was easy to do for many of the less well known radio sources, and difficult to do for the well-studied BL Lac objects. No measurement made before 1968 was considered, because the errors were generally $\sigma(p) > 1\%$, which would prevent a simple division into high and low polarization at the $p = 3\%$ level. Our search through the literature was thorough, but it might not be complete. It is impossible to determine how many times some of the well-known BL Lacs were observed before they gave their first high (published) polarization. With this caveat, the polarizations in column (7) are close to an unbiased "single pass" measurement of the sample.

The polarimetry in Tables 1–3 is not corrected for low signal-to-noise ratio bias, because our data are being compared with data from the literature, which are not usually corrected for bias. Prescriptions to remove the bias have been published by Simmons and Stewart (1985). The analysis in this paper employs a simple division of sources into high ($p > 3\%$) and low ($p < 3\%$) polarization. Almost all of the sources with $p > 3\%$ have $p/\sigma(p) > 3$, so the distinction between observed and unbiased polarization does not affect our discussion of the highly polarized sources. For example, an observed polarization of $3\% \pm 1\%$ gives an unbiased value of 2.83% with confidence intervals of $1.6 \leq p \leq 3.6\%$ (68% confidence), $0.7 \leq p \leq 4.7\%$ (95% confidence), and $0 \leq p \leq 5.2\%$ (99% confidence). The reference for the polarimetry is given in column (10), and in the footnotes to Table 3. Reference (1) is this paper plus Impey and Tapia (1988). The highest published degree of polarization and its reference are given in columns (11) and (12). Column (13) gives the total number of published observations.

Table 1 lists 90 radio quasars with $S(5\text{ GHz}) > 2$ Jy, and Table 2 lists 50 radio quasars with $1.5\text{ Jy} < S(5\text{ GHz}) < 2$ Jy and $\alpha(2.7, 5\text{ GHz}) > -0.5$. Table 3 lists a heterogeneous set of 23 more radio-selected quasars. The last sample includes optically bright sources with relatively weak radio emission, i.e., flatter values of α_{ro}. Identifications and redshifts for the 2 Jy sample are 97% and 83% complete, respectively. Identifications and redshifts for the 1.5 Jy flat spectrum sample are 94% and 82% complete, respectively. Polarimetry is 92% complete for the 2 Jy sample, and 86% complete for the 1.5 Jy flat spectrum sample. For the first time, we can interpret the polarimetric properties of a large and complete sample of radio quasars.

TABLE 1

2 JANSKY RADIO SOURCES

Source (1)	Name (2)	z (3)	S_{5GHz} (Jy) (4)	V (5)	b^{II} (deg) (6)	p ± σ(p) (%) (7)	θ ± σ(θ) (deg) (8)	Date (U.T.) (9)	Ref (10)	p_{max} (%) (11)	Ref (12)	Obs (#) (13)
0047−579		1.797	2.41	18.5	−59.5	1.2±1.2	...	1986 Jun 1	1	1.2	1	1
0106+013	4C 01.02	2.107	2.41	18.4	−61.0	2.2±1.1	29±15	1979 Aug 28	3	7.1	3	6
0133+476	OC 457	0.860	2.92	19.0	−14.3	20.8±0.7	67± 1	1986 Dec 22	1	20.8	1	1
0134+329	3CR 48	0.367	5.35	16.2	−28.7	1.4±0.2	148± 5	1977 Sep 9	2	1.8	2	8
0202+149		...	2.43	20.9	−44.0	3.2±2.8	...	1984 Nov 22	7	4.0	7	2
0208−512		1.003	3.31	17.5	−61.8	11.5±0.4	88± 1	1985 Jan 31	1	11.5	1	1
0212+735		2.370	2.20	19.0	+12.0	7.8±1.9	97± 7	1981 Feb 1	5	7.8	5	2
0234+285	4C 28.07	1.207	2.15	18.9	−28.5	11.3±0.2	150± 1	1986 Dec 23	1	11.3	1	1
0235+164	AO	0.940	2.24	19.0	−39.1	0.3±0.1	2± 9	1976 Feb 21	1	44.7	8	46
0237−233	PHL 8462	2.224	3.39	16.6	−65.0	0.3±0.3	...	1978 Oct 8	3	0.3	3	1
0332−403		1.445	2.66	18.5	−54.1	14.8±1.8	113± 3	1985 Jan 30	1	14.8	1	1
0336−019	CTA 26	0.852	2.61	18.4	−42.5	19.4±2.4	22± 4	1979 Dec 23	4	19.4	4	2
0403−132		0.571	2.89	17.2	−42.7	3.8±0.5	170± 4	1985 Feb 10	1	20.2	4	9
0407−658		...	3.43	18.0	−40.9	0.7±0.4	136±15	1984 Apr 3	1	0.7	1	1
0409−752		...	4.42	...	−36.1	...	...	...	...	...	...	...
0438−436		2.852	6.19	19.8	−41.6	4.7±1.0	27± 6	1984 Apr 3	1	4.7	1	3
0440−003	NRAO 190	0.844	2.93	18.5	−28.5	2.7±1.6	85±17	1980 Jan 17	3	12.6	7	3
0451−282		2.559	2.26	19.0	−37.0	1.8±0.5	66± 9	1984 Apr 1	1	1.8	1	2
0454−463		0.858	2.32	18.0	−38.8	0.8±0.4	1±16	1984 Mar 31	1	0.8	1	1
0454−234		1.009	2.06	18.5	−34.9	7.2±0.9	109± 4	1984 Mar 31	1	27.3	1	2
0518+165	3CR 138	0.759	4.11	18.8	−11.3	2.2±2.2	...	1980 Apr 11	3	2.2	3	2
0528+134		...	3.98	20.0	−11.0	0.3±1.0	...	1984 Nov 2	7	0.3	7	1
0537−441		0.894	4.00	15.5	−31.1	10.4±0.5	136± 1	1984 Mar 30	1	18.8	1	2
0538+498	3C 147	0.545	8.12	17.8	+10.3	1.2±0.6	147±15	1978 Feb 10	3	1.6	3	2
0605−085	OH−010	0.870	3.49	18.0	−13.5	2.1±0.4	138± 5	1984 Mar 30	1	10.0	1	3
0637−752		0.651	5.85	15.8	−24.3	0.3±0.2	111±15	1984 Mar 30	1	0.3	1	1
0736+017	OI 061	0.191	2.00	16.5	+11.4	1.1±0.4	23±10	1985 Feb 9	1	8.4	4	20
0738+313	OI 363	0.630	2.08	17.5	+23.6	0.2±0.2	...	1977 Dec 7	2	0.2	2	1
0742+103		...	3.68	21.9	+16.6	...	...	...	...	...	...	...
0743−673		1.512	2.02	17.0	−20.1	0.9±0.4	171±11	1984 Mar 30	1	0.9	1	1
0748+126		0.889	2.29	17.8	+18.8	1.0±1.0	...	1984 Apr 1	1	1.0	1	1
0804+499	OJ 508	1.430	2.05	17.5	+32.6	8.6±0.7	179± 2	1986 Dec 24	1	8.6	1	5
0809+483	3CR 196	0.871	4.38	17.6	+33.2	0.7±0.6	...	1978 Oct 28	3	1.1	3	2
0814+425	OJ 425	...	2.21	18.5	+33.4	8.7±1.4	162± 5	1986 Dec 22	1	8.7	1	2
0834−201		2.752	3.73	19.4	+12.2	1.0±1.5	...	1985 Jan 31	1	1.0	1	1
0836+710	4C 71.07	2.170	2.59	16.5	+34.4	1.1±0.5	102±12	1986 Dec 22	1	1.1	1	1
0851+202	OJ 287	0.306	2.65	14.5	+35.8	10.8±0.3	156± 1	1985 Feb 1	1	37.2	11	288
0859−140	OJ−199	1.327	2.30	16.6	+20.7	1.1±0.7	49±17	1979 Nov 24	2	1.1	2	1
0923+392	4C 39.25	0.699	8.10	17.9	+46.2	0.5±0.5	...	1978 Nov 27	3	0.9	3	3
0954+556	4C 55.19	0.909	2.17	17.5	+47.9	9.6±1.8	129± 5	1976 Mar 25	1	9.6	1	2
1055+018	4C 01.28	0.888	3.47	18.0	+52.8	5.0±0.5	146± 3	1984 Mar 30	1	5.5	1	2
1104−445		1.598	2.07	18.2	+14.2	0.4±0.3	...	1984 Mar 30	1	0.4	1	1
1127−145	OM−146	1.187	6.57	16.9	+43.6	1.3±0.4	23±10	1979 Apr 2	2	1.3	2	1
1136−135	OM−161	0.557	2.13	17.8	+45.4	0.3±0.3	...	1984 Mar 30	1	0.3	1	1
1144−379		...	2.29	16.2	+23.0	5.4±0.2	99± 1	1984 Mar 30	1	8.5	1	3
1151−348		0.258	2.82	17.5	+26.3	0.6±0.4	...	1984 Apr 1	1	0.6	1	1
1226+023	3CR 273	0.158	42.86	13.0	+64.4	0.5±0.1	27± 2	1984 Mar 23	1	2.5	9	59
1245−197		...	2.46	20.5	+42.9	...	...	...	...	...	...	...
1253−055	3CR 279	0.536	14.95	16.8	+57.1	9.0±0.4	67± 1	1985 Feb 1	1	19.0	6	26
1328+254	3CR 287	1.055	3.22	17.7	+81.0	0.6±0.7	...	1979 Apr 2	3	0.6	3	1
1328+307	3CR 286	0.846	7.46	17.0	+80.7	1.3±0.5	47±11	1978 May 12	3	1.3	3	1
1334−127		0.541	2.25	18.5	+48.4	10.6±0.5	8± 1	1984 Apr 1	1	16.1	15	4
1424−418		...	3.13	17.5	+17.3	6.6±0.3	80± 1	1984 Apr 1	1	9.5	1	2
1458+718	3CR 309.1	0.905	3.73	16.8	+42.1	0.7±0.5	...	1978 Jun 9	2	0.9	1	2
1502+106	OR 103	1.839	2.32	18.9	+54.6	3.0±0.6	160± 5	1984 Apr 3	1	10.7	1	2
1508−055	OR−015	1.185	2.43	16.0	+42.9	1.5±0.5	67± 9	1978 Jul 1	2	2.0	2	2
1510−089	OR−017	0.361	3.08	17.8	+40.1	1.9±0.4	79± 6	1978 Apr 4	4	7.8	4	9
1519−273		...	2.35	18.5	+24.4	11.4±0.6	65± 1	1978 Apr 1	1	11.4	1	2
1538+149	4C 14.60	...	2.14	17.2	+48.8	17.4±0.5	145± 1	1980 Jun7	10	20.0	10	3
1548+056		1.426	2.23	18.5	+42.2	4.7±1.1	14± 7	1984 Apr 3	1	4.7	1	2
1555+001		1.770	2.25	19.3	+37.7	1.2±1.3	...	1986 Jun 1	1	1.2	1	1
1610−771		1.710	3.92	19.0	−18.9	3.8±0.7	78± 5	1985 Apr 12	1	3.8	1	2
1611+343	OS 319	1.404	2.67	17.5	+46.4	1.7±0.7	134±11	1978 May 12	3	1.7	3	2
1622−253		...	2.08	18.7	+16.3	2.8±0.9	14± 9	1986 Jun 3	1	2.8	1	1
1633+382	4C 38.41	1.814	2.93	18.0	+42.3	2.6±1.0	97±11	1980 Jun 20	3	2.6	3	3
1641+399	3CR 345	0.594	7.82	16.3	+40.9	4.0±0.3	103± 2	1973 Jan 8	1	35.3	12	88
1656+053	OS 094	0.879	2.16	16.7	+27.4	1.3±0.2	78± 5	1984 Mar 30	1	1.3	1	2
1740−517		...	3.04	19.2	−11.5	1.8±1.8	...	1986 Jun 3	1	1.8	1	1
1741−038		1.046	3.69	18.5	+13.1	1.2±1.9	...	1985 Apr 12	1	9.2	15	2
1828+487	3CR 380	0.691	6.82	16.8	+23.6	0.4±0.4	...	1977 Sep 8	2	0.4	2	2
1928+738	4C 73.18	0.360	3.34	16.5	+23.5	0.8±0.4	163±15	1979 Dec 21	5	1.2	1	2
1954−388		0.630	2.06	17.1	−29.0	10.9±0.3	179± 1	1984 Apr 3	1	10.9	1	3
2052−474		1.489	2.52	17.8	−40.4	2.7±1.5	129±18	1985 Apr 12	1	2.7	1	1

