# THE POLARIZATION OF EXTENDED RADIO SOURCES AT 6 CM WAVELENGTH

## II.* GALACTIC SOURCES

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*Abstract*

Maps are presented of the polarization and total intensity distributions over the supernova remnants 13S6A, MSH 15−56, RCW 103, and W44. They were obtained at 6 cm wavelength with a 4′ arc resolution. It has not proved possible to interpret the polarization characteristics in terms of a simple expansion against the interstellar magnetoionic medium.

## I. INTRODUCTION

The two models developed by Van der Laan (1962*a*, 1962*b*) to explain the radio emission from supernova remnants postulate an ordered magnetic field structure within the remnants. An earlier polarization study of an extended remnant (PKS 1209−51, 1209−52) at wavelengths of 11 and 20 cm with the Parkes 64 m radio telescope (Whiteoak and Gardner 1968) revealed total intensity distributions and magnetic field patterns in good agreement with either model. However, in the case of another large supernova remnant, Vela X (Milne 1968), the agreement was poor. Since most other remnants are less than 30′ arc in angular size, adequate resolution with the Parkes telescope is obtained only at wavelengths shorter than 11 cm. There are two other advantages associated with observations at short wavelengths. The general low degree of polarization found for supernova remnants at 11 cm (Davies and Gardner 1970) suggests the presence of either Faraday or "beam-width" depolarization (Gardner and Whiteoak 1966), both of which would be reduced at shorter wavelengths. There is also less uncertainty in intrinsic polarization angles derived from observations at shorter wavelengths.

The present paper contains the results of a linear polarization study of four bright supernova remnants carried out with the Parkes telescope at a wavelength of 6 cm. The objects were sufficiently intense to make the variations of background polarized emission near the sources negligible.

## II. OBSERVATIONS

The supernova remnants were observed at Parkes in 1968 during a linear polarization survey which included discrete sources (Gardner, Whiteoak, and Morris 1969) and extended extragalactic sources (Part I, Gardner and Whiteoak 1971, present issue pp. 899–911). The observations were made with a 6 cm cryogenically-cooled parametric receiver on loan from the National Radio Astronomy Observatory,

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Charlottesville, U.S.A. The equipment and general methods of observation and reduction have been described by Gardner, Whiteoak, and Morris (1969); the methods of observation for extended sources have been further discussed in Part I. Two points are worthy of repetition: the telescope beamwidth with the hybrid-mode feed system was $4'\cdot 0$ arc; the main sources of instrumental polarization were (1) a gain variation with feed rotation and (2) beam ellipticity. Effect (1) was removed by using observations of unpolarized sources. For an unpolarized point source, the effect (2) would cause a spurious polarization directed circumferentially which maximized at about $1\frac{1}{2}\%$ of the peak intensity of the source at a radius of $2'\cdot 5$ to $3'\cdot 0$ arc. Because of the complexity of the brightness distribution of extended objects, no attempt was made to correct for the effect.

The four remnants observed were 13S6A, MSH 15−*56*, RCW 103, and W44. The source MSH 15−*56* was also observed with an 11 cm broad-band correlation radiometer (Batchelor, Brooks, and Cooper 1968). This radiometer was equipped with a hybrid-mode feed system and the beamwidth was $8'\cdot 1$ arc. The measurements were corrected for the instrumental polarization ($0\cdot 5\%$) resulting from the modulation of the gain with feed rotation.

## III. Results

The distributions of linear polarization over the four sources are shown in two forms: (*a*) as vectors superimposed on total intensity isophotes and (*b*) as isophotes of polarization brightness temperature $T_b^p$. For reference purposes, the maps (*a*) also contain a galactic coordinate grid.

### (*a*) *13S6A (1343−60)*

Figure 1(*a*) shows the polarization vectors superimposed on the distribution of total brightness temperature for this source. The polarization data (percentage polarization $P$ at position angle $PA$) for two positions in the source have been listed by Gardner, Whiteoak, and Morris (1969). They are:

$$\text{Position } 13^{\mathrm{h}}42^{\mathrm{m}}41^{\mathrm{s}},\ -60^{\circ}14'\cdot 0, \qquad P = 7\cdot 9\% \pm 0\cdot 3\% \ \text{ at } PA = 80^{\circ}$$

$$\text{Position } 13^{\mathrm{h}}43^{\mathrm{m}}42^{\mathrm{s}},\ -60^{\circ}07'\cdot 1, \qquad P = 4\cdot 6\% \pm 0\cdot 2\% \ \text{ at } PA = 44^{\circ} \pm 1^{\circ}$$

The intensity distribution of the source contains three maxima with an overall separation of 10′ arc along an axis at a position angle of 50°. Figure 1(*b*) shows the distribution of polarization brightness temperature over the source. A cross marks the position of each total intensity maximum. The overall polarization is low; it maximizes at 10% near the central intensity maximum.

