THE POLARIZATION OF EXTENDED RADIO SOURCES AT 6 CM WAVELENGTH

I. EXTRAGALACTIC SOURCES

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Abstract

Maps are presented of the linear polarization distributions over eight extragalactic radio sources. They were obtained at 6 cm wavelength with a 4′ arc resolution. Low brightness extensions show polarization of up to 70% with magnetic fields aligned perpendicular to their elongations.

I. Introduction

The Parkes 64 m radio telescope has been used during the past few years to investigate the polarization distribution over extended extragalactic radio sources. Published results include observations at 11·3 cm (Davies and Gardner 1970), interferometer observations at 21·3 cm (Morris and Whiteoak 1968), and an extensive survey of a major southern source PKS 1322−42 (Cen A) at wavelengths of 11·3 cm and longer (Cooper, Price, and Cole 1965). To investigate these sources with higher resolution, a series of observations was carried out at 6 cm wavelength in 1968. Polarization distributions for eight sources are presented here.

II. Observations

The observations were made using a 6 cm cryogenically-cooled parametric receiver on loan from the National Radio Astronomy Observatory, Charlottesville, U.S.A. They were carried out concurrently with a survey of small-diameter sources (Gardner, Whiteoak, and Morris 1969) and observations of extended galactic sources (Part II, Whiteoak and Gardner 1971, present issue pp. 913–24).

The equipment and general methods of observation have been described by Gardner, Whiteoak, and Morris (1969). The hybrid-mode feed system resulted in a half-intensity beamwidth of 4′·0 arc. A flux density scale was adopted on the assumption that the source Hydra A was equivalent to a point source of flux density 13·0 f.u. at 6 cm. The ratio of brightness temperature T_b to flux density S is $T_b = 0 \cdot 87 S$.

The polarized intensity was obtained by switching between orthogonal linear polarizations at 39 Hz; the total power record provided the source intensity I. A source was observed by means of a series of scans with the telescope feed set successively at position angles PA of 0°, 45°, 90°, and 135°. In terms of the Stokes parameters Q and U, the method yields

$$PA = 0^\circ, \quad I_0 - I_{90} \equiv Q\,; \qquad PA = 45^\circ, \quad I_{45} - I_{135} \equiv U\,;$$

$$PA = 90^\circ, \quad I_{90} - I_{180} \equiv -Q\,; \qquad PA = 135^\circ, \quad I_{135} - I_{225} \equiv -U\,.$$

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By differencing the appropriate pairs, the required Stokes parameters were calculated and combined to yield the amplitude $((Q^2+U^2)^{\frac{1}{2}})$ and direction $(\frac{1}{2}\tan^{-1}(U/Q))$ of polarization. This combination in pairs corrects for small differences in the coupling of the two orthogonal feed outputs and in the different losses of the two sides of the input switch. Amplitudes were transformed into polarization brightness temperatures T_b^p. The determination of the zero of the position angle scale and the zenith angle dependence of telescope gain have been discussed by Gardner, Whiteoak, and Morris (1969).

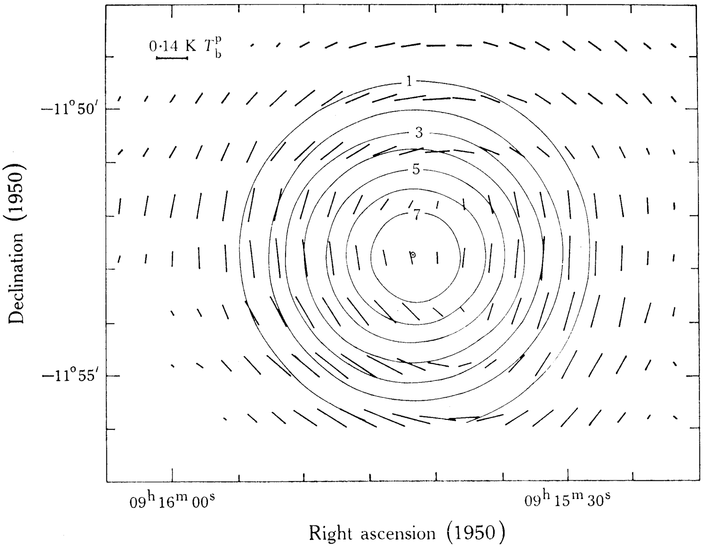

Fig. 1.—Polarization vectors superimposed on the total intensity distribution for PKS 0915−11 (Hya A). The contour interval is 1·41 K in brightness temperature.

The major instrumental polarization effects resulting from the rotation of the feed have been discussed by Davies and Gardner (1970). They are:

(1) A 360° modulation probably due to a slight displacement of the electrical centre of the feed from its rotational axis. From feed rotations on the sides of the small-diameter HII regions G265·1+1·5 (RCW 36), and G348·7−1·0 (RCW 122) it was evaluated as 0·2% of the central intensity, and has been neglected.

