THE LINEAR POLARIZATION OF RADIO SOURCES BETWEEN 11 AND 20 CM WAVELENGTH

III.* INFLUENCE OF THE GALAXY ON SOURCE DEPOLARIZATION AND FARADAY ROTATION

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Summary

The dependence on galactic latitude of the 11 and 20 cm polarization of 355 extragalactic sources reveals no definite evidence of depolarization within the Galaxy. The distribution of Faraday rotation can be explained in terms of a field along the local spiral arm, deformed by magnetic "loops" in the solar neighbourhood.

I. Introduction

The effects of the magnetoionic medium of the Galaxy on the observed polarization of extragalactic radio sources have been extensively discussed (for references prior to 1966 see Bologna, McClain, and Sloanaker 1966; Gardner and Whiteoak 1966; Seymour 1966; Gardner, Whiteoak, and Morris 1967; Davies 1968). The existence of galactic Faraday rotation has been generally accepted since the initial detection of a variation of rotation with galactic latitude (Gardner and Whiteoak 1963). However, it has not been possible to interpret the overall distribution of rotation with galactic coordinates in terms of a simple model of magnetic fields.

The effect of the interstellar medium on source polarization has been a subject of divided opinion. Bologna *et al.* (1965) and, subsequently, Bologna, McClain, and Sloanaker (1966) concluded from the distribution of 21 cm polarization with galactic coordinates that depolarization (i.e. decreasing polarization with increasing wavelength) decreased with galactic latitude and that it was a function of line of sight distance through the Galaxy. Davies (1968) reached a similar conclusion using a depolarization parameter equivalent to the wavelength at which the degree of polarization is one-half its maximum value. However, for many sources the extrapolation necessary to determine the maximum polarization cannot be carried out successfully with his data. From an 11 and 21 cm investigation, Maltby (1966) concluded that a small galactic depolarization was present, but only for latitudes less than 6°.

It is the purpose of this paper to investigate the galactic effects using the data on the linear polarization of sources obtained with the Parkes 210 ft telescope at frequencies of 2650, 1660, and 1410 MHz (Gardner, Morris, and Whiteoak 1969).

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The data are for 366 sources with declinations less than $+27°$; of these, 355 are believed to be extragalactic objects on the basis of identification or of spectrum and angular size.

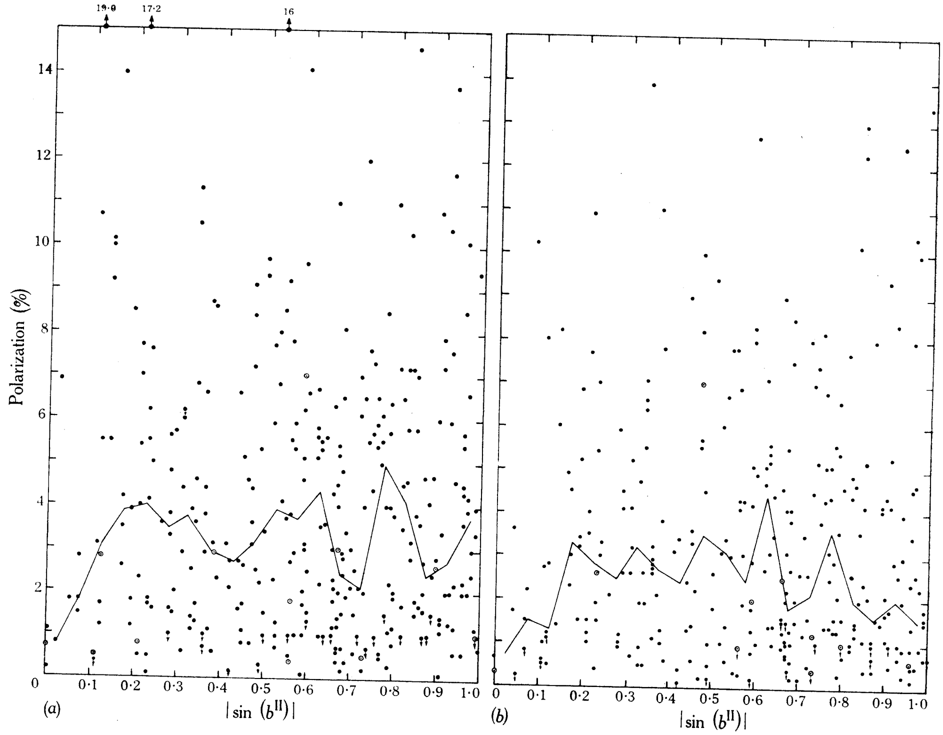

Fig 1.—Distribution of (*a*) 11 cm polarization P_{11} and (*b*) 20 cm polarization P_{20} with galactic latitude. The solid lines connect median values at intervals of $0 \cdot 05$ in $|\sin(b^{II})|$.