From a comparison with the limited 11 cm polarization observations of Davies and Gardner (1970), the Faraday rotation for the source appears to be small. For the

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Fig. 1.—Polarization data for 13S6A:

(*a*) Polarization vectors superimposed on contours of brightness temperature. The contour interval is $0\cdot 69$ K. A grid of new galactic coordinates is also shown.

(*b*) Contours of polarization brightness temperature $T_b^p$. The contour interval is $0\cdot 069$ K. Positions of maximum total intensity are shown by crosses.

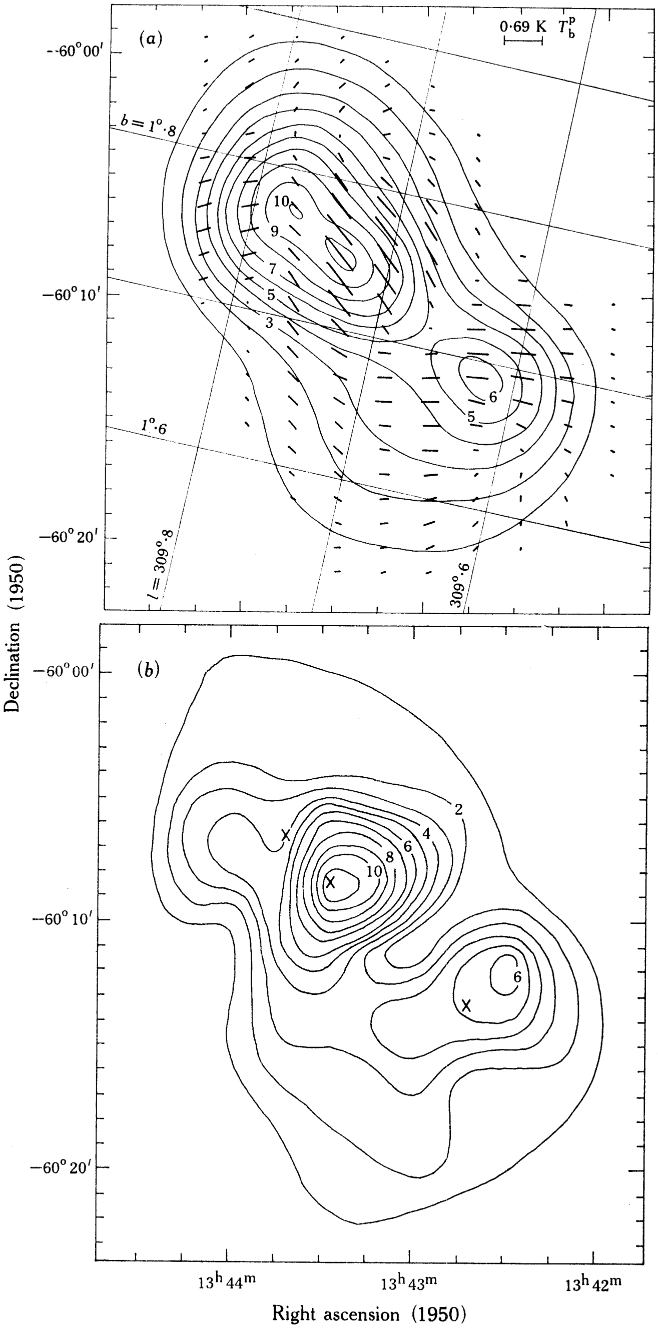
(a)
0·69 K $T_b^p$
$-60°00'$
$-60°10'$
$-60°20'$
$b = 1°.8$
$1°.6$
$l = 309°.8$
$309°.6$
10
9
7
5
3
6
5
(b)
$-60°00'$
$-60°10'$
$-60°20'$
2
4
6
8
10
6
Declination (1950)
$13^h 44^m$
$13^h 43^m$
$13^h 42^m$
Right ascension (1950)

Fig. 1

eastern total intensity peak the position angle of polarization at 11 cm is 48°, which is 4° greater than the value at 6 cm. The change corresponds to a rotation measure of $+8\ \mathrm{rad\,m^{-2}}$. If this rotation is not exceeded in other regions of the source the directions of the vectors in Figure 1(*a*) will be close to the intrinsic directions of polarization, orthogonal to the transverse component of the magnetic field. Under these conditions, in the southern area of the source the transverse component is well ordered and approximately perpendicular to the galactic plane. Towards the north of the source there is a considerable variation in field direction which could be due to interplay between the polarization from an extended component and that from a more compact central component.

