Asymmetric depolarization in double radio sources with one-sided jets

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SUMMARY
Total intensity and polarization maps at wavelengths of 6 and 20 cm are presented for 47 double radio sources with one-sided jets. There is a strong asymmetry in the degree of depolarization between λ6 and 20 cm: of the 37 sources with significant depolarization, 34 show less depolarization on the jet side than on the counter-jet side. There is also a significant asymmetry in the spectral index of the two sides: the jet-side spectral index is flatter by typically Δα = 0.1. By comparison, the asymmetries in flux density, peak brightness and separation from the nucleus are minor, and cannot be significant contributors to the depolarization asymmetry.

1 INTRODUCTION
The model of twin-jet ejection (e.g. Begelman, Blandford & Rees 1984) explains many of the properties of classical double radio sources, but it fails to explain why the radio power emitted by the two jets is often very different. Indeed, in the great majority of FR II-type radio sources (Fanaroff & Riley 1974), a jet can be detected on one side only. The two radio lobes fed by the twin jets are in general symmetrical. They are similar in size, in radio luminosity and in distance from the nucleus, but they often differ appreciably in polarization. Davis, Stannard & Conway (1983) and Conway & Strom (1985) showed that the difference was primarily in the degree to which Faraday effects depolarize the emission at long wavelengths. Laing (1988) first suggested that the polarization asymmetry and the jet asymmetry were connected, and we have recently given a preliminary account (Garrington et al. 1988, hereafter Paper I) of observations of 25 sources which confirm the rule that stronger Faraday depolarization occurs systematically on the counter-jet side.

We have now obtained observations of 22 sources additional to those in Paper I. In this paper (Paper II) we give details of both sets of observations, and maps of all 47 sources. This is the first large sample of sources with one-sided jets to be observed at more than one wavelength with scaled arrays. We have analysed the maps to find parameters describing the flux and polarization properties of each component to see which parameters are related to the jet asymmetry. In several maps the depolarization asymmetry is strong and may be seen by direct inspection. We have expressed the depolarization of each component in terms of a model of the Faraday distribution function (Burn 1966), and we give the Faraday dispersion and (where possible) the rotation measure of each component. A discussion of the interpretation of these results is contained in an adjoining paper, Paper III.

2 SOURCE SELECTION
The 47 sources in our sample, which were chosen from published and unpublished collections of high-resolution maps of quasars and radio galaxies, are listed in Table 1. The first three columns give the source name(s), the identification and redshift. The redshifts were taken from Spinrad et al. (1985) for 3C sources, Hewitt & Burbidge (1987) for quasars and Burbidge & Crowne (1979) for radio galaxies, except for 0712+53 and 1732+16 whose redshifts were taken from Burns & Gregory (1982) and Véron-Cetty & Véron (1989), respectively. One source, 1009+74 has an estimated redshift taken from Riley, Eales & Baldwin (1984). Other parameters are derived from the present observations, namely the total flux density S_{20} at λ20 cm, the spectral index α (defined in the sense S ∝ ν^−α between λ6 and 20 cm), the core flux density S_c at λ6 cm and the core ratio R_c defined by Orr & Browne (1982) as the ratio of the core to extended flux density at an emitted wavelength of 6 cm.

Table 1 also shows the radio power P_{20} at an emitted wavelength of 20 cm, the largest angular size (LAS), and the corresponding linear size (LLS). Throughout we use H_0 = 50 km s^{-1} Mpc^{-1} and q_0 = 0.5. The following column identifies which component is the jet-side; seven doubtful cases are noted (see below). In the final column a reference is given for the map used in selecting the source.

Each source was required to have two well-separated lobes and some evidence of a one-sided jet. In the majority of sources (31 out of 47) the jet fulfills the strict criteria adopted by Bridle & Perley (1984). In nine of the remaining cases the
### Table 1. List of sources and basic properties.