TABLE 1—*Continued*

Source (1)	Name (2)	z (3)	S_{5GHz} (Jy) (4)	V (5)	b^{II} (deg) (6)	$p \pm \sigma(p)$ (%) (7)	$\theta \pm \sigma(\theta)$ (deg) (8)	Date (U.T.) (9)	Ref (10)	p_{max} (%) (11)	Ref (12)	Obs (#) (13)
2106−413		...	2.35	18.5	−42.8	0.8±1.3	...	1986 Jun 4	1	0.8	1	1
2121+050		1.878	2.01	17.5	−32.1	10.7±2.9	68± 6	1984 Sep 17	7	10.7	7	2
2128+047		...	2.09	...	−31.8	...	...	...	...	...	...	...
2128−123		0.501	2.07	16.0	−41.0	0.3±0.2	...	1978 Oct 8	2	2.3	14	4
2131−021	4C−02.81	0.557	2.12	18.7	−36.5	16.9±4.0	93± 1	1985 Jun 19	15	16.9	15	1
2134+004	PHL 61	1.936	12.25	16.8	−35.6	0.4±0.4	...	1978 Jun 9	3	1.6	7	4
2145+067	4C 06.69	0.990	4.51	16.5	−34.1	0.6±0.2	138±11	1977 Sep 8	2	0.6	2	3
2200+420	BL Lac	0.069	4.00	14.0	−10.4	4.9±0.4	147± 2	1978 Oct 10	1	23.0	6	$\sim 10^3$
2201+315	4C 31.63	0.298	2.31	15.5	−18.8	0.2±0.1	80±18	1977 Sep 8	2	0.2	2	1
2203−188		0.618	4.38	19.5	−51.2	0.2±1.1	...	1986 Jun 1	1	1.2	7	2
2204−540		1.206	2.41	18.1	−49.9	1.5±2.9	...	1985 Apr 12	1	1.5	1	1
2223−052	3CR 446	1.404	4.52	18.4	−48.8	13.6±0.4	133± 1	1977 Sep 12	4	17.3	11	36
2230+114	CTA 102	1.037	3.69	17.3	−38.6	7.3±0.3	118± 1	1978 Jul 1	4	10.9	4	6
2243−123		0.630	2.45	16.4	−57.1	3.3±0.4	153± 3	1986 Jun 2	1	3.4	1	2
2251+158	3CR 454.3	0.859	17.39	16.1	−38.2	2.9±0.3	144± 3	1978 Jun 8	4	16.0	6	42
2326−477		1.302	2.53	16.8	−64.1	1.0±0.3	103± 8	1986 Jun 2	1	1.0	1	1
2345−167	OZ−176	0.576	3.67	18.5	−71.9	4.9±1.5	70± 8	1978 Nov 27	4	18.5	4	4

References.—(1) This paper plus Impey and Tapia 1988; (2) Stockman, Moore, and Angel 1984; (3) Moore and Stockman 1984; (4) Moore and Stockman 1980; (5) Biermann *et al.* 1981; (6) Angel and Stockman 1980; (7) Fugmann and Meisenheimer 1988; (8) Impey, Brand, and Tapia 1981; (9) Courvoisier *et al.* 1988; (10) Wills *et al.* 1980; (11) Smith *et al.* 1985; (12) Smith *et al.* 1987; (14) Brindle *et al.* 1986; (15) Kühr and Schmidt 1989.

IV. STATISTICAL PROPERTIES OF THE POLARIZED EMISSION

This survey gives the fraction of quasars with high optical polarization, and the dependence of that fraction on other radio and optical properties. For the first polarization measurement, the fraction of 2 Jy quasars with $p > 3\%$ is 33 out of 86 or 37%. The fraction of flat spectrum 1.5 Jy quasars with $p > 3\%$ is 23 out of 43 or 53%. These rates are in good agreement with other studies, once the dependence of blazar emission on radio properties is taken into account. Figure 2 gives the histogram of values from the first polarization measurement of each quasar for the 2 Jy and 1.5 Jy samples (col. [7] of Tables 1 and 2). The identification statistics and numbers of polarized and unpolarized sources in the three radio samples are listed in columns (2), (3), and (4) of Table 4. The final three lines in Table 4 give the percentage of quasars with polarization above 3%. The first is derived from the number of quasars with $p > 3\%$ in column (7) of Tables 1 and 2 (sources with unknown polarization are omitted). The second is derived from the number of quasars with $p_{max} > 3\%$ in column (11) of Tables 1 and 2. The third estimate accounts for the duty cycle of variable polarization, as described in the next section.

Early polarimetric surveys only found high polarization in $\sim 15\%$ of quasars. The low fraction was due to a preponderance of steep spectrum radio sources (Moore and Stockman 1981, 1984; Stockman, Moore, and Angel 1984). Surveys of flat spectrum radio sources have produced much higher blazar detection rates. Biermann *et al.* (1981) found high polarization in five out of six quasars, and the larger surveys of Kühr and Schmidt (1989), Fugmann and Meisenheimer (1988), and Wills (1989) have detection rates in the range 40%–50%. What makes the survey described here unique is the lack of selection effects and the very complete optical information.

Tables 5 and 6 list relevant optical and radio information for the 2 Jy and 1.5 Jy samples. Column (1) has the source name, and the presence of strong lines (> 10% of continuum) or polarization ($p_{max} > 3\%$) is indicated in columns (2) and (3). Radio spectral index α_r, S_{core}/S_{ext} measured on milliarcsecond scales and radio polarization measured on arcsecond scales are in columns (4)–(6). Column (7) has the spectral index between 5 GHz and the V band, α_{ro}. Column (8) has the position angle

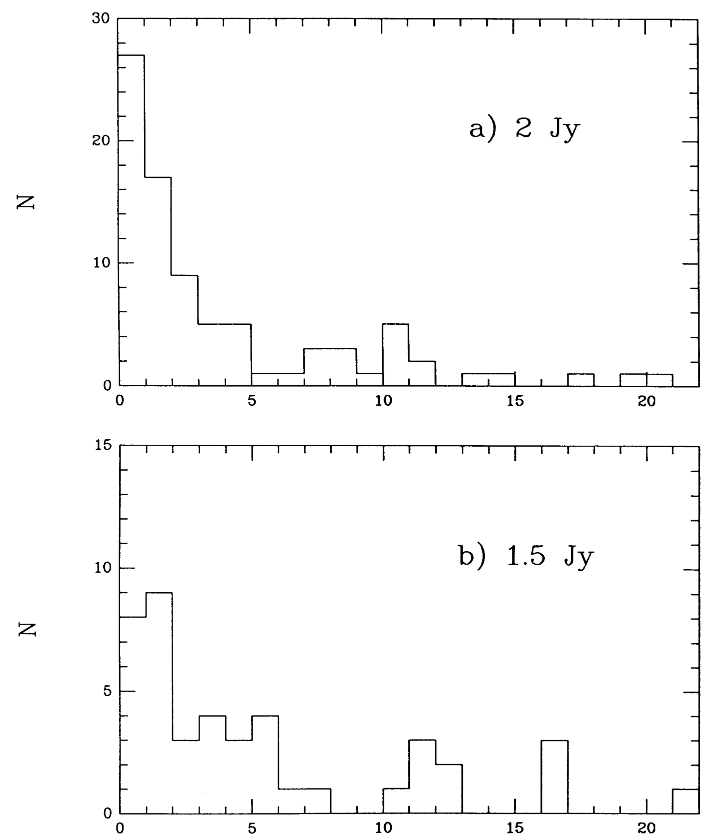

Fig. 2.—Distribution of the first published measurement of optical polarization for quasars in the (*a*) 2 Jy and (*b*) 1.5 Jy samples.

TABLE 2

1.5 JANSKY RADIO SOURCES: FLAT SPECTRUM

Source (1)	Name (2)	z (3)	S_{5GHz} (Jy) (4)	V (5)	b^{II} (deg) (6)	$p \pm \sigma(p)$ (%) (7)	$\theta \pm \sigma(\theta)$ (deg) (8)	Date (U.T.) (9)	Ref (10)	p_{max} (%) (11)	Ref (12)	Obs (#) (13)
0003−066		0.347	1.55	18.6	−66.7	3.5±1.6	160±12	1984 Sep 22	7	3.5	7	2
0016+731		1.781	1.65	18.0	+10.7	1.1±0.7	...	1986 Dec 22	1	1.1	1	1
0048−097	OB−081	...	1.98	17.4	−72.4	11.4±0.3	103± 1	1973 Oct 23	1	27.1	14	8
0113−118		0.672	1.94	18.5	−73.4	...	...	...	...	...	...	...
0119+041	OC 033	0.637	1.87	19.5	−57.6	4.2±1.1	59± 6	1984 Nov 12	7	4.2	7	2
0135−247	OC−259	0.832	1.70	16.9	−79.3	0.6±1.0	...	1986 Jun 5	1	0.6	1	1
0153+744		2.338	1.52	18.0	+12.4	1.1±0.3	106± 7	1986 Dec 22	1	1.1	1	1
0229+131	4C 13.14	2.065	1.53	17.7	−42.7	1.3±0.8	...	1978 Oct 8	3	1.8	7	4
0400+258	OF 200	2.109	1.79	18.0	−19.6	...	...	...	...	...	...	...
0405−123	OF−109	0.574	1.96	17.1	−41.8	0.8±0.2	136± 5	1978 Feb 10	2	0.8	2	3
0420−014	OF−035	0.915	1.73	17.8	−33.1	11.9±0.5	115± 1	1985 Feb 3	1	20.2	4	9
0458−020	4C−02.19	2.286	1.78	18.4	−25.3	10.6±4.0	127±10	1985 Apr 14	1	17.3	1	4
0500+019		...	1.88	20.2	−22.8	2.9±2.9	...	1984 Nov 17	7	4.1	7	2
0506−612		1.093	1.73	16.9	−36.1	1.1±0.5	83±12	1985 Jan 26	1	1.1	1	1
0539−057		1.700	1.56	18.5	−18.1	4.6±0.8	139± 4	1984 Nov 15	7	4.6	7	1
0606−223		1.926	1.50	20.0	−19.0	5.6±1.3	37± 5	1984 Nov 18	7	6.4	7	2
0607−157		0.324	1.82	17.5	−16.2	0.7±0.4	...	1985 Jan 26	1	0.7	1	1
0711+356	OI 318	1.620	1.52	17.0	+19.7	1.2±1.0	...	1986 Dec 24	1	1.2	1	1
0735+178	OI 158	0.424	1.85	16.5	+18.1	16.2±0.5	149± 1	1985 Feb 3	1	36.0	13	145
0743−006		0.994	1.99	17.5	+11.7	1.1±0.4	94±11	1984 Oct 3	15	1.1	15	4
0820+225		...	1.63	19.2	+29.7	5.2±1.2	1± 6	1984 Mar 4	15	5.2	15	1
0859+470	4C 47.29	1.462	1.78	18.7	+41.6	1.0±0.8	...	1986 Dec 24	1	1.0	1	1
0906+430	3CR 216	0.670	1.80	18.5	+42.8	3.8±0.4	53± 2	1986 Dec 24	1	21.0	6	4
0953+254	OK 290	0.712	1.66	17.5	+51.0	0.7±0.4	91±17	1978 Apr 4	3	2.2	3	2
1034−293	OL−259	...	1.51	16.5	+24.8	7.3±0.4	13± 1	1978 Apr 3	1	7.6	1	2
1057−797		...	1.62	19.4	−18.3	...	...	...	...	...	...	...
1148−001	4C−00.47	1.982	1.90	17.6	+58.8	0.7±0.7	...	1978 May 28	3	0.7	3	2
1255−316		1.924	1.73	18.7	+30.9	2.2±1.0	153±12	1985 Jan 27	1	2.2	1	1
1308+326	OP 313	0.996	1.52	19.0	+83.3	12.1±1.5	68± 3	1976 Jun 27	1	25.0	6	67
1354−152		1.890	1.53	18.5	+44.5	1.4±0.5	46±10	1986 Jun 3	1	1.4	1	1
1354+195	4C 19.44	0.720	1.54	16.5	+73.0	0.3±0.3	...	1978 Jun 8	2	0.3	2	1
1451−375		0.314	1.90	16.7	+19.0	1.5±0.2	70± 3	1985 Jan 27	1	1.5	1	1
1504−166	OR−102	0.876	1.98	18.5	+35.1	5.3±0.7	52± 4	1985 Jan 31	1	5.3	1	1
1600+335		...	1.51	...	+48.7	...	...	...	...	...	...	...
1619−680		...	1.86	...	−13.0	...	...	...	...	...	...	...
1622−297		...	1.92	...	+13.3	...	...	...	...	...	...	...
1642+690	4C 69.21	0.751	1.58	19.2	+36.6	16.6±1.7	8± 3	1987 Apr 6	1	16.6	1	1
1655+077		0.621	1.65	20.8	+28.6	5.0±7.0	...	1986 Jun 3	1	5.0	1	1
1739+522	4C 51.37	1.375	1.46	18.5	+31.7	3.7±0.2	172± 2	1986 Jul 13	1	3.7	1	1
1749+701		...	1.81	16.5	+30.7	11.5±0.3	112± 1	1980 Jun 7	10	11.5	10	4
1749+096	4C 09.57	0.322	1.58	16.8	+17.6	6.0±1.8	143± 8	...	6	31.3	14	6
1823+568	4C 56.27	0.664	1.60	18.4	+26.1	16.8±0.7	20± 1	1986 Jul 13	1	16.8	1	4
1903−802		0.500	1.84	19.0	−27.6	...	...	...	...	...	...	...
1936−155		1.657	1.69	19.4	−17.4	12.2±3.4	172± 8	1983 Nov 1	7	12.2	7	2
2155−152	OX−192	0.672	1.77	18.0	−48.0	22.6±1.1	7± 2	1980 Aug 9	15	32.7	14	4
2216−038	4C−03.79	0.901	1.50	16.4	−46.6	1.1±0.4	139±11	1977 Sep 8	2	1.1	2	1
2227−088		1.561	1.77	18.0	−51.7	6.6±5.3	...	1985 Apr 15	1	6.6	1	1
2245−328		2.268	1.85	18.6	−62.9	2.3±1.1	73±13	1986 Jun 1	1	2.3	1	1
2255−282		0.926	1.78	16.8	−64.9	2.0±0.4	112± 6	1986 Jun 2	1	2.0	1	1
2355−534		1.006	1.71	17.8	−62.1	3.7±0.6	126± 4	1986 Jun 4	1	3.7	1	2