The classification of 13S6A as a galactic source has been questioned in recent years. On the basis of its radio structure, Milne (1969) has suggested that the source is extragalactic. However, the total intensity distribution at 6 cm is not typical of either a radio galaxy or a supernova remnant. The spectral index (−0·67 according to Shaver and Goss 1970; −0·60 according to Milne 1970) could apply to either type of source. Shaver and Goss (1970) have interpreted the presence of HI in absorption against the source at velocities of $-30\ \mathrm{km\,s^{-1}}$ and $-50\ \mathrm{km\,s^{-1}}$ as evidence for an extragalactic origin. However, the absorption is consistent with the source being no more distant than 5 kpc, where it would be located in a spiral feature that is tangential to the line of sight at a longitude of 305° (Whiteoak and Gardner 1970). At this location the source would have an overall extent of 30 pc and a distance from the galactic plane of 150 pc; neither of these values is excessive for supernova remnants. The rotation measure ($+8\ \mathrm{rad\,m^{-2}}$) is very low for a low-latitude source near longitude 310°; it is considerably less than the value of $+176\ \mathrm{rad\,m^{-2}}$ for PKS 1323−61 (Gardner, Morris, and Whiteoak 1969), an extragalactic source within 3° of 13S6A. If 13S6A is extragalactic, the low rotation measure must result from a cancellation of the Faraday rotation by rotation within the source. However, systematic rotation within sources is generally believed to be small. If the source is galactic, the low rotation could be due to magnetic fields with a very small net component along the line of sight, while the large rotation of 1323−61 could indicate an appreciable line-of-sight component behind 13S6A. The general radio emission from the galactic plane in this direction extends to much higher positive latitudes than that of the source (Day, Thomas, and Goss 1969), so that it is possible that the interstellar electron density behind 13S6A may be enough to account for this extra rotation. In all, it is felt that the evidence favours the identification of 13S6A with a supernova remnant.

### (*b*) *MSH 15−56*

Figure 2(*a*) shows the 6 cm polarization vectors superimposed on the total intensity distribution for this source. The distribution of polarization brightness temperature is shown in Figure 2(*b*), the cross denoting the position of maximum

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Fig. 2.—Polarization data for MSH 15−*56* at 6 cm:

(*a*) Polarization vectors superimposed on contours of brightness temperature. The contour interval is 0·75 K.

(*b*) Contours of polarization brightness temperature. The contour interval is 0·090 K. The position of maximum total intensity at 6 cm is shown by a cross.