<table>
<thead>
<tr>
<th>Name</th>
<th>id</th>
<th>z</th>
<th>(S_{20})</th>
<th>(S_{65})</th>
<th>R</th>
<th>(\log P_{20})</th>
<th>LAS</th>
<th>LLS</th>
<th>J</th>
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<td></td>
<td>(\text{mJy})</td>
<td>(\text{mJy})</td>
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<td>(\text{WHz}^{-1})</td>
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<td>1952.1</td>
<td>1.14</td>
<td>2.0</td>
<td>0.00012</td>
<td>29.76</td>
<td>10.7</td>
<td>88</td>
<td>SE</td>
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<td>1514.9</td>
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<td>1024.3</td>
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<td>S</td>
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<td>2441.8</td>
<td>0.83</td>
<td>116.0</td>
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<td>595.9</td>
<td>0.96</td>
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<td>198.0</td>
<td>0.1556</td>
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<td>6.1</td>
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<td>0.1616</td>
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#### List A (small sources)

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<th>R</th>
<th>(\log P_{20})</th>
<th>LAS</th>
<th>LLS</th>
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| list B (large sources)

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<th>R</th>
<th>(\log P_{20})</th>
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<td>(\text{WHz}^{-1})</td>
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</table>


Evidence for a jet consisted of the core in the direction of one of the hotspots, together with one or more compact knots in the same direction. The final seven cases, containing only a core extension or one knot, are noted in Table 1 as doubtful. The choice of jet side and the estimate of jet quality was made independently by two of us (STG and RGC), and in no case did our choice of jet side differ. No reference was made to any polarization characteristic when selecting sources.

For instrumental reasons (see Section 3) the list was subdivided by angular size into List A containing 25 small sources, and List B containing 22 larger sources, the division...
being at an angular size of about 30 arcsec. The sources described in Paper I were those in List A. With hindsight we now realize that the subdivision is significant [because of the correlation between angular size and redshift noted by Miley (1971)], the sublists are in effect separated by redshift], and we have preserved the distinction between the two sublists in Table 1.

The list is not a statistically complete sample to a fixed flux limit, but it does contain the majority of FR II sources which are known to have radio jets. Our sample favours quasars (40 quasars: 7 radio galaxies), reflecting the fact that jets are found more commonly in quasars than in galaxies (Bridle & Perley 1984). Although core-dominated sources often have one-sided jets, many of these were excluded from this sample because they did not have bright enough lobes. Even so, a wide range of core strengths is found among the sample.

Observations were not made of several sources for which measurements were already available. Our subsequent discussion in Paper III will include such measurements where relevant. Observations of five sources which fulfilled the selection criteria were lost due to instrumental problems, and a further three sources are excluded from this analysis because the maps were of insufficient sensitivity to measure polarization in the extended structure.

3 OBSERVATIONS

The observations were made between 1986 May and November with the Very Large Array (VLA) of the National Radio Astronomy Observatory which is an aperture synthesis telescope with 27 antennas and a maximum baseline of 35 km (Thompson et al. 1980). For most sources, standard VLA frequencies in C- and L-bands were used, giving effective bandwidths of 100 MHz centred at 4860 (6 cm) and 1490 MHz (20 cm). A few sources were observed with 50-MHz bandwidth either at 1435 or at 1465 MHz, to avoid man-made interference. Three sources, which were initially too close to the Sun, were observed later at 1417 MHz with a 12.5-MHz bandwidth. The 20-cm data of 1354 + 19 and 1055 + 20 were supplied by D. Murphy and the 20-cm data of 1323 + 65 were supplied by A. Reid.

The smaller sources, those in List A, were observed with the VLA configured as the A-array at 20 cm and as the B-array at 6 cm to give matched spatial frequency coverage at the two wavelengths and a common resolution of 1.3 arcsec. The sources in List B were observed with the B-array at 20 cm and the C-array at 6 cm, giving a common resolution of 4.5 arcsec. The observations were made in snapshot mode, each of the target sources being observed for about 8 min near transit. Brief observations of unresolved sources from the VLA Calibrator List (Perley 1982) were interspersed among the target sources.

