A LINEAR POLARIZATION SURVEY OF THE SOUTHERN SKY AT 408 MC/S

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[*Manuscript received July* 26, 1965]

Summary

The results of 408 Mc/s linear polarization observations of the southern sky using the 210 ft steerable reflector at Parkes are presented. Combination of this survey with the northern sky survey of the Leiden group shows that almost all of the polarization at this frequency lies in a band about 60° wide, which contains the great circle that passes through the galactic poles and intersects the plane at $l^{\mathrm{II}} = 340°$ and 160°. This large-scale distribution of linear polarization at 408 Mc/s may be explained on the basis of synchrotron radiation theory if the Sun lies almost at the centre of a spiral arm that has a magnetic field directed along it towards $l^{\mathrm{II}} = 70°$ and 250°. The concentrations of relativistic electrons may be confined to regions of higher than average magnetic field strength (5×10^{-5} G) elongated in the direction of the arm. The observations show that the magnetic fields in these "synchrotron" regions are very ordered. The distance to the polarized regions may be about 150 pc. At high latitudes, close correlation is observed between features of the distribution of background polarization and Faraday rotation of extragalactic sources.

Evidence from other observations such as the rotation measures of sources, polarization of starlight, and the H-line Zeeman experiment suggest that the magnetic fields in the HII regions, dust clouds, and concentrations of neutral hydrogen are ordered and lie in approximately the same direction as the magnetic fields in the synchrotron regions. It appears that the local synchrotron regions are manifestations of a larger-scale field extending throughout the spiral arms.

I. Introduction

In 1961, the Leiden group (Westerhout *et al.* 1962) using the 80 ft reflector at Dwingeloo showed beyond doubt that at 408 Mc/s the galactic radio emission had a linearly polarized component. Shortly afterwards, Wielebinski, Shakeshaft, and Pauliny-Toth (1962) confirmed this result using a 30 ft reflector. These positive results (together with the spectral index of the radiation) showed almost conclusively that the synchrotron mechanism was responsible for the non-thermal radio emission from the Galaxy. A large-scale survey of the 408 Mc/s polarization of the northern sky was then carried out at Leiden by Brouw, Muller, and Tinbergen (1962) and Berkhuijsen and Brouw (1963), and at Cambridge by Wielebinski and Shakeshaft (1964).

This paper presents the results of a linear polarization survey of the southern sky at 408 Mc/s using the 210 ft steerable reflector at Parkes during 1963–4. Combination of the northern and southern sky surveys gives the large-scale distribution of the polarized radio emission, which should provide much information on the structure of the magnetic fields in the local spiral arm of the Galaxy, for at 408 Mc/s,

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the polarized component probably originates within a few hundred parsecs (see Westerhout *et al.* 1962; and Section V).

Previous knowledge about galactic magnetic fields was derived mainly from polarization measurements of starlight (Hall 1958) and the Zeeman experiment (Davies *et al.* 1964). Other more indirect forms of evidence such as stability of the spiral arms, retention of high energy cosmic rays in the Galaxy, intensity of non-thermal continuum radio emission, and star formation have been used in attempts to estimate the strength and the distribution of the magnetic fields in the Galaxy.

The starlight polarization and Zeeman measurements only give information about the magnetic fields in localized regions of dust clouds and dense neutral hydrogen clouds respectively. It is unlikely that either of these regions is the source of synchrotron radio emission (i.e. a region of relativistic electrons and magnetic fields). Therefore, the study of the polarization of the more widely distributed synchrotron radiation can provide information on the field structure in the more tenuous general medium of interstellar space.

Recent studies of the polarization of discrete sources provide a powerful method of investigating the magnetic fields in the Galaxy. It is now certain that most of the observed Faraday rotation occurs in regions of ionized hydrogen and magnetic fields within the Galaxy (Gardner and Davies 1966). The rotation measure of a radio source (most of which are extragalactic) provides information about the sense of the magnetic field and the product of the electron density and the field strength through the Galaxy in the particular direction of the source. In Section V, a comparison is made between the distribution of the 408 Mc/s polarization and the rotation measures of the radio sources, which shows that at high latitudes the rotating medium for the source radiation is fairly local.

II. Equipment

The 210 ft steerable reflector was fed by a pair of parallel dipoles with a plane reflector giving a tapered illumination that fell to approximately 4% at the edge of the aperture. The resulting main beam was circular and 48 min of arc between half-power points. The aerial feed could be rotated at 3°/s through one complete revolution in either direction.

The receiver was a double sideband crystal mixer (local oscillator frequency, 408 Mc/s) with an input temperature of 300°K and a bandwidth of 8 Mc/s. The receiver was switched between the aerial feed and a reference load at liquid nitrogen temperature. With a 2 s time constant, peak-to-peak noise fluctuations were about 0·5 degK. A constant noise-source signal could be injected through a directional coupler into the aerial side of the switch to check the sensitivity of the receiver during the observations.

The whole system was calibrated using the radio source Hydra A. The flux density of Hydra A at 408 Mc/s was taken to be 134×10^{-26} W m^{-2} (c/s)$^{-1}$, following Kellermann (1964). This gave a main beam brightness temperature T_b of 118°K when the source was at the centre of the aerial beam.

III. Observational Procedure and Data Reduction

The observational procedures and data reduction processes used in the present survey are similar to those described by previous workers (Brouw *et al.* 1962; Westerhout *et al.* 1962; Weilebinski and Shakeshaft 1964). They are outlined below under the headings of (*a*) the instrumental polarized component, (*b*) the survey, (*c*) data reduction, (*d*) calibration points, and (*e*) correction for Faraday rotation in the ionosphere.

(*a*) *The Instrumental Polarized Component*

If the radio emission incident on the reflector has a linearly polarized component, one full rotation of the dipole feed should produce a double sine wave in the output of the receiver. However, radiation from the ground in far side lobes or spillover of the primary feed usually produces a similar double sine wave output. In order to determine the spurious component, scans across a number of regions well removed from the galactic plane were made with different orientations of the primary feed. Two positions were selected from those scans that showed no variation with feed orientation. These positions at $04^h\,00^m$, $-46°$, and $04^h\,30^m$, $-4°$, were then tracked from rising to setting. During this period, the primary feed was rotated continuously backwards and forwards through an angle of about 300°. Each rotation produced a double sine wave pattern at the recorder. The feed angle of the maximum of this pattern remained constant to within $\pm 7°$ showing that no real polarized component was present. As the Parkes reflector has an altazimuth mount, the feed angle (which is the angle between the dipoles and the vertical plane containing the beam axis) changes with respect to the position angle in celestial coordinates so that the feed angle of maximum should be a function of hour angle for a source with a real component of linear polarization.

