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Synthesis Observations of Southern Radio Sources at 1410 MHz with the Parkes Interferometer. II * Polarization and Brightness Distributions Across Seven Sources

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Abstract

The Parkes two-element interferometer, which provides a maximum resolution of $\sim 1'$ arc at a frequency of 1410 MHz, has been used to obtain the distributions of polarization and brightness across seven extended sources. The results seem to be consistent with a previous interpretation in which the magnetic fields of evolved sources are orthogonal to the direction of elongation but those of relatively young sources are parallel to this direction.

Introduction

Most of the linear polarization data available for southern radio sources are integrated values obtained with equipment of relatively low resolving power. Such results are of limited use in detailed studies since it is known from other observations of resolved sources that the polarization can vary considerably in magnitude and direction across a source. The Parkes interferometer (Batchelor *et al.* 1969) has a maximum angular resolution of $\sim 1'$ arc at a frequency of 1410 MHz, but it was not possible initially to perform a complete aperture synthesis because the instrument lacked phase stability. The subsequent phase stabilization carried out in 1970 has been described in Part I (Schwarz *et al.* 1973). The present paper describes observations made with the interferometer of the polarization and brightness distributions across the sources PKS 0518−45 (Pic. A), 0618−37 (MSH 06−3*7*), 0843−33, 1322−42 (Cen. A), 1733−56, 2152−69 (MSH 21−6*4*) and 2356−61 (23−6*4*). Previous interferometer observations of some of these sources, made at similar frequencies by Morris and Whiteoak (1968) and Seielstad and Weiler (1969, 1971), yielded only one-dimensional distributions for the polarization.

Observations

The use of the 64 and 18 m reflectors at Parkes as an east-west interferometer, and the procedures adopted for observation and data analysis, have been described in Part I. The instrument operates at 1410 MHz and yields a maximum angular resolution of $\sim 1'$ arc. The 18 m telescope was equipped with a conical horn while the 64 m telescope had a hybrid-mode feed equipped with two orthogonal probes. One probe was always kept parallel to the direction of polarization of the conical horn (the 'parallel' configuration), the other probe therefore being perpendicular

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to this direction (the 'crossed' configuration). The receiver could be switched from one probe to the other so that either configuration could be used.

The sequence of actions required to obtain observations of both the polarized and unpolarized radiation at a selected interferometer spacing was controlled by a PDP-9 computer attached to the 64 m telescope. For the polarization observations the crossed configuration was selected, and both telescope feeds were set at a series of nine orientations 40° apart. At each setting, the outputs of the sine and cosine phase-sensitive detectors of the interferometer were integrated for 30 s. After the last integration, calculations were made of the second harmonic amplitudes and phases of the variation of the integrated values with feed setting. The phases were subsequently converted to position angles by addition of the parallactic angle, and corrected for the Faraday rotation through the ionosphere (see Gardner *et al.* 1969*a*) and for the zero offset of the feed orientations. This offset was obtained to an accuracy of $\pm 1°$ by the radiation of a linearly polarized signal into the feed of the 64 m telescope. Finally, the harmonic components were combined to yield the amplitudes and phases of the visibility functions for the polarized Stokes parameters Q and U.

Observations of the total intensity were carried out both before and after each set of feed rotations by switching to the parallel configuration. The measurements contained contributions of linearly polarized intensity which were removed at a later stage of reduction.

The results were corrected for two instrumental effects. Differences in the gains and phase delays of the crossed and parallel feed configurations were determined by observation of the polarized small-diameter source PKS 0521−36. The polarization of the source was known only to 20% accuracy, and the interferometer results have a similar uncertainty. The other effect was due to instrumental circular polarization in the 18 m telescope, which produced a residual response with the crossed configuration. Elliptical polarization was produced in the feed of the 64 m telescope by coupling one probe to the other through a directional coupler and line-stretcher. By the variation of this polarization during observations of Ori. A, a setting was obtained for which the residual was minimized to 3% of the total intensity. The effectiveness of the subsequent removal of this residual was shown by observations of the unpolarized source PKS 1934−63, which yielded an apparent linear polarization of $\leqslant 0 \cdot 2\%$.

The gain and phase calibration of the interferometer were made approximately every hour by observation of small-diameter sources. These sources, their intensities and adopted positions, and the extended sources for which they were used as calibrators, are listed in Table 1. The source data were taken from the Parkes catalogue (Ekers 1969*a*), except for the intensity of PKS 1018−42, which is variable (the listed value is an unpublished 64 m value obtained close to the date of the polarization observations). However, there is evidence that the right ascensions of some of the calibrators may be too high by as much as 2 s, and the coordinate calibration of the associated maps may be similarly in error.

