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COMPACT RADIO SOURCES: THE DEPENDENCE OF VARIABILITY AND POLARIZATION ON SPECTRAL SHAPE

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ABSTRACT

VLA observations have been made at 20, 6, and 2 cm of an unbiased sample of 40 flat-spectrum ($\alpha > -0.5$; $S \propto \nu^{\alpha}$) radio sources selected from the S4 (6 cm strong source) survey. We have explored the polarization properties of these sources and examined their variability over a 6–8 year baseline at 6 cm by comparing our flux density values with the original S4 measurements. Most of the flux density in these sources is from regions unresolved ($\lesssim 0\farcs2$) on the VLA.

We find that the source properties divide fairly clearly when one classifies the sources according to simple spectral shape categories; viz, straight, simple-convex ("humped"), and complex. The complex sources are significantly more variable and reach higher polarizations. The straight sources are relatively quiescent and show signs of substantial Faraday depolarization. The simple-convex sources are also relatively quiescent and show none of the high polarizations seen among the complex sources. The complex sources exhibit, on average, about the same degree of polarization at all three wavelengths, but, for a given source, the degree of polarization shows little correlation from one wavelength to another. The VLBI structures may also be related to these spectral shape categories.

Possible interpretations of these relations are discussed. We also argue that if the complex, variable sources are relativistically "beamed" toward us, then their unbeamed counterparts have not been found, at least in this subset of the S4 survey.

Subject headings: polarization — quasars — radio sources: galaxies — radio sources: spectra — radio sources: variable

I. INTRODUCTION

Considerable effort in recent years has gone into the understanding of conditions in compact radio sources (see, e.g., the review of Kellermann and Pauliny-Toth 1981). They are found in the nuclei of radio galaxies, in the inner regions of QSOs with prominent large-scale structure, and sometimes alone in QSOs and BL Lac objects. Since these sources are thought to be closely associated with the central engines of active galaxies, it is clearly important to understand them and the influences of local environment on their properties.

We have begun a program to explore these sources through their spectral, polarization, and variability properties. In the initial phases of the program, we have examined the broadband spectral, variability, and polarization characteristics (centimeter and millimeter bands) of a sample of about 20 strong, active sources (Jones *et al.* 1981; Rudnick *et al.* 1982). However, like most studies of compact radio sources, that group was biased toward sources with high variability, strong polarization, and other "special" characteristics which made them easier to observe.

In order to better understand the properties of compact sources in general, we set out to construct a sample of sources containing both a range of compact structures and relatively little contamination by extended emission and for which other information (e.g., VLBI maps) was or could readily become available. It has been established that sources with flat ($\alpha > -0.5$; $S \propto \nu^{\alpha}$) spectra usually have substantial compact structure (Broderick and Condon 1975) and are variable in total and polarized flux (see Kellermann and Pauliny-Toth 1981 and references therein). We therefore chose a flat-spectrum sample, as described below, to be observed at the VLA.[1]

II. SOURCE SAMPLE AND OBSERVATIONS

We selected our sources from the Green Bank-Bonn S4 survey (Pauliny-Toth *et al.* 1978). The selection criteria required: (1) S4 flux density > 1 Jy at 6 cm, (2) $\alpha > -0.5$ between 11 cm and 6 cm or between 6 cm and 2.8 cm, and (3) Predicted S4 flux density > 1 Jy at 2.0 cm, from Witzel *et al.* (1978). The first two criteria are those applied by Witzel *et al.* (1978) and include the 56 sources listed in their Table 1 and in our Table 2. We did not observe 14 sources from this list which violated criterion (3) because of observing time limitations. This mainly had the effect of removing from our observing list sources with $S_{6\,\mathrm{cm}} \sim 1$ Jy and $\alpha \sim -0.5$. Our final sample thus consisted of 42 sources. It should be kept in mind that these selection criteria are somewhat arbitrary and certainly imperfect when dealing with variable sources. That is, individual sources may in principle either meet or fail the selection criteria at any given epoch. Because of criterion (3) the observed sample cannot be used to examine

[1] The VLA (Very Large Array) is a facility of the National Radio Astronomy Observatory, operated by Associated Universities, Inc., under contract with the National Science Foundation.

spectral index distributions, but it is unbiased with respect to variability, polarization, and spectral shape (beyond influence of the two point slope criterion mentioned above).

The sources were observed with a 12–16 antenna subarray of the VLA (Thompson *et al.* 1980) during 1980 October 23–25. Each source was observed once or twice for a period of ~ 5 minutes at each of 1.465, 1.665, 4.885 GHz and ~ 7–10 minutes at 15.035 GHz. The data from the first two bands were added together after analysis to form a single measurement which we will label 20 cm. The two upper bands will be labeled 6 cm and 2 cm, respectively. Flux densities were tied to the KPW scale (see Kellermann, Pauliny-Toth, and Williams 1969) using 3C 286 as the primary calibrator [S(1.465, 1.665, 4.885, 15.035 GHz) $\equiv$ 14.51, 13.55, 7.41, 3.40 Jy].