REFERENCES.—(1) This paper plus Impey and Tapia 1988; (2) Stockman, Moore, and Angel 1984; (3) Moore and Stockman 1984; (4) Moore and Stockman 1980; (6) Angel and Stockman 1980; (7) Fugmann and Meisenheimer 1988; (10) Wills *et al.* 1980; (13) Puschell *et al.* 1983; (14) Brindle *et al.* 1986; (15) Kühr and Schmidt 1989.

difference between VLBI structure axis and optical polarization, $\Delta\theta_1 = |\theta_{\rm VLBI} - \theta_{\rm opt}|$. Column (9) has the difference between the radio and optical polarization position angles, $\Delta\theta_2 = |\theta_{\rm rad} - \theta_{\rm opt}|$. Luminosities at radio and optical wavelengths and $V/V_{\rm max}$ for each source are listed in columns (10)–(12). The last three paramenters assume $q_0 = 0.5$, $H_0 = 75$ km s^{-1} Mpc^{-1}. VLBI position angles were taken from Rusk (1988), VLBI compactness measures from Preston *et al.* (1985), redshifts from Hewitt and Burbidge (1987, 1989), and radio polarimetry from Tabara and Inoue (1980).

a) Duty Cycle of Polarization

High linear polarization is a key indicator of synchrotron emission, but the polarization percentage of the observed flux is almost always variable. Most sources with maximum polarization above 3% will spend some of the time at $p < 3\%$. An unbiased measure of the polarized fraction must take into account the duty cycle of high and low polarization states. One way to calculate the duty cycle is to study the distribution of polarization in blazars or BL Lacs with many measurements.

TABLE 3

STRONG RADIO SOURCES

Source	Name	z	S_{5GHz} (Jy)	V	b^{II} (deg)	p ± σ(p) (%)	θ ± σ(θ) (deg)	Date (U.T.)	Ref	p_{max} (%)	Ref	Obs (#)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
0117−155	3C 38	...	1.61	20.0	−76.4	1.9±1.4	...	1986 Jun 5	1	2.0	7	3
0118−272		...	1.15	16.5	−83.5	17.4±0.3	151± 1	1985 Feb 1	1	17.4	1	2
0138−097		...	1.23	18.0	−68.8	3.6±1.5	168±11	1985 Jan 30	1	13.9	1	5
0301−243		...	0.35	15.6	−60.4	10.6±0.2	52± 1	1985 Feb 10	1	10.6	1	1
0302−623		...	1.41	18.9	−51.6	0.7±1.3	...	1985 Jan 30	1	0.7	1	1
0402−362		1.417	1.43	17.2	−48.5	0.6±0.3	66±14	1985 Jan 30	1	0.6	1	1
0426−380		...	1.17	19.0	−46.0	1.8±0.4	90± 7	1985 Feb 1	1	1.8	1	1
0823−223		0.910	1.78	17.5	+ 8.7	4.0±0.1	100± 1	1984 Apr 3	1	9.1	1	2
0823+033		...	1.32	18.0	+22.4	13.9±0.4	162± 1	1985 Jan 26	1	23.0	1	4
0919−260		2.300	1.32	19.0	+16.5	1.8±0.5	100± 8	1985 Jan 26	1	1.8	1	1
1116−462		0.710	1.35	17.0	+13.4	1.0±0.3	146± 7	1985 Jan 26	1	1.0	1	1
1116+128		2.118	1.42	19.3	+63.9	1.7±1.0	...	1985 Jan 29	1	1.7	1	1
1244−255		0.633	1.36	18.0	+37.1	8.4±0.2	110± 1	1985 Jan 27	1	11.2	1	2
1309−216		1.491	0.23	18.9	+39.6	12.3±0.9	160± 2	1985 Apr 14	1	12.3	1	1
1349−439		...	0.76	18.0	+17.7	21.5±0.4	2± 1	1984 Apr 2	1	21.5	1	6
1424+240		...	0.28	16.2	+68.2	4.7±0.3	14± 2	1984 Apr 2	1	4.7	1	3
1532+016		1.420	1.17	18.7	+43.2	3.5±0.2	131± 2	1985 Apr 13	1	5.0	1	2
1606+106		...	1.45	18.5	+40.8	2.1±0.9	134±12	1986 Jun 4	1	2.1	1	1
1953−325		1.242	0.63	20.5	−26.7	2.0±1.2	...	1986 Jun 5	1	2.0	1	1
2206−251		...	0.27	17.7	−55.0	20.1±0.8	128± 1	1985 Apr 14	1	20.1	1	1
2240−260		...	1.00	17.5	−61.1	15.1±0.5	140± 1	1986 Jun 5	1	15.1	1	1
2254−204		...	0.43	17.5	−63.8	9.3±1.5	64± 4	1985 Apr 16	1	14.3	1	2
2354−117		0.949	1.32	19.0	−69.8	2.0±0.4	105± 6	1986 Jun 1	1	2.0	1	1

REFERENCES.—(1) This paper plus Impey and Tapia 1988; (7) Fugmann and Meisenheimer 1988.

The last columns of Table 1 and Table 2 show the difficulty of this approach. A few bright sources have been extensively studied, with more than 10 measurements. However, most polarized quasars have only been measured a couple of times. The best information on the time scale and range of polarization variations is based on a subset which may not be typical. Polarimetry is often confined to the most highly polarized sources, and multiple measurements are often taken during an active phase, so the data cannot be considered independent. This can cause a correlation between p_{max} and the number of observations. Conversely, sources found to be unpolarized are rarely observed more than once. Jannuzi, Smith, and Elston (1989) have shown the importance of this bias for X-ray–selected BL Lac objects. A number of BL Lacs have low polarization measured several times before a value of $p > 3\%$ is registered. Fugmann (1988) has used the best available data to estimate the probability of a blazar having $p > 3\%$ in a single measurement and calculates that at least $\frac{2}{3}$ of strong radio quasars with $\alpha_r > -0.2$ have high polarization.

TABLE 4

IDENTIFICATION AND POLARIZATION STATISTICS

Parameter (1)	2 Jy (2)	1.5 Jy (3)	3CR (4)
Selection frequency	5 GHz	5 GHz	178 MHz
Spectral index selection	...	$\alpha > -0.5$	...
Sources:			
Total	165	75	297
Quasars	90 (55%)	50 (67%)	51 (17%)
Galaxies	62 (37%)	13 (17%)	165 (56%)
Unidentified	13 (8%)	12 (16%)	81 (27%)
Quasars:			
$p > 3\%$	33 (37%)	23 (46%)	7 (14%)
$p < 3\%$	53 (59%)	20 (40%)	26 (51%)
p unknown	4 (4%)	7 (14%)	18 (35%)
Fraction:			
$p > 3\%$	37%	53%	...
$p_{max} > 3\%$	47%	55%	...
$p_{var} > 3\%$	56%	63%	...

We can estimate the unbiased fraction of sources with high polarization due to the 90% completeness of the polarimetry for the 2 Jy and 1.5 Jy samples. The remaining 10% tend to be optically faint quasars. There are 41 quasars from Tables 1 and 2 with only two published polarization measures. Figure 3 plots the first value against the second; the median time difference between the two observations is 1 year. The overall distribution of polarization is similar to the distribution of p_1 in for the subset plotted in Figure 3, so the 41 quasars are representative of the polarimetric properties of the complete sample. The first measurement gives 19 out of 41 with $p_1 > 3\%$. At the time of the second measurement, seven quasars with $p_1 > 3\%$ dropped to below 3%, and four quasars with $p_1 < 3\%$ rose to above 3%. Therefore, the addition of a second epoch raises the highly polarized fraction from an average of $41\% \pm 10\%$ to $56\% \pm 12\%$.

Given a sufficient number of observations, perhaps *all* quasars have $p_{max} > 3\%$. However, two simple arguments indicate that not all quasars have high polarization. First, 13 out of 19 quasars with three or four epochs of polarimetry have $p_{max} > 3\%$. This fraction of $68\% \pm 19\%$ is not much higher than the fraction for two epochs, despite the bias that only "interesting" quasars receive multiple observations. Second, consider quasars where the first measurement gave $p_1 < 3\%$. Figure 3 indicates a second observation typically elevates 20% of the quasars to the high polarization group (the average of four and seven out of 28). We can apply this reasoning to the 16 quasars with $p_1 < 3\%$ which have *more than* two observa-