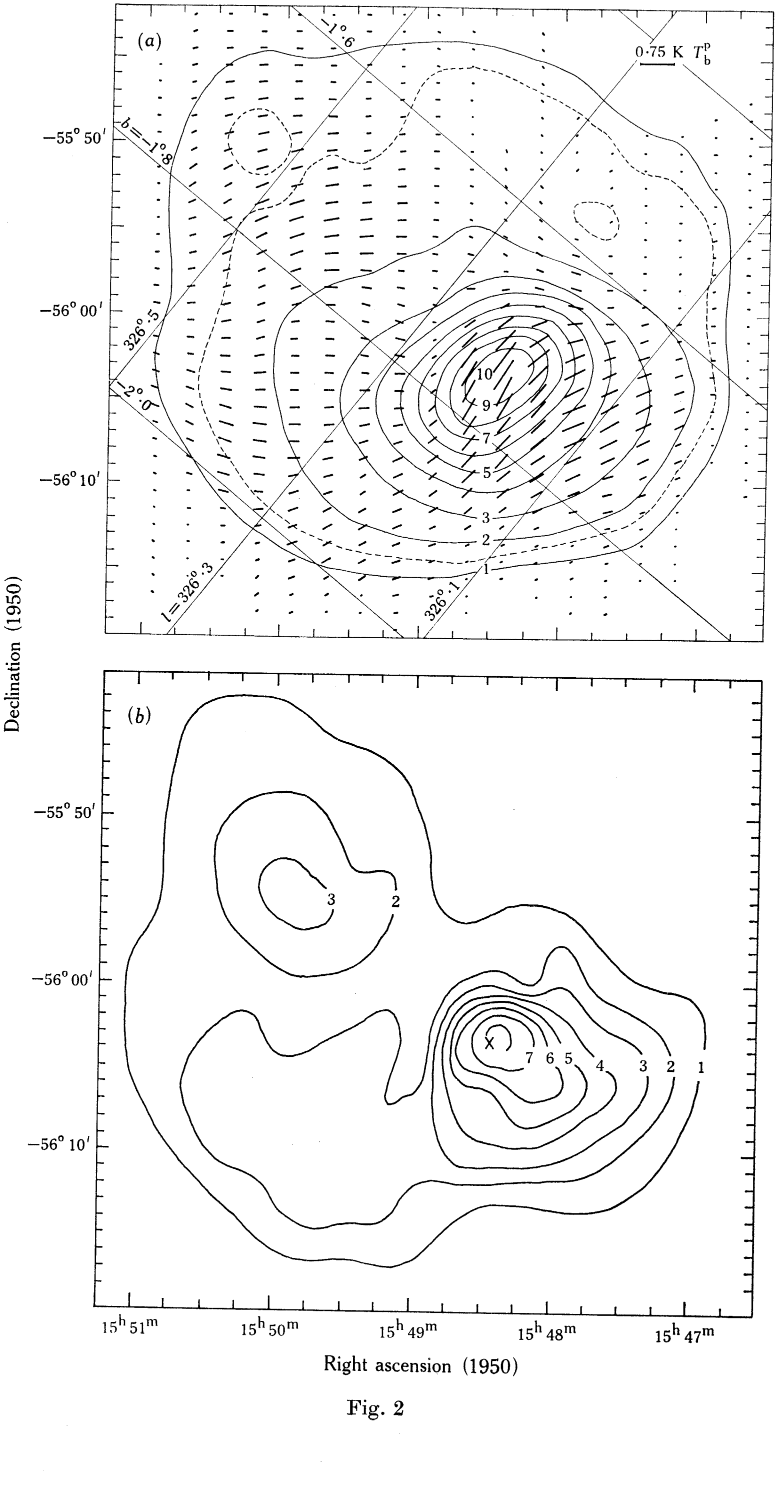
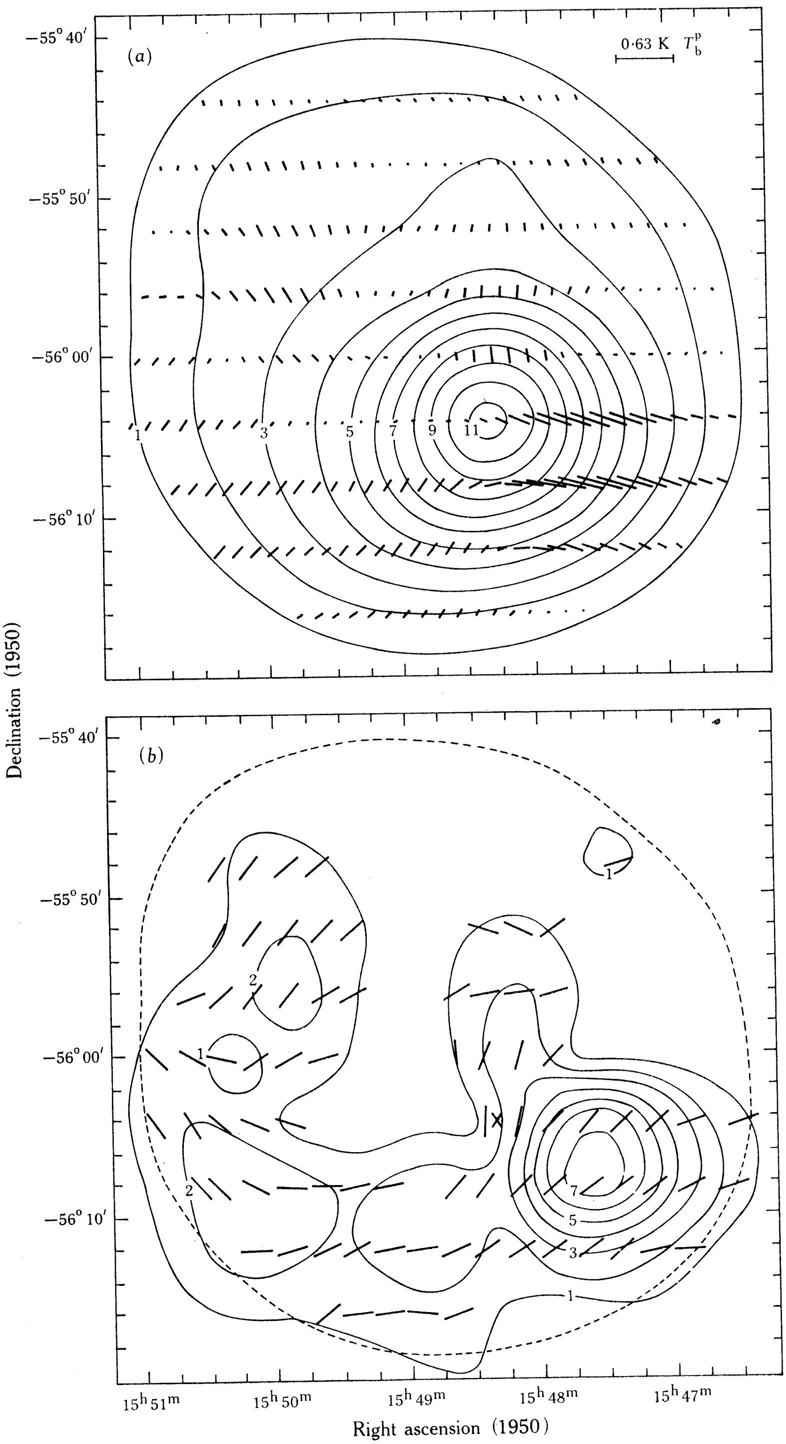

(a)
0·75 K $T_b^p$
$b = -1°.8$
$-1°.6$
$-2°.0$
$326°.5$
$l = 326°.3$
$326°.1$
10
9
7
5
3
2
1
(b)
3
2
7 6 5 4 3 2 1
−55° 50′
−56° 00′
−56° 10′
Declination (1950)
15h 51m
15h 50m
15h 49m
15h 48m
15h 47m
Right ascension (1950)