Instrumental and source polarizations were determined using the standard VLA analysis procedures (Bignell 1980), defining the polarization angle of 3C 286 to be 33° at all bands. Normally, the fractional polarizations do not require a separate gain calibration, since each receiver is calibrated independently through the total intensity measurements, and the digital circuitry is assumed perfect. However, we discovered a relative delay between the left and right circular polarization signals at 20 cm, causing a reduction ($\sim 20\%$) in the effective bandwidth, and hence signal strength, for linear polarization. We have, therefore, scaled our results at 20 cm *assuming* a fractional polarization of 9.4% for 3C 286 (Simard-Normandin, Kronberg, and Neidhofer 1981). This introduces a *scale* error of $\sim 5\%$ into the 20 cm polarizations. Residual instrumental polarizations contribute an error (and bias in quadrature) of $\sim 0.1\%$ at 6 cm and ~ 0.2–0.3% at 2 cm and 20 cm.

Variations in the instrumental phase $\sim 30°$ occurred at 2 cm and 20 cm during the observations. This precluded useful measurements of the position angles at these bands, although it had little effect on the instrumental or fractional source polarizations. At 6 cm instrumental phase variations were only $\sim 5°$, corresponding to uncertainties in polarization angle of $\sim 2°.5$.

The observational results are presented in Table 1. The fractional polarizations have been *corrected* by subtraction in quadrature for bias due to noise and random residual instrumental effects. This is a very good approximation to the analytic solution for the noise correction, as described by Wardle and Kronberg (1974). The total intensities are essentially noise free, the errors reflecting calibration uncertainties.

We have made no attempt to map these sources but have examined the visibility data for evidence of resolution. For all sources listed in Table 1, most of the observed flux comes from an unresolved, compact core. We also observed 1828 + 48 (3C 380), but it is strongly resolved on our longest baselines (~ 17 km) at all three wavelengths. Since this makes the polarization and flux density measurements difficult to interpret without a complete map, we exclude the source from further discussion. In several other cases the visibility data suggest sufficient structure that caution is warranted in interpreting the polarization. These polarization measurements are followed by an asterisk in Table 1. In many cases, we can see evidence for extended structure at the short baselines at 20 cm. Typically, this extended emission raises the short baseline visibilities by $\sim 5\%$ and should not affect our polarization measurements. In Table 2, we list some structure information in an abbreviated way, to permit judgment on its possible effects on the polarization data.

Table 2A also lists additional useful information about the observed sources, including alternate source names, type of optical counterpart, and a radio spectral class, defined below. The optical designation is taken from Kühr *et al.* (1980) except for some sources labeled by them as QSO, and which are known BL Lac objects. For those sources listed either in Hewitt and Burbidge (1980) or Burbidge and Crowne (1979) we have included the redshifts in Table 2 as well. In Table 2B, we have included information on the sources in the sample defined by Witzel *et al.* 1978 on which we did *not* obtain VLA data (sources which meet only criteria [1] and [2]).

III. DISCUSSION OF RESULTS

a) Spectral Forms

As mentioned above, our sample contains a variety of spectral forms. It is useful to examine the polarization and variability behavior of the sources according to some simple designation of their spectral shape. To assist in this task, we have used the broadband spectral compilation of Kühr *et al.* Although those data were not from a single epoch, they were sufficient for a crude characterization of the spectral shapes of individual sources. Since the principal aim of our program is to examine compact, variable sources, we first separate out those with power-law (i.e., straight) spectra which might indicate extended, transparent emission. We classify the remaining spectra into two groups on the basis of their complexity. We isolated sources whose spectra show a simple smooth peak (simple-convex) anticipating that these would result from fairly simple, partially opaque structure (e.g., Marscher 1977) or possibly transparent emission from non-power-law electron distributions, such as a relativistic Maxwellian (e.g., Jones and Hardee 1979). These sources, therefore, are interesting to consider as a group, separate from the sources with more complex spectra. The three general categories which we identify are thus summarized below.

i) *S—Straight*

The data in Kühr *et al.* are consistent with a single power law $\alpha < 0$ over a frequency range $\gtrsim 20$. In several cases where there is evidence of curvature outside our observing range (1.4–15 GHz), the S classification is allowed to stand. Six of the observed sources, and 10 (of the 14) from Witzel *et al.*'s list which were not observed, fit into this category.

ii) *$\cap$—Simplex-convex*

A smooth single-peaked convex spectrum is consistent with the Kühr *et al.* data. Again, deviations from this shape which are significantly out of our observing range