II. Galactic Depolarization

The distributions of 11 and 20 cm polarization with the modulus of the sine of galactic latitude for all extragalactic sources are shown in Figures 1(*a*) and 1(*b*). The numbers of objects in the plots are 307 and 331 respectively. The solid lines connect median values calculated at intervals of $0 \cdot 05$ in $|\sin(b^{II})|$.

As found by Bologna *et al.* (1965) and Bologna, McClain, and Sloanaker (1966) and confirmed by Maltby (1966), the median 20 cm polarization decreases at very low latitudes. However, the trend at 11 cm is very similar; if the decrease were due to galactic depolarization it would be considerably smaller at the shorter wavelength. Figure 2 shows the polarization ratio (the ratio of 20 to 11 cm polarization) also plotted against $|\sin(b^{II})|$. Since there is no general decrease in polarization ratio with decrease in latitude, there is no detectable galactic depolarization in these data. For many individual sources the polarization ratios exceed $1 \cdot 0$. This is probably due mainly to the addition of radiation from source components with different spectral characteristics, as found in many quasi-stellar objects (see Gardner and Whiteoak

1969). The lower median polarizations near the plane may be due to contamination of the sample by unrecognized galactic sources or may be statistical since fewer sources were observed at low latitudes.

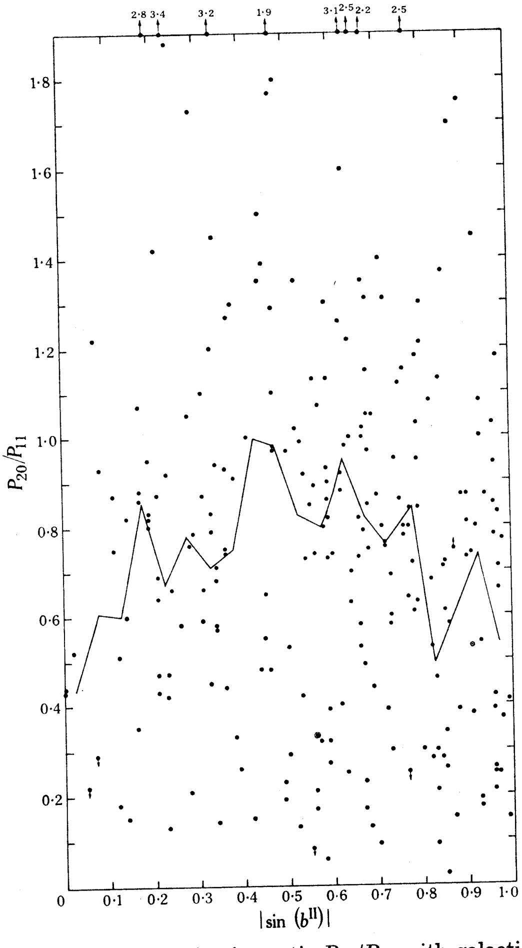

Fig. 2.—Distribution of polarization ratio P_{20}/P_{11} with galactic latitude.

To investigate the conclusion of Bologna, McClain, and Sloanaker (1966) that depolarization was correlated with line of sight distances through the Galaxy, path lengths D were calculated using the model of the Galaxy adopted by these authors, namely, an oblate spheroid with semimajor axis R of 15 kpc, semiminor axis of 5 kpc, and with the Earth located in the central plane at a distance of 10 kpc from the centre. The numbers of sources within three ranges of polarization at 20 cm are shown below grouped in three ranges of the ratio R/D.

	$R/D < 2 \cdot 3$	$2 \cdot 3 \leqslant R/D < 3 \cdot 25$	$R/D > 3 \cdot 25$
$P_{20} < 1 \cdot 5$	32(31)	39(22)	34(17)
$1 \cdot 5 \leqslant P_{20} < 4 \cdot 0$	34(20)	31(27)	33(24)
$P_{20} \geqslant 4 \cdot 0$	34(20)	30(22)	37(30)

A small R/D corresponds to a large path length. The values in parentheses refer to the corresponding numbers of Bologna, McClain, and Sloanaker (1966). In contrast with the previous study, the present results show no systematic variation of polarization with R/D. Therefore it is concluded that there is no correlation of depolarization with path length for a model of the Galaxy consisting of an extended halo in the form of an oblate spheroid. The weak trend in the data of Bologna, McClain, and Sloanaker (1966) must be characteristic of their particular selection of sources (about one-half of the sources observed at Parkes were included in their investigation).