Fig. 2



−55° 40′
−55° 50′
−56° 00′
−56° 10′
(a)
0·63 K $T_b^p$
1
3
5
7
9
11
Declination (1950)
−55° 40′
−55° 50′
−56° 00′
−56° 10′
(b)
1
2
1
2
7
5
3
1
15ʰ 51ᵐ
15ʰ 50ᵐ
15ʰ 49ᵐ
15ʰ 48ᵐ
15ʰ 47ᵐ
Right ascension (1950)


Fig. 3

total intensity. The percentage polarization at the position of peak intensity is $10\cdot1\pm0\cdot2$ at a position angle of $154°\pm1°$ (source designated 1548−56 by Gardner, Whiteoak, and Morris 1969). The corresponding distributions obtained at 11 cm (but with half the angular resolution) are shown in Figures 3(*a*) and 3(*b*). The percentage polarization at the position of peak total intensity is $0\cdot8\pm0\cdot5$ at a position angle of $38°\pm25°$ (Gardner, Morris, and Whiteoak 1969). The dashed line in Figure 3(*b*) represents the outermost contour of Figure 3(*a*). Also shown in Figure 3(*b*) are the intrinsic polarization directions, as determined from the polarization angles at 6 and 11 cm. There was some uncertainty in the derivation because of the large and variable Faraday rotation across the source; the rotation measures are predominantly negative yet range from $+100\ \mathrm{rad\,m^{-2}}$ in the south-east region to around $-200\ \mathrm{rad\,m^{-2}}$ in the north-west. The magnetic field lines transverse to the line of sight are orthogonal to the vectors in Figure 3(*b*) and are therefore largely radial.

The results shown in these figures, particularly Figure 2(*a*), suggest the presence of two distributions: a broad extended region and a superimposed smaller but more intense region. At both wavelengths there are three corresponding polarization maxima. The relative displacement of the south-western peaks at 6 and 11 cm is probably the result of the different beamwidths coupled with a large variation in polarization direction. Except for the area near the total intensity peak where the depolarization is high, the degree of polarization at 6 cm is generally no greater than twice the value at 11 cm. At 6 cm the polarization is about 10% over most of the source.

Milne (1970) has suggested that this source is located in the Sagittarius arm at a distance of $3\cdot2$ kpc. The distance estimate is consistent with the HI absorption observations of Goss *et al.* (1972).

### (*c*) *RCW 103* (*1613−50*)

Figure 4 shows the polarization vectors superimposed on the total intensity distribution of the source. The percentage polarization at the position of the total intensity maximum is $2\cdot5\pm0\cdot5$ at a position angle of $106°\pm2°$ (Gardner, Whiteoak, and Morris 1969). The 11 cm percentage polarization in the same direction is $1\cdot9\pm0\cdot2$ at a position angle of $161°\pm4°$. The degree of polarization maximizes at about 6% in the north-eastern and south-western regions of the source. If the Faraday rotation is constant across the source, with a rotation measure of $-100\ \mathrm{rad\,m^{-2}}$ the intrinsic position angles of polarization are about 20° less than the 6 cm polarization angles. The intensity distribution shows an incomplete shell structure that is common to many supernova remnants. The shell-like appearance is more prominent in the 75 cm observations of Kesteven (1968).

This galactic source is located at a distance between $3\cdot9$ and $5\cdot5$ kpc (Milne 1970). It has a spectral index of $-0\cdot34$ according to Milne (1969), or $-0\cdot54$ according

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Fig. 3.—Polarization data for MSH 15−*56* at 11 cm:

(*a*) Polarization vectors and contours of brightness temperature. The contour interval is $1\cdot23$ K.

(*b*) Vectors showing intrinsic position angle of polarization superimposed on contours of polarization brightness temperature. The contour interval is $0\cdot062$ K. The dashed line represents the outermost contour of (*a*) and the position of maximum total intensity at 11 cm is shown by a cross.