(2) A 180° modulation of telescope gain. From the point source observations this instrumental polarization was found to vary from 0·8% at a zenith angle of 30° to 1·8% at a zenith angle of 60°. The effect was less for extended sources, and corrections ranging from 0·5% to 1·5% were applied to the results. Any residual errors should be less than 0·5%.

(3) A variation with period 180° due to beam ellipticity. This was investigated by rotations on the edges of, and scans through, the two HII regions mentioned in (1). It results in a spurious polarization distribution, typified by that around the low-polarization source PKS 0915−11 (Hya A), which is shown in Figure 1. In this

figure the instrumental effect (2) has already been removed. The polarization has a circumferential direction and an amplitude which increases radially to about $1\cdot5\%$ of the central intensity at a radius of $2'\cdot5$ to $3'\cdot0$ arc and then decreases to below the limit of detectability at $5'$ arc. The small residual polarization at the source maximum ($0\cdot5\%$ at a position angle of $20°$) is believed to be genuine. It is partly responsible for the systematic amplitude variation at a set radius. There were indications that the spurious polarization varied with zenith angle. Because of this, and the complexity of some of the observed brightness distributions, no attempt was made to correct for the effect. Therefore, the presence of circumferential polarization distributions in the subsequent figures must be regarded with caution.

III. Results

The observations of the eight individual sources are shown as maps of the total intensity distribution with the polarization intensity vectors superimposed. The discussion of PKS 0320−37 (For A) is also accompanied by a separate distribution of the isophotes of polarization brightness temperature.

In the comments on the individual sources that follow, a correction to transform the observed position angles of polarization into intrinsic directions is given if the rotation measure R_M (Gardner, Morris, and Whiteoak 1969) is available, and on the assumption that it is constant over the source. At 6 cm wavelength the correction in degrees equals $0\cdot206\,R_M$. The orientations of the magnetic fields transverse to the line of sight are perpendicular to these intrinsic directions.

(a) *PKS 0320−37 (For A)*

The distributions of intensity and polarization are shown in Figure 2(*a*). The Faraday rotation in the source direction is small and the intrinsic angles differ by less than $1°$ from those shown.

The radio components straddle the galaxy NGC 1316 (denoted by a cross) for which Glanfield and Cameron (1967) give the position $03^h 20^m 47^s$, $-37° 23'\cdot1$ (1950). In addition to the structure shown by the contours, declination scans at $03^h 20^m 49^s$ and at right ascensions displaced by 10^s revealed an effective point source of flux density $0\cdot15\pm0\cdot05$ f.u. centred at $03^h 20^m 49^s$, $-37° 22'$, that is, well within the optical limits of the galaxy. This flux density yields a spectral index of $0\cdot5\pm0\cdot2$ when combined with the 75 cm value of $0\cdot5$ f.u. (Cameron 1969).

The two main components are very different in shape: the eastern is circular while the other is crescent-shaped. The disparity is even more marked in the distribution of polarized brightness (Fig. 2(*b*)). Here, the eastern component consists of two highly polarized (25–30%) regions about $10'$ arc apart along the major axis of the source. The structure of the western component is more complex; there is a polarization peak near the intensity maximum but the highest polarization brightness (and maximum polarization of 45%) is coincident with a spur of total intensity situated to the north of the component. For this spur, the magnetic field is essentially orthogonal to the elongation. Towards the southern edge of the western component, the polarization is low and the magnetic field is circumferential.