III. Faraday Rotation by the Galaxy

The distribution in galactic coordinates of the Faraday rotation of extragalactic sources listed by Gardner, Morris, and Whiteoak (1969) is shown in Figure 3. The selection includes only those sources for which the estimated values of rotation measure (Gardner and Whiteoak 1963) were considered reliable (classes 1 and 1− in Table 4 of Gardner, Morris, and Whiteoak 1969), i.e. having a well-defined Faraday rotation between 11 and 20 cm. The sources are represented by circles with diameters indicative of the magnitude of the rotation. Each circle is accompanied by its associated rotation measure; full circles (positive rotation measures) denote magnetic fields with components directed towards the Sun. Sources at galactic latitudes lower than 45° and observed at only 11 and 20 cm wavelengths are shown as crosses. Their assigned rotation measures are the minimum numerical values and could be in error by an integral number of 96 rad m^{-2}. The continuous curve across the figure represents the +27° declination line, i.e. the northern limit of the 210 ft telescope. Sources shown north of this line are those with reliable data for at least three frequencies in the catalogues of Morris and Berge (1964), Bologna *et al.* (1965), and Maltby and Seielstad (1966). The dashed lines near the equator mark the approximate limits of low-velocity neutral hydrogen with brightness temperature exceeding 40°K (McGee, Murray, and Milton 1963). The sinusoid about the equator represents the approximate position of Gould's Belt.

Previously, the general distribution of rotation measures showed a variation with a 360° period in longitude which was ascribed to a magnetic field along the axis of the local arm, directed towards $l^{\mathrm{II}} = 95°$ (see review by Gardner and Whiteoak 1966). For the present results a sine wave with the same period was fitted to the rotation measures in several latitude ranges; the field directions obtained are listed below.

	$b^{\mathrm{II}} > +10°$	+10° to −10°	−10° to −20°	−20° to −30°	−30° to −40°	−40° to −90°
Directed longitude	—	76°	78°	98°	102°	—

The results at low latitudes suggest an axial magnetic field directed approximately towards $l^{\mathrm{II}} = 80°$. This value probably only approximates the direction of the field of the local spiral arm since each rotation measure represents an integration along a line of sight not only through the local arm but in many cases through other arms. The error in fitting each sinusoid was about 10°; hence the increase of the field direction with increasing southern latitudes appears real, and represents a local feature of the galactic field pattern. No unique field direction could be determined between $b^{\mathrm{II}} = -40°$ and $-90°$, or for b^{II} exceeding +10°. Irrespective of the source deficiency north of declination $+27°$, any axial component appears to be masked by a variation with a period considerably less than 360°.

Gardner, Whiteoak, and Morris (1967) pointed out that the rotation measures in directions $l^{II} = 180°$, $b^{II} = -30°$, and $l^{II} = 15°$, $b^{II} = +10°$ were too large (both positively and negatively) for directions nearly perpendicular to the axial magnetic field. It was suggested that the anomalies were due to loops of magnetic field frozen into spurs of gas flowing away from the solar neighbourhood as revealed in the HI distribution. The latitude extent of the anomalies implies that the expansion is

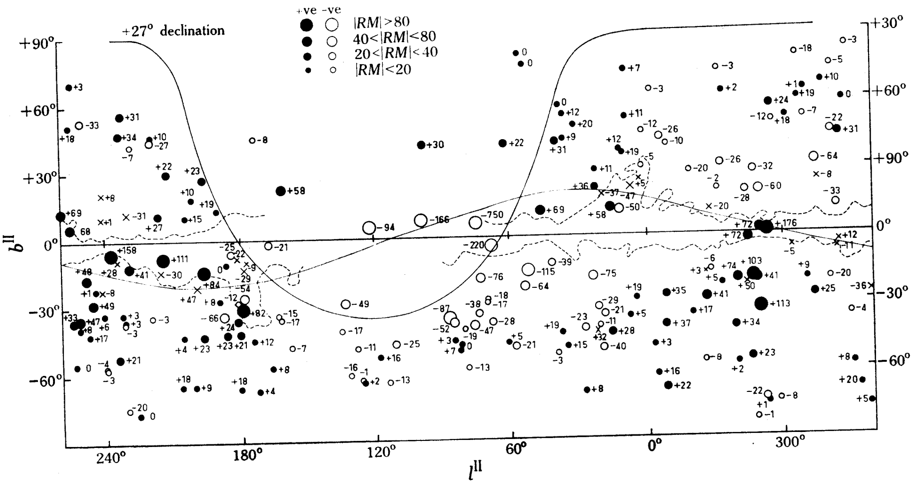

Fig. 3.—Distribution of rotation measures RM of extragalactic sources. Boundaries of low-velocity neutral hydrogen with $T_b > 40°K$ are shown by dashed lines. Gould's Belt (the sinusoid about the equator) and the 27° declination line are also shown.