TABLE 1

Observed S4 Flux Densities and Polarizations

Source	2 cm		6 cm			20 cm	
	S(Jy)	m_c(%)	S(Jy)	m_c(%)	χ(°)	S(Jy)	m_c(%)
0026+34	0.72	<0.5	1.2	0.6	54(5)	1.8	<0.5
0133+47	2.4	1.3	2.0	2.6	−75	1.75	2.1
0218+35	0.64	9.0*	1.1	2.4	7	1.2	<0.5
0248+43	1.0	1.3	1.4	1.3	81	0.8	1.8
0316+41	48.7	<0.5	56.3	<0.2	...	14.8	<0.5
0602+67	0.39	1.0	0.5	0.8	−56(14)	0.5	1.2
0710+43	0.72	<1.2	1.6	0.4	16(7)	2.1	<0.5
0804+49	1.7	1.2	1.7	0.9	41	0.85	1.6
0814+42	1.9	1.1	2.0	1.7	2	1.4	2.7
0831+55	1.5	<0.5	5.5	<0.2	...	8.25	<0.5
0833+58	1.1	3.3	1.2	2.0*	21	0.6	3.7*
0850+58	0.54	2.6(0.4)	1.0	1.0	−70	0.8	2.4
0859+47	1.2	2.2	1.7	2.1*	73*	2.1	1.5*
0906+43	1.4	0.6	1.2	3.0	74	2.8	<0.5*
0923+39	[6.3]	<0.5	7.1	1.0	24	2.4	<0.5*
0945+40	[0.9]	3.4	1.0	6.5	15	1.45	7.1
0954+55	[1.4]	3.5	1.8	2.5	−17	2.65	1.6*
0954+65	[0.8]	4.0	0.6	4.0	−20	0.7	2.9
1030+41	[0.6]	2.4	0.5	2.2	58	0.55	1.8
1150+49	[0.5]	2.7	0.5	5.2*	−60	0.50	3.2(1.5)*
1216+48	[1.0]	1.1	0.8	2.9	30	0.8	2.9
1418+54	[1.4]	2.1	1.5	2.7	−26	1.16	1.1
1435+63	[0.6]	4.1	0.9	1.9	−29	1.15	0.5
1504+37	[0.5]	1.7(0.7)	0.8	<0.2*	...	1.0	<0.5
1624+41	[0.7]	2.8(0.6)	1.2	0.5	16	1.7	<0.5
1633+38	[1.8]	<0.5	...	...	...	1.6	1.1
1637+57	[1.3]	2.5	1.6	2.3	−66	1.1	1.5
1638+39	[0.9]	1.0	0.8	0.6	−2(5)	0.4	1.6
1641+39	[12.1]	3.0	8.1	4.0	33	7.25	3.7
1642+69	[1.6]	5.3	1.6	2.4	−43	1.45	3.9
1652+39	[0.9]	1.3	1.2	1.6	−22	1.4	1.8
1739+52	[0.8]	2.5	0.9	1.5	78	0.8	1.2
1749+70	[0.7]	3.8	0.9	1.9	−87	1.2	1.7
1751+44	[0.5]	4.8	0.8	1.5*	14*	0.6	2.0
1823+56	[1.0]	7.7(0.6)	1.4	5.3*	33*	1.3	3.2*
1954+51	[0.8]	0.9	1.2	...	...	1.1	2.1
2021+61	[1.7]	1.5	2.3	...	...	2.3	2.3
2200+42	6.8	4.0	7.0	2.4	−23	4.3	4.3
2351+45	0.64	3.6	1.3	2.0	79	1.55	<0.5
2352+49	0.91	0.5	1.6	0.7	90(4)	2.25	<0.5

Notes.—Errors in flux density are ~5% at each band, due to calibration uncertainties. Values in brackets are accurate only to ~20%. Errors in fractional polarization are ~0.1% at 6 cm and ~0.25% at 2 and 20 cm. Quoted polarization values *have been corrected* for noise and error bias. When the observed polarization was less than the estimated error, an upper limit of 2 × error has been listed. Polarizations marked * may be confused by extended emission. Unless noted in parentheses, errors in polarization angle are dominated by instrumental drifts and are ~3°.

do not affect the classification. Seven observed (and two not observed) sources fit into this category. These spectra all would generally be classified as C^- (e.g. Kellermann, Pauliny-Toth, and Williams 1965). But, in addition, we require a single peak somewhere in the observed spectrum (CC^- in Kühr *et al.*). This eliminates from the class, for example, straight power-law spectra which steepen at high frequencies or which turn over at low frequencies. Two examples of the ∩ class (for which good broadband spectra are available from Owen, Spangler, and Cotton 1980, hereafter OSC) are shown in Figure 1.

iii) *C—Complex*

This category includes the remaining 24 (plus five not observed) sources.

Our classification of this sample is listed in Table 2. In most cases our choice is consistent with that of Kühr *et al.*, but the choice is somewhat subjective in a number of cases; our classification is thus not identical with theirs. Despite these slight ambiguities, the classes are sufficiently distinct, and the physical basis for them sufficiently strong, that they serve the purposes at hand.