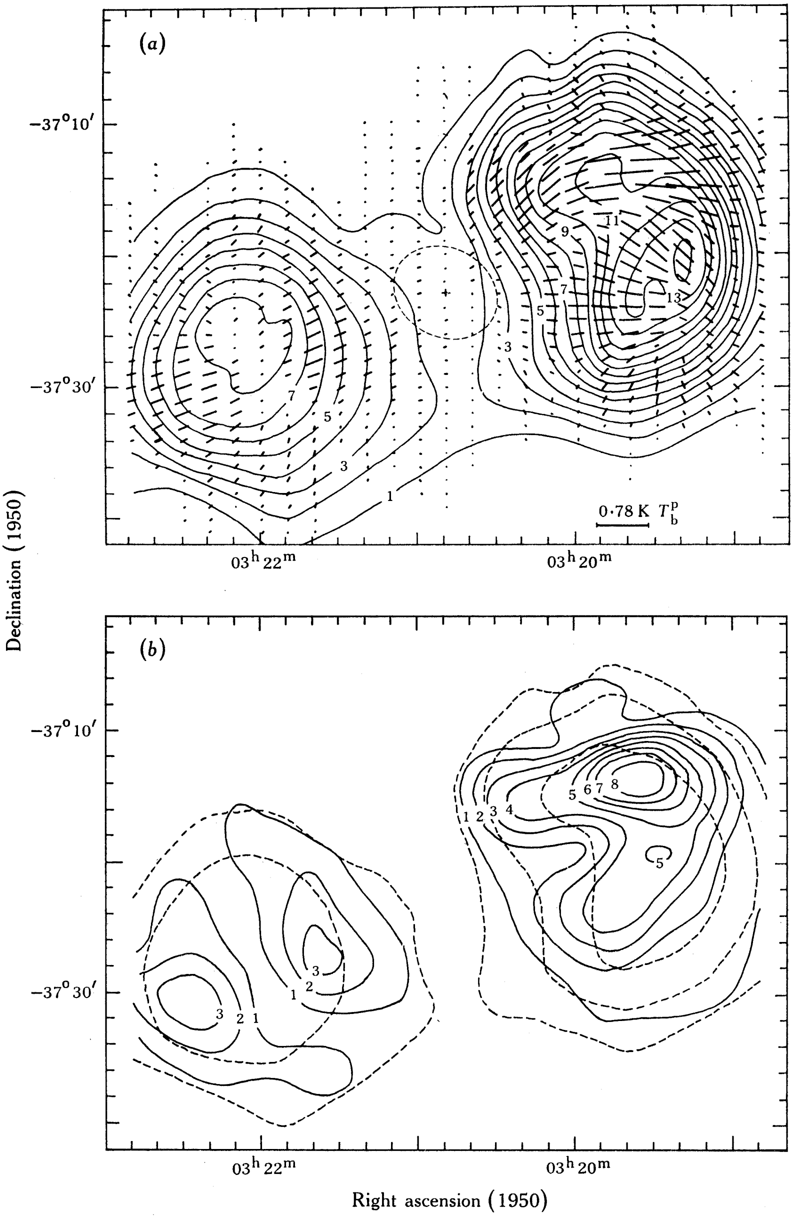

Fig. 2.—Polarization data for PKS 0320−37 (For A):

(*a*) Vectors of linear polarization superimposed on contours of total brightness temperature. The contour interval is 0·155 K. The centre of NGC 1316 is indicated by the cross while the outer limits of the galaxy (Arp 1964) are represented by the dashed line.

(*b*) Distribution of polarized brightness T_b^p. The contour interval is 0·082. The dashed lines represent the brightness temperature contours 2, 5, and 10 of (*a*).

In a previous discussion based on 11 cm observations and a $7' \cdot 4$ arc beam (Gardner and Whiteoak 1966), component characteristics such as outer contour steepness, elongation transverse to line of centres, and radial polarization at the outer edges were interpreted as the result of interaction with an intergalactic medium. The smaller scale complexities evident at 6 cm in the western component might possibly be distortions caused by uneven resistance of the medium. For example, a greater resistance to the south might turn the polarization directions from 110° (source major axis) towards 80°. There is no obvious connection with the optical trailing arms noted by Arp (1964). The more symmetrical shape of the eastern component suggests that the influences of the intergalactic medium and of a magnetic field orthogonal to the source axis are small. While the intensity distribution of this component is akin to that of a moderately thick shell, the polarization distribution is more than that expected from a thin shell expanding against a magnetic field (as typified by, for example, the supernova remnant PKS 1209−51; Whiteoak and Gardner 1968). Such a situation might arise if the magnetic field were randomly directed within the expanding plasmoid, with field order imposed only near the outer edges as a result of compression by the intergalactic medium in the presence of a magnetic field orthogonal to the source axis.

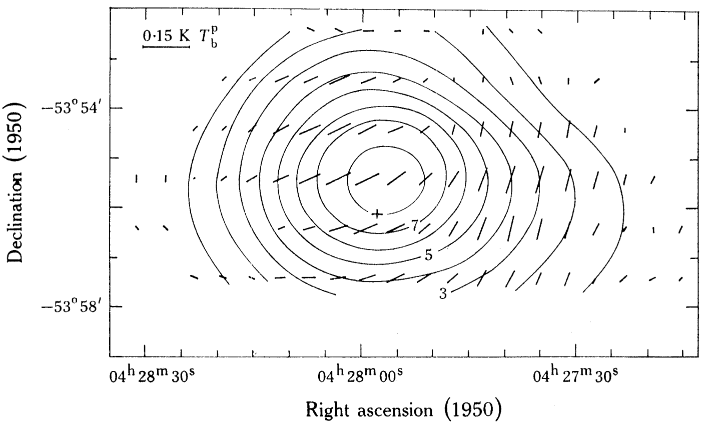

Fig. 3.—Polarization vector distribution for PKS 0427−53. The contour interval of the brightness isophotes is $0 \cdot 155$ K. The position of the associated galaxy is shown by a cross.