TABLE 5

2 JANSKYS: RADIO AND OPTICAL DATA

Source (1)	$p_{max} > 3\%$ (2)	L/C>0.1 (3)	α_r (4)	log R (5)	p_r (%) (6)	α_{ro} (7)	$\Delta\theta_1$ (deg) (8)	$\Delta\theta_2$ (deg) (9)	log L_r (erg/s/Hz) (10)	log L_o (erg/s/Hz) (11)	V/V_{max} (12)
0047−579	N	Y	0.34	−0.76	...	−0.84	...	...	34.52	31.01	0.87
0106+013	Y	Y	0.26	0.39	2.0	−0.83	...	87	34.65	31.22	0.88
0133+476	Y	Y	0.62	−0.32	0.6	−0.90	70	34	34.05	30.05	0.70
0134+329	N	Y	−0.85	−1.69	4.1	−0.73	49	42	33.93	30.33	0.30
0202+149	...	...	−0.38	−0.64	0.0	−1.03	...	...	...	...	...
0208−512	Y	Y	−0.12	0.22	...	−0.79	10	...	34.43	30.80	0.64
0212+735	Y	N	−0.12	−0.11	3.1	−0.87	55	61	34.88	31.10	0.94
0234+285	...	Y	−0.91	0.13	0.8	−0.86	...	...	34.65	30.43	0.94
0235+164	Y	N	0.59	0.95	1.4	−0.87	25	85	34.00	30.14	0.90
0237−233	N	Y	−0.70	−0.46	5.9	−0.72	...	...	35.32	32.00	0.71
0332−403	Y	Y	0.44	−0.20	1.3	−0.85	...	86	34.39	30.78	0.79
0336−019	Y	Y	0.41	0.03	0.7	−0.84	...	11	34.05	30.28	0.78
0403−132	Y	Y	−0.14	−1.35	2.6	−0.75	58	7	33.93	30.36	0.67
0407−658	N	...	−1.22	...	0.5	−0.83	...	...	...	...	...
0409−752	...	...	−0.95	...	1.1	...	...	...	...	...	...
0438−436	Y	Y	0.27	−1.09	1.0	−1.03	70	29	35.23	30.98	0.51
0440−003	Y	Y	−0.58	−0.51	3.1	−0.85	...	76	34.36	30.27	0.69
0451−282	N	Y	0.02	−0.19	4.6	−0.88	...	34	34.87	31.19	0.93
0454−463	N	Y	0.03	−0.82	2.8	−0.80	...	13	34.11	30.44	0.87
0454−234	Y	Y	0.25	0.22	2.9	−0.83	...	14	34.11	30.41	0.98
0518+165	N	Y	−0.69	−1.23	10.9	−0.91	...	...	34.44	30.00	0.49
0528+134	N	...	0.47	−0.69	...	−1.00	...	...	...	...	...
0537−441	Y	Y	0.06	0.05	0.4	−0.65	...	...	34.37	31.49	0.52
0538+498	N	Y	−0.76	−2.30	0.0	−0.89	86	...	34.46	30.07	0.21
0605−085	Y	Y	0.20	−0.74	2.6	−0.83	22	65	34.25	30.46	0.59
0637−752	N	Y	0.21	−0.64	2.6	−0.70	...	87	34.26	31.05	0.33
0736+017	Y	Y	−0.26	−0.40	3.4	−0.67	59	23	32.87	29.59	1.0
0738+313	N	Y	0.28	−0.23	2.9	−0.75	...	...	33.78	30.33	0.96
0742+103	...	...	−0.08	0.07	0.4	−1.15	...	...	...	...	...
0743−673	N	Y	−0.66	−0.62	1.4	−0.71	87	34	34.74	31.43	0.99
0748+126	N	Y	0.49	−0.09	...	−0.78	...	...	34.00	30.56	0.89
0804+499	Y	N	0.49	−0.11	0.8	−0.75	87	46	34.25	31.17	0.98
0809+483	N	Y	−0.88	−2.86	2.9	−0.82	...	...	34.64	30.62	0.48
0814+425	Y	N	0.68	0.22	1.7	−0.83	13	31	...	...	...
0834−201	N	Y	−0.18	...	0.3	−0.95	...	...	35.25	31.10	0.69
0836+710	N	Y	−0.33	−1.04	9.1	−0.69	61	0	35.00	32.01	0.84
0851+202	Y	N	−0.06	−0.03	11.6	−0.53	89	74	33.37	30.83	0.70
0859−140	N	Y	−0.56	−0.80	1.9	−0.69	56	24	34.64	31.45	0.89
0923+392	N	Y	1.00	−0.48	0.8	−0.90	...	...	34.27	30.28	0.24
0954+556	Y	Y	−0.23	...	3.8	−0.75	...	45	34.20	30.70	0.93
1055+018	Y	Y	0.34	−0.02	2.6	−0.83	19	44	34.22	30.48	0.60
1104−445	N	Y	0.14	0.50	4.0	−0.80	...	...	34.46	31.01	0.97
1127−145	N	Y	−0.02	−0.51	5.5	−0.80	0	51	34.82	31.22	0.36
1136−135	N	Y	−0.36	−0.88	2.4	−0.78	...	...	33.82	30.09	0.94
1144−379	Y	N	0.99	1.50	2.1	−0.65	...	61	...	...	...
1151−348	N	Y	−0.69	−1.51	0.3	−0.78	...	...	33.32	29.47	0.64
1226+023	N	Y	−0.01	−1.42	3.1	−0.65	39	64	34.03	30.82	0.02
1245−197	...	...	−0.63	...	0.1	−1.00	...	...	...	...	...
1253−055	Y	Y	0.31	−0.34	2.5	−0.86	22	58	34.10	30.45	0.11
1328+254	N	Y	−0.59	...	4.4	−0.80	...	...	34.60	30.77	0.65
1328+307	N	Y	−0.53	−2.64	11.0	−0.82	0	14	34.76	30.83	0.28
1334−127	Y	Y	0.20	0.08	2.7	−0.84	...	85	33.71	29.78	0.88
1424−418	Y	...	0.39	−0.70	0.8	−0.78	24	34	...	...	...
1458+718	N	Y	−0.66	−1.68	5.0	−0.74	...	...	34.55	30.98	0.56
1502+106	Y	Y	0.48	0.35	3.3	−0.87	...	32	34.45	30.87	0.90
1508−055	N	Y	0.19	−0.94	2.9	−0.64	...	3	34.31	31.57	0.85
1510−089	Y	Y	0.27	0.44	2.3	−0.81	86	31	33.53	29.67	0.59
1519−273	Y	...	0.27	0.47	...	−0.84	...	...	...	...	...
1538+149	Y	N	0.61	−0.37	5.4	−0.73	3	2	...	...	...
1548+056	Y	Y	0.21	−0.15	1.9	−0.83	...	52	34.39	30.77	0.92
1555+001	N	Y	0.15	0.74	0.7	−0.90	...	...	34.56	30.67	0.92
1610−771	Y	Y	−0.10	−0.45	6.9	−0.92	43	29	34.89	30.76	0.60
1611+343	N	Y	0.10	−0.03	2.6	−0.77	15	55	34.50	31.15	0.79
1622−253	N	...	−0.14	−1.15	...	−0.84	...	...	...	...	...
1633+382	N	Y	0.77	0.21	1.9	−0.82	19	88	34.42	31.22	0.76
1641+399	Y	Y	−0.53	−0.41	3.0	−0.77	36	67	34.47	30.76	0.23
1656+053	N	Y	0.49	0.03	2.0	−0.69	...	82	33.97	30.99	0.93
1740−517	N	...	−0.67	...	...	−0.92	...	...	...	...	...
1741−038	Y	...	0.36	−1.55	0.9	−0.88	...	...	...	...	...
1828+487	N	Y	−0.53	−1.42	6.8	−0.80	...	...	34.54	30.71	0.28
1928+738	N	Y	−0.01	−0.46	3.6	−0.71	2	65	33.60	30.19	0.53
1954−388	Y	Y	0.25	−0.48	4.7	−0.72	...	47	33.78	30.49	0.97
2052−474	N	Y	−0.48	−0.79	5.1	−0.79	...	47	34.75	31.09	0.83
2106−413	N	...	0.17	−0.15	3.5	−0.84	...	...	...	...	...

TABLE 5—*Continued*

Source (1)	$p_{max}>3\%$ (2)	L/C>0.1 (3)	α_r (4)	log R (5)	p_r (%) (6)	α_{ro} (7)	$\Delta\theta_1$ (deg) (8)	$\Delta\theta_2$ (deg) (9)	log L_r (erg/s/Hz) (10)	log L_o (erg/s/Hz) (11)	V/V_{max} (12)
2121+050	Y	Y	0.84	0.26	0.9	−0.75	...	14	34.24	31.46	1.0
2128+047	...	...	−0.72	−0.75	0.0	0.00	...	...	...	...	...
2128−123	N	Y	0.07	−0.58	0.7	−0.63	...	...	33.64	30.71	0.96
2131−021	...	N	0.16	0.16	5.7	−0.85	...	...	33.72	29.73	0.94
2134+004	N	Y	0.76	−0.87	0.2	−0.85	...	...	35.07	31.77	0.27
2145+067	N	Y	0.21	−0.20	1.4	−0.74	...	68	34.45	31.19	0.48
2200+420	Y	N	−0.15	−0.68	2.5	−0.53	41	28	32.30	29.67	0.37
2201+315	N	Y	0.23	−0.89	0.3	−0.60	40	87	33.26	30.41	0.83
2203−188	N	Y	−0.29	...	2.9	−0.97	...	...	34.20	29.51	0.44
2204−540	N	Y	0.52	−0.32	1.1	−0.81	...	...	34.21	30.75	0.85
2223−052	Y	Y	−0.05	−0.75	2.4	−0.89	33	47	34.79	30.79	0.52
2230+114	Y	Y	−0.50	−0.88	3.6	−0.78	28	80	34.62	30.92	0.58
2243−123	Y	Y	−0.18	−0.60	3.7	−0.68	...	22	33.94	30.77	0.81
2251+158	Y	Y	0.50	−0.32	5.4	−0.82	59	44	34.86	31.20	0.13
2326−477	N	Y	−0.02	−0.78	4.6	−0.71	...	24	34.47	31.35	0.82
2345−167	Y	Y	0.58	0.57	1.1	−0.88	45	27	33.90	29.85	0.52

tions. Only five of them have $p_{max} > 3\%$ after a larger number of polarization measurements. Our lower limit on the percentage of quasars that ever have $p > 3\%$ is 56%, in agreement with the calculation by Fugmann (1988) using an independent method.

b) *Low-Polarization Quasars*

The choice of $p = 3\%$ as a threshold for blazar activity is arbitrary. It is set to ensure that interstellar polarization is a minor contributor to sources with high polarization. Figure 4*a* shows the distribution of polarization for 105 field stars around the radio sources. Over $\frac{2}{3}$ of the stars have $p < 0.5\%$. On the other hand, with the exception of rare objects like PHL 5200, polarization above 3% is invariably due to the synchro-

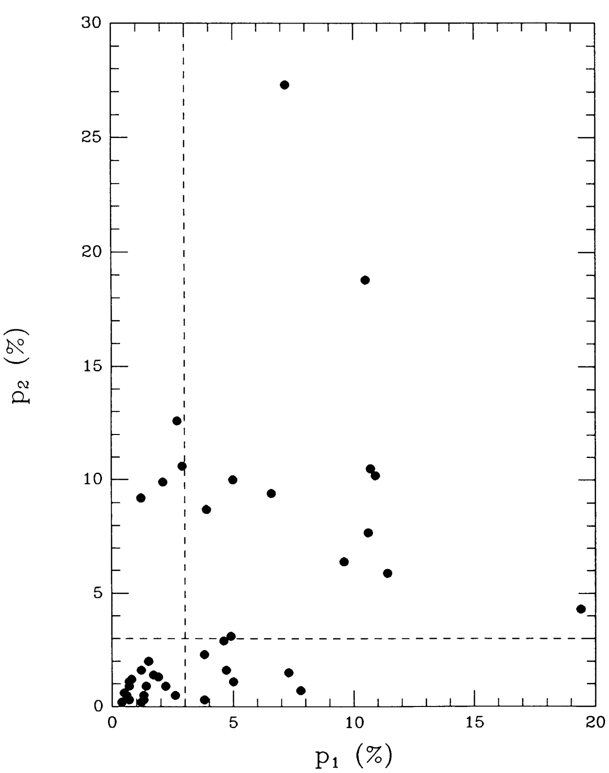

FIG. 3.—First-epoch polarization measurement plotted against second-epoch measurement for the 41 quasars with only two published epochs of polarimetry. Dashed lines are plotted at $p = 3\%$.

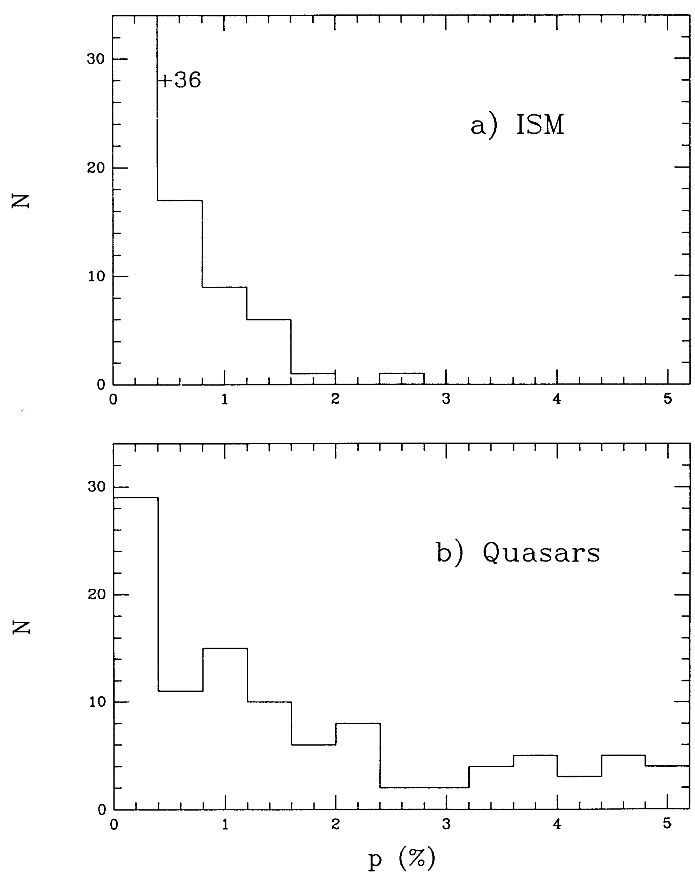

FIG. 4.—Histograms of (*a*) interstellar polarization for 105 field stars at high Galactic latitude, and (*b*) polarization for all 2 Jy quasars. The first in of the ISM histogram contains 70 stars. Polarimetry has been corrected for low signal-to-noise ratio bias.