part of the general expansion of Gould's Belt (Clube 1967). In addition, the pattern of rotation measures between $l^{II} = 300°$ and $l^{II} = 60°$ is unusual in that the signs above and below the equator are opposite. We regard this apparent reversal as due to the superposition at northern latitudes of a local magnetic field anomaly on a general axial field. This pattern and the observations (Whiteoak and Gardner 1968) of two supernova remnants at $l^{II} = 300°$, $b^{II} = +10°$ and $l^{II} = 330°$, $b^{II} = +15°$ (both at unusually high latitudes) suggest that the anomaly is a looped magnetic field associated with a distortion of the spiral arm out of the galactic plane and possibly associated with the Northern Galactic Spur. The distortion postulated is schematically shown in Figure 4(a). Figure 4(b) shows the distribution in galactic coordinates of the corresponding signs of rotation measure together with directions of optical polarization of starlight. The extension to high latitudes precludes a distance exceeding a few hundred parsecs.

Our general interpretation of axial fields plus loops conflicts with the recent conclusions of Mathewson (1968) and Mathewson and Nicholls (1968). They suggest a helical field very similar to that proposed by Ireland (1961) near the Sun to account for the directions of polarization of stars within $1\frac{1}{2}$ kpc of the Sun. They require, in addition, a longitudinal "disk" field to explain the general pattern of rotation measures. Although the optical data made available by these investigators approximately fit the helical model, they are also consistent with an axial field directed towards $l^{\mathrm{II}} = 50°$. In fact, Seymour (1969) has recently concluded, from a statistical study of stars (though a more restricted selection) within 500 pc of the Sun, that the data are better fitted by an axial field model. For stars within 200 pc of the Sun, Appenzeller (1968) found a low latitude field aligned parallel to Gould's Belt in Perseus ($l^{\mathrm{II}} = 145°$). This orientation defies explanation in terms of the magnetic helix. The direction of optical polarization at $l^{\mathrm{II}} = 300°$ (Fig. 1 of Mathewson 1968) departs from the general pattern expected with either a helical or axial field. However, together with the direction near $l^{\mathrm{II}} = 60°$, it could be explained in terms of the magnetic loop proposed earlier. The optical directions of polarization differ in the directions of the two poles: at southern latitudes the field direction is towards $l^{\mathrm{II}} = 85°$; at northern latitudes it is towards 65°. As pointed out earlier, the radio observations also indicate an increasing angle with increasing southern latitude.

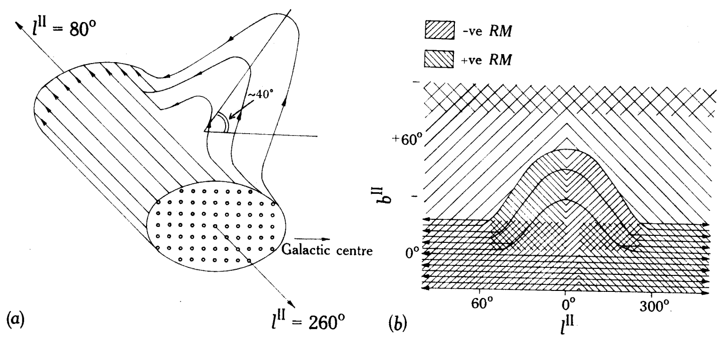

Fig. 4.—Showing (*a*) a three-dimensional schematic representation of a section of the spiral arm containing a looped magnetic field, and (*b*) the distribution of signs of rotation measure resulting from the model of the longitudinal field plus magnetic loop. The arrowed lines in (*b*) depict the directions of the associated polarization of starlight.

On a small scale, the variation of rotation measure from source to source increases with decreasing latitude, suggesting that it is mostly due to the interstellar medium. It may be due to small-scale fluctuations in field strength and electron density, possibly coupled with field reversals along each line of sight. However, the variation is not large enough to produce general galactic depolarization at 20 cm, which would require variations approaching 100 rad m^{-2} across the angular extent of a source.

IV. Conclusions

The question of interpretation of galactic polarization effects is still open. If the existence of a main field along the local arm is accepted, the major discrepancy between radio and optical polarization lies in the different low latitude field orientations ($l^{\mathrm{II}} = 80°$ for the radio observations, $l^{\mathrm{II}} = 50°$ in the optical case). It could be due to additional Faraday rotation occurring in other spiral arms along the line of sight, or to the local influence of Gould's Belt or the looped fields. More radio data and distance information regarding optical polarization will be required in order to explain this discrepancy and to contribute significantly to the determination of the galactic magnetic field.

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