(b) PKS 0427−53

The distributions of polarization and intensity are shown in Figure 3. The Faraday rotation of this source may be somewhat uncertain because of the effects of changes in resolution with wavelength, but the present observations when combined with those of Gardner, Morris, and Whiteoak (1969) suggest that the intrinsic angles are 5° lower than those shown. The polarization at the peak position is $5 \cdot 4\% \pm 0 \cdot 4\%$ at position angle $120° \pm 2°$ (Gardner, Whiteoak, and Morris 1969). The source has been identified with a $13 \cdot 2^m$ double galaxy at the position $04^h 27^m 58^s$, $-53° 56' 07'' \cdot 4$ (Westerlund and Smith 1964), which is shown by a cross in Figure 3.

From interferometer observations, Ekers (1969) has interpreted the source structure as double with component dimensions $3'\cdot0\times3'\cdot0$ and $1'\cdot3\times0'\cdot5$ and a component separation of $3'\cdot8$ at a position angle of 74°. The brightness contours of Figure 3 are in accord with a similar separation ($3'\cdot6$) and orientation (75°) but suggest an absence of beam broadening perpendicular to the source axis, i.e. a source width less than 2′. The western component is weaker but more highly polarized (14% at 165°) than the eastern component (5% at 120°). The magnetic field in each component is approximately directed towards the galaxy.

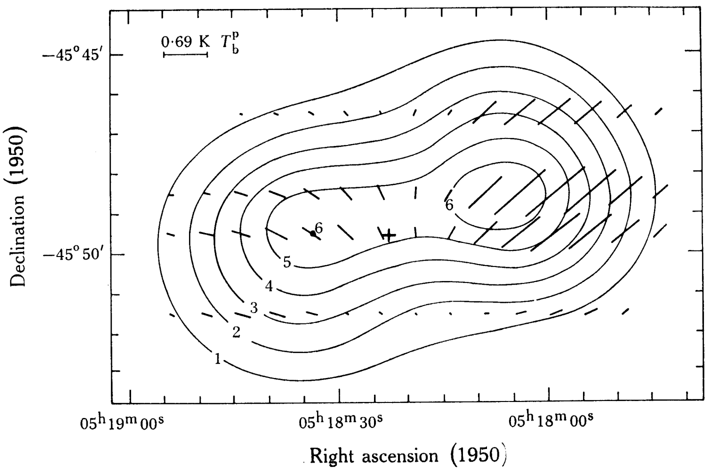

Fig. 4.—Polarization vector distribution for PKS 0518−45 (Pic A). The contour interval of the brightness isophotes is 1·37 K. The position of the associated galaxy is shown by a cross.

(c) *PKS 0518−45 (Pic A)*

The results for this source are shown in Figure 4. The intrinsic angles are 10° less than those shown. The position of the associated galaxy (shown by a cross) is $05^{\mathrm{h}}\,18^{\mathrm{m}}\,22^{\mathrm{s}}\cdot6$, $-45°\,49'\,36''$ (Bolton, Gardner, and Mackey 1964).

Ekers (1969) found that the source was double with components of dimensions $3'\cdot0\times1'\cdot5$ separated by $4'\cdot1$ at a position angle of 105°. The present total intensity results show a 5′ separation with the components extended along the major axis and with additional emission in between (possibly centred on the galaxy). The polarization maxima have a $6'\cdot5$ separation, i.e. the polarization seems to be concentrated at the outer edges of the components. The same situation occurs at 11 cm (Davies and Gardner 1970) and 21 cm (Morris and Whiteoak 1968). The polarization data for the two positions of intensity maximum are (Gardner, Whiteoak, and Morris 1969):

Eastern component, $4\cdot3\%\pm0\cdot2\%$ at a position angle of $60°\pm2°$

Western component, $8\cdot7\%\pm1\cdot0\%$ at a position angle of $131°\pm1°$

The difference between the position angles at the two component maxima (71°) is essentially constant from 6 to 11 cm (Seielstad 1967; Davies and Gardner 1970), so that there is little differential Faraday rotation across the source. This is also supported by the relative constancy of the degree of polarization between 6 and 50 cm wavelength (Gardner and Davies 1966). For the eastern and western components, the magnetic field makes angles of 35° and 14° respectively to the lines joining the components to the galaxy.

(*d*) *PKS 0634–20*

The intensity isophotes and polarization vectors are shown in Figure 5. The position of the associated galaxy is $06^{h}34^{m}22^{s}$, $-20°32'\cdot4$ (Bolton, Gardner, and Mackey 1964), which is denoted by a cross in the figure. The intrinsic angles are 8° lower than those observed.