TABLE 2

ADDITIONAL SOURCE PROPERTIES

Source	Other Name	Optical Counterpart	Redshift	Radio Spectral Class	V_6 (Variability)	Structure: Core	Structure: Extended (20 cm)
A. Observed Sources							
0026+34....	OB 343	EF	...	S	<0.03	<0.″2	<4% at 7500λ
0133+47....	OB 457	QSO	0.860	C	−0.21	0.″0015 × 0.″001 (6 cm)	<4% at 7500λ
0218+35....	OB 330	Gal	...	C	−0.03	<0.″8[a]	~7% at 7500λ
0248+43....	...	QSO	...	∩	0.07	<0.″13	<6% at 7500λ
0316+41....	3C 84	Gal	0.0177	C	0.08	~0.″0006 × ~0.″001 (6 cm)	~10% at 3000λ
0602+67....	...	EF	...	C	−0.34	<0.″18	<10% at 7500λ
0710+43....	OI 417	Gal	...	∩	<0.03	~0.″001 (50%, 6 cm)	<4% at 7500λ
0804+49....	OJ 508	QSO	...	C	−0.09	~0.″001 (30%, 6 cm)	~5%[b]
0814+42....	OJ 425	QSO	...	C	0.08	~0.″001 (6 cm)	~8% at 7500λ
0831+55....	DA 251	Gal	...	∩	<0.03	~0.″003 (60%) + 0.″02 + ? (6 cm)	<8% at 7500λ
0833+58....	...	QSO	...	∩	0.03	<0.″20	~30% at 15000λ
0850+58....	4C 58.17	QSO	1.322	C	−0.15	~0.″005 (90%, 6 cm)	[c]
0859+47....	4C 47.29	QSO	1.462	S	<0.03	~0.″001 (60%, 6 cm)	~10% at 7500λ[d]
0906+43....	3C 216	QSO	0.670	C	−0.17	<0.″17	[e]
0923+39....	4C 39.25	QSO	0.699	∩	−0.10	~0.″002 double (6 cm)	[f]
0945+40....	4C 40.24	QSO	1.252	C	−0.14	~0.″001 (6 cm)	~15% at 7500λ
0954+55....	4C 55.17	QSO	0.909	S	−0.10	[g]	~10% at 15000λ[g]
0954+65....	...	QSO	...	C	−0.39	~0.″0004 (6 cm)	<12% at 7500λ
1030+41....	...	QSO	1.120	C	−0.35	<0.″21	~12% at 7500λ
1150+49....	4C 49.22	QSO	0.334	C	−0.35	<0.″23[h]	<25% at 7500λ[n]
1216+48....	ON 428	QSO	...	C	−0.13	<0.″21	<12% at 7500λ
1418+54....	OQ 530	BL	...	C	0.13	<0.″13	<10% at 7500λ
1435+63....	...	QSO	2.060	S	−0.14	0.″28	<25% at 15000λ
1504+37....	OR 306	EF	...	C	−0.14	[i]	<12% at 7500λ
1624+41....	DA 411	EF	...	S	−0.03	~0.″002 (70%, 6 cm)	~3% at 15000λ
1633+38....	4C 38.41	QSO	1.814	C	...	~0.″001 [85%] + >0.″03 [15%] (18 cm)	<10% at 7500λ
1637+57....	OS 562	QSO	0.745	∩	0.05	<0.″21	<12% at 10000λ[j]
1638+39....	NRAO 512	QSO	...	C	−0.16	<2.″5	<25% at 7500λ
1641+39....	3C 345	QSO	0.595	C	−0.13	~0.″0025 (core-jet, 6 cm)	~15% at 15000λ
1642+69....	4C 69.21	QSO	...	C	0.05	<0.″17	~12% at 10000λ
1652+39....	Mrk 501	BL	0.034	C	−0.07	~0.″001 + ~0.″02 + ? (6 cm)	<5% at 15000λ
1739+52....	4C 51.37	QSO	1.375	C	−0.34	~0.″0006 (40%, 6 cm)	~7% at 15000λ
1749+70....	...	BL	...	C	−0.09	~0.″005 [85%] + >0.″34 [15%] (6 cm)	<8% at 7500λ
1751+44....	OT 486	QSO	...	C	−0.10	[k]	<25% at 7500λ
1823+56....	4C 56.27	QSO	...	C	−0.08	<0.″17	~12% at 7500λ[l]
1954+51....	OV 591	QSO	1.230	S	−0.07	~0.″001 (60%, 6 cm)	<25% at 7500λ
2021+61....	OW 637	QSO	...	∩	<0.03	~0.″0065 double (3.6 cm)	<4% at 7500λ
2200+42....	BL Lac	BL	0.0688[m]	C	0.17	~0.″0015 (6 cm)	<6% at 7500λ
2351+45....	4C 45.51	Gal	...	S	−0.04	~0.″002 (75%, 6 cm)	<20% at 7500λ
2352+49....	DA 611	Gal	0.2370	S	−0.04	<0.″20	<6% at 7500λ
B. Witzel *et al.* sources not observed in current program							
0010+40....	4C 40.01	RSO[n]	...	C			
0108+38....	OC 314	EF	...	∩			
0402+37....	4C 37.11	Gal	...	S			
0711+35....	OI 318	QSO	1.620	∩			
0723+67....	3C 179	QSO	0.846	S			
0755+37....	3C 189	Gal	0.0433	S			
0812+36....	OJ 321	QSO	1.025	C			
0828+49....	OJ 448	QSO	...	C			
0945+66....	4C 66.09	EF	...	S			
1003+351 ..	3C 236	Gal	0.0989	S			
1213+35....	4C 35.28	QSO	...	S			
1732+38....	OT 355	Gal	...	C			
1807+69[o]...	3C 371	Gal	0.0500	C			
1828+48[o]...	3C 380	QSO	0.692	S			
2323+43....	OZ 438	Gal	...	S			
2324+40....	3C 462	Gal	...	S			