The Fourier inversion of the total intensity results was effected in the manner outlined in Part I. For the polarization measurements, the iterative beam-removing technique was applied to derive the distributions of Q and U, but only at the positions where the total intensities were above a certain threshold value. The distributions of polarized intensity and direction of polarization were derived from these results.

For the sake of consistency, the total intensities were reprocessed using restrictions similar to those used in the processing of the polarization. Finally, all amplitudes were corrected for the primary beamwidth of the interferometer (20′ arc).

The integrated results, which are a by-product of the reduction procedure, are listed for comparison purposes in Table 2 together with the corresponding observations obtained with the 64 m telescope (beamwidth 14′·5 arc) by Gardner *et al.* (1969*a*). The columns of this table are self-explanatory. It can be seen that the overall agreement is satisfactory.

Table 1. Calibration source data

Calibration source (PKS)	S_{1410} (f.u.)*	Adopted position (1950) R.A. h m s	Dec. ° ′ ″	Extended sources (PKS)
0521−36	14·7	5 21 13·3	−36 30 15	0518−45 0618−37 0843−33
1018−42	3·7	10 17 56·3	−42 36 19	0843−33
1424−41	2·8	14 24 47·7	−41 52 52	1322−42 1733−56
1934−63	13·0	19 34 49·0	−63 49 12	1733−56 2152−69 2356−61
2331−41	4·5	23 31 45·6	−41 42 14	2152−69 2356−61

* 1 flux unit (f.u.) = 10^{-26} W m^{-2} Hz^{-1}.

Table 2. Comparison of integrated and single-dish results

PKS source number	S_{1410} (f.u.) Inte-grated	Single dish	Polarization (%) Inte-grated	Single dish	Position angle (°) Inte-grated	Single dish
0518−45	65	66	2·4±0·4	3·1±0·4	50±4	50±5
0618−37	2·3	2·7	13·3±1·5	11·0±1·5	70±3	71±3
0843−33	1·9	2·2	14·7±2·0	13·9±1·2	140±4	155±3
1322−42	156		7·7±0·4	7·5	162±2	175±3
1733−56	7·6	7·4	2·0±0·5	1·9±0·5	148±6	169±5
2152−69	30	30	1·1±0·2	2·5±0·2	105±4	118±3
2356−61	17·2	22	4·1±0·4	4·9±0·3	73±2	66±2