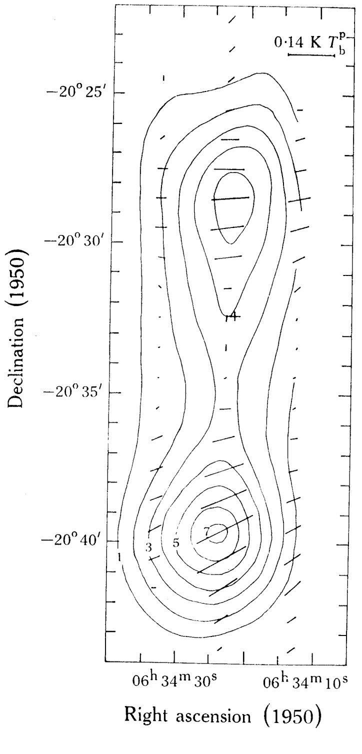

Fig. 5.—Polarization vector distribution for PKS 0634–20. The contour interval of the brightness isophotes is 0·14 K. The position of the associated galaxy is shown by a cross.

The source structure is basically double, with two intensity peaks separated by $11'\cdot0$ at a position angle of 178°. These components are extended along the source axis, with additional emission between them located near the galaxy position. There is no measurable beam broadening perpendicular to the axis (i.e. the extent in this direction is less than 2′).

The polarization is largely in the outer components, with the following values at positions of peak intensity (Gardner, Whiteoak, and Morris 1969):

Northern component,	$14\cdot5\% \pm 0\cdot6\%$ at a position angle of $95° \pm 1°$
Southern component,	$19\cdot0\% \pm 0\cdot4\%$ at a position angle of $116° \pm 1°$

In addition, there is polarized emission near the galaxy position which is aligned approximately orthogonal to the polarization of these components.

Apart from the angle change due to Faraday rotation, the polarization distribution is similar to that at 11 cm (Davies and Gardner 1970). The source is an example in which the magnetic fields are aligned along the major axis in the outer components but are orthogonal near the centre of the source.

(*e*) *PKS 1322–42* (*Cen A*)

Two areas of this large source were mapped. Figure 6(*a*) contains the intense central double source and part of the extended northern region. The observations were obtained by scanning at 3′ intervals in declination. Figure 6(*b*) shows the brightest region of the southern extension obtained with a 5′ spacing. Within the small rectangle in Figure 6(*a*) the vector lengths have been reduced by a factor of eight. The position of the galaxy NGC 5128 is shown by a cross at $13^{h} 22^{m} 32^{s}$, $-42° 45'·4$ (Glanfield and Cameron 1967). Over the region shown, Cooper, Price, and Cole (1965) obtained rotation measures ranging between -64 and -68 rad m^{-2}. However, a comparison of the 6 cm polarization directions with the 11 cm values of Cooper, Price, and Cole (1965) shows rotation measures which change from -66 rad m^{-2} at declination $-42° 37'$ to -82 rad m^{-2} at declination $-42° 06'$. Thus the intrinsic angles are about 15° higher than those shown in the figures.

The measured separation of the central components was $7'·0$ at a position angle of 47°, in reasonable agreement with the results of Cooper, Price, and Cole (1965) and Cameron (1969). The polarization data of these two components are (Gardner, Whiteoak, and Morris 1969):

North-eastern component,	$14·2\% \pm 1·0\%$ at a position angle of $136° \pm 2°$
South-western component,	$3·4\% \pm 0·8\%$ at a position angle of $118° \pm 2°$

The variation of the polarization in the vicinity of the south-western component (Fig. 6(*a*)) suggests the presence of two almost orthogonally polarized regions that are simultaneously accepted by the telescope beam, one presumably associated with the component and the other with the surrounding area. Therefore, one cannot satisfactorily determine the rotation measure for this component. For the north-eastern component, the magnetic field direction is virtually parallel to the major axis.

The main features of the northern extended area are the high degree of polarization and the uniformity of polarization direction. There is a broad intensity maximum at $13^{h} 24^{m} 15^{s}$, $-42° 27'$, where the magnetic field direction (144°) is roughly orthogonal to the elongation of the extended area. The maximum polarization approaches 70%, and generally exceeds 50% within the area bounded by intensity contour 4 and declination $-42° 35'$. There is considerable polarization variation near $13^{h} 23^{m}$, $-42° 37'$, which might be due to the presence of polarization contributions from the extended region and the north-eastern central component.

The intensities are considerably lower for the southern region of Figure 6(*b*). The polarization maximizes at close to 50%, with values generally exceeding 30%.