3.1 Calibration and mapping

Initial calibrations were carried out at the VLA site using standard procedures on the DEC 10 computer. The interspersed observations of unresolved sources were used to derive an initial calibration of both phase and amplitude. The flux-density scale was determined from concurrent observations of 3C48 and 3C286, assuming flux-density values for these sources as given in Table 2.

Table 2. Flux densities used for absolute flux calibration.

<table>
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<tr>
<th>Frequency</th>
<th>1465 MHz</th>
<th>4885 MHz</th>
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<tbody>
<tr>
<td>3C48</td>
<td>15.77 Jy</td>
<td>5.60 Jy</td>
</tr>
<tr>
<td>3C286</td>
<td>14.51 Jy</td>
<td>7.41 Jy</td>
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</tbody>
</table>

The value for 3C286 is in accordance with the scale of Baars et al. (1977), but continued monitoring with the VLA has shown that the flux density of 3C48 is now some 3 per cent higher than the value given by Baars et al. (R. Perley, private communication).

Corrections for the instrumental polarization were derived for each antenna of the array using further observations of unresolved calibrator sources made at several different hour angles (and hence parallactic angles) during each run. From the internal consistency of these observations we believe the instrumental polarization to be accurate to 0.3 per cent or better. Polarization position angles were measured relative to those of 3C286 and 138, which were taken to be 33° ± 2° and −12° ± 2°, respectively, at both wavelengths. No corrections were applied for ionospheric Faraday rotation, which is not more than a few degrees, and which should be substantially uniform across each source.

After calibration, the sources were mapped using the NRAO aips package. An iterative procedure was carried out using the mx program, together with self-calibration in phase to correct residual atmospheric errors. In most cases the solutions converged after three or four such iterations. Some of the stronger sources were also self-calibrated in amplitude. The amplitude and phase corrections derived in this way were applied to all polarizations, and used to produce maps of the Stokes parameters I, Q and U. Maps of the polarized flux density $p = (Q^2 + U^2)^{1/2}$ and position angle $\chi = 0.5 \tan^{-1}(U/Q)$ were then produced from the Q and U maps. Since any residual errors in the calibration of amplitude or phase are common to all polarizations, they do not affect values of fractional polarization, at least to first order.

The expected rms noise fluctuation of the thermal noise for an integration time of 8 min is 0.1 and 0.15 mJy beam$^{-1}$ at 20 and 6 cm, respectively. The fluctuations observed off-source in the I maps range from $\sigma_I = 0.1$ to 0.8 mJy beam$^{-1}$, increasing with source intensity, consistent with a dynamic range of between 1000 and 2000 (peak: rms).

The off-source fluctuations in the Q and U maps are close to the total noise, but the uncertainty on-source is increased by systematic errors of calibration of up to 0.3 per cent (see above). The effect of these errors is to produce sidelobes in the polarization maps around the features which are brightest in total intensity. Polarization sidelobes, of order 0.2 per cent, may be seen around bright cores of some sources, giving an independent check on the level of the systematic errors in fractional polarization.

4 RESULTS

4.1 Flux and polarization values

Values of the flux and polarization of each component of the source have been found by the following procedure. All maps (at both wavelengths) were set to zero outside the lowest reliable contour of the 20-cm I map (usually 5$\sigma_I$).
Rectangular areas or ‘boxes’ were chosen around each of the two components, taking care to exclude the flat-spectrum core. The integrated values within each box of \( I, Q, U \) and \( p \), were recorded. The intensity and polarization were also recorded at the position of the brightest peak on either side, as were the values at the position of the central core which were used to derive the values of \( R \) quoted in Table 1.