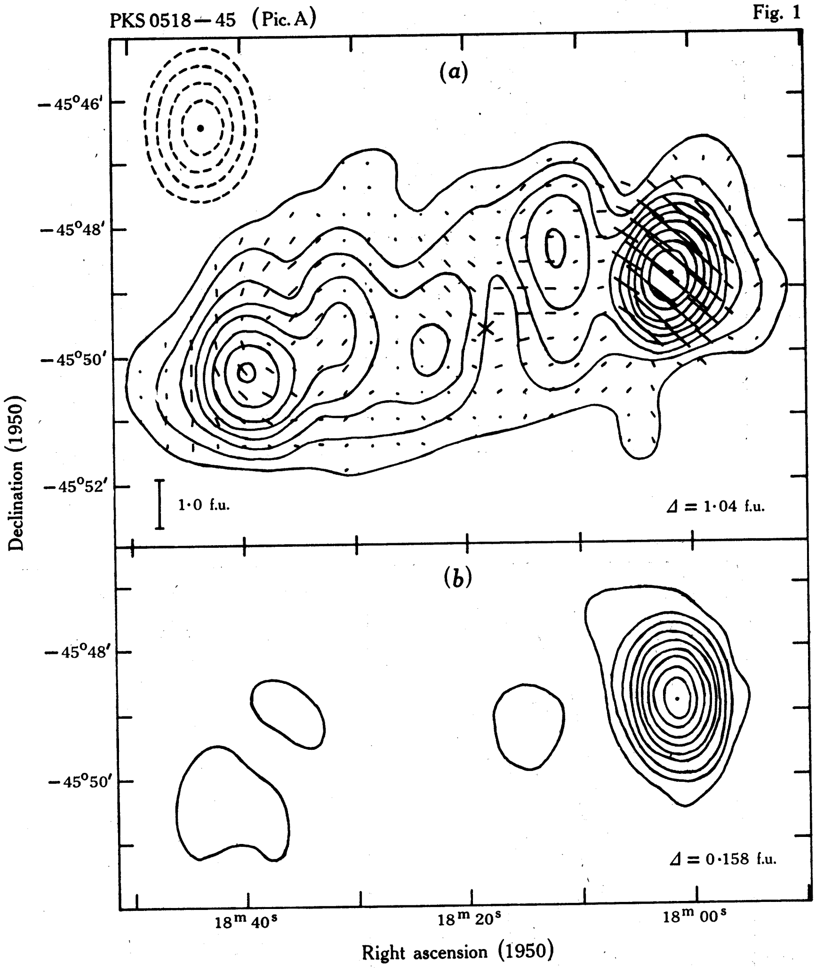
Results

Figs 1–7 show the results for the sources PKS 0518−45, 0618−37, 0843−33, 1322−42, 1733−56, 2152−69 and 2356−61. Each figure shows in (*a*) vectors of polarized beam flux density superimposed on the distribution of total intensity and in (*b*) the distribution of polarized intensity. The beam flux density Δ of the first contour, which is the same as the contour interval, is given in the figure. In (*a*) the dashed-line distribution represents the synthesized beam-shape of the interferometer and a cross denotes the centre of the galaxy believed to be associated with the source. Most of the optical identifications have been obtained from the Parkes catalogue (Ekers 1969*a*).

PKS 0518−45 (*Pic. A*) (Fig. 1). With an angular resolution of 1′·0×1′·3 (to half-intensity) the total-intensity distribution (Fig. 1*a*) shows the well-known elongated shape and the two outlying components. The components have dimensions to half-intensity of $\sim 1'$ arc (after correction for the beamwidth of the interferometer), a peak-intensity ratio of 0·8 and a separation of $6'\cdot 8$ arc along an axis with a position angle of 102°. Between these components are two fainter peaks with a separation of $3'\cdot 8$ arc at position angle 115°. These parameters are similar to those determined by Ekers (1969*b*) from observations obtained with the same interferometer but without phase information. The strong western component has a high percentage polarization of 17% at a position angle of 48°. From a comparison with the 6 cm results of Gardner *et al.* (1969*b*), the Faraday rotation is 131° and the intrinsic position angle of polarization is 97°, i.e. the projected magnetic field is orthogonal to the major axis of the source. In the eastern region of the source, the percentage polarization is lower ($\sim$4%) and the polarized radiation is concentrated around the outer edge of the intensity peak. However, the apparent deficiency of polarized radiation at the inner edge may be due to the marked variation in direction of polarization, which has a scale similar to the interferometer beamwidth. Because of this variation, a realistic value of the Faraday rotation cannot be obtained by comparing the present results with the 6 cm observations at the intensity peak of Gardner *et al.* (1969*a*). For the same reason the unexpected Faraday rotation of −80° derived by Seielstad and Weiler (1969), partly on the basis of the east-west distribution of polarization at 1420 MHz, is questionable. If the Faraday rotation is similar to that for the western component, the intrinsic polarization angles are consistent with a field aligned along the eastern circumference of the component. However, the lower polarization and varying direction of polarization suggest that the field pattern is more complicated than that of the western component, and the interpretation is rather uncertain. The associated optical identification, a $15^m\cdot 7$ D galaxy, is located close to the radio centroid. As with the extended southern sources For. A (Gardner and Whiteoak 1971) and Cen. A (Wade *et al.* 1971), there is a small unpolarized peak in the radio emission near the associated galaxy.

PKS 0618−37 (Fig. 2). The observations of this source were limited in number and the synthesized beam-shape has the half-power dimensions of $0'\cdot 8 \times 2'\cdot 7$. The intensity distribution consists basically of two components of small angular size with a peak intensity ratio of 0·8 and a separation of $1'\cdot 3$ arc along an axis at a position angle of 75°. These parameters are similar to those listed by Ekers (1969*b*). The percentage polarization is approximately the same at both intensity maxima (14–18%), but the direction of polarization differs by $\sim$30°. The polarization results are consistent with the east-west strip distributions determined by Seielstad and Weiler (1969). Single-dish observations of the integrated polarization at several wavelengths suggest that the Faraday rotation is only −2° (unpublished Parkes results). On this basis, it appears that the source belongs to the category for which the projected magnetic fields in the components are almost orthogonal to the direction of component separation. The $16^m\cdot 6$ db galaxy that has been suggested as the optical object associated with the radio emission is located within $1'$ arc of the radio centroid.