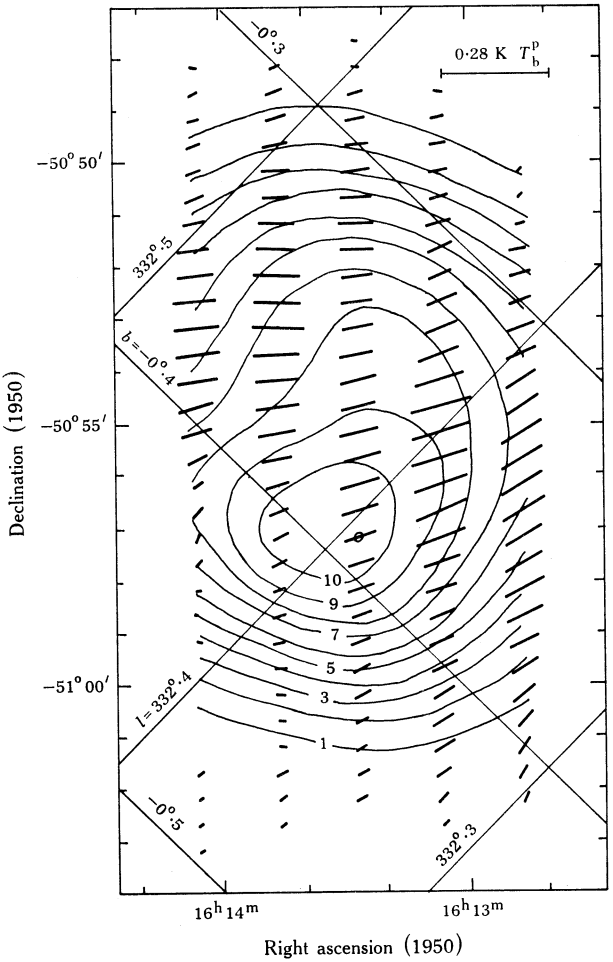


Fig. 4.—Polarization vectors superimposed on contours of brightness temperature for RCW 103. The contour interval is 0·28 K.

to Shaver and Goss (1970), values characteristic of supernova remnants. It is one of the few supernova remnants that are associated with observable filaments of Hα emission (Beard 1966). The filaments (RCW 103) are centred at longitude 332°·4 and extend in right ascension along contour 10 in Figure 4. This is as shown in Figure 5 of Kesteven (1968), but differs from Figure 9 of Milne (1969), in which the isotherms are in error by 5′ arc in declination.

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Fig. 5.—Polarization data for W44:

(*a*) Polarization vectors superimposed on contours of brightness temperature. The contour interval is 0·33 K.

(*b*) Contours of polarization brightness temperature. The contour interval is 0·066 K. The dashed line represents the outermost contour (contour 1) of (*a*) and the positions of peak total intensity are shown by crosses.

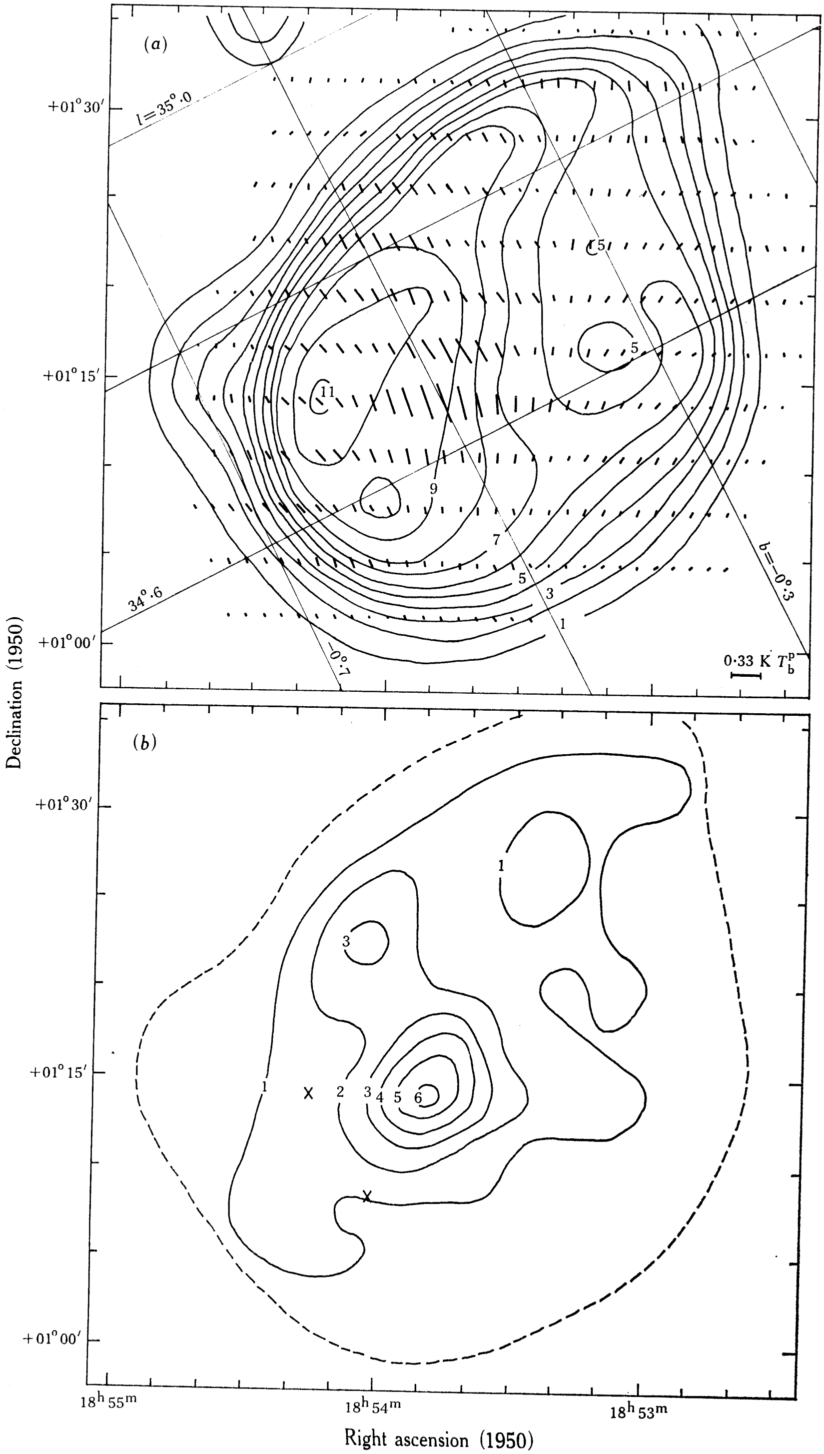
(a)
(b)
$l = 35°.0$
34°.6
$b = -0°.3$
$-0°.7$
+01° 30′
+01° 15′
+01° 00′
0·33 K $T_b^p$
Declination (1950)
18h 55m
18h 54m
18h 53m
Right ascension (1950)