All the observations were carried out at zenith angles greater than 30°. At 30° the amplitude of this instrumental polarized component was about 2·5 degK and decreased with increasing zenith angle to less than 1 degK at a zenith angle of 60° (the telescope's horizon). This remained the same both before and after transit and it was concluded that there was no effect due to change of azimuth. As the survey progressed, two other unpolarized regions at $12^h\,10^m$, $-12°$, and $06^h\,10^m$, $-28°$, were also used to determine the spurious polarized component.

Rotations were also made while the reflector tracked a strong radio source, 30 Doradus, known to be unpolarized at higher frequencies, to see if increase in aerial temperature caused any modification of the spurious polarization rotation curve. No such effect was found.

(*b*) *The Survey*

The survey was carried out over four intervals of 10 days each during the months of February, July, and September 1963 and February 1964. The survey covers from declinations $-90°$ to $+14°$ for right ascensions 0^h to 3^h and 22^h to 24^h, $+26°$ for right ascensions 3^h to 14^h, and $-6°$ for right ascensions 14^h to 22^h.

Observations were made only at night, generally commencing about 1 hr after sunset and finishing at sunrise. Thus, the effect of solar radiation and rapid changes in the ionosphere were avoided. The observational procedure was to track a point whilst rotating the dipoles through about 300°. Such rotations were made at a 2° grid of points over the survey region.

In general, the measured points were spaced at intervals of approximately 2° in right ascension along even-degree declination circles, although in some interesting regions a closer spacing was used in both right ascension and declination. The bracket of declinations covered at a particular right ascension was such that the aerial remained approximately at the same azimuth and zenith angle during the night's observation (i.e. the average rate at which right ascension increased was equal to the sidereal rate). Thus, the spurious polarization component to be subtracted from the survey rotation curves was approximately the same throughout the night. This procedure also simplified correction for ionospheric Faraday rotation

TABLE 1

SECONDARY CALIBRATION POINTS

Position (1963)	Position Angle of E Vector θ_{eq} (outside-ionosphere)	Polarization Brightness Temperature T_b^p (°K)
$01^h 11^m$, $-64° 30'$	157	5·0
$01^h 40^m$, $-34°$	148	6·1
$14^h 00^m$, $-20°$	135	4·5
$15^h 10^m$, $-40°$	92	3·6
$18^h 40^m$, $-14°$	154	7·0
$20^h 48^m$, $-36°$	87	5·2
$23^h 20^m$, $-16°$	65	5·9

(see (*e*) of this section). The following night, some of the previous night's measurements were repeated, interlaced among the new positions. Most observations were made near zenith angle 50° as the amplitude of the spurious polarization component was smaller than at higher elevations. At the beginning of each observing period, the spurious polarized component was determined as a function of zenith distance by continuously tracking, whilst rotating the feed, one of the positions given above in (*a*) of this section. On subsequent nights, this calibration was checked at a particular zenith angle every 3–4 hr.

A number of strongly polarized positions distributed over the survey region were chosen for checking the overall system. Initially two positions ($14^h 28^m$, $+14°$, and $02^h 00^m$, $+09° 30'$) were selected from the Leiden survey as primary calibration points (see (*d*) of this section) and one or the other was observed at least once every night. As the survey progressed, a number of newly detected positions of strong polarization were chosen to act as secondary calibration points (see Table 1). Some of them were measured at two-hourly intervals during each night and the records were reduced immediately as a running check on the observations.

(c) *Data Reduction*

The spurious polarization component was subtracted vectorially from the rotation curves of the survey points (see Fig. 1). The amplitude of the resulting sine wave and the feed angle of maximum were determined. This amplitude, when measured in units of brightness temperature, is the polarization brightness temperature T_b^p. The position angle of the plane of vibration of the incident E vector (θ_{eq}) was obtained by adding the parallactic angle for the particular hour angle and declination of measurement to the feed angle of maximum. These results are presented in Table 3 (Section IV).

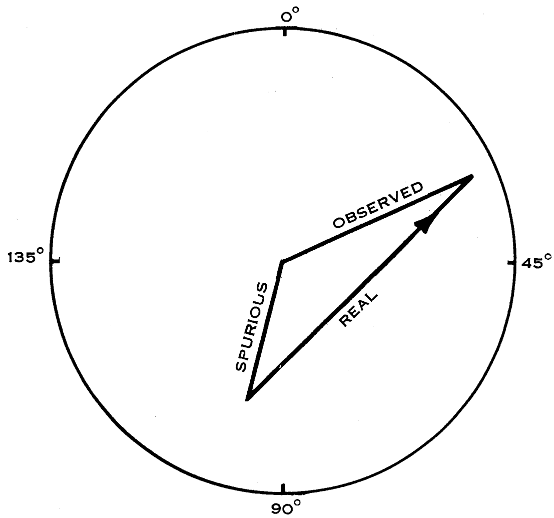

Fig. 1.—Vectorial subtraction of the spurious polarized component from the observed double sine wave rotation curve.

The probable error for points with polarization brightness temperatures between 1·6 and 2·6°K is about 10° for θ_{eq} and 0·6 degK for T_b^p (the errors arise mainly in the measurement of the observed and instrumental polarization components); for points greater than 2·6°K, the probable error is about 5° for θ_{eq} and 0·4 degK for T_b^p. The increase of accuracy for these points is due to the increased ratio of real to spurious polarization component, and to the fact that most of them were measured at least twice.

(d) *Calibration Points*

The primary calibration points were at $14^h 28^m$, +14°, and $02^h 00^m$, +09° 30′. The first of these was observed by the Leiden group more than 500 times and was one of their main calibration points.

The secondary calibration points at southern declinations are listed in Table 1. These were observed over a wide range of hour angles during the observations. Measurements at some of these positions were also made around sunset or sunrise when a variation of θ_{eq} due to changing Faraday rotation in the ionosphere was observed. As pointed out by the Leiden and Cambridge workers such observations provide an excellent test of the genuine nature of the polarized radiation.

(e) *Correction for Ionospheric Faraday Rotation*

To obtain the polarization angles outside the ionosphere, it is necessary to correct for ionospheric Faraday rotation. At 408 Mc/s, it is given by the relation

$$\xi = 1\cdot 42\times 10^{-13} H_{300} F \int N \, \mathrm{d}h \qquad \text{radians,} \tag{1}$$

where N = number of electrons/cm^3,
h = height above Earth (cm),
H_{300} = magnetic field at 300 km (gauss), and
$F = \sin i + \cos i \tan z \cos(a-\beta)$,

with

i = angle of dip of the magnetic field,
β = magnetic declination (east),
a = azimuth of the source, and
z = zenith distance of the source.