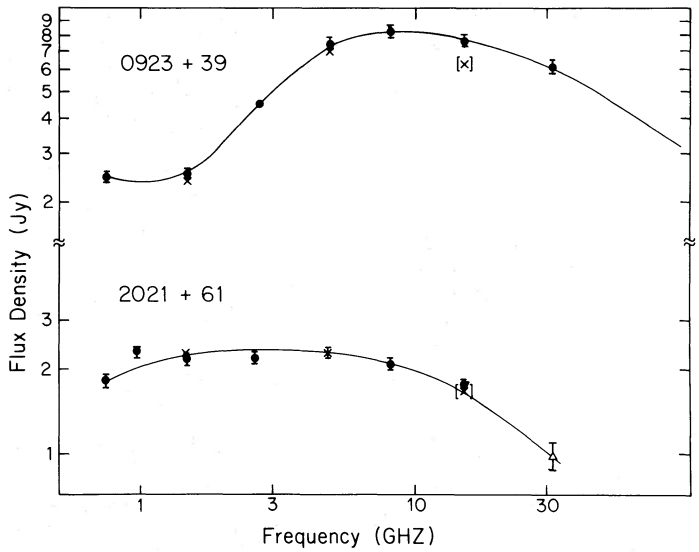

FIG. 1.—Broad-band spectra of two sources classified by us as simple-convex (∩). Data are from: ×—this paper (brackets indicate uncertain value); ·—OSC; △—Witzel *et al.* 1978.

Our own data can be used for crude spectral analysis; the more detailed flux measurements of OSC provide good quality spectra for 19 sources in our list. These data generally do not contradict our classification as derived from Kühr *et al.*, despite the fact that the latter paper used a heterogeneous and nonsimultaneous set of measurements.

b) *Flux Variability*

Since all of the sources we observed have measured 6 cm fluxes in the S4 survey [S_6(S4), 1972 December–1974 December], we can use our 6 cm measurements [S_6(RJ)] to examine the variability of sources in our sample over a period of 6–8 years. Most of the sources have varied, and, as one expects for a flux-limited sample, the majority of the sources have gotten weaker at the current epoch.

As a convenient and simple measure of variability, we define (following OSC),

$$V_{6(\mathrm{RJ,\,S4})} = \log_{10}\left[\frac{S_6(\mathrm{RJ})}{S_6(\mathrm{S4})}\right] .$$

For our sample as a whole the median $|V_6(\mathrm{RJ, S4})| \approx 0.11$ (corresponding to a fractional change of $\sim 30\%$) over a period of 6–8 years. Comparing our measurements

NOTES TO TABLE 2

NOTES.—The optical counterpart and redshift references and the spectral classification scheme are described in the text.

VLBI information on the cores (representative only) was abstracted from the following sources: Pauliny-Toth *et al.* (1981) 0923+39, 2200+42; Cohen *et al.* (1971) 1807+69; van Breugel *et al.* (1981) 0831+55, 1652+39, 1807+69; Weiler and Johnston (1980) 1652+39, 2200+42; Pearson *et al.* (1981) 2200+42; Bååth *et al.* (1981) 1749+70, 2200+42; Marscher and Shaffer (1980) 0133+47, 1633+38; Preuss *et al.* (1979) 0316+41; Readhead *et al.* (1979) 1641+39; Wittels *et al.* (1981) 2021+61; Bååth *et al.* (1980) 0923+39; Pearson and Readhead (1981) 0133+47, 0316+41, 0710+43, 0804+49, 0814+42, 0831+55, 0850+58, 0859+47, 0945+40, 0954+65, 1624+41, 1739+52, 1954+51, 2351+45.

Other limits on core sizes are derived from the current visibility data, assuming circular Gaussian sources. These limits depend on the signal-to-noise ratio for each source. The measurements or limits on extended structure are quoted in terms of fractional increase in the 20 cm visibility data at the short baselines listed. These data are *not* meant as a sensitive or complete description of the structure outside the core, but merely as an indicator of possible confusion for the core polarization results. Polarization values which may be confused are so indicated in Table 1.

[a] A large scatter (6 cm ± 15%, 2 cm ± 30%) in the visibilities may be masking resolution problems.
[b] Modulation of 20 cm amplitudes at ~5%, indicative of structure on arcsecond scale.
[c] Triple source, dominated by nuclear core (R. A. Perley, private communication). Possible slight confusion at 20 cm.
[d] Extended halo, ~15% of flux at 20 cm.
[e] Heavily resolved at 20 cm with large scatter in visibilities at 6 cm.
[f] Large-scale structure causes confusion at 20 cm, but contributes only ~4% of flux at 6 cm short baselines.
[g] Some evidence for large-scale structure, and possible confusion at all three frequencies.
[h] Triple source with some fine scale structure (R. A. Perley, private communication), possible small confusion at all three frequencies.
[i] Resolved by 5% from 5–20 × $10^4\lambda$ at 6 cm.
[j] Some structure on scale of 2 ± 0″.5 (Kapahi 1981).
[k] Resolved by 4% from 3–5 × $10^4\lambda$ at 6 cm.
[l] Heavily resolved (25%) at 20 cm. Only small resolution ~5% visible at 6 cm.
[m] Redshift of associated galaxy.
[n] Optical identification from (Kapahi 1979).
[o] These sources met our criteria for observation, but no useful data were obtained.

to those of OSC made in early 1978 (an interval of $\sim$ 34 months) we derive for those 19 common sources a median $|V_6| \sim 0.07$ ($\sim 17\%$). On still shorter time scales, the OSC measurements compared to those made by them a year earlier yield median $|V_6| \approx 0.03$ ($\approx 7\%$).