PKS 0843−33 (Fig. 3). Because of the limited north-south resolution of the interferometer at the declination of PKS 0843−33, the synthesized beamwidth has half-power dimensions of $0'\cdot 8 \times 2'\cdot 6$. The elongated intensity distribution shows a source with dimensions, corrected for beam-smoothing, of $\leqslant 0'\cdot 5 \times 4'\cdot 0$, with the major axis at a position angle of 170°. A similar interpretation has been given by Ekers (1969*b*). The polarization is rather uniformly aligned in direction, with a value



Figs 1–7 (*following pages*). Results at 1410 MHz for the indicated sources, showing:

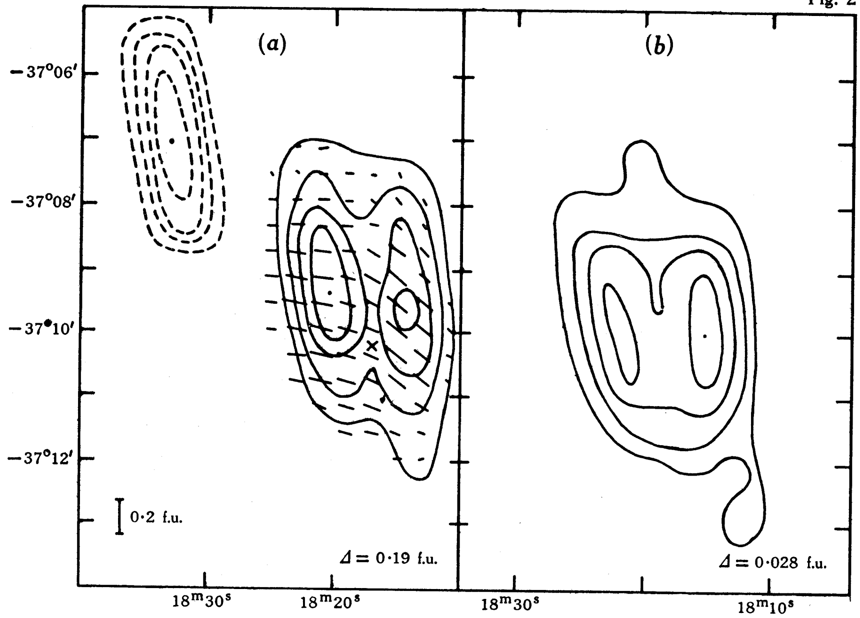
(*a*) polarization vectors superimposed on the distribution of total intensity (the beam flux density of the first contour and of the contour interval is given by Δ);

(*b*) the distribution of polarized intensity (the beam flux density of the first contour and of the contour interval is given by Δ).

The distribution shown by the dashed lines in (*a*) represents the synthesized beam-shape.