The magnetic constants used were $i = 64°$ and $\beta = 11°$ (east).

TABLE 2

PRIMARY CALIBRATION POINTS

Position (1963)	Berkhuijsen and Brouw (1963)		Present Survey (smoothed)	
	θ_{eq} (outside-ionosphere)	T_b^p (°K)	θ_{eq} (inside-ionosphere)	T_b^p (°K)
$14^h 28^m$, $+14°$	126	5·0	104	5·9
$02^h 00^m$, $+09° 30'$	28	5·3	7	6·5

The sense of rotation was such that for all points in the survey the observed values of the polarization angle were less than the values outside the ionosphere.

The "outside-ionosphere" polarization angles for our primary calibration points ($14^h 28^m$, $+14°$; $02^h 00^m$, $+09°$ $30'$) were known from the work of Brouw and Berkhuijsen (1962) and Berkhuijsen and Brouw (1963). To compare our measurements (0°·8 aerial beam) with those of the Leiden group (2° beam), rotations were made over a $\frac{1}{2}°$ grid of points covering an area of 16 sq degrees around these two positions. The Stokes parameters for the linearly polarized component of the radiation, $Q = T_b^p \cos 2\theta_{eq}$ and $U = T_b^p \sin 2\theta_{eq}$, were integrated using a weighting function appropriate to the 2° aerial beam pattern. The results are shown in Table 2 for a measurement in July 1963.

A total electron content of 4×10^{12} electrons/cm^3 is required to account for the observed difference in θ_{eq} in terms of Faraday rotation in the ionosphere. This value is in good agreement with the observations of Berkhuijsen *et al.* (1964). If this Faraday rotation (ξ_1) is known for one position at some particular time, then from equation (1) it may be seen that the Faraday rotation for any other part of the sky is given by

$$\xi_2 = \frac{F_2}{F_1}\xi_1. \tag{2}$$

In this way the value of the Faraday rotation obtained by observations of the primary calibration points was used to determine the outside-ionosphere polarization angles for the secondary calibration points (Table 1). Repeated observation of these points during each night plus at least one observation of a primary calibration point enabled the ionospheric Faraday rotation to be calculated for the survey points using the same relation. A subsequent inspection of the $f_0\,F_2$ records provided by the Ionospheric Prediction Service showed that the ionosphere had in fact remained fairly constant in the periods between the calibration observations.

This correction for Faraday rotation in the ionosphere was rather small, particularly in the southern sky where the component of the Earth's magnetic field along the line-of-sight is small. For example, the correction to be added to the observed polarization angles for regions around the south pole was about 5°, increasing to about 20° at the equator and 30° at the declination of +26°. There could be systematic errors of up to 7° in some of the polarization angles measured at positive declinations.

(*f*) *The Johnston Island Explosion*

During the initial setting-up period for the polarization survey, a violent disturbance of the ionosphere occurred during the observations. This was produced by the explosion at 1210 U.T. (2210 E.A.S.T.) on November 1, 1962, of a 1 megaton bomb 10 km above Johnston Island. Measurements of some polarized points between declinations −60° and −80° before (2000 E.A.S.T.) and after (0300 E.A.S.T.) the explosion showed rotations of the polarization angles of some 80°. If this was due purely to an increase in electron density, it would indicate a total electron content for the ionosphere greater than its noonday value.

(*g*) *An Attempt to detect the Magnetosphere*

At the suggestion of Dr. E. G. Bowen, for several hours each night for a period of 5 days in October 1964, 408 Mc/s polarization measurements of an extended region of polarization that happened to coincide with the direction of the anti-solar point at that time were made in an attempt to detect Faraday rotation in the tail of the magnetosphere. The attempt was unsuccessful.

Similarly, it may be possible to use these regions emitting polarized 408 Mc/s radio waves to study the magnetic fields in the solar corona, if compensation can be made for the spurious effects arising from the Sun in the aerial side lobes.

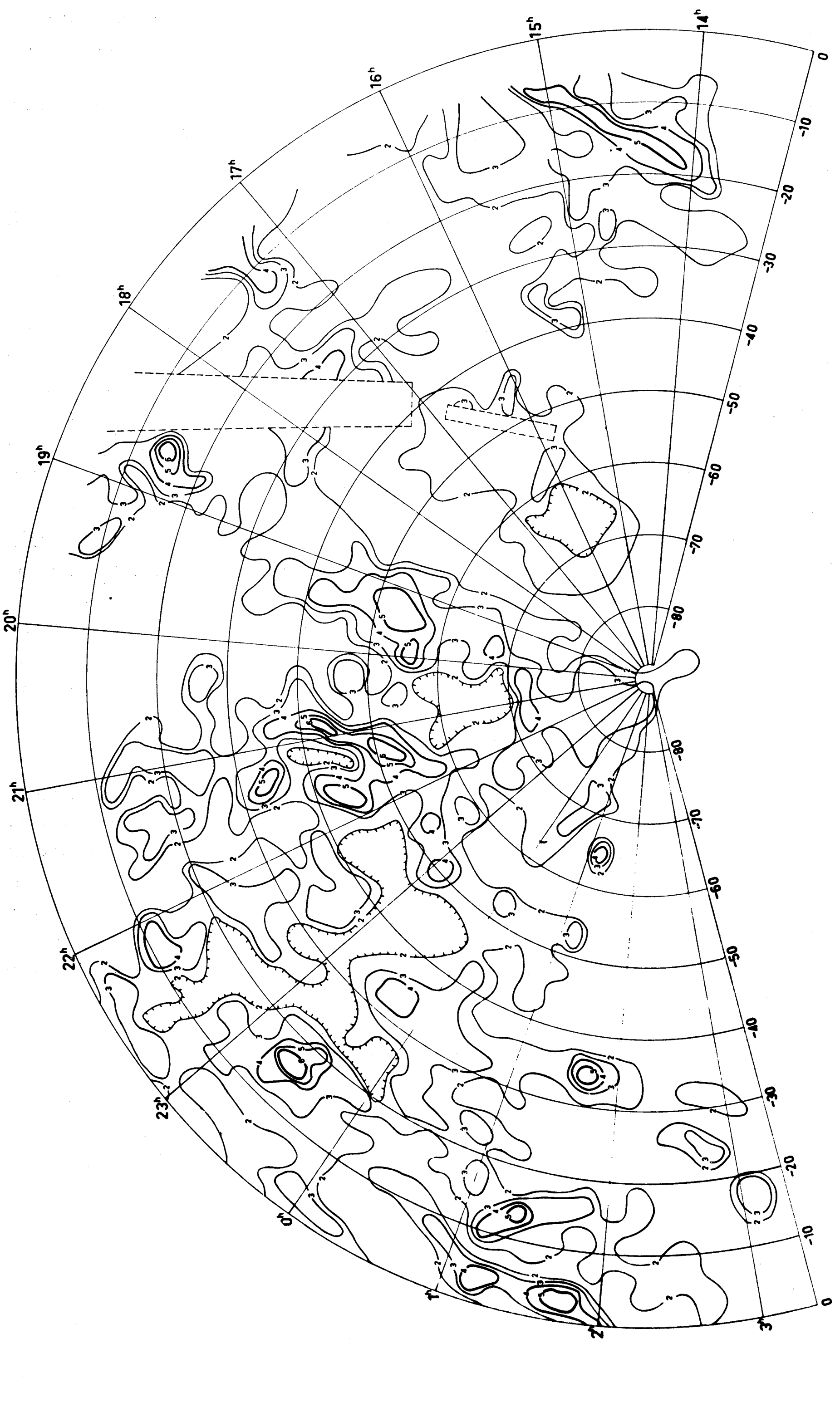
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Fig. 2(a)