Fig. 5

### (*d*) *W44*

Figure 5(*a*) shows the polarization vectors superimposed on the total intensity distribution of this source, while the isophotes of polarization brightness temperature are shown in Figure 5(*b*). In the latter figure, crosses mark the positions of peak total intensity and the dashed line represents the outermost contour of Figure 5(*a*). Gardner, Whiteoak, and Morris (1969) list the polarization results at two positions in the source:

1852+01 at $18^{\mathrm{h}}\,52^{\mathrm{m}}\,52^{\mathrm{s}}$, $+01°\,16'\cdot8$, $P = 2\cdot2\% \pm 0\cdot2\%$ at $PA = 124° \pm 4°$

1854+01 at $18^{\mathrm{h}}\,54^{\mathrm{m}}\,04^{\mathrm{s}}$, $+01°\,16'\cdot8$, $P = 3\cdot2\% \pm 0\cdot2\%$ at $PA = 35° \pm 2°$

The polarization maximizes between these regions at around 14·5% at a position angle of 21°. The total intensity distribution has the thin-shell appearance found in many supernova remnants. In common with the remnants that have been already discussed, the position of greatest polarization amplitude is displaced from the positions of total intensity maximum. For the eastern side of the source the contours of polarization brightness temperature conflict with those determined by Kundu and Velusamy (1969) at the same wavelength but with a 6′ arc beamwidth. However, the distribution is consistent with 3 cm results obtained with a 3′·5 arc beamwidth (data kindly provided by M. R. Kundu in advance of publication).

The Faraday rotation was estimated using the 3 cm polarization data of Kundu and the 6 cm observations from Parkes. At the position of peak polarization the rotation from 3 to 6 cm is about −25°, equivalent to a rotation measure of −130 rad $\mathrm{m}^{-2}$. Therefore, the intrinsic angles are 30° greater than the corresponding 6 cm angles. The magnetic fields transverse to the line of sight on the eastern side of the source are uniformly directed and approximately orthogonal to the galactic plane; the situation elsewhere is rather indefinite because the polarization amplitude is small and the Faraday rotation is uncertain.

Milne (1970) has listed the spectral index of the source as −0·40. He has also estimated a distance of 1·5 kpc based on surface brightness, but the absorption-line observations of hydroxyl (Goss, Caswell, and Robinson 1971) and HI (Radhakrishnan *et al.* 1972) suggest a more likely value of 3 kpc. At the larger distance the source would be located in the Sagittarius arm within 15° of the direction in which the arm is tangential to the line of sight.

## IV. Discussion

There are two main types of model advanced to explain the radio emission of supernova remnants. The model of Shklovsky (1960) consists of an expanding plasma sphere in which there is approximate equipartition of the magnetic field energy and the particle energy. The magnetic fields are randomly oriented. During expansion there is continuous synchrotron emission and a progressive decrease in total energy. For this model the radio emission is virtually unpolarized. In Van der Laan's (1962*a*, 1962*b*) models a shock wave precedes the plasma sphere, and the observed radio emission emanates from the compressed volume between the shock wave and the plasma boundary. The intensity and polarization distributions depend on the orientation of the interstellar magnetic field in the vicinity of the explosion (Whiteoak and Gardner 1968). For a field transverse to the line of sight there is emission from a thin shell, with two intense highly polarized regions diametrically opposed. Within these regions the field is circumferential. The model is exemplified by the remnant PKS 1209−51, 1209−52. For a field directed along the line of sight, the total intensity has a uniform shell-like distribution, the transverse field directions are radial, and the degree of polarization is dependent on the directional homogeneity of the magnetic field lines.

The evolution of a supernova explosion may well begin according to the Shklovsky model. As the expansion proceeds, the braking effect of the interstellar medium introduces some degree of order into the plasma magnetic fields. At a later stage, when the plasma field has decayed to a level below the field in the compressed interstellar medium between the expanding plasma and the shock wave, the features of Van der Laan's models prevail.