PKS 0618−37

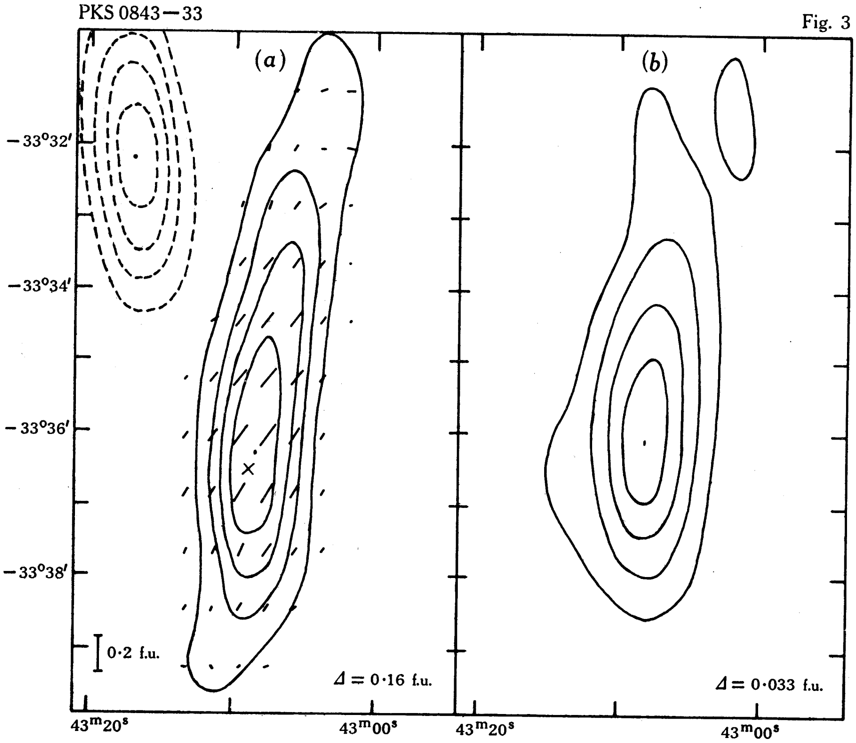
Fig. 2



Declination (1950)

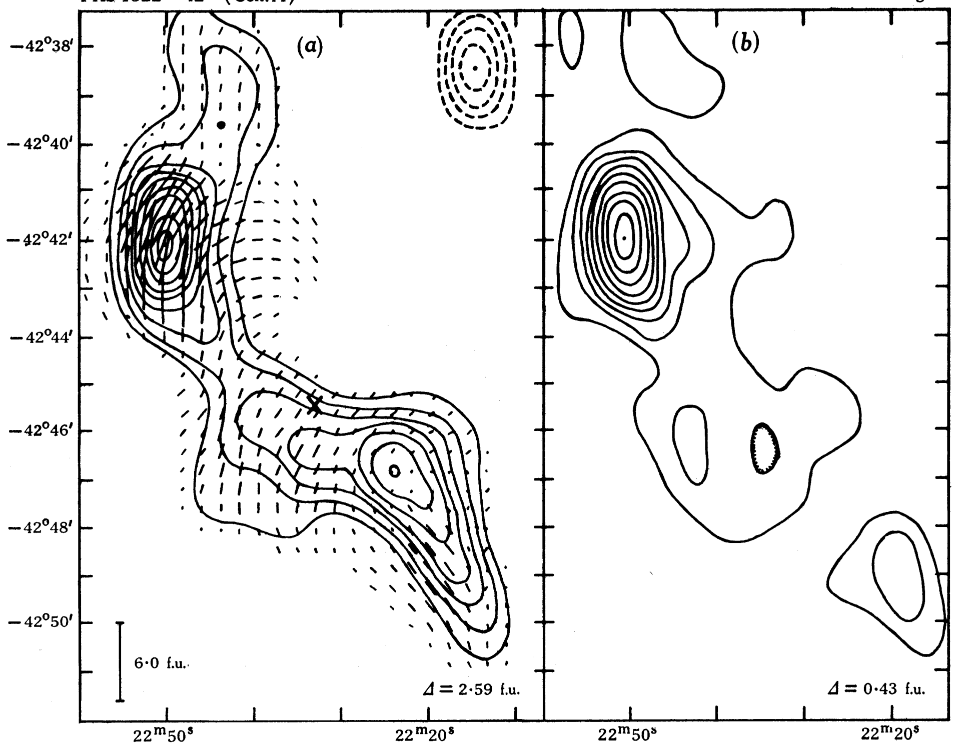
PKS 0843−33

Fig. 3



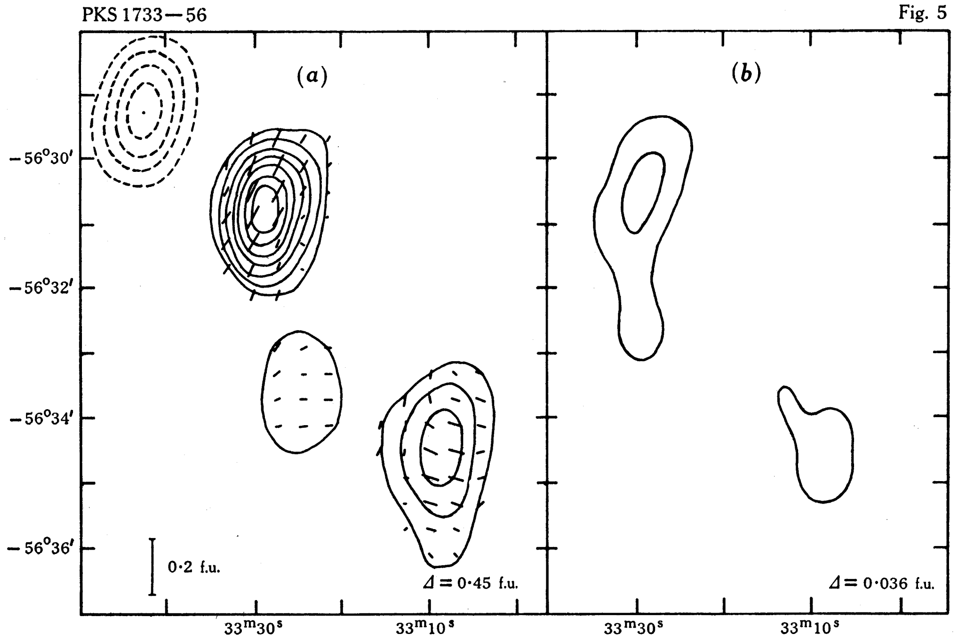
Right ascension (1950)