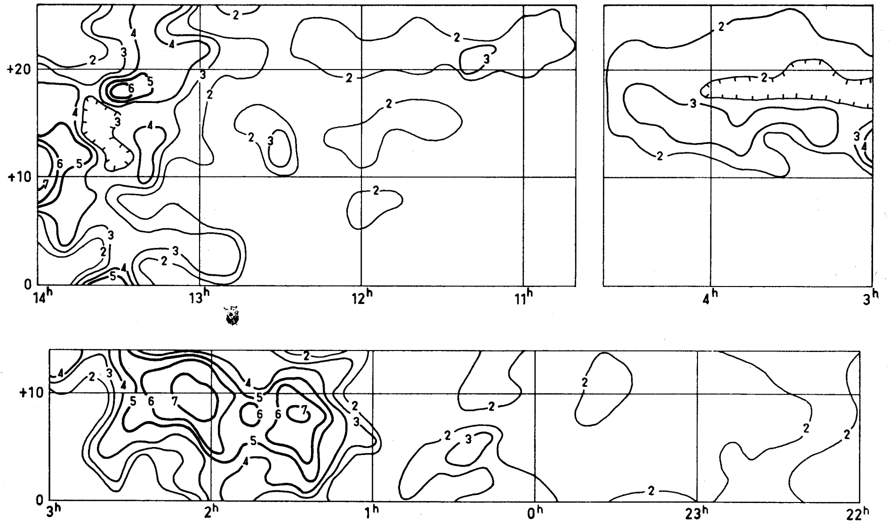


Fig. 2(*b*)

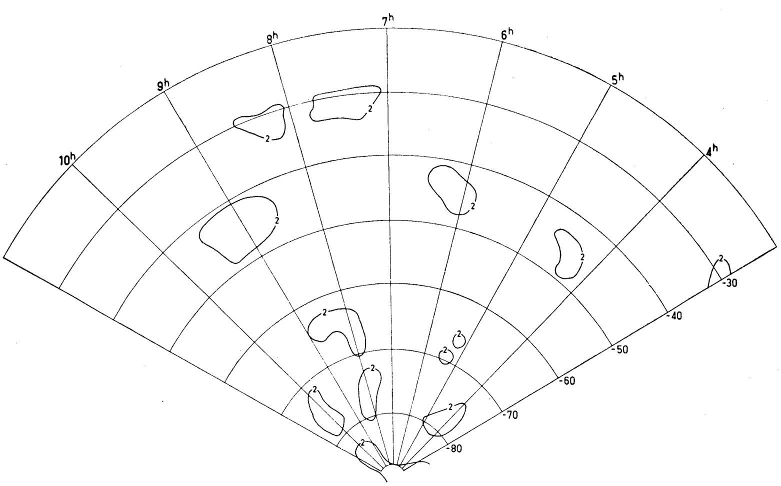


Fig. 2(*c*)

Figs 2(*a*) to 2(*c*).—Schematic contours in equatorial coordinates of polarization brightness temperature obtained from measurements at 408 Mc/s with the 210 ft telescope at a 2° grid of points over the survey region. The contour unit is 0·8 degK.

IV. Presentation of Results

The results are presented in three forms, (*a*) Table 3, (*b*) contours of polarization brightness temperature, and (*c*) vector presentation of θ_{gal} and T_b^p.

(*a*) *Table* 3*

This table lists (1) the declination circles along which measurements were made (2° steps in general) with a corresponding group of right ascensions for each value (epoch 1963), (2) the position angles θ_{eq} of the plane of vibration of the incident E vector measured from the direction to the celestial north pole (uncorrected for ionospheric Faraday rotation), (3) the polarization brightness temperatures T_b^p (°K), (4) the galactic position angles θ_{gal} of the plane of vibration of the incident E vector measured from the direction to the galactic north pole (this is obtained by adding to θ_{eq} the galactic parallactic angle and the correction for Faraday rotation in the ionosphere), and (5) the new galactic longitudes and latitudes l^{II} and b^{II} to the nearest degree.

(*b*) *The Contours*

The polarization brightness temperatures are plotted both in equatorial and galactic coordinates. The isophotes are shown in Figures 2(*a*), 2(*b*), and 2(*c*) (equatorial) and Figure 3 (galactic). The contour unit of polarization brightness temperature is 0·8 degK. To conserve space, some of the unpolarized regions have not been included in the contour maps in equatorial coordinates. Contour number 1, i.e. the 0·8 degK contour, has been omitted. It was felt that at this low level of T_b^p the results were not significant.

As the contours are based on a network of points whose separation is about two and a half times the half-power aerial beamwidth, some fine structure may have been missed. However, some trial scans similar to those in Figure 5 show that they give a fair picture of the distribution of polarized radiation over the survey region. Figure 3 shows the contours of T_b^p in galactic coordinates where the limits of the survey are shown by the thick full line. The isophotes of the present survey are drawn in full lines (contour unit 0·8 degK) and the dashed lines are the isophotes (contour unit 1·0 degK) obtained by plotting the polarization temperatures given by Berkhuijsen and Brouw (1963).

(*c*) E *Vector Presentation*

In Figure 4 the E vectors are plotted as lines centred on the positions of the observed points. The angle at which each line is drawn relative to the galactic north pole in the direction of increasing longitude is θ_{gal}, and the length of each line is proportional to T_b^p. Comparison with the Leiden surveys shows that there is good agreement in the overlap region, considering the difference in aerial beams of the two surveys.

A striking demonstration of the polarization at 408 Mc/s is shown in Figure 5, which presents the results of scanning the telescope through one of the highly polarized

* This table is available on request to the Chief, Division of Radiophysics, CSIRO, University Grounds, Chippendale, N.S.W.