TABLE 6

1.5 JANSKYS: RADIO AND OPTICAL DATA

Source	p_{max} >3%	L/C>0.1	α_r	log R	p_r (%)	α_{ro}	$\Delta\theta_1$ (deg)	$\Delta\theta_2$ (deg)	log L_r (erg/s/Hz)	log L_o (erg/s/Hz)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
0003−066	Y	N	0.03	−0.43	...	−0.81	...	...	33.23	29.31
0016+731	N	Y	0.16	−0.25	1.1	−0.77	...	...	34.43	31.20
0048−097	Y	N	0.74	1.08	6.7	−0.74	...	5	...	...
0113−118	...	Y	0.14	−0.48	0.6	−0.82	...	...	33.82	30.00
0119+041	Y	Y	0.31	0.01	...	−0.90	...	...	33.73	29.54
0135−247	N	Y	0.35	−0.50	...	−0.68	...	...	33.87	30.85
0153+744	N	Y	−0.32	−0.29	0.0	−0.76	50	...	34.82	31.49
0229+131	N	Y	−0.41	−0.50	3.0	−0.74	...	...	34.77	31.48
0400+258	...	Y	0.16	−0.35	4.0	−0.78	...	...	34.57	31.38
0405−123	N	Y	−0.31	−0.70	1.5	−0.71	60	46	33.80	30.40
0420−014	Y	Y	−0.24	0.19	0.8	−0.76	...	54	34.11	30.59
0458−020	Y	Y	−0.14	−0.07	4.1	−0.81	...	80	34.78	31.31
0500+019	N	...	−0.47	−0.16	0.4	−0.95	...	...	...	...
0506−612	N	Y	−0.09	...	2.2	−0.69	...	85	34.20	31.13
0539−057	Y	Y	1.41	...	...	−0.80	...	...	33.83	30.95
0606−223	Y	Y	0.55	−0.14	...	−0.92	...	...	34.26	30.48
0607−157	N	Y	−0.38	−0.43	0.5	−0.74	...	...	33.29	29.69
0711+356	N	Y	−0.31	0.73	1.3	−0.68	...	...	34.53	31.50
0735+178	Y	N	0.02	−0.37	3.5	−0.66	90	59	33.47	30.35
0743−006	N	N	0.57	−1.03	0.2	−0.75	...	...	33.99	30.79
0820+225	Y	...	−0.19	−1.20	1.6	−0.86	...	43	...	...
0859+470	N	Y	−0.09	0.08	4.1	−0.83	...	...	34.43	30.71
0906+430	Y	N	−0.46	−0.23	0.9	−0.82	80	55	33.92	30.00
0953+254	N	Y	0.58	0.74	3.3	−0.73	...	59	33.70	30.46
1034−293	Y	N	0.33	0.58	...	−0.64	...	...	...	...
1057−797	...	...	0.58	−0.04	...	−0.88	...	...	...	...
1148−001	N	Y	−0.48	−0.94	4.2	−0.75	...	...	34.86	31.47
1255−316	N	Y	0.24	−0.84	...	−0.83	...	...	34.46	31.00
1308+326	Y	N	−0.05	−0.09	...	−0.84	78	...	34.06	30.20
1354−152	N	Y	−0.06	−0.42	2.7	−0.80	...	42	34.53	31.06
1354+195	N	Y	−0.15	−0.30	3.2	−0.64	...	...	33.84	30.87
1451−375	N	Y	0.37	−0.44	1.7	−0.68	...	87	33.20	29.98
1504−166	Y	Y	0.19	−0.18	0.9	−0.82	88	63	34.01	30.26
1600+335	...	...	−0.75	−0.10	...	...	...	...	...	...
1619−680	...	...	0.07	0.07	...	...	...	...	...	...
1622−297	...	...	−0.14	−0.82	4.6	...	...	...	...	...
1642+690	Y	Y	−0.26	−0.20	5.0	−0.86	7	83	33.91	29.83
1655+077	...	Y	0.43	−0.21	...	−0.99	...	...	33.63	29.00
1739+522	Y	Y	0.07	0.41	1.9	−0.80	11	75	34.24	30.73
1749+701	Y	N	−0.33	−0.35	3.4	−0.66	4	31	...	...
1749+096	Y	N	1.08	0.38	10.0	−0.67	50	65	33.05	29.96
1823+568	Y	N	0.17	−0.14	4.0	−0.80	3	16	33.72	30.03
1903−802	...	...	0.29	...	2.4	−0.86	...	...	33.55	29.51
1936−155	Y	Y	0.26	0.05	...	−0.88	...	...	34.35	30.56
2155−152	Y	N	0.15	−0.12	6.0	−0.78	...	16	33.78	30.20
2216−038	N	Y	0.36	0.06	0.7	−0.63	...	47	33.86	31.13
2227−088	N	Y	0.28	0.09	2.4	−0.78	...	...	34.32	31.06
2245−328	N	Y	−0.13	−0.04	...	−0.83	...	...	34.78	31.22
2255−282	N	Y	0.41	−0.23	...	−0.68	...	...	33.94	31.00
2355−534	Y	Y	0.48	0.92	3.4	−0.76	...	31	33.96	30.69

tron process. The variability argument in the last section gives an estimate of the number of quasars with $p_{max} > 3\%$ which may lie below 3% in an individual measurement. However, there may be sources where the synchrotron polarization never rises above 3%.

The low level quasar polarizations are presented in Figure 4*b* for the 2 Jy and 1.5 Jy samples combined. All values have been corrected for low signal-to-noise bias according to the prescription of Simmons and Stewart (1985). Comparison of the two panels shows that there is intrinsic quasar polarization down to the 1% level, confirming the results of Stockman, Moore, and Angel (1984). The quasar 3C 273 provides the best evidence that synchrotron polarization may be found at levels below $p = 3\%$. Impey, Malkan, and Tapia (1989) and Wills (1989) have found both a miniblazar component and a quiescent, low-polarization component in this bright quasar. The blazar properties have been diluted down to a level where $p_{max} = 2.5\%$ (Courvoisier *et al.* 1988). It is not known how many of the flat spectrum quasars with $p_{max} < 3\%$ exhibit similar behavior.

c) Radio Structure

Quasars show a clear relationship between radio structure and the incidence of polarized optical emission. This is seen by the different polarized fractions in the 1.5 Jy and 3C samples (Table 4). Radio sources selected at a low frequency are more likely to have steep radio spectra and be less compact (Fig. 1). VLBI data can be used to calculate the fraction of the flux in a milliarcsecond core. All measures of compactness or S_{core}/S_{ext} are derived from the VLBI survey of Preston *et al.* (1985). In

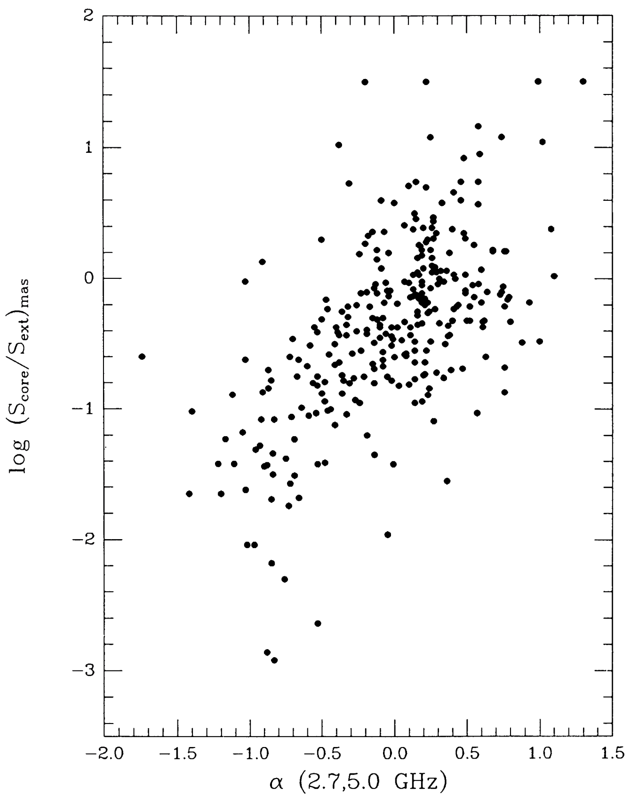

FIG. 5.—Ratio of core to extended radio flux density at 2.29 GHz plotted against radio spectral index between 2.7 and 5 GHz for a large number of quasars. Compactness on milliarcsecond scales is derived from VLBI observations published by Preston *et al.* (1985).

fact, they are only crude estimates, using the visibilities with fringe spacings of about 3 mas. The correlated flux density is assumed for the core component, and the total minus correlated flux density is assumed for the extended component. Accurate compactness estimates require a VLBI map, but visibility functions are appropriate when the source structure is simple. Figure 5 plots compactness on VLBI scales versus radio spectral index between 2.7 and 5 GHz and can be compared with Figure 1. The arcsecond and milliarcsecond measures of compactness are related to spectral index with similar scatter. Compactness is not correlated with redshift, despite the fact that interferometry of more distant sources probes larger physical regions.

Figure 6*a* shows milliarcsecond compactness plotted against first epoch polarization for the 2 Jy and 1.5 Jy samples. The probability that these two quantities are uncorrelated is less than 0.001%. A similar correlation is shown by Wills (1989), using radio compactness defined on arcsecond scales. The correlation between p and redshift noted by Wills is not seen in this data set. On the other hand, a correlation between p_{max} and redshift is seen. However, high-redshift sources are typically fainter and have fewer polarization measurements. Nonuniform polarization sampling can produce a correlation between p_{max} and redshift. The fraction of quasars with $p > 3\%$ is plotted against milliarcsecond compactness in Figure 6*b*. Data for 105 quasars are included, and the dashed lines give the 1 σ errors.

The results in Figure 6 can be applied to other quasar samples. For example, the 3CR quasars are selected at the lower frequency of 178 MHz and so include sources with more extended radio emission. We can predict the fraction of highly polarized quasars in the 3CR sample, knowing the distribution of values of compactness. The prediction is $\sim$25%, in good agreement with the 21% $\pm$ 8% found to have $p > 3\%$ (seven out of 33 with measured polarizations in a total sample of 51). Note that the polarized fraction is leveling off at a value around $\frac{2}{3}$ for $S_{core} > S_{ext}$. If the variability characteristics are independent of radio structure, then virtually *every* quasar with $S_{core} > S_{ext}$ is highly polarized. Alternatively, the trend in Figure 6 can be explained if the duty cycle of high-polarization states is correlated with radio compactness.

d) *Emission-Line Strength*

The radio sources in this survey were observed without regard to optical brightness or emission line strength, as far as possible. The first radio sources to be searched for optical polarization due to synchrotron emission had weak emission lines: the BL Lacertae objects (Angel and Stockman 1980). Later, Moore and Stockman (1981) described the properties of highly polarized AGNs with normal strength emission lines. These were the highly polarized quasars or HPQs. The two classes of object shared the continuum properties of a compact synchrotron source and were amalgamated with the term "blazar." We note that a number of variable AGNs look either like BL Lacs or quasars depending on the level of the contin-

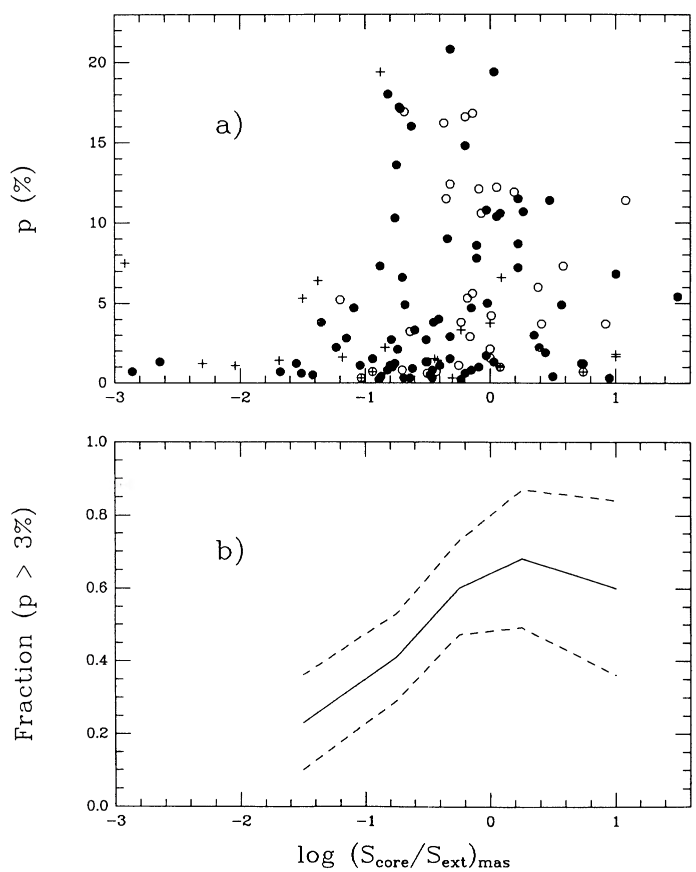

FIG. 6.—Radio compactness on milliarcsecond scales plotted against (*a*) first-epoch optical polarization for quasars in the 2 Jy (*filled circles*), 1.5 Jy (*open circles*), and 3CR (*crosses*) samples, and (*b*) the fraction of 2 Jy and 1.5 Jy quasars with $p > 3\%$. Dashed lines give the 1 σ errors.

uum. Also, the standard definition of a BL Lac object is ambiguous since it depends on the signal-to-noise ratio and coverage of the spectrum.