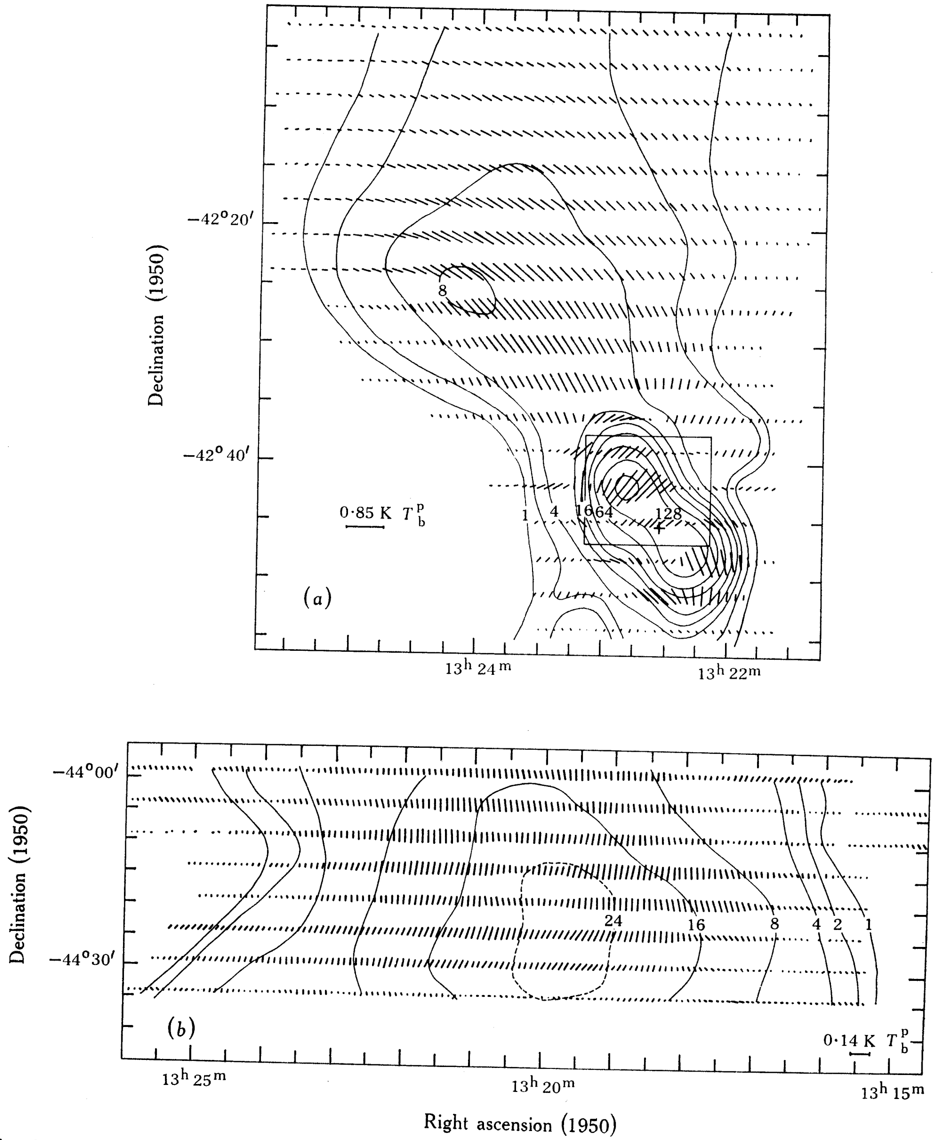

Fig. 6.—Polarization data for PKS 1322−42 (Cen A):

(*a*) Distribution of the polarization vectors superimposed on the brightness isophotes of the northern and central regions. The smallest contour interval is 0·17 K. Within the small rectangle located around the bright central double source, the vector lengths have been reduced by a factor of eight. The position of the associated galaxy NGC 5128 is shown by the cross.

(*b*) Distribution of the polarization vectors over the brightest region of the southern extension. The smallest contour interval of the brightness isophotes is 0·014 K.

The directions of polarization are very uniform, and equivalent to a magnetic field orthogonal to the direction of source elongation.

Aside from the features discussed, there is very little that can be added to the interpretation of the structure made previously (Gardner and Whiteoak 1966).

(*f*) *PKS 1332−33, 1333−33, 1334−33* (*MSH 13−33*)

This triple source has a well-aligned magnetic field perpendicular to the axis of separation (Gardner and Davies 1963). For the 6 cm investigation (Fig. 7) only the central component was mapped in polarization. The intrinsic directions are 7° greater than those shown. The cross denotes the galaxy IC 4296, at the position $13^h 33^m 48^s$, −33° 43′·0 (Becvar 1959).