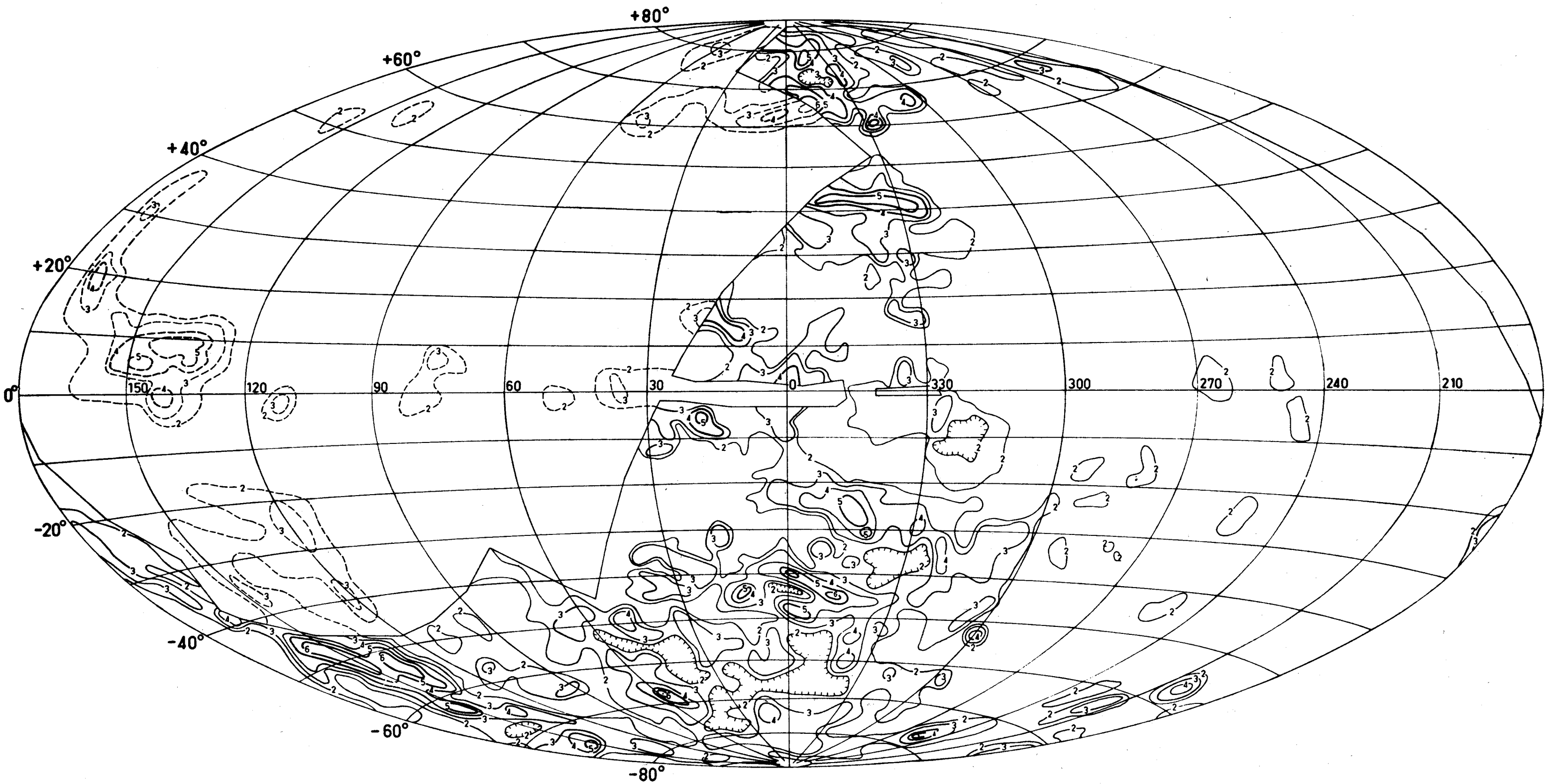


Fig. 3.—The contours of polarization brightness temperature at 408 Mc/s are drawn on this Aitoff projection in new galactic coordinates. The thick line represents the limits of the Parkes survey. The full contour lines are the isophotes of the Parkes survey (contour unit 0·8 degK). The broken lines are the isophotes of the Leiden survey (obtained by plotting the results of Berkhuijsen and Brouw 1963; contour unit 1·0 degK).

regions shown in Figure 2(*a*) with different orientations of the dipole feed; (*a*) was obtained with the dipoles set at a position angle of 50° and (*b*) with the dipoles at a position angle of 140°.

V. Discussion of Results

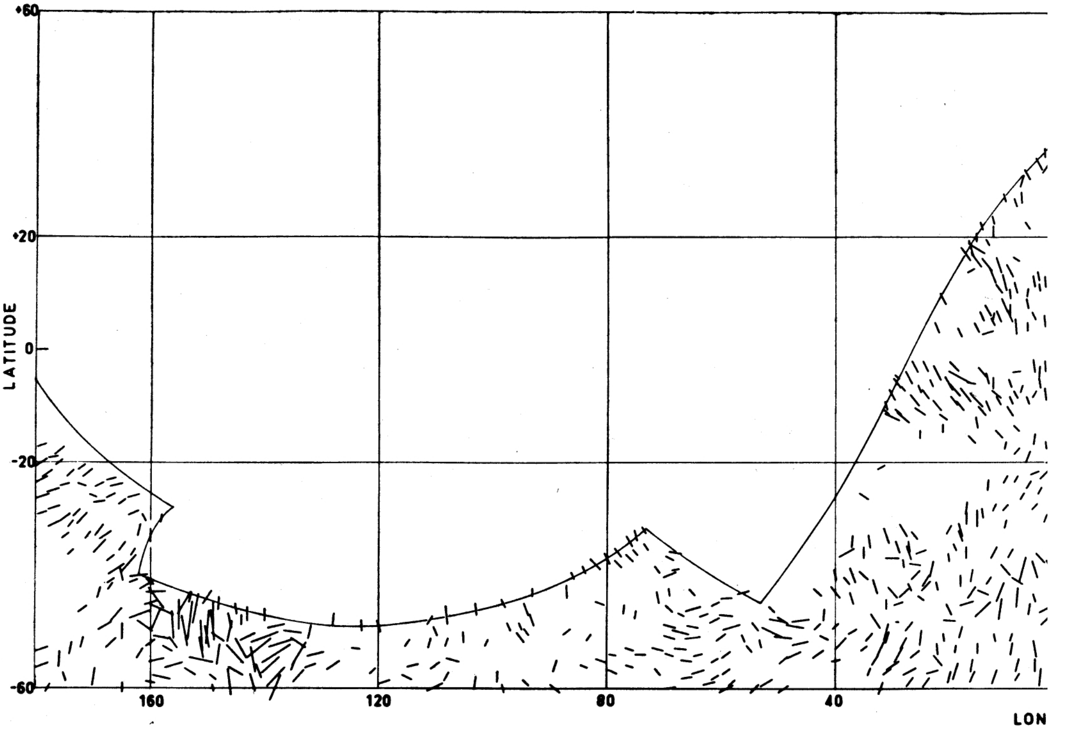
The most outstanding feature of the large-scale distribution of the 408 Mc/s polarized radio emission (Fig. 3) is that almost all of the polarization lies in a band about 60° wide, which contains the great circle that passes through the galactic poles and intercepts the plane at $l^{\mathrm{II}} = 340°$ and 160° (Mathewson and Milne 1964). The centre of this band is the small circle (parallel to this great circle) that cuts the plane at $l^{\mathrm{II}} = 350°$ and 150°.