For the purposes of this study, a BL Lac object has been defined as a stellar counterpart where the lines are less than 10% of the continuum strength. A spectrum was located for each radio source, using the quasar catalog of Hewitt and Burbidge (1987, 1989) as a primary reference. The spectra range widely in quality, but broad lines at 10% of the continuum level can be readily seen. BL Lac objects are rare. Only nine sources in the 2 Jy sample and 11 sources in the 1.5 Jy sample have suitably weak lines. Figure 7 reveals a striking difference in the polarization properties of radio sources with weak and strong emission lines. While 44 out of 128 (34%) of the quasars have $p > 3\%$, 19 out of 20 of the BL Lac objects have $p > 3\%$. The duty cycle of BL Lac objects in the high-polarization state must be very high. The probability that weak-lined and strong-lined sources have the same polarization properties is less than 10^{-5}. This result is confirmed for the 2 Jy sample alone, with a probability of 0.002. Since the number of BL Lac objects is small, this result depends on the status of the 10 radio sources without either polarimetry or emission line data. However, if all 10 have weak lines *and* weak polarization, the probability only drops from 10^{-5} to 0.004.

e) Other Radio and Optical Properties

Tables 5 and 6 include a listing of maximum radio polarization, usually measured at 5 GHz and taken from the compilation of Tabara and Inoue (1980). Our sample shows no correlation between radio and optical polarization, although a few sources with very high radio polarization (above 10%) also have high optical polarization. A lack of correlation is not surprising since there is no evidence that the radio and optical emission comes from the same location in the source. Faraday optical depths may be large at radio wavelengths and negligible at optical wavelengths. Unlike the optical polarization, the radio polarization is not related to S_{core}/S_{ext} (Okudaira *et al.* 1989). Polarization position angles at radio and optical wavelengths are not aligned, nor is there an alignment between the position angle of the VLBI structure axis and the optical polarization. This is probably because most of the quasars have a single polarization measurement, with no good sampling of the position angle variations. When a *preferred* polarization position angle can be defined, the angle difference peaks at 0° (Rusk and Sequist 1985; Impey 1987).

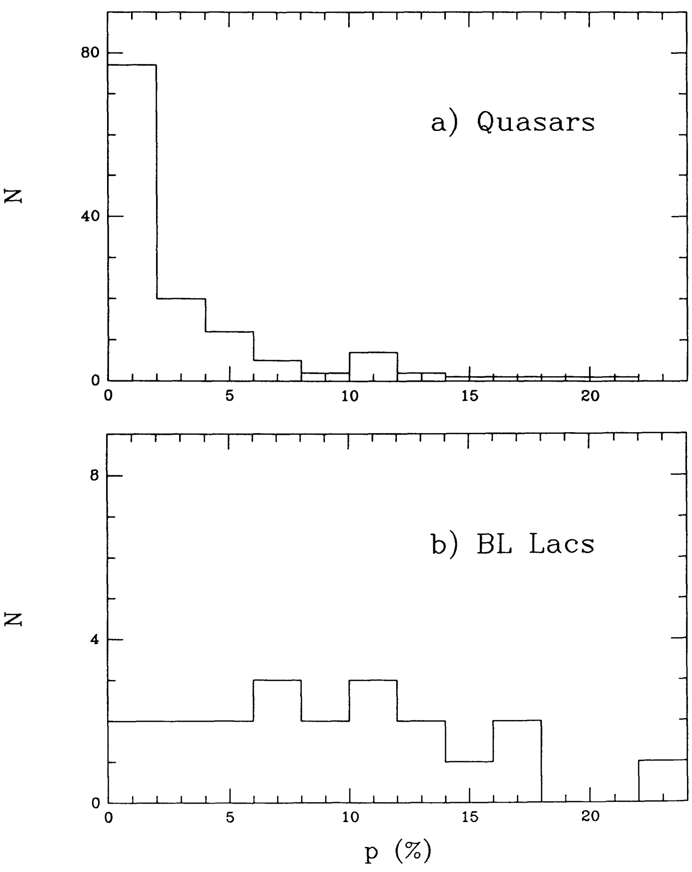

FIG. 7.—Distribution of first-epoch polarization for (*a*) quasars with strong emission lines and (*b*) BL Lac objects. Data from the 2 Jy and 1.5 Jy samples are combined.

The spectral index between 5 GHz and the V band is listed in Tables 5 and 6. Nonparametric tests show no difference between the distribution of α_{ro} for sources with high or low polarization, and weak or strong emission lines. The difference in α_{ro} between quasars and BL Lacs seen in the data of Ledden and O'Dell (1985) and the preliminary analysis of Impey and Tapia (1988) is not confirmed with this larger set of sources. The mean values are $\alpha_{ro} = -0.77 \pm 0.09$ (quasars) and -0.73 ± 0.11 (BL Lacs). Earlier indications that BL Lac objects have flatter radio-to-optical spectra were probably due to inhomogenous samples. Demonstrating a lack of emission lines requires a high signal-to-noise ratio spectrum of a bright source. For example, the 38 BL Lacs in the review article of Angel and Stockman (1980) have $\alpha_{ro} = -0.56 \pm 0.11$.

Another issue is the luminosity of the highly polarized sources compared to those with low polarization. Nonparametric tests show no significant difference between the redshift distributions of sources with $p_{max} < 3\%$ and $p_{max} > 3\%$. Nor is there any dependence of radio or optical luminosity on polarization in the 2 Jy sample. The redshift distribution of the BL Lac objects is of particular interest, since some of them may be a gravitationally lensed population (Ostriker and Viestri 1985; Ostriker 1989). High-quality data have revealed weak lines in the spectra of many BL Lac objects, and 14 out of the 20 in the 2 Jy and 1.5 Jy samples now have redshifts. BL Lac objects have lower redshifts than quasars at the 3% significance level. The incomplete redshifts prevent a firm conclusion, since the BL Lac objects without redshifts are mostly faint ($V > 18$) and may be at large distances. Figure 8 shows the redshift distributions of the quasars and BL Lac objects. Overall, the BL Lac objects reflect the redshift distribution of the quasar population and do not show a peak at low redshifts which might be due to microlensing. It may be argued that the microlensing signature should be weak in a radio-selected sample, since the radio-emitting region is larger than the optical-emitting region, and therefore the amplification probability is lower. However, there is no evidence for microlensing in either the redshift distribution or the evolution function of the radio-selected BL Lac objects.

The results of statistical tests on the quasars are summarized in Tables 7 and 8. Nonparametric statistics were used to look for differences between quasars of high and low polarization and strong and weak emission lines. Three tests were used: the T-test (TT), the Kolmogorov-Smirnov test (KS), and the Mann-Whitney test (MW). The last of these is especially powerful for small samples. The numbers quoted are the prob-

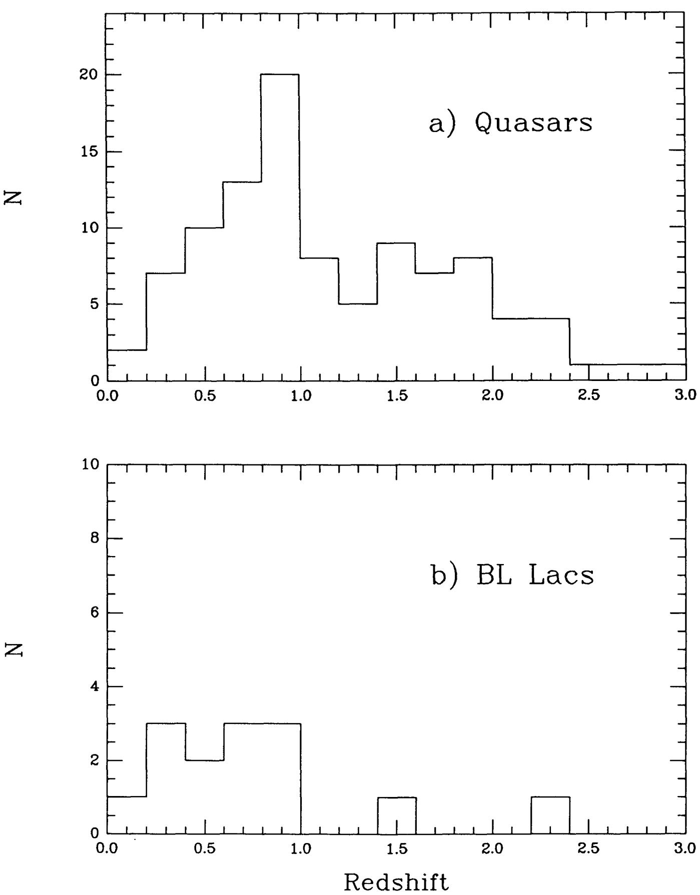

FIG. 8.—Redshift distribution of (*a*) quasars and (*b*) BL Lac objects in the 2 Jy and 1.5 Jy samples. Redshifts for the BL Lac objects are only 70% complete.

abilities that the null hypothesis is correct, i.e. that the two distributions are drawn from the same parent distribution. The statistics are calculated for the 2 Jy sample (cols. [2]–[4]), and for the larger sample including the 1.5 Jy and 3CR quasars (cols. [5]–[7]). Only results with 95% significance or greater are entered in the two tables. Table 7 shows that polarized quasars have brighter V magnitudes and flatter values of α_{ro} than unpolarized quasars; however, it is not significant when only 2 Jy quasars are used. This bias is caused by the fact that only the optically bright 3CR sources have polarimetry. The main result of this paper is established with a high degree of confidence: that high optical polarization in quasars is associated with compact radio structure and weak emission lines.

V. RELEVANCE TO BEAMING MODELS AND UNIFIED SCHEMES

The study of highly polarized AGNs has generally concentrated on the nonthermal emission mechanism behind the observed radiation. Arguments based on energetics have been used to show that relativistic source motion boosts the optical continuum in blazars; the most influential paper on this subject was by Blandford and Rees (1978). Until now, little progress has been made in the statistical study of polarized AGNs, due to the bizarre nature of the variability and the lack of a complete sample to study.

a) Luminosity Functions and V/V_{max}

We can calculate a luminosity function for the 2 Jy sample. In particular, the sample is divided into low- and high-polarization objects, and 81% or 73 quasars have both redshifts and polarimetry. Figure 9 shows the two luminosity functions, and there is weak evidence that the blazar space density increases with respect to the quasar space density in the highest luminosity bin. The effect is significant at the 95% level, rebinning the data preserves the result. Urry and Shafer (1984) showed that the luminosity function of a beamed population will be much flatter than that of the unbeamed parent population. In the 2 Jy sample, the polarized and unpolarized quasars evolve in the same way. There is also a correlation between radio luminosity and α_{ro}, in the sense that more luminous radio quasars have a larger ratio of radio to optical emission. This can occur if the optical radiation has less Doppler boosting than the radio radiation.