The central component extends more or less along the axis of the source. Its size (5′ by < 1′ when corrected for beam broadening) is consistent with that observed

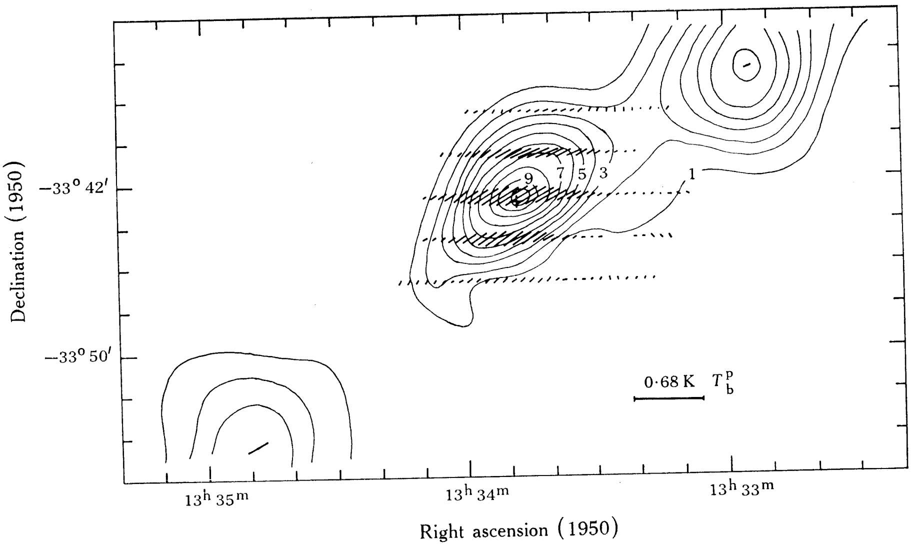

Fig. 7.—Polarization vector distribution for PKS 1333−33, the central component of the triple source MSH 13−33. The vectors for the intensity peaks of the outer components are taken from Gardner, Whiteoak, and Morris (1969). The contour interval is 0·135 K in brightness temperature. The position of the associated galaxy IC 4296 is shown by a cross.

by Schilizzi and McAdam (1970) at 75 cm wavelength. A comparison between the 6 and 75 cm observations suggests that the central component might have a flatter spectrum than the outer components.

The polarization data at the intensity peaks of the components are (Gardner, Whiteoak, and Morris 1969):

PKS 1332−33, 7·0% ±1·4% at a position angle of 112° ±2°

PKS 1333−33, 26·3% ±1·0% at a position angle of 119° ±1°

PKS 1334−33, 36·4% ±1·0% at a position angle of 119° ±1°

The central component shows a change of polarization direction across it such that the intrinsic polarization at either extremity is more closely directed towards the adjacent outer component. For each outer component, the intrinsic direction of polarization (110° and 126°) is similar to the direction to the galaxy (119° and 131°).

The interpretation has been adequately discussed earlier (Gardner and Davies 1963; Gardner and Whiteoak 1966). The new information added by the 6 cm observations elucidates the polarization structure of the central component.

(*g*) *PKS 1648+05* (*Her A*)

The results for this source are shown in Figure 8. There is some uncertainty in rotation measure due to a nonlinear polarization angle versus (wavelength)^2 relationship, but the intrinsic angles should be only about 4° lower than those shown. The associated galaxy is marked by a cross at the position $16^h 48^m 40^s$, $+05° 04'\cdot 6$ (Clarke, Bolton, and Shimmins 1966).

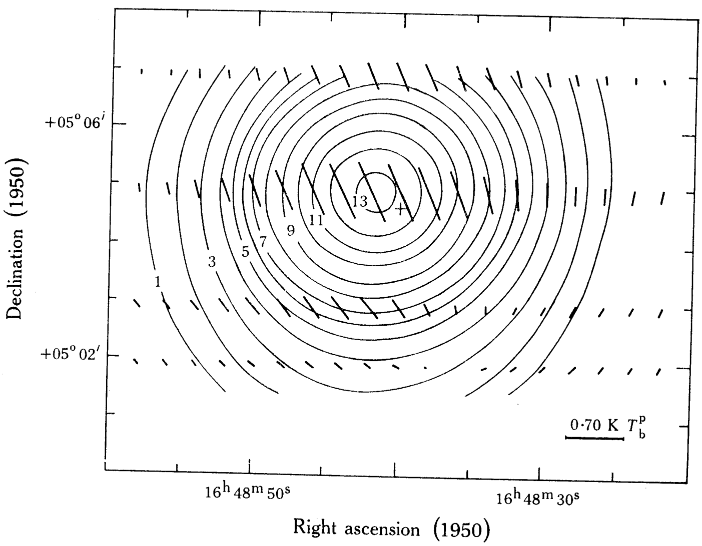

Fig. 8.—Polarization vector distribution for PKS 1648+05 (Her A). The contour interval of the brightness isophotes is 0·70 K. The position of the associated galaxy is shown by a cross.