The fact that the polarized radio emission lies within this band may be explained by the synchrotron radiation theory if the Sun is inside a spiral arm that has relativistic electrons moving around magnetic lines of force, which are directed along the arm towards $l^{\mathrm{II}} = 70°$ and 250°. Under such conditions an observer would see a bright band of radiation about him (Tunmer 1958). The width of the band would be determined by the degree of isotropy of the electron flux. The most intense part of the band would be where the line-of-sight is perpendicular to the magnetic field, i.e. along the great circle through the poles and the plane $l^{\mathrm{II}} = 340°$ and 160°. Optimum conditions for the detection of polarization of the synchrotron radio emission would also exist where the line-of-sight is perpendicular to the magnetic field, as there would be no depolarization of the radiation by Faraday rotation. (The reason for the polarized regions being distributed slightly asymmetrically about the great circle may be that the magnetic field lines are expanding outwards about the axis in the direction of $l^{\mathrm{II}} = 250°$.)

If this explanation is correct, the intrinsic direction of the E vectors of the radiation, which are perpendicular to the magnetic field at emission, would be nearly parallel to this great circle. In the stronger polarized regions in Figure 4, the E vectors of the 408 Mc/s emission do indeed lie approximately parallel to this great circle. In fact the ordered arrangement of the E vectors in these regions is remarkable (each region covers over 300 sq degrees) and must mean that the magnetic fields in the emission regions are very ordered as they run along the spiral arm. This evidence strongly supports the above interpretation, although measurements at other frequencies are needed to confirm this.

Muller *et al.* (1963) and Berkhuijsen *et al.* (1964) have made linear polarization measurements of the northern sky at 610 Mc/s. Their results show a region of zero Faraday rotation extending from $l^{\mathrm{II}} = 130°$, $b^{\mathrm{II}} = -40°$, up to $l^{\mathrm{II}} = 140°$, $b^{\mathrm{II}} = +10°$. The E vectors in this band are approximately parallel to the great circle that cuts the plane at right angles at $l^{\mathrm{II}} = 160°$. These results give additional support to the proposed model.

In the north galactic polar map shown in Figure 4(*c*), the 408 Mc/s E vectors are orientated roughly parallel to the line joining $l^{\mathrm{II}} = 290°$ and 110° rather than to $l^{\mathrm{II}} = 340°$ and 160°. The Leiden group found that in their section of the map the 610 Mc/s E vectors were more ordered than the 408 Mc/s E vectors. Combining their 408 and 610 Mc/s results, the intrinsic polarization angles were calculated



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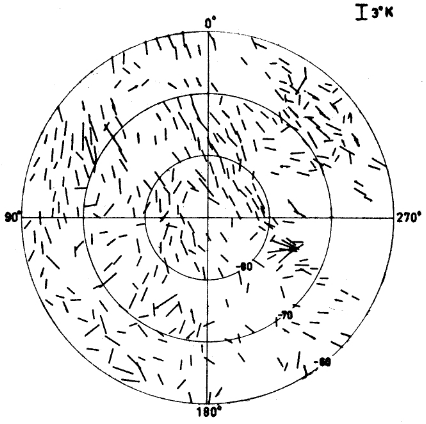

Fig. 4(*b*)

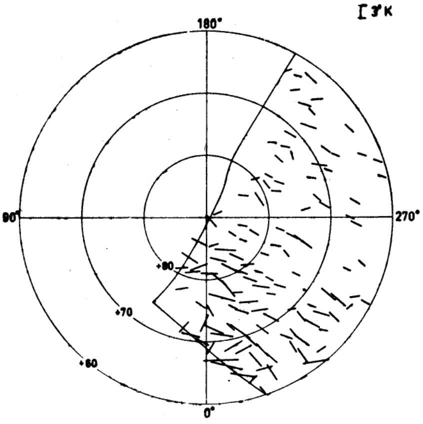

Fig. 4(*c*)

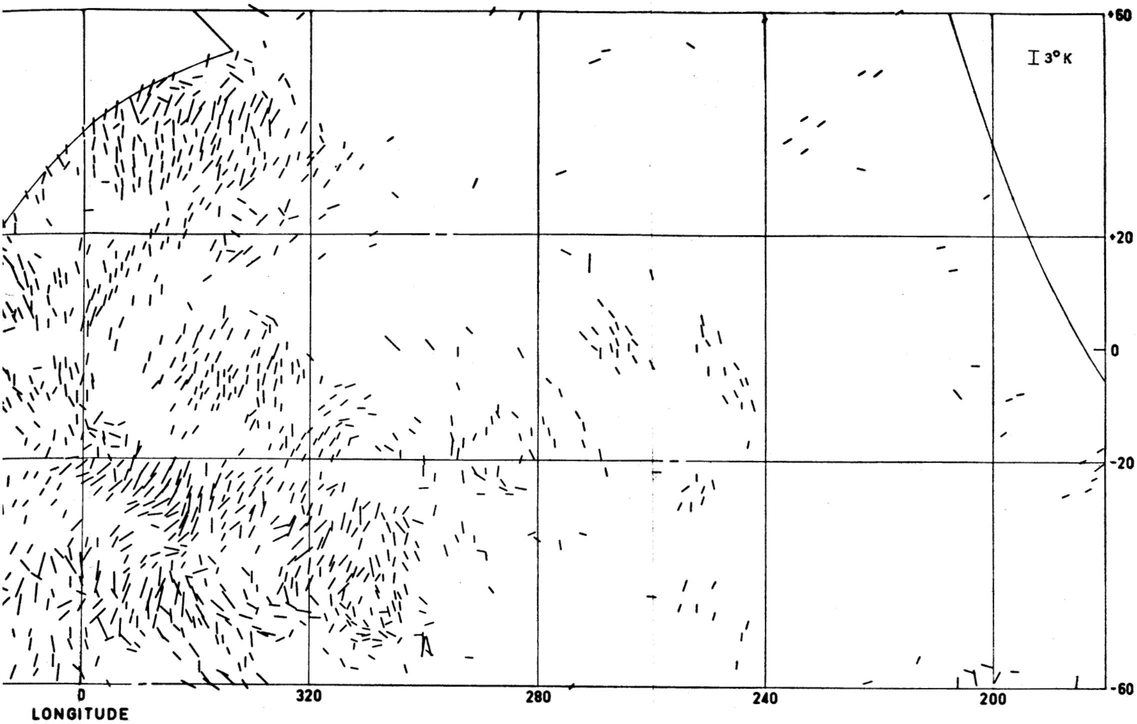

Fig. 4(*a*)