PKS 1322−42 (Cen. A) Fig. 4



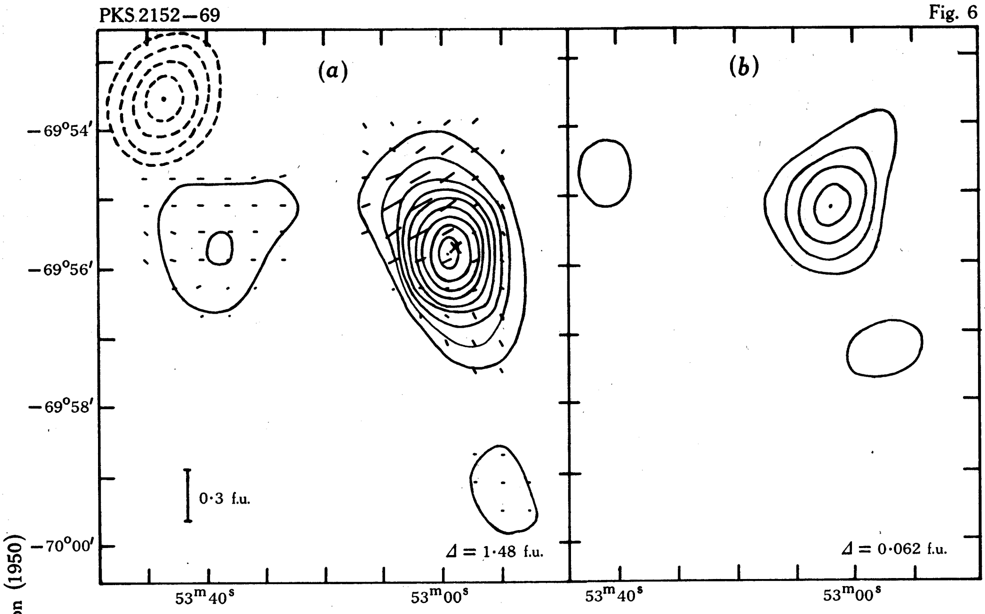
Declination (1950)

PKS 1733−56 Fig. 5

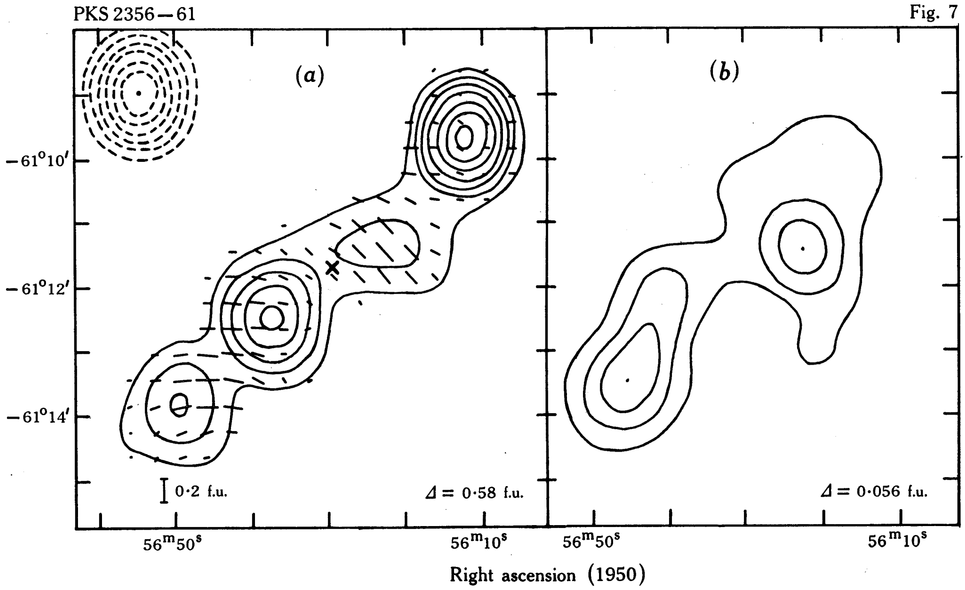


Right ascension (1950)