The two-point spectral index \( \alpha \) between 6 and 20 cm was found both from the flux densities \( S_{\text{box}} \) and the peak intensity \( I_{\text{peak}} \) on each side. The values of \( S_{\text{box}} \) and \( I_{\text{peak}} \) at 20 cm are listed in Table 3 together with the spectral indices derived from the \( I_{\text{peak}} \) values. In addition, Table 3 lists the separation, i.e. the peak–core distance, for each component. Suffixes \( j \) and \( c \) identify values for the jet and counter-jet sides throughout.

The technique of ‘boxing’, although widely used, involves truncation that always produces an underestimate of the true flux density. Quoted values of \( S_{\text{box}} \) should therefore be treated with caution. The effect was particularly severe for four of the smallest sources, namely 0802+10, 1318+11,
Asymmetric depolarization

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1656 + 57 and 1857 + 56, where it was not possible to choose boxes surrounding the components without some overlap with the flat-spectrum core. For these sources we have set $S_{\text{box}} = S_{\text{peak}}$, i.e. the flux and polarization values refer to the peak pixel.

From the integrals $\Sigma Q$ and $\Sigma U$ for each box we have formed the vector mean fractional polarization

$$m = (\Sigma Q^2 + (\Sigma U^2))^{1/2} \Sigma I,$$

and the associated mean position angle

$$\chi = 0.5 \tan^{-1} \left(\frac{\Sigma U}{\Sigma Q}\right).$$

We have also found the scalar mean fractional polarization

$$m' = \frac{\Sigma P}{\Sigma I}.$$

Table 5. Component percentage polarization and position angle at 6 cm.

<table>
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<tr>
<th>Name</th>
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<th>$m_0$</th>
<th>$m_0$</th>
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Table 6. Values of component DP, $\Delta$ (cm$^{-3}$ M g pc) and RM (rad m$^{-2}$).

<table>
<thead>
<tr>
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<th>error</th>
<th>$D_{P2}$</th>
<th>error</th>
<th>$\Delta_1$</th>
<th>$\Delta_2$</th>
<th>$\text{RM}_{\text{m}}$</th>
<th>$\text{RM}_{\text{d}}$</th>
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Values of $m$, $\chi$, and $m'$ are given in Tables 4 and 5, while DP is given in Table 6. The errors in fractional polarization have been estimated as follows: the rms error due to thermal noise is

$$\sigma_{m_{\text{noise}}} = \frac{N^{1/2} \sigma_r}{\Sigma I},$$

where $N$ is the number of non-blank beam areas in the box and $\sigma_r$ is the noise in the $Q$ and $U$ maps; the noise in $I$ is small enough to be ignored. Including any systematic error due to calibration, estimated at 0.3% per cent in fractional polarization, the overall error is

$$\sigma_m = [\sigma_{m_{\text{noise}}} + (0.3\text{ per cent})]^2.$$
Components are considered unpolarized if $\Sigma_{\gamma} < 3N^{1/2} \sigma_\gamma$, or if $m < 0.3$ per cent. The effect of noise on quantities such as $m$ and $m'$ which are always positive is to produce an upward bias (e.g. Simmons & Stewart 1985). However, since the bias is small for $\Sigma_{\gamma} > 3N^{1/2} \sigma_\gamma$, no noise corrections have been applied to the values in Tables 4 and 5.

When comparing these results with integrated polarization measurements at different wavelengths (usually at low resolution), the vector mean polarization $m$ will be the correct quantity to use. On the other hand, given observations made at matched resolution, as here, it is preferable to use the scalar mean polarizations $m'$ to calculate $DP$, since it maximizes the signal-to-noise ratio, while making optimum use of the available resolution of the maps. Both $m$ and $m'$ are mean values weighted by the $I$ distribution within the box, and avoid problems arising from spuriously high values of fractional polarization found at the edge of the source.