Figs 4(*a*) to 4(*c*).—The 408 Mc/s polarization results are plotted as lines centred on the positions (new galactic coordinates) of the observed points. The angle at which each line is drawn relative to the galactic north pole in the direction of increasing longitude is θ_{gal} and the length of each line is proportional to the polarization brightness temperature (Table 3).

on the assumption that only one polarized component was in the aerial beam. They were found to lie parallel to the line joining $l^{II} = 340°$ and $160°$. Apparently there must be some ionized region with a component of magnetic field towards the Sun in front of the emitting region in this part of the band. It is interesting to note that the well-known northern spur (Hanbury Brown, Davies, and Hazard 1960) cuts across the polarized band in the area, and it may well produce this rotation of the 408 Mc/s E vectors.

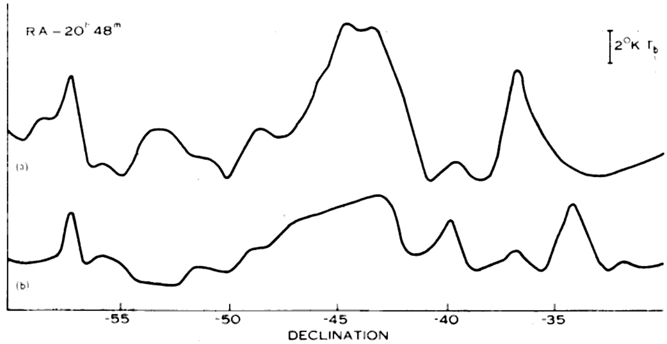

Fig. 5.—The profiles of two scans in declination at R.A. $20^h 48^m$ with different orientations of the 408 Mc/s primary feed; (*a*) dipoles set at a position angle of 50°, (*b*) dipoles at a position angle of 140°.

Davies and Hazard (1962) have suggested that the radio emission from a spiral arm is due to old fragments of supernovae remnants. However, if this is the case, it is difficult to explain why the preferred direction of the E vectors in the stronger polarized regions is approximately parallel to the great circle passing through the poles and cutting the plane at $l^{II} = 340°$ and $160°$. It is also difficult to explain the degree of order of the E vectors, as great turbulence is expected in the magnetic fields of old supernovae remnants. Of course, some contribution to the non-thermal spiral arm radio emission must be made by these objects, and perhaps some of the polarization observed at 408 Mc/s arises in them. However, on the basis of the present evidence, it seems more reasonable to assume that the majority of the synchrotron emission arises in regions of magnetic fields and relativistic electrons that are part of the structural features of the spiral arm itself.

Additional evidence in support of the model is given by the polarization measurements of starlight, which show that the magnetic fields associated with dust clouds in the spiral arm are very ordered and aligned in the direction $l^{II} = 60°$ and $l^{II} = 240°$ (Smith 1956). This is close to the direction predicted from the radio polarization results. Of course, dust clouds may not be the source of synchrotron emission. However, it may be that the magnetic fields associated with these different features that constitute a spiral arm are all aligned in the direction of the arm.

The direction of the local spiral arm estimated from other evidence (e.g. the concentrations of neutral hydrogen, bright O and B stars, and HII regions) ranges from $l^{II} = 70°$ to $l^{II} = 90°$ (Weaver 1953; Westerhout 1957). This is in good agreement with that predicted from the polarization studies. It is also interesting to note that the low velocity H-line studies of McGee and Murray (1961) place the Sun inside the local spiral arm, in agreement with the model put forward on the basis of the polarization results. They find that the Sun is almost on the plane of the Galaxy. The 408 Mc/s polarization temperatures are higher on the anti-centre side of the band, which may mean that the Sun lies towards the inner edge of the local arm.

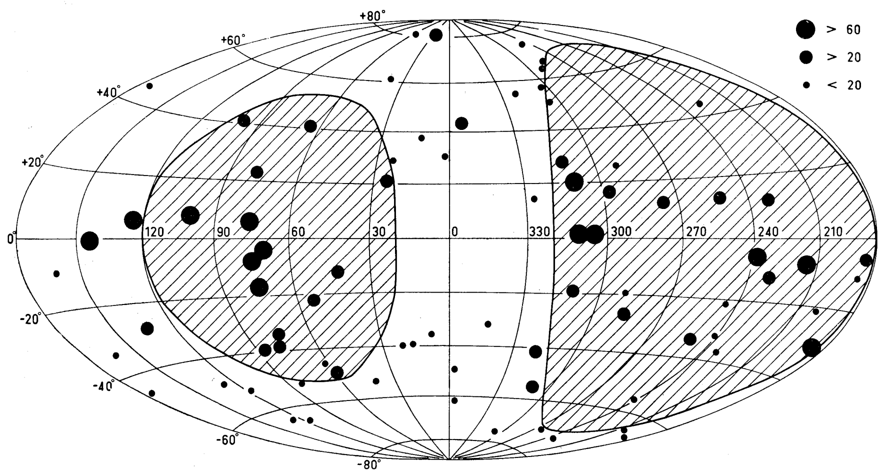

Fig. 6.—The rotation measures of the discrete radio sources (Gardner and Davies 1966) are separated into three groups (> 60, > 20, < 20), irrespective of the sense of rotation, and plotted on this Aitoff projection in new galactic coordinates. The unshaded area is the 60° wide band that contains most of the 408 Mc/s polarization.