None of the four supernova remnants that have been discussed above closely resemble Van der Laan's models. For 13S6A the total intensity distribution is not that expected from a single isotropic explosion. Apart from the total intensity peak associated with the highest polarization, the results may conform approximately to Van der Laan's model, with the transverse field direction perpendicular to the galactic equator. At this longitude the line of sight is virtually tangential to the spiral feature containing the source, so that such a field direction probably represents a small inclination of the magnetic field to the axis of the spiral feature.

For MSH 15−*56*, the substantially radial directions of the magnetic field bear some resemblance to the Van der Laan model with a magnetic field initially along the line of sight. The south-western peak of the total intensity distribution implies that the explosion was anisotropic. The change in the sense of the Faraday rotation, although occurring over only a few minutes of arc in galactic latitude, is consistent with the general pattern of galactic Faraday rotation at the longitude of the source, with positive rotation measures at southern latitudes and negative values near and north of the galactic equator. On the other hand, the abruptness of the change may imply the presence of rotation within the supernova itself.

For RCW 103 the total intensity distribution and location of the optical filaments are in rough accord with the Van der Laan model, with a magnetic field transverse to the line of sight and parallel to the galactic equator. However, the polarization results, in particular the positions of the maxima and the directions associated with these maxima, do not fit the model. Perhaps the evolution of the source is at a stage where the source possesses characteristics of both Shklovsky's and Van der Laan's models.

The source W44 is another case suggesting an anisotropic initial explosion. The total intensity structure and the distribution and direction of polarization cannot be interpreted in terms of a simple Van der Laan model.

In conclusion, the sources discussed here do not conform to a simple Van der Laan model. The small net polarizations indicate considerable cancellation within the source which would be consistent with Shklovsky's model. Any attempts to derive magnetic field patterns from the small residual polarization vectors would be misleading. It is significant that the one case for which Van der Laan's model holds

(PKS 1209−51, 1209−52) is located at a high galactic latitude. Perhaps the expected field alignment at low galactic latitudes is destroyed by expansion which is irregular because of large fluctuations in the density of the interstellar medium. At high latitudes, the density of the medium may be more uniform.

Observations of the sources at an even shorter wavelength are clearly necessary. In addition to the improved resolution, this would enable the determination of more accurate Faraday rotation; the interpretation of the present results has been hampered by the general lack of knowledge of the variation of Faraday rotation over the sources.

## V. Acknowledgments

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## VI. References

Batchelor, R. A., Brooks, J. W., and Cooper, B. F. C. (1968).—*IEEE Trans. Antennas Propag.* AP **16**, 228.
Beard, M. (1966).—*Aust. J. Phys.* **19**, 875.
Davies, R. D., and Gardner, F. F. (1970).—*Aust. J. Phys.* **23**, 59.
Day, G. A., Thomas, B. MacA , and Goss, W. M. (1969).—*Aust. J. Phys. astrophys. Suppl.* No. 11, 11.
Gardner, F. F., Morris, D., and Whiteoak, J. B. (1969).—*Aust. J. Phys.* **22**, 79.
Gardner, F. F., and Whiteoak, J. B. (1966).—*A. Rev. Astr. Astrophys.* **4**, 245.
Gardner, F. F., and Whiteoak, J. B. (1971).—*Aust. J. Phys.* **24**, 899.
Gardner, F. F., Whiteoak, J. B., and Morris, D. (1969).—*Aust. J. Phys.* **22**, 821.
Goss, W. M., Caswell, J. L., and Robinson, B. J. (1971).—OH absorption in the direction of W44. *Astr. Astrophys.* (in press).
Goss, W. M., Radhakrishnan, V., Brooks, J. W., and Murray, J. D. (1972).—21-cm absorption measurements on low-latitude sources south of declination −46°. *Astrophys. J. Suppl. Ser.* **203** (in press).
Kesteven, M. J. L. (1968).—*Aust. J. Phys.* **21**, 739.
Kundu, M. R., and Velusamy, T. (1969).—*Astrophys. J.* **155**, 807.
Milne, D. K. (1968).—*Aust. J. Phys.* **21**, 201.
Milne, D. K. (1969).—*Aust. J. Phys.* **22**, 613.
Milne, D. K. (1970).—*Aust. J. Phys.* **23**, 425.
Radhakrishnan, V., Goss, W. M., Murray, J. D., and Brooks, J. W. (1972).—21-cm absorption measurements on 41 galactic sources north of declination −48°. *Astrophys. J. Suppl. Ser.* **203** (in press).
Shaver, P. A., and Goss, W. M. (1970).—*Aust. J. Phys. astrophys. Suppl.* No. 14, 133.
Shklovsky, I. S. (1960).—*Soviet Astr.* **37**, 369.
Van der Laan, H. (1962*a*).—*Mon. Not. R. astr. Soc.* **124**, 125.
Van der Laan, H. (1962*b*).—*Mon. Not. R. astr. Soc.* **124**, 179.
Whiteoak, J. B., and Gardner, F. F. (1968).—*Astrophys. J.* **154**, 807.
Whiteoak, J. B., and Gardner, F. F. (1970).—*Astrophys. Lett.* **5**, 10.