PKS 2152−69 Fig. 6



PKS 2356−61 Fig. 7



of 20% near the intensity peak. Unpublished observations of polarization with the 64 m telescope yield an average rotation measure of 69 rad m^{-2}, and a value of 156° for the intrinsic position angle of polarization. If the differential Faraday rotation across the source is small, as suggested by the uniformity in alignment of the vectors in Fig. 3 and by the small variation of percentage polarization with wavelength (see Gardner *et al.* 1969*a*), the source is similar to PKS 0518−45 and 0618−37 in that the projected magnetic field is approximately orthogonal to the major axis. The optical identification, NGC 2663, is approximately located at the continuum maximum.

PKS 1322−42 (*Cen. A*) (Fig. 4). At 1410 MHz this source has highly polarized radiation extending over several square degrees (Cooper *et al.* 1965). However, for the present observations the primary beam of the interferometer was centred only on the continuum maximum. With the synthesized beamwidth of $0'\cdot9 \times 1'\cdot6$, the intensity distribution (Fig. 4*a*) shows the well-known double nature of the central region of the source. The two main components, with a peak-intensity ratio of 0·7, have a separation of 6′·8 arc along an axis at a position angle of 45°. The northern component is slightly elongated in a north-south direction (the estimated corrected dimensions are $<0'\cdot5 \times 1'\cdot4$). The eastern extension of the southern source may be due to a faint component known to be coincident with the nucleus of the associated galaxy NGC 5128 (Wade *et al.* 1971; Whiteoak and Gardner 1971). This component is present in the one-dimensional interferometer results of Fomalont (1968) and Morris and Whiteoak (1968). The offset of the component from the position of the galaxy in Fig. 4*a* may be due to errors in the adopted position of the reference source PKS 1424−41.

The large disparity in the polarization of the main continuum peaks is similar to the results of Gardner *et al.* (1969*b*) at 6 cm. The northern component has a polarization at the peak of 17% while the southern component contains no polarization higher than 2%. To the west of the northern component is located a highly polarized region where the total intensity is below that corresponding to the first contour (2·59 f.u.). The position angle of polarization for the northern component (175°) is similar to the integrated value obtained with the Parkes 64 m telescope by Gardner *et al.* (1969*a*) at a similar wavelength. If it is assumed that the single-dish values at other wavelengths are representative of the polarization for this component, the intrinsic position angle of polarization is 153° (unpublished Parkes results). Therefore the direction of the magnetic field is within 20° of the direction of separation of the two components. This relationship was not present in the sources discussed previously. However, since the structure of this source is not simple, a comparison of the field direction with the shape of the total-intensity distribution may be more significant. The shape of the source can be interpreted in terms of a plasma outflow from NGC 5128, with a flow direction that has been modified by the motion or rotation of the galaxy relative to the intergalactic medium. Near the strong northern component the outflow is proceeding in a north-west direction, i.e. in a direction almost orthogonal to that of the magnetic field.

If the Faraday rotation in other directions is similar to that near the northern component, the field near the galaxy is approximately parallel to the elongation of the intensity distribution in that direction. In the south-west extension of the source, where the polarization is ~30%, the configuration of orthogonality is present.

Seielstad and Weiler (1971) have derived the east-west distribution of polarization over the source. Their results show polarization for the eastern component similar to that in Fig. 4, but further comparison is meaningless because of the large variation in direction of polarization with declination.

PKS 1733−56 (Fig. 5). The synthesized beam has the half-power dimensions of $0'{\cdot}8 \times 1'{\cdot}3$. The intensity distribution of the source consists basically of two distinct components with a peak-intensity ratio of 0·5 and half-intensity dimensions (corrected for beam smoothing) of no greater than $0'{\cdot}5 \times 1'{\cdot}0$. They have a separation of $4'{\cdot}6$ arc along an axis at a position angle of 38°. These parameters are in good agreement with the model derived by Ekers (1969*b*). A fainter region may be present between the two components. The percentage polarization is similar for both components (3–4%) but the directions of polarization are virtually orthogonal. This difference of direction probably explains the low values for the integrated polarization: 0·5% at 11 cm (Gardner *et al.* 1969*b*) and 1·5% at 6 cm (Gardner *et al.* 1969*a*). The average Faraday rotation is uncertain and no conclusion is possible for the field configuration.