### 4.2 Faraday rotation

We have used the component polarization position angles in Tables 4 and 5 to derive two-point Faraday rotation measures, $RM$, which are given in Table 6. Since position angles are ambiguous by $\pi$, the $RM$ values calculated from 6 and 20 cm are ambiguous by $\pm n86$ rad m$^{-2}$:

$$RM = (27A\chi \pm n86) \text{ rad m}^{-2}.$$  

(7)

Since values of $RM$ of order 100 rad m$^{-2}$ are common (e.g. Simard-Normandin, Kronberg & Button 1981) this ambiguity is important and can only be resolved by adding data at other wavelengths. For eight sources, indicated by an asterisk in Table 6, the component polarization data of Conway et al. (1983) were used to plot $\chi$ versus $\lambda^2$ from 6 to 31 cm and resolve the ambiguities in $\Delta\chi$. For a further 12 sources, indicated by a dagger (†), integrated $RMs$ were available (Tabara & Inoue 1980), and the value of $n$ was chosen to bring the component $RM$ values closest to the integrated value. For the remaining sources, $n$ was chosen to minimize the absolute value of $RM$. The $RM$ values are not quoted where the error in $\chi_{30}$ or $\chi_{6}$ is greater than 30$^\circ$.

The median difference in $RM$ between the two sides, $\Delta RM$, is 12 rad m$^{-2}$. We believe that the differences in $RM$ are free from ambiguity, since Conway et al. (1983), using data at four wavelengths, found that differences in $RM$ in double sources were always small.

### 4.3 Faraday dispersion

Wavelength-dependent depolarization (the major effect being investigated here), depends upon $F(\phi)$, the variation from point to point in the source of the Faraday depth

$$\phi = \int n B_z dl,$$  

(8)

where $n$ is the thermal electron density, $B_z$ is the longitudinal magnetic field, and the integral is carried out along the line-of-sight from the point considered to the observer.

As explained by Burn (1966) it is not possible to deduce the distribution function $F(\phi)$ directly from observation. Instead one must model the source, and calculate the resulting observable, in this case $DP$. Here we assume a Gaussian distribution for $F(\phi)$ with standard deviation $\Delta$. The depolarization $DP$ between wavelengths 20 and 6 cm is

$$DP = \exp[-2k^2\Delta^2(\lambda_1^2 - \lambda_2^2)/(1 + z)^4].$$  

(9)

We depart from convention by defining $\Delta$ and $\phi$ in units of cm$^{-3}$ $\mu$G pc rather than in the more usual radial m$^{-2}$, in which case $k = 0.81$ and

$$\Delta = 22(1 + z)^2 (-\ln DP)^{1/2}.$$  

(10)

A common measure of depolarization is $\lambda_{1/2}$, the wavelength at which polarization has fallen by a factor 2. For the Gaussian model

$$\lambda_{1/2} = 18.3(-\ln DP)^{-1/4} \text{ cm}.$$  

(11)

Equation (10) has been used to calculate the values of $\Delta$ in Table 6. Where $DP$ is very small, or is close to unity, we have set conservative limits to $\Delta$ corresponding to $DP = 3\sigma_{DP}$ and $DP = 1 - 3\sigma_{DP}$, respectively. The fact that measurements are available at only two wavelengths inevitably restricts the range in $DP$. This in turn leads to an observational selection in the derived values for $\Delta$. As we discuss in Paper III, this selection effect becomes relevant when discussing the ratio of $\Delta$ values, in particular the ratio of $\Delta$ between jet and counter-jet components.

For $0033 + 18$, $0123 + 32$ and $0824 + 29$, data at 49 cm (Strom & Conway 1985) are consistent with the upper limits for $\Delta$ in Table 6. In two sources ($0802 + 10$ and $1857 + 56$) the counter-jet component appears to be completely depolarized at both wavelengths. We have estimated $\Delta$ assuming $\lambda_{1/2}$ to be less than 6 cm.

### 5 DISCUSSION

The astrophysical interpretation of depolarization, and of asymmetry between the jet and counter-jet sides, is reserved for a separate paper (Paper III). Here we wish to establish the statistical significance of the asymmetry in $DP$ (or $\Delta$), and to assess the significance (or otherwise) of side-side asymmetries in other radio parameters, bearing in mind trends already noted by, for example, Bridle & Perley (1984) and Saikia (1984).