The source is an unequal double with a 2′ component separation at a position angle of 101° (Maltby and Moffet 1962), and the 6 cm results do not show much broadening of the 4′ beam. However, both intensity and polarization maxima may be slightly displaced to the east of the centre defined by the outermost contours. The percentage polarization at the intensity peak is $8\cdot 9 \pm 0\cdot 2$ at a position angle of $24° \pm 1°$ (Gardner, Whiteoak, and Morris 1969). The equivalent magnetic field direction (110°) is close to the major axis of the source. The distinctive pattern of polarization at the edges of the source is due to the instrumental polarization effect (3) discussed in Section II, and illustrated in Figure 1.

(*h*) *PKS 1717−00* (*3C 353*)

The results are shown in Figure 9. The intrinsic angles are 7° lower than those observed at 6 cm. The associated galaxy has a position of $17^h 17^m 53^s\cdot 5$, $-00° 55'\cdot 8$ (Bolton and Ekers 1966).

In approximate agreement with Fomalont (1968), the intensity distribution fits a double-source model, the source components having a 2 : 1 intensity ratio and a 10^s separation east–west. The right ascensions of the components are $17^h 18^m 00^s$ and $17^h 17^m 50^s$. The observed intensity peak is $4^s \cdot 5$ east of the galaxy; its percentage polarization is $5 \cdot 0 \pm 0 \cdot 2$ at a position angle of $87° \pm 1°$ (Gardner, Whiteoak, and Morris 1969).

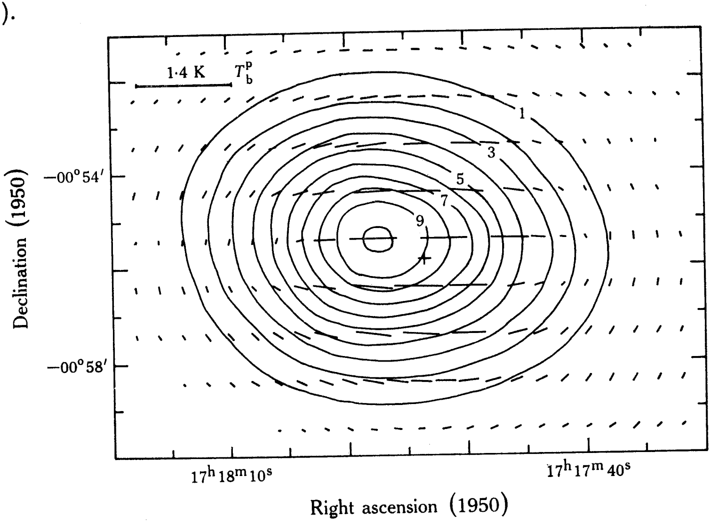

Fig. 9.—Polarization vector distribution for PKS 1717−00 (3C 353). The contour interval of the brightness isophotes is 1·38 K. The associated galaxy is shown by a cross.

The polarization direction is uniform across the source, except at the periphery where the instrumental polarization discussed in Section II is significant. The polarization appears to be centred on the galaxy position, although both components could be polarized at much the same orientation, with the degree of polarization higher for the western than for the eastern component. The magnetic field direction (172°) is practically orthogonal to the major axis of the source. The deviations from linearity of the polarization position angle versus $(\text{wavelength})^2$ relationship (Gardner and Davies 1966) are more readily understood if the source contains two components with different rotation measures. However, the 21 cm interferometer results of Morris and Whiteoak (1968) show similar directions of polarization for the two peaks, but with a considerable variation in direction across each component.

IV. Discussion

As pointed out previously (Gardner and Whiteoak 1969), most of the sources discussed in this paper contain components in which the magnetic field transverse to the line of sight is either approximately parallel or perpendicular to the source elongation axis. In the highly polarized extended outer regions, in which the fields are well aligned, the latter case prevails. The evolutionary interpretation advanced earlier (Gardner and Whiteoak 1966) does not account for the low degrees of polarization often encountered even at 6 cm wavelength. They seem to indicate the presence of disordered magnetic fields rather than Faraday depolarization. One might envisage a model in which at the time of ejection the turbulent plasmoid has an almost random field structure. With subsequent evolution the plasma expands and moves away from the galaxy, and the field alignment is increased under the compressing effects of the interaction with the intergalactic medium. This could account for the higher polarization on the periphery of a source component, exemplified by the eastern component of PKS 0320−37 (For A).

V. Acknowledgments

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