The last column of Table 5 gives the value of V/V_{max} for each 2 Jy quasar. The mean value is $\langle V/V_{max} \rangle = 0.68 \pm 0.03$, the signature of a population that is strongly evolving with cosmic time. Other determinations of $\langle V/V_{max} \rangle$ for flat spectrum samples are similar: 0.72 ± 0.05 for quasars with $S_{1400\,MHz} > 2$ Jy (Blake 1978) and 0.68 ± 0.04 for quasars with $S_{2700\,MHz} >$ 1.5 Jy (Peacock *et al.* 1981). There is no difference between the distributions of $\langle V/V_{max} \rangle$ for high- and low-polarization sources. Six out of nine BL Lac objects have redshifts in the 2 Jy sample. The mean values are $\langle V/V_{max} \rangle = 0.67 \pm 0.03$ for strong-lined quasars and $\langle V/V_{max} \rangle = 0.81 \pm 0.08$ for BL Lac objects. Therefore, radio-selected BL Lac objects show no evidence of the weak evolution that is seen in X-ray selected samples (Maccacaro *et al.* 1989).

TABLE 7

HIGH-POLARIZATION VERSUS LOW-POLARIZATION QUASARS[a]

	ALL QUASARS			2 Jy QUASARS		
PARAMETER (1)	MW (2)	KS (3)	TT (4)	MW (5)	KS (6)	TT (7)
Redshift	...	...	...	...	...	...
V magnitude	0.0068	<0.001	0.002	...	...	...
α_{ro}	0.0015	<0.01	0.004	...	...	...
α_r	$<10^{-5}$	<0.001	$<10^{-4}$	0.0023	<0.01	0.008
S_{core}/S_{ext}	$<10^{-5}$	<0.001	$<10^{-4}$	0.0002	<0.01	$<10^{-4}$
p_{rad}	...	...	0.029	...	...	...
L_r	...	...	...	...	...	...
L_o	0.0015	...	0.025	...	...	...
V/V_{max}	...	...	0.042	...	...	...

[a] Probability that two samples are drawn from same distribution.

TABLE 8

QUASARS VERSUS BL LACERTAE OBJECTS[a]

	All Quasars			2 Jy Quasars		
Parameter (1)	MW (2)	KS (3)	TT (4)	MW (5)	KS (6)	TT (7)
Redshift	0.016	<0.05	0.032	...	...	...
V magnitude	...	...	...	...	...	...
α_{ro}	...	...	...	...	...	...
α_r	0.001	<0.01	...	0.047	...	...
S_{core}/S_{ext}	0.0001	<0.001	0.019	0.012	<0.05	...
p_{opt}	$<10^{-5}$	<0.001	$<10^{-4}$	0.0019	<0.01	$<10^{-4}$
L_r	0.0016	<0.01	0.039	...	...	0.029
L_o	0.0029	<0.05	...	...	...	...
V/V_{max}	0.03	...	...	...	...	...

[a] Probability that two samples are drawn from same distribution.

b) *Relativistic Motion and Unified Schemes*

The evidence that the optical emission in blazars is relativistically boosted or beamed is indirect and is based on a few highly luminous sources. The most convincing indication of bulk relativistic motion in radio sources comes from the apparent superluminal motion of VLBI components (Pearson and Zensus 1987). Most superluminal sources also show blazar characteristics at optical wavelengths (Impey 1987). Two issues can be addressed. The first is whether or not both the radio and optical emission can be explained with a single model of relativistic motion. The second is whether or not the statistics of polarization fit in with "unified" models of AGN. In the most successful type of unified model, the differences between compact and extended radio sources are due to Doppler boosting of the core emission and projection effects (Orr and Browne 1982).

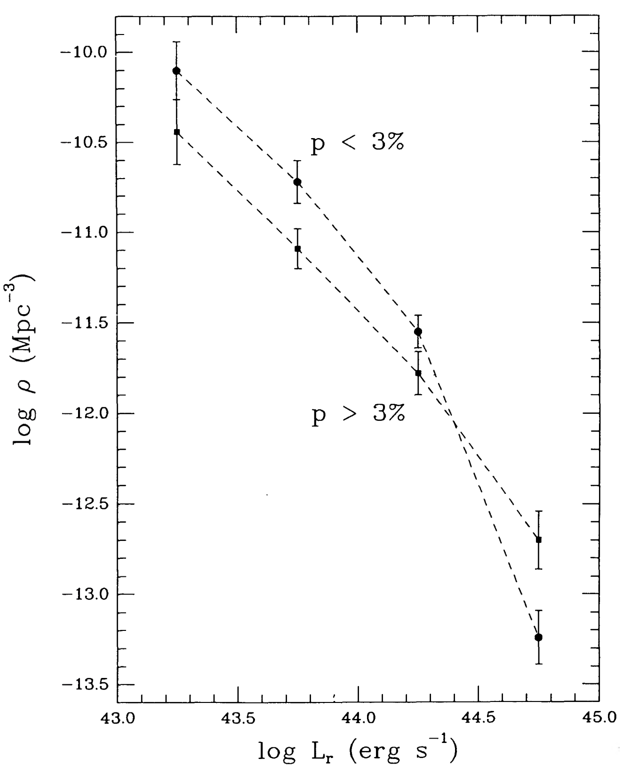

FIG. 9.—Radio luminosity function of 2 Jy quasars, divided into sources of high and low polarization.

The simple beaming model assumes that extended radio emission is emitted isotropically, and core emission is beamed into a solid angle defined by the speed of the flow. We assume that there is both a beamed and an isotropic component at optical wavelengths: high polarization is a characteristic of beamed radiation, and the unpolarized radiation found in extended radio sources is emitted isotropically. For oppositely directed jets with relativistic speed βc, the Doppler boosting factor is $R(\theta) = S_T/2[(1-\beta\cos\theta)^{-(2-\alpha)} + (1+\beta\cos\theta)^{-(2-\alpha)}]$, where θ is the angle to the line of sight and the transverse flux $R_T = R(\pi/2)$. This represents an idealized version of what in reality may be a complex hydrodynamic flow (Lind and Blandford 1985). R_T is the ratio of core to extended flux densities for an orientation independent sample; Orr and Browne (1982) used the 3CR quasars to derive $R_T = 0.024$. The beaming of the radio emission is a factor of 1200 for $\gamma = 5$, corresponding to a range of $R_T < R < \gamma^2(2\gamma^2 - 1)R_T$. The optical emission (denoted by S) has $\alpha = -0.7$ and the flux amplification is an even stronger function of jet speed βc. Browne and Murphy (1987) showed that for a face-on jet with low R, $S(\theta)/S_T = 1$, and for an end-on jet with high R, $S(\theta)/S_T = 1/2(2R/R_T)^{1.35}$. If the polarized radiation is beamed, there should be a rapid rise in the contribution of polarized optical flux with increasing compactness of the radio source.

We use VLBI data for calculating radio compactness, compared with earlier studies that have used VLA data. There is a good correlation between radio compactness measured at arcsecond and milliarcsecond scales for a large set of radio quasars (see Figs. 1 and 5). This indicates that VLBI visibilities can generate a parameter that measures compactness. Browne and Perley (1986) found that R values generated from VLA visibilities and VLA maps agreed to a factor of 2. As expected, $R_{VLBI} < R_{VLA}$, indicating that flux on arcsecond scales has been resolved out with the VLBI experiment. At milliarcsecond scales, the value of R_T corresponding to extended and isotropic radio emission is 0.008.

The unified scheme of Orr and Browne assumes extended radio sources to be the randomly oriented population. It successfully accounts for the source counts and redshift distribution of compact radio sources (Orr and Browne 1982; Kapahi and Kulkarni 1986) but is less successful in matching the observed distribution of R for compact sources (Browne and

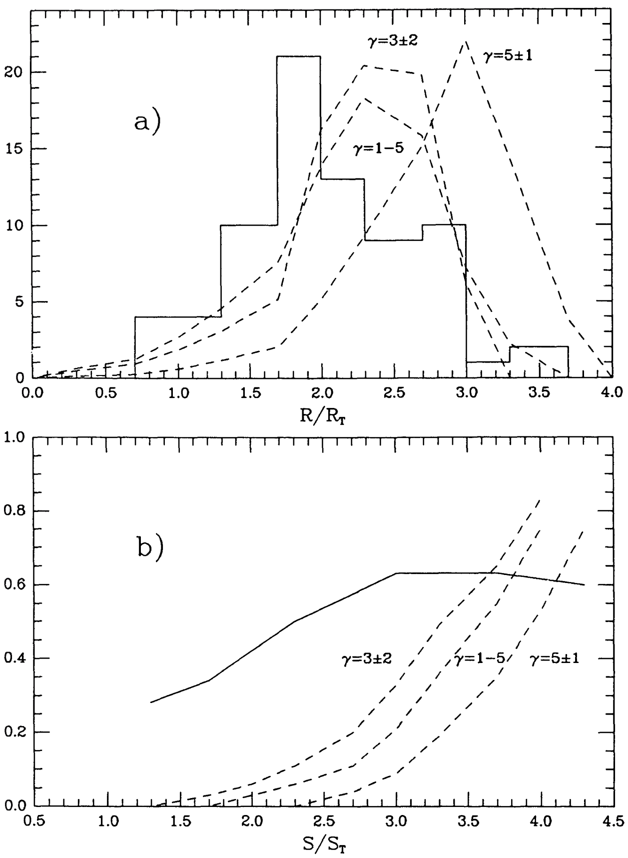

FIG. 10.—(*a*) The normalized distribution of R/R_T plotted for three different distributions of Lorentz factor, γ (*dashed lines*). The 2 Jy data are plotted as the solid histogram. At milliarcsecond scales, a transverse value of $R_T = 0.008$ is assumed. (*b*) The normalized distribution of the beaming factor for optical emission, S/S_T, assuming that radio core emission and polarized optical emission have similar beaming patterns (*dashed lines*). The observed fraction of polarized sources is the solid curve. The offset in S/S_T between the models and the data gives the amount of unpolarized, isotropic optical flux.

Perley 1986). The parent population for the compact sources is still unknown (Phinney 1985). Figure 10*a* shows the observed distribution of radio R/R_T (*solid histogram*, where $R = S_{\rm core}/S_{\rm ext}$ is measured on milliarcsecond scales), compared with the predictions for three distributions of the Lorentz factor, γ (*dashed curves*). R values are calculated at an observed rather than a rest frequency, neglecting the redshift introduces a scatter of no more than a factor of 3. The distributions of Lorentz factor are a Gaussian with mean and dispersion $\gamma = 5 \pm 1$, a Gaussian with mean and dispersion $\gamma = 3 \pm 2$, and a uniform distribution from 1 to 5. Values of γ up to 5 are indicated by the proper motion of VLBI components, but lower values are also required to match the many 2 Jy sources in the range $20 < R/R_T < 500$.

An analogous test of the beaming model can be carried out with the optical data. We assume that the polarized blazar emission is beamed into the same cone as the radio emission and that the luminosity of the optical polarized component is proportional to the core radio luminosity. The data plotted in Figure 10*b* are the fraction of highly polarized quasars as a function of R/R_T from Figure 6 (*solid curve*), transformed into an optical beaming factor $S/S_T = 1.27(R/R_T)^{1.35}$ (since $R > R_T$). For beamed optical radiation, we calculate $n(S)dS \propto (S)^{3/2}d(\cos\theta)$ and determine the fraction of sources with $S > S(\theta)$. The same three distributions of γ are used in Figures 10*a* and 10*b*. The beaming model predicts a much faster rise in the fraction of polarized sources than is seen in the 2 Jy data, due to the strong Doppler favoritism for high-γ sources. Evidently, different beaming geometries are required for the radio and optical emission. Models are now being developed where the bulk velocity increases with distance along the jet, while the emission spectrum shifts to lower frequencies (Ghisellini and Maraschi 1989). Our results can be explained if the bulk relativistic motion of the optical-emitting plasma is slower than the bulk relativistic motion of the radio-emitting plasma.

Another number we can extract from Figure 10*b* is the ratio of unbeamed optical emission to S_T, given by the value of S/S_T where the fraction of beamed sources begins to rise rapidly. For the 2 Jy data, this rise occurs at $S/S_T \sim 10$. In the models, the rise occurs in the range $200 < S/S_T < 1000$. Therefore, the dilution by isotropic, unpolarized flux is a factor of 20–100, and only when the beamed component is boosted by at least this factor will the radiation be highly polarized. A similar conclusion was reached by Browne and Murphy (1987), using arguments independent of polarization information. The pessimist (or realist) would argue that we are pushing the beaming model too far, and the polarimetry adds little to the current debate. The optimist would counter that the union of optical and radio data will constrain aspects of beaming such as the distribution of Lorentz factors and create new tests for the unified schemes.