#### 5.1 Depolarization

The fractional polarization $m'$ at 16 and 20 cm is shown in Fig.1, the value for the jet side being plotted against that of the counter-jet side at each wavelength. At 6 cm most sources show a polarization of 5–15 per cent, and there is no significant difference between the two sides. At 20 cm the general level has fallen, markedly so in the case of counter-jet components. Fig. 2 shows the plot for the ratio $DP$ and confirms immediately that the jet side depolarizes less than the counter-jet side in most sources. There is a group of seven sources which are virtually free from depolarization on both sides, with $DP > (1 - 3\sigma_{DP})$, and five further sources show essentially equal depolarization (although only one of these, $0712 + 53$, shows strong depolarization). Of the remainder, $DP_j$ is less than $DP_{\delta j}$ for one source ($2203 + 29$), but for 32 sources $DP_j$ is significantly higher than $DP_{\delta j}$, taking $(DP_j - DP_{\delta}) > 3\sigma$ as significant. If we include the two sources ($0802 + 10$ and $1857 + 56$) in which the counter-jet components appear depolarized at both wavelengths, there are 34 sources with $DP_j$ greater than $DP_{\delta j}$. The chance prob-
Asymmetric depolarization

Figure 1. Fractional polarization $m^\prime$ at 20 (upper) and 6 cm (lower) for the jet and counter-jet components. Filled circles denote small sources (List A) and open circles denote large sources (List B).

Figure 2. Depolarization ratio $DP$ of the jet and counter-jet side components. Filled and open circles denote List A and B sources, respectively.

Ability of this asymmetry in $DP$, measured by a Wilcoxon signed rank test (Wilcoxon 1945), is $<10^{-6}$.

As explained in Section 2, the sample is divided into two sublists which differ markedly in angular size, redshift and luminosity. The small sources (List A) are indicated in Fig. 2 by black circles, while sources in List B are shown as white circles. The depolarization asymmetry is found in both lists, but Fig. 2 shows that it is stronger in the sources of List A. The difference in $DP$ between the two lists is consistent with the known trend in the integrated polarization values, which was originally interpreted as an increase of depolarization with redshift by Kronberg, Conway & Gilbert (1972) as a size-dependent effect by Strom (1973), and as a luminosity-dependent effect by Leahy (1985).

5.2 Intensity

Fig. 3 compares the flux densities $S_j$ and $S_{\alpha j}$, and the peak intensities $I_j$ and $I_{\alpha j}$. The median ratios of $S_j/S_{\alpha j}$ and $I_j/I_{\alpha j}$ are 1.24 and 1.37, respectively, showing that the jet-side components are stronger at 20 cm than counter-jet-side components, though at a marginal significance level. (The chance probabilities for the asymmetries in $S$ and $I$ are, respectively, 2.4 and 6.4 per cent, using a Wilcoxon test; if we had used a simple sign test, the differences would not be significant at the 5 per cent level.)

Inspection of the higher-resolution maps used to select the sources shows that in 32 sources the peak intensity is higher on the jet side, in nine the peak intensity is higher on the counter-jet side, and in six the two peak intensities are similar to within a factor of 2. We conclude that the excess intensity on the jet side found in our present maps is real, and that it occurs in the hotspot; there is little evidence for excess in the more extended lobe emission. Bridle & Perley (1984) and Laing (1989) also found the brighter hotspot to be on the jet side in the majority of FR II sources with one-sided jets.

5.3 Spectral index

Fig. 4 compares the spectral indices $\alpha_j$ and $\alpha_{\alpha j}$ determined from the flux densities $S_j$ and $S_{\alpha j}$. The figure shows a clear tendency for the jet sides to have flatter spectra; the median difference in spectral index $\alpha_j - \alpha_{\alpha j}$ is $-0.10$. The spectral indices determined from the $I_j$ and $I_{\alpha j}$ values are slightly lower (typically by 0.05), but show a similar asymmetry.