It is evident that over longer time scales the sources characteristically show increased amplitude in their variations, and that over periods of $\sim$ 10 years, changes $\gtrsim 100\%$ are probably typical. This is a significant statement about flat spectrum sources *in general*; other monitoring programs (e.g., Altschuler and Wardle 1976; Aller, Aller, and Hedge 1981; Andrew *et al.* 1978) tend to select and concentrate on sources which are known to show short term activity, while we have introduced no *a priori* prejudice about variability.

The tendency to be variable shows a good correlation with spectral form (also see Kesteven, Bridle, and Brandie 1977, who examined the incidence of variability as a function of the radio "color-color" classification). Figure 2 shows a histogram of $|V_6(\mathrm{RJ, S4})|$ for straight (S), simple-convex ($\cap$) and complex (C) spectra. For the C spectra alone the median $|V_6| \approx 0.14$ ($\sim 40\%$), and several sources have indeed varied by 100% ($|V_6| > 0.3$) over a period of 6–8 years. These typical variations are consistent with canonical synchrotron theory (e.g., Jones, O'Dell, and Stein 1974). In contrast to the complex sources, both the S and $\cap$ sources yield only median $|V_6| \approx 0.03$ ($\approx 7\%$).

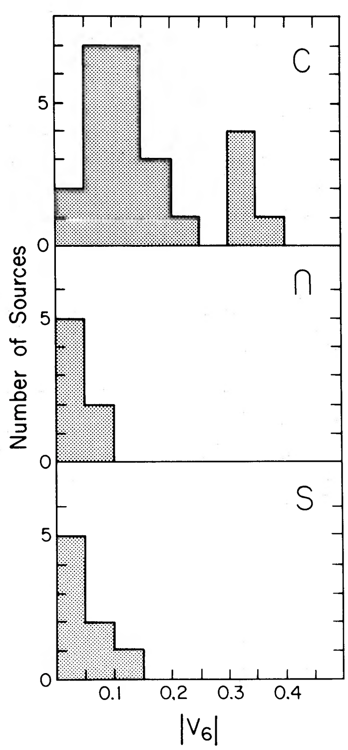

FIG. 2.—Histograms of $|V_6(\mathrm{RJ, S4})|$, the variability of sources at 6 cm. Sources are separated by their spectral shape. Definitions of variability and shape are found in the text.

Some earlier studies of variability have noted that those sources with centimeter spectral indices $\alpha \sim 0$ (i.e., especially flat) are the most likely to show variations (e.g., Altschuler and Wardle 1977). In this regard it is noteworthy that all five of our sources for which $|V_6| > 0.30$ ($> 100\%$ variation) between the S4 and current epochs are "complex" sources with 2–20 cm spectral indices between ± 0.1.

c) *Polarization*

Centimeter wavelength studies of flat-spectrum ($\alpha \gtrsim -0.5$) radio sources reveal characteristic polarizations of several percent (e.g., Aller 1970; Berge and Seielstad 1972; Wardle and Kronberg 1974; Altschuler and Wardle 1976). As described below, however, the polarization properties also depend on spectral shape.

Table 3 gives median fractional polarizations, *m*, for our S4 sample. Sources have been divided into the spectral categories described above. Both the complex and convex sources show little wavelength dependence *as a group*. The straight sources, however, show significant signs of wavelength dependent depolarization. The simple-convex sources do not show the high polarizations sometimes seen in the complex sources (see Fig. 3).

Within individual sources the wavelength dependence of the polarization is different for each of the spectral categories. Figure 3*a* shows a plot of the degree of polarization at 2 cm versus that at 6 cm. Symbols indicate the spectral category. For the complex sources it is clearly a scatter diagram. This is in agreement with our more complete studies of strong millimeter, active sources (Rudnick *et al.* 1982). For the simple-convex sources, however, the values of m_2 and m_6 may show less scatter. In agreement with the group properties seen in Table 3, the individual straight-spectrum sources do seem to be strongly depolarized. For all but one of these straight sources, the wavelength dependence of the fractional polarization between 2 and 20 cm is consistent with a source which is Faraday depolarized below 2 cm. Using the simple homogeneous spherical model of Cioffi and Jones (1980), the internal rotation measures required would range from $\lesssim 50$ rad m^{-2} in 0026+34 or 0859+47 to $\gtrsim 10^3$ rad m^{-2} in 1624+41. The data for 0954+55 cannot be fitted by such a model because the 20 cm polarization is too large. However, we note that this source is partially resolved at 20 cm on the VLA, which makes the measurement hard to interpret. Figure 3*b* is a plot of m_6 versus m_{20}. The scatter may be less than in Figure 3*a*, but, for the complex sources, the values m_6