VI. CONCLUSIONS

Polarization and other properties have been compiled for several large samples of radio-selected quasars, including 90 sources stronger than 2 Jy at 5 GHz. With nearly complete polarimetry and redshift information for a large and complete sample, we draw the following conclusions:

1. About 40% of the 2 Jy sample have optical polarization above 3% in a single measurement. A duty cycle calculation based on multiple measurements shows that the underlying fraction of quasars with high polarization is about $\frac{2}{3}$.

2. Over a hundred field stars have been used to measure interstellar polarization in the fields of the quasars. The interstellar contribution to a quasar polarization of 3% is small. Intrinsic polarization between 1% and 3% is seen in one in five of the quasars; it is not known if this is synchrotron emission.

3. The fraction of quasars showing optical blazar emission ($p > 3\%$) increases with increasing compactness of the radio source. Allowing for a duty cycle correction, essentially every quasar with $S_{\rm core} > S_{\rm ext}$ on VLBI scales is highly polarized.

4. High polarization is strongly correlated with weak emission lines in the quasar spectrum. About 10% of flat spectrum quasars have emission lines of less than 1/10 of the continuum strength, but they are virtually all polarized (BL Lac objects).

5. High optical polarization is not correlated with high radio polarization. There is no difference in the $\alpha_{\rm ro}$ distributions of high- and low-polarization sources, or sources with strong and weak emission lines.

6. The redshift information is incomplete, but BL Lac objects have somewhat lower redshifts than strong-lined quasars. However, they do not have the redshift distribution of a putative population of gravitational lenses. Their distribution of $V/V_{\rm max}$ also indicates much stronger evolution than is found for X-ray–selected BL Lac objects.

7. The strong statistical link between compact radio structure, apparent superluminal motion, and strong optical polar-

ization can be understood if both the optical and the compact radio emission are relativisitically beamed.

8. In the context of beaming models, the observed rise in the blazar fraction with radio compactness is too gradual for the radio and optical emission to have the same beaming pattern. The beamed optical emission must be Doppler boosted by a factor of ~ 100 before it exceeds the unpolarized emission typical of a steep spectrum quasar.

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REFERENCES

Angel, J. R. P., and Stockman, H. S. 1980, *Ann. Rev. Astr. Ap.*, **18**, 321.
Barthel, P. D. 1989, *Ap. J.*, **336**, 606.
Bennett, C. L., Lawrence, C. R., and Burke, B. F. 1984, *Ap. J. Suppl.*, **54**, 211.
Biermann, P., *et al.* 1981, *Ap. J. (Letters)*, **247**, L53.
Blake, G. M. 1978, *M.N.R.A.S.*, **183**, 21P.
Blandford, R. D., and Rees, M. J. 1978, in *Pittsburgh Conference on BL Lac Objects*, ed. A. M. Wolfe (Pittsburgh: University of Pittsburgh), p. 328.
Bolton, J. G. 1977, in *IAU Symposium 74, Radio Astronomy and Cosmology*, ed. D. L. Jauncey (Dordrecht: Reidel), p. 85.
Borra, E. F., and Corriveau, G. 1984, *Ap. J.*, **276**, 449.
Bridle, A. H., and Perley, R. A. 1984, *Ann. Rev. Astr. Ap.*, **22**, 319.
Brindle, C., Hough, J. H., Bailey, J. A., Axon, D. J., and Hyland, A. R. 1986, *M.N.R.A.S.*, **221**, 739.
Browne, I. W. A., and Murphy, D. W. 1987, *M.N.R.A.S.*, **226**, 601.
Browne, I. W. A., and Perley, R. A. 1986, *M.N.R.A.S.*, **222**, 149.
Condon, J. J., Jauncey, D. L., and Wright, A. E. 1978, *A.J.*, **83**, 1036.
Condon, J. J., O'Dell, S. L., Puschell, J. J., and Stein, W. A. 1981, *Ap. J.*, **246**, 624.
Courvoisier, T. J.-L., Robson, E., Hughes, D., Blecha, A., Bouchet, P., Krisciunas, K., and Schwarz, H. 1988, *Nature*, **335**, 330.
Dolan, J. F., and Tapia, S. 1986, *Pub. A.S.P.*, **98**, 792.
Feretti, L., Giovannini, G., Gregorini, L., Parma, P., and Zamorani, G. 1984, *Astr. Ap.*, **139**, 55.
Fugmann, W. 1988, *Astr. Ap.*, **205**, 86.
Fugmann, W., and Meisenheimer, K. 1988, *Astr. Ap.*, **207**, 211.
Ghisellini, G., and Maraschi, L. 1989, *Ap. J.*, **340**, 181.
Hewitt, A., and Burbidge, G. 1987, *Ap. J. Suppl.*, **63**, 1.
———. 1989, *Ap. J. Suppl.*, **69**, 1.
Impey, C. D. 1987, in *Superluminal Radio Sources*, ed. J. A. Zensus and T. J. Pearson (Cambridge: Cambridge University Press), p. 233.
Impey, C. D., and Brand, P. W. J. L. 1982, *M.N.R.A.S.*, **201**, 849.
Impey, C. D., Brand, P. W. J. L., and Tapia, S. 1981, *M.N.R.A.S.*, **198**, 1.
Impey, C. D., Brand, P. W. J. L., Wolstencroft, R. D., and William, P. M. 1982, *M.N.R.A.S.*, **209**, 245.
Impey, C. D., Malkan, M. A., and Tapia, S. 1989, *Ap. J.*, **347**, 96.
Impey, C. D., and Tapia, S. 1988, *Ap. J.*, **333**, 666.
Jannuzi, B. T., and Green, R. F. 1989, in *BL Lac Objects*, ed. L. Maraschi, T. Maccacaro, and M.-H. Ulrich (Berlin: Springer), p. 135.
Jannuzi, B. T., Smith, P. J., and Elston, R. 1989, *Ap. J.*, submitted.
Jones, T. W., Rudnick, L., Owen, F. N., Puschell, J. J., Ennis, D. J., and Werner, M. W. 1981, *Ap. J.*, **243**, 97.
Kapahi, V. K., and Kulkarni, V. K. 1986, in *IAU Symposium 119, Quasars*, ed. G. Swarup and V. K. Kapahi (Dordrecht: Reidel), p. 297.
Kinman, T. D. 1975, *Ap. J. (Letters)*, **197**, L49.
Kühr, H., and Schmidt, G. D. 1989, preprint.
Kühr, H., Witzel, A., Pauliny-Toth, I. I. K., and Nauber, A. 1981, *Astr. Ap. Suppl.*, **45**, 367.
Landau, R., *et al.* 1986, *Ap. J.*, **308**, 78.
Ledden, J. E., and O'Dell, S. L. 1985, *Ap. J.*, **298**, 630.
Lilly, S. J., and Longair, M. S. 1984, *M.N.R.A.S.*, **211**, 833.
Lind, K., and Blandford, R. D. 1985, *Ap. J.*, **295**, 358.
Maccacaro, T., Gioia, I. M., Schild, R. E., Wolter, A., Morris, S. L., and Stocke, J. T. 1989, in *BL Lac Objects*, ed. L. Maraschi, T. Maccacaro, and M.-H. Ulrich (Berlin: Springer), p. 222.
Marscher, A. P., Marshall, R. E., Mushotzsky, R. F., Dent, W. A., Balonek, T. J., and Hartman, M. F. 1979, *Ap. J.*, **233**, 498.
Miley, G. K. 1980, *Ann. Rev. Astr. Ap.*, **18**, 165.
Moore, R. L., and Stockman, H. S. 1981, *Ap. J.*, **243**, 60.
———. 1984, *Ap. J.*, **279**, 465.
Okudaira, A., Tabara, H., Kato, T., and Inoue, M. 1989, in *BL Lac Objects*, ed. L. Maraschi, T. Maccacaro, and M.-H. Ulrich (Berlin: Springer), p. 26.
Orr, M. J. L., and Browne, I. W. A. 1982, *M.N.R.A.S.*, **200**, 1067.
Ostriker, J. P. 1989, in *BL Lac Objects*, ed. L. Maraschi, T. Maccacaro, and M.-H. Ulrich (Berlin: Springer), p. 420.
Ostriker, J. P., and Viestri, M. 1985, *Nature*, **318**, 446.
Owen, F. N. 1986, in *IAU Symposium 119, Quasars*, ed. G. Swarup and V. K. Kapahi (Dordrecht: Reidel), p. 173.
Peacock, J. A. 1986, *M.N.R.A.S.*, **217**, 601.
Peacock, J. A., Perryman, M. A. C., Longair, M. S., Gunn, J. E., and Westphal, J. A. 1981, *M.N.R.A.S.*, **194**, 601.
Pearson, T. J., and Readhead, A. S. C. 1988, *Ap. J.*, **328**, 114.
Pearson, T. J., and Zensus, J. A. 1987, in *Superluminal Radio Sources*, ed. J. A. Zensus and T. J. Pearson (Cambridge: Cambridge University Press), p. 1.
Perley, R. A. 1982, *A.J.*, **87**, 859.
Phinney, E. S. 1985, in *Santa Cruz Workshop on Active Galactic Nuclei*, ed. J. Miller (Mill Valley, Ca.: University Science Books), p. 453.
Preston, R. A., Morabito, D. D., Williams, J. G., Faulkner, J., Jauncey, D. L., and Nicolson, G. D. 1985, *A.J.*, **90**, 1599.
Puschell, J. J., Jones, T., Phillips, A., Rudnick, L., Simpson, E., Sitko, M., Stein, W., and Moneti, A. 1983, *Ap. J.*, **265**, 625.
Rieke, G. H., Lebofsky, M. J., and Kinman, T. D. 1979, *Ap. J. (Letters)*, **232**, L151.
Rusk, R. E. 1988, Ph.D. thesis, University of Toronto.
Rusk, R. E., and Seaquist, E. R. 1985, *A. J.*, **90**, 30.
Saikia, D. J., and Salter, C. J. 1988, *Ann. Rev. Astr. Ap.*, **26**, 93.
Sanders, D. B., Phinney, E. S., Neugebauer, G., Soifer, B. T., and Matthews, K. 1989, *Ap. J.*, **347**, 29.
Simmons, J. F. L., and Stewart, B. G. 1985, *Astr. Ap.*, **142**, 100.
Sitko, M. L., Schmidt, G. D., and Stein, W. A. 1985, *Ap. J. Suppl.*, **59**, 323.
Smith, P. S., Balonek, T. J., Elston, R., and Heckert, P. A. 1987, *Ap. J. Suppl.*, **64**, 459.
Smith, P. S., Balonek, T. J., Heckert, P. A., and Elston, R. 1985, *Ap. J.*, **305**, 484.
Spinrad, H. 1986, *Pub. A.S.P.*, **98**, 269.
Spinrad, H., Djorgovski, S., Marr, J., and Aguilar, L. A. 1985, *Pub. A.S.P.*, **97**, 932.
Stocke, J. T., Leibert, J., Schmidt, G., Gioia, I. M., Maccacaro, T., Schild, R. E., Maccagni, D., and Arp, H. C. 1985, *Ap. J.*, **298**, 619.
Stocke, J. T., Morris, S. L., Gioia, I., Maccacaro, T., Schild, R. E., and Wolter, A. 1989, in *BL Lac Objects*, ed. L. Maraschi, T. Maccacaro, and M.-H. Ulrich (Berlin: Springer), p. 242.
Stockman, H. S., Moore, R. L., and Angel, J. R. P. 1984, *Ap. J.*, **279**, 485.
Tabara, H., and Inoue, M. 1980, *Astr. Ap. Suppl.*, **39**, 379.
Ulrich, M.-H., and Meier, D. L. 1984, *A.J.*, **89**, 203.
Urry, C. M., and Shafer, R. A. 1984, *Ap. J.*, **280**, 469.
Wills, B. J. 1989, in *BL Lac Objects*, ed. L. Maraschi, T. Maccacaro, and M.-H. Ulrich (Berlin: Springer), p. 109.
Wills, D., Wills, B. J., Breger, M., and Hsu, Jin-Chung 1980, *A.J.*, **85**, 1555.

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