Excluding systematic errors in the flux scale, which will affect both components equally, the errors of measurement
in the intensities of bright features are not more than 5 per cent. Additional errors may occur in reckoning the total flux density of low-brightness regions, but even so the uncertainties in are unlikely to exceed 10 per cent. The corresponding errors in are about 0.05 for peak intensity, and 0.10 for flux density. Thus the scatter shown in Fig. 4 may be due largely to measurement errors. However, the systematic bias in the difference in spectral index is clearly significant: the chance probability of this asymmetry is $1.5 \times 10^{-6}$.

Figure 3. Flux densities (upper) and peak brightnesses (lower) for the jet and counter-jet components.

Figure 4. Spectral indices determined from the box flux densities of the jet and counter-jet components at 20 and 6 cm.

Figure 5. Arm lengths for the jet and counter-jet components.

Since hotspots generally have flatter spectra than their associated lobes (Alexander & Leahy 1987), the asymmetry in spectral index may simply be caused by the trend, noted above, for the jet-side hotspot to be the brighter of the two. We have modelled this effect quantitatively, and find that the observed flux-density ratio and the observed difference in
$a_j - a_{\text{cl}}$ can be reproduced provided that the hotspots have a spectral index $a_{\text{cl}} < 0.5$. It is not yet clear whether such flat spectra are common in hotspots (Meisenheimer 1989). If this is not the case then there must be a genuine intrinsic difference between the spectral indices of the two components. In order to resolve this question, one needs scaled array maps at still higher resolution than here.

5.4 Arm length

Fig. 5 compares the arm lengths $\theta_j$ and $\theta_{\text{cl}}$, i.e. the separations of the jet and counter-jet sides from the core. In the sample as a whole there is no significant asymmetry: the median value of the ratio $r_{\theta} = \theta_j/\theta_{\text{cl}}$ is 1.07. Saikia (1984) found a median separation ratio of 1.03 for a sample of 36 sources which partly overlaps with ours.

We noted in Paper I that among the small sources (List A) there is a weak asymmetry in arm length in the sense $\theta_j > \theta_{\text{cl}}$ (the median ratio is 1.15). We attributed this to a selection effect: jets are hard to detect if the arm length is small. This difference in arm length, either real or from a selection effect, could in principle influence the DP asymmetry, because in individual sources depolarization is strongest near the core (Strom & Conway 1985).

Fig. 6 shows depolarization $DP$ plotted against arm length expressed in kpc for each side in turn. Differences of arm length cannot be the primary cause of depolarization asymmetry in our sample: while $DP$ and $\theta$ are correlated on the counter-jet side, they are not correlated on the jet side. In other words, it must be the jet-sidedness rather than any difference in arm length which governs the asymmetry in $DP$.

We can illustrate this fact further by plotting (Fig. 7) $r_{\theta} = \theta_j/\theta_{\text{cl}}$ against $r_{DP} = DP_j/DP_{\text{cl}}$. There is little correlation between these two quantities; many sources have $r_{\theta} < 1$, and the majority of these have depolarization asymmetry in the usual sense.

Pedelt et al. (1989) have discovered a correlation between arm length and depolarization in a sample of high-redshift radio galaxies. We discuss the implications of this result in Paper III.

6 CONCLUDING SUMMARY

We have presented scaled array polarization maps at 6 and 20 cm of 47 powerful double radio sources with one-sided jets. For each component we have tabulated values of flux density and polarization. There is a strong asymmetry in the degree of depolarization between 6 and 20 cm: of the 37 sources with significant depolarization, 34 show less depolarization on the jet side than on the counter-jet side. There is also a significant asymmetry in the spectral index of the two sides: the jet-side spectral index is flatter by typically $\Delta \alpha = 0.1$. By comparison, the asymmetries in flux density, peak brightness and separation from the nucleus are minor, and cannot be significant contributors to the depolarization asymmetry.
ACKNOWLEDGMENTS