TABLE 3

MEDIAN POLARIZATION VALUES

Radio Spectral Class	20 cm	6 cm	2 cm
C (24 sources)	≈1.8%	≈2.3%	≈2.3%
∩ (6 sources)	≈1%	≈1.2%	≈1.3%
S (7 sources)	<0.3%	≈1.9%	≈2.8%

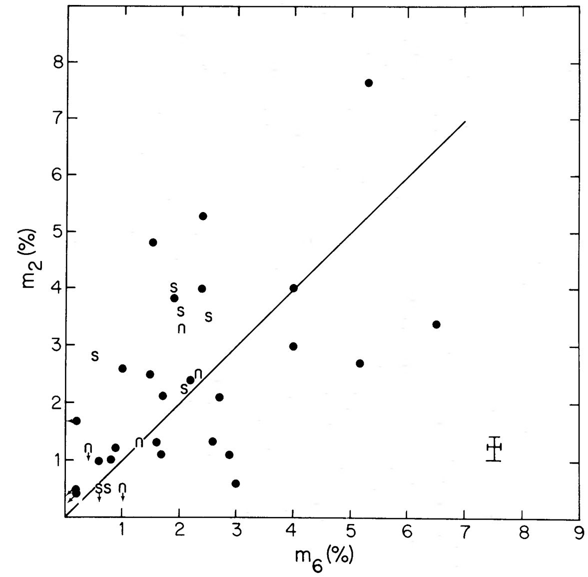

FIG. 3*a*

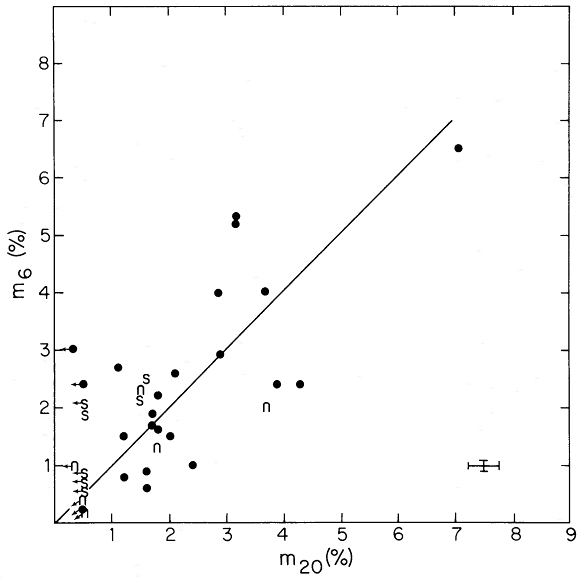

FIG. 3*b*

FIG. 3.—(*a*) Fractional polarizations at 2 cm vs. those at 6 cm. • = complex; ∩ = simple-convex; S = straight. (*b*) Fractional polarizations at 6 cm vs. those at 20 cm. All polarizations have been *corrected* for noise bias. Typical error bars are shown. The highest ∩ points are for 0833+58, which is probably confused.

and m_{20} are still poorly correlated. The complex sources and especially the straight sources show signs of depolarization at 20 cm.

To fully understand these trends one should also compare the position angles at different wavelengths. Unfortunately, as discussed in § II, we have reliable angles only at 6 cm, because of instrumental problems. For comparison with source structure, we have located VLBI major axis position angles for 0133+47, 0923+39, 1641+39, 1749+70, and 2200+42 at 6 cm (references in Table 2). These yield |structure-polarization| angular differences of 39°, 72°, 74°, 24°, and 30°, respectively. In this small sample there is no indication of a relationship between VLBI structure and polarization angle (see also Altschuler and Wardle 1977). Evidence does exist for such a structure/polarization relationship on much larger scales (e.g., Clarke, Kronberg, and Simard-Normandin 1980; Willis *et al.* 1981).

IV. INTERPRETATION

We have examined the flux variability and polarization properties of an unbiased sample of flat-spectrum ($\alpha > -0.5$) radio sources. In both areas the source characteristics seem to divide naturally by spectral shape into three categories: sources with straight, power law spectra ($\alpha < 0$), sources with simple but convex spectra, and those with more complex spectra.

The straight-spectrum sources are the easiest to understand. They are probably transparent. Because they are of comparable luminosity, we would thus expect them to be relatively large compared to the other classes. They show little evidence for variability on time scales of a few years. Many of these sources show signs of significant Faraday depolarization, although even at 2 cm, where that effect should be small, they seem to be less polarized than typical steeper, straight spectrum sources (e.g. Wardle and Kronberg 1974). Note, however, that from our VLA observations we generally can set size limits at 2 cm of $\lesssim 0\farcs2$. This corresponds to a size of ~ 5 kpc for $z \approx 1.2$ (the median redshift of those in this group with measured angles). Thus, they may lie well within their parent galaxies. A rough equipartition magnetic field would be $\gtrsim 10^{-4}$ gauss. For a rotation measure $\sim 10^3$ rad m^{-2} (cf. § II*c*), the internal electron density would be $\lesssim 10^{-2}$ cm^{-3}. This value is quite reasonable if it represents material swept up within a galaxy. These sources are small in comparison to typical steep spectrum sources (e.g., Miley 1980). Kapahi (1981) has shown that, in the S4 survey, a large fraction of the steep ($\alpha < -0.5$) sources are also small. Phillips and Mutel (1980, 1981) have identified a possibly related population of small sources ($\sim 0\farcs1$) with steep spectra and small near-equal double structure. Below 1 GHz their spectra turn over, indicating self-absorption, a tendency which is seen in most of our straight-spectrum sources as well.