PKS 2152−69 (Fig. 6). The synthesized beam is almost circular ($0'{\cdot}9 \times 1'{\cdot}1$). The distribution of total intensity is similar to that obtained in the earlier set of observations described in Part I. There are two components of quite different peak intensity, the ratio of the intensities being 5 : 1 for the present results, but Ekers (1969*b*) has shown that this ratio varies with frequency. The components have a separation of $3'{\cdot}3$ arc along an axis at a position angle of 90°. The main component is extended along an axis at a position angle of 10°, and has corrected dimensions of $<0'{\cdot}5 \times 1'{\cdot}3$. It contains the associated $13^m{\cdot}8$ D galaxy near the position of peak intensity. Owing to the large ratio of the peak intensities and to the location of the optical identification, Ekers suggested that the two components were unrelated sources.

The direction of polarization changes by 90° across the main component, suggesting the presence of additional unresolved structure. The existence of two maxima of polarized radiation in the outer regions of the distribution of total intensity may be due either to two distinct components or to a single component containing a sharp variation in direction of polarization across it. The percentage polarization is ~6% in the northern region, and about half this value south of the centre. The direction of polarization in the most polarized region is similar to that for the integrated polarization and, if this relationship holds for other frequencies, the intrinsic direction of polarization is 24° (unpublished Parkes results). Therefore, the magnetic field may be orthogonal to the direction of elongation for the source. However, near the southern boundary, unless the Faraday rotation is different, the field is along the direction of elongation.

PKS 2356−61 (Fig. 7). The model that Ekers (1969*b*) derived for this source consisted of a series of components all aligned along an axis with a position angle of 132°. The intensity distribution in Fig. 7*a*, obtained with a synthesized resolution of $1'{\cdot}0 \times 1'{\cdot}3$, shows a total of four components. Similar but independent results were also reported in Part I. The mean axis of elongation has a position angle of 138°, and the separation between continuum maxima is $2'{\cdot}1$ arc. The half-intensity widths of the two strongest components are both about $0'{\cdot}5$ arc. The associated 16^m D galaxy is located close to the radio centroid.

The source is unusual in that the highest degrees of polarization ($>15\%$) occur near the faintest component and also between the two southernmost intensity maxima. The integrated Faraday rotation, calculated from observations with the 64 m telescope, is 45° (unpublished Parkes results). If this value is representative of the rotation for each component then it implies a projected magnetic field that is directed along the source, showing the same small changes in direction from component to component that are present in the shape of the intensity distribution.

Conclusions

For the sources that have been sufficiently resolved with the interferometer, the distribution of the polarized radiation often bears little relationship to that of total intensity. In most cases the projected magnetic fields in regions of high polarization are aligned either orthogonal to or parallel to the direction in which the source is elongated. Qualitatively these results support Gardner and Whiteoak's (1966) interpretation in terms of an outflowing plasma from a galaxy, with a subsequent compression of the outermost plasma as it is slowed down by the ram pressure of the intergalactic magnetoionic medium. Further refinements, such as the consequences of the motion of the galaxy through this medium, have recently been considered by Miley *et al.* (1972) and by Miley and van der Laan (1973) for explaining sources similar to PKS 1322−42, where there is no simple alignment between the galaxy and the radio components. In a more evolved source, typified by PKS 0518−45, the compression of the plasma results in the formation of two distinct components of radio emission in the outer regions of the outflows. Compressed magnetic fields oriented orthogonal to the direction of the outflow are either associated with or at the outer edges of the components. Manifestations of a less evolved source are present in PKS 2356−61 and in the inner regions of older sources such as PKS 1322−42. Here the intergalactic medium has had little influence on the outflow, the double structure is not so distinct and the magnetic field is primarily in the direction of motion.

The present results indicate the need for more polarization studies of extended sources at higher frequencies and with as high an angular resolution as possible. Stronger conclusions could be drawn from the present observations if the distribution of Faraday rotation over the sources was known. High-resolution observations at several frequencies would enable a more complete analysis of the distribution of magnetic fields within a source and of the relationship between the fields and the intensity structure.

Acknowledgments

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