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REFERENCES


APPENDIX: THE MAPS

Figs A1 to A47 show the resulting total intensity maps at 6 and 20 cm for each source, with superposed vectors representing the polarized flux density and position angle. The resolution of the maps varies from 1.3 to 6.0 arcsec, depending on which array was used (see above), but is always the same at 6 and 20 cm. Successive contours increase by factors of 2 in brightness, and one negative contour, equal in magnitude to the lowest contour, is included in each map. Values of the peak brightness and of the lowest contour are given in the caption of each map, together with the scale of the polarization vectors. Polarization vectors are not shown below the bottom contour, or where the polarized signal is less than the lowest reliable value, typically 0.5 mJy beam⁻¹.

NOTES TO INDIVIDUAL SOURCES

Descriptions are given below of jets which have been identified from unpublished maps. Laing (unpublished) indicates a VLA map at 6 cm; Shone (1985) refers to a MERLIN map at 18 cm, while Reid (1987) refers to a MERLIN map at 73 cm.

List A
3C14. A very straight, narrow jet leads from the core to the S component (Laing, unpublished).
3C41. There is a jet in the S component (Laing, unpublished).
3C191. The present observations do not resolve the core completely from the S component. Quoted values of flux and
Asymmetric depolarization refer to the peak pixel of each component (see text).

**3C207.** VLBI observations (Hough 1986) show a secondary component 0.5 mas to the E of the core.

**0858 + 58.** The jet to the S is knotty and bent (Shone 1985). Barthel *et al.* (1986) have detected superluminal motion in the core.

**1115 + 53.** The central component in the figure contains a flat-spectrum core and a steep-spectrum component to the W (Shone 1985; Reid 1987).

**1318 + 11.** The present maps do not resolve the components from the core and quoted values of flux and polarization refer to the peak pixel on each side.

**1323 + 65.** The bent knotty jet to the SW is seen also at 18 cm (Shone 1985). The status of the diffuse component to the NW, which is also visible at 73 cm (Reid 1987), is uncertain. This component has been excluded.

**1634 + 58.** There is a slight extension of the core to the N (Shone 1985).

**1656 + 57.** There is a jet extending from the bright core to the E (Shone 1985). The present maps do not resolve the components from the core and quoted values refer to a single pixel on each side.

**3C352.** A straight jet runs through the N component (Laing, unpublished).

**1732 + 16.** The jet to the N consists of a string of knots (Laing, unpublished).

**List B**

**3C34.** There are two knots colinear with the optical object and the E hotspot (Laing, unpublished).

**0712 + 53.** The luminosity of this source is at the division between FRI and FRII (Fanaroff & Riley 1974). The jet to the W does not terminate in a hotspot (Burns & Gregory 1982). The source lies within the outlines of a large cD galaxy (Burns & Owen 1979).

**3C215.** A very distorted jet consisting of a series of knots leads to the E component. There may be a very faint counter-jet (D. Hough, unpublished).

**0957 + 00.** The isolated feature to the NE may be a background source; it has been excluded.

**1009 + 74.** There is a bright knot between the core and the southern hotspot (Laing, unpublished).

**1055 + 20.** The jet is continuous from the core into the N component, where it appears to bend by 90° (Murphy 1988).

**1354 + 19.** The jet to the S is quite straight, and terminates 3 arcsec from the S hotspot (D. Murphy, unpublished).

**3C334.** The jet to the SE is confirmed in a recent high-sensitivity map by Bridle *et al.* (as shown in Norman, Clarke & Burns 1988).

**1732 + 65.** A narrow ridge of emission is found to the E of the core (Shone 1985; Reid 1987).

**3C441.** We follow Laing (1988) in identifying the knot to the N as a jet, but this identification is doubtful.

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**Figure A1.**
Figure A2.

Figure A3.
Asymmetric depolarization
Figure A25.

Figure A26.

Figure A27.
Figure A31.

Figure A32.

Figure A33.