The sources which show large amplitude variability have complex spectra. These complex sources reach higher fractional polarizations than the others, while showing little correlation in the degree of polarization between wavelengths separated only by a factor of 3 (see Fig. 3). This, plus the complex nature of the spectra, strongly suggests that one is dealing with composite sources with distinct regions visible at different wavelengths. If the source magnetic field is tangled, then the degree of tangling is evidently a function of location or of scale length, producing the observed character in the degree of polarization. Observations with complete position angle information over a broad band (Rudnick *et al.*

1982) suggest, however, that the direction of the organized magnetic field component does not change very much with location in most complex sources. This is probably consistent with a jet picture for such sources, but conclusions regarding structural implications should await a careful comparison between implied magnetic field directions and source structural axes and more careful theoretical calculations as well.

The complex sources have a luminosity distribution similar to those of either the straight or convex sources within our sample. However, they are more numerous, which argues against their being versions of the other classes modified in appearance due to relativistic beaming (e.g., Scheuer and Readhead 1979). If complex sources are, in fact, beamed, we have *not* found their unbeamed twins among the S4 survey. Since relativistic beaming amplifies apparent luminosity, the complex sources could represent some otherwise fainter group of sources. In that case the similarity of their apparent luminosities to the other S4 sources in our subset would be accidental.

Sources with simple-convex spectra stand apart from both the straight and complex sources. Their fluxes do not vary as strongly as the complex sources. Their polarizations do not show the strong depolarization seen in the straight sources.

The simple-convex spectra in our sample are each too broad to be explained by a single homogeneous, power-law component which is self-absorbed at low frequencies. Statistical analyses have shown that it takes special conditions to produce broad, *smooth* spectra such as those in Figure 1 by superposing several such components (e.g., Cook and Spangler 1980). Two other possible explanations exist. Tapered sources structures (e.g., Condon and Dressel 1973; de Bruyn 1976; Marscher 1977; Blandford and Königl 1979) can produce broad, gently peaked spectra through the effective superposition of an infinite number of components. Nearly homogeneous sources can produce broad gently peaked spectra if the electron energy distribution is non-power law and if the emission is largely transparent (e.g., Jones and Hardee 1979; Cook and Spangler 1980).

Some structural (VLBI) data exist which bear on this. Detailed VLBI maps have been made at one or more wavelengths for 0923+39 (Pauliny-Toth *et al.* 1981; Bååth *et al.* 1981) and 2021+61 (Wittels, Shapiro, and Cotton 1981), both simple-convex sources in the present sample. Also 2134+00, a source of this spectral class which is discussed in Jones *et al.* (1981), has been mapped with VLBI (Pauliny-Toth *et al.* 1981). All three are strongly asymmetric doubles. For 2021+61, it appears that one component dominates the short wavelength emission, while the other dominates at long wavelengths. Thus, the spectral shape does seem to result from a simple superposition of possibly homogeneous components. On the other hand, in the other two cases it seems that one component dominates over the whole band. Superposition of discrete components does not seem to be important in these two, therefore.

We conclude that none of the three alternate explanations will account for the simple-convex class as a whole; all three may well have a hand in producing such sources. It would be especially interesting to examine the structure of those which exhibit no wavelength dependence to their polarization, since this characteristic suggests transparent emission. It is noteworthy that none of the mapped sources exhibit the "core-jet" structure found in a number of active, complex spectrum sources such as 1641+39 (Readhead *et al.* 1979). Since these "jets" involve high speed motions which can result in rapid variability, the absence of jets in the simple convex sources may be related to their quiescence.

V. SUMMARY

We have classified flat-spectrum sources into three spectral shape categories; straight, simple-convex, and complex, and examined their polarization and variability characteristics through multiband VLA observations.

The straight sources are small (<5 kpc) in comparison with steeper, straight-spectrum sources, are not variable, and show evidence for Faraday depolarization. These may be transparent sources confined within a galaxy.

The simple-convex sources vary only slightly and have small polarizations ($\sim 1\%$) which are similar between frequencies for each individual sources in our sample. One plausible interpretation of these sources is that they possess non-power-law electron distributions.

The complex sources are highly variable and show considerable scatter between their fractional polarizations at different wavelengths. Their variability increases as one goes from time scales of 1–2 years to 6–8 years. They are very similar to the better studied strong millimeter, active sources.

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Note added in proof.—Examination of the polarization characteristics of a larger sample of sources suggests that luminosity also plays a key role, in addition to spectral shape.

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