The rotation measures for discrete radio sources provide information about the distribution of magnetic fields and ionized hydrogen through the Galaxy in the directions of the sources. Morris and Berge (1964) concluded from a study of the rotation measures of 37 sources that the direction of the local field was towards $l^{\mathrm{II}} = 70°$ and 250°. Gardner and Davies (1966) using 86 sources obtained the direction of the field as $l^{\mathrm{II}} = 90°$ and 270°. (The sense of the magnetic field above the plane $b^{\mathrm{II}} > 20°$ is opposite to the field at southern latitudes, but here we are concerned more with the general alignment of the magnetic field.) These directions are in fair agreement with the direction of the field in the synchrotron regions of the local arm. This agreement must mean that the fields in the ionized hydrogen regions producing the source Faraday rotation at latitudes greater than about 10° must be fairly local and directed along the same spiral arm as the synchrotron regions.

To demonstrate the close agreement between the source and background polarization results, we have drawn in the 60° wide band (unshaded) that contains most of the 408 Mc/s polarization onto Figure 6, where the rotation measure data of Gardner and Davies (1966) are plotted. It is quite striking how the sources with low rotation measure fall outside the shaded areas. Altogether 36 sources fall inside the band at latitudes greater than 10°. Their mean rotation measure is 11. Gardner and Davies place an upper limit of 5 on the rotation measure due to Faraday rotation in the source itself, so the remainder occurs in the ionized hydrogen and magnetic fields in the local spiral arm.

The available observational evidence indicates that the magnetic fields that permeate the various regions constituting a spiral arm (i.e. HII regions, dust clouds, neutral hydrogen clouds, and synchrotron regions) are roughly aligned along the same general direction as the spiral arm. It also appears that the local magnetic field revealed by the distribution of 408 Mc/s polarization is part of a larger-scale field extending throughout the spiral arms.

It is noticed from Figures 3 and 4 that the 408 Mc/s polarization is not smoothly distributed over the band but has a patchy, almost striated, appearance. The stronger regions appear to be extended in the longitude direction by some 30° to 50°, but only 10° to 15° in the latitude direction. Does this patchy distribution reflect concentrations of the relativistic electrons, or is it produced by depolarizing regions of ionized hydrogen and magnetic fields in the intervening space? In this regard, it is interesting to note that Davies and Hazard (1962) from a 237 Mc/s survey of the galactic plane near the anti-centre found that a large fraction of the continuum emission arises in a number of localized regions and that any contribution by a uniform component is small. This evidence suggests that the areas of the observed 408 Mc/s polarization may delineate the intrinsic shape of the nearby synchrotron regions in the local arm.

However, it appears that in some places at least nearby HII regions cause depolarization of the radiation from the synchrotron regions. Evidence for this may be found in a comparison of the high and low frequency galactic continuum surveys where absorption of the low frequency radio emission reveals the presence of local concentrations of electrons. The 400 Mc/s (Pauliny-Toth and Shakeshaft 1962) and 178 Mc/s (Turtle and Baldwin 1962) continuum surveys clearly show a band of radiation centred on $l^{\mathrm{II}} = 150°$ and extending up to high latitudes on either side of the plane that is identified here with the band of 408 Mc/s polarization. However, comparison with the 38 Mc/s isophotes of Blythe (1957) shows absorption features along parts of the band. As an example, the intense feature on the high frequency surveys of the southern spur centred on $l^{\mathrm{II}} = 153°$, $b^{\mathrm{II}} = -32°$, occurs in absorption on the 38 Mc/s survey. This same area shows no polarization at 408 Mc/s although the adjoining regions are polarized. This strongly suggests that the HII region causing the absorption is also responsible for depolarizing the radio emission by Faraday rotation. It is interesting to note that, in principle, a combination of measurements of Faraday rotation and the absorption of the radiation in a HII region provides a method for the determination of magnetic field strengths in the region. This is based on the fact that Faraday rotation is proportional to the electron density, the component of the magnetic field in the line-of-sight, and the depth of the region, while the absorption of the background radio emission in the region is proportional to the square of the electron density and the depth of the region.

In an attempt to gain more information on this question of the distribution of polarization within the band, the rotation measures of sources were examined to see if the lowest rotation measures occurred in the same direction as the 408 Mc/s polarized patches. However, no such systematic trend could be detected with the small number of sources available.

We have seen that the mean rotation measure of the radio sources in the band at latitudes greater than 10° is 11, whereas an upper limit of 5 has been placed on the contribution to the rotation measure by the source itself. Recent polarization measurements at 620 Mc/s by Mathewson, Broten, and Cole (1966) at Parkes give an average of 1·5 for the rotation measures of the stronger extended regions in Figure 3. Therefore, the contribution to the rotation measures of the sources by the local arm is definitely greater than for the 408 Mc/s polarized regions. It appears likely that the 408 Mc/s polarized regions lie closer to the Sun than a fair proportion of the ionized hydrogen and magnetic fields causing the Faraday rotation of the source radiation. If the mean radius of the local arm is 400 pc (Mills 1959; McGee and Milton 1964), then the distance to the polarized regions may be only 100–200 pc. It should also be noted that, if more extended synchrotron regions exist at greater distances such that their radiation experiences a similar amount of Faraday rotation as the source radiation, polarization could probably not be detected for these regions owing to rapid depolarization by differential Faraday rotation in the aerial beam.

Some further evidence for a distance determination may be obtained from a comparison of the 408 Mc/s polarization temperatures with the temperatures that might be expected from a spiral arm on the basis of other evidence. Continuum surveys clearly show the existence of the band of radiation about us due to the local spiral arm. This band of local emission together with the integrated radiation from the other spiral arms should theoretically produce four broad minima centred at $l^{\text{II}} = 70°$, $b^{\text{II}} = \pm 35°$, and $l^{\text{II}} = 250°$, $b^{\text{II}} = \pm 35°$. On most surveys, three minima are clearly seen at $l^{\text{II}} = 80°$, $b^{\text{II}} = -55°$, $l^{\text{II}} = 240°$, $b^{\text{II}} = +35°$, and $l^{\text{II}} = 230°$, $b^{\text{II}} = -40°$, which lie close to the predicted positions (e.g. see Dröge and Priester 1956; Pauliny-Toth and Shakeshaft 1962). A possible fourth minimum may be masked by a nearby spur of emission from the galactic plane. From these surveys, the brightness temperature at 408 Mc/s of the band of radiation is estimated at 10°K using a spectral index of $-0 \cdot 6$ for the radiation emission. (This temperature estimate, made on the basis of lower frequency surveys, would be for unpolarized radiation.)

Additional information is obtained from the observations of Davies and Hazard (1962) at low galactic latitudes in the anti-centre region in the vicinity of $l^{\text{II}} = 200°$. The observed average temperature of the disk component was about 80°K at 237 Mc/s. In this direction, this probably represents the total contribution from the outer spiral arm. This would give a brightness temperature of about 20°K at 408 Mc/s, which agrees well with the estimate of 10°K for the "half-arm" contribution obtained from high latitude observations of the local emission. The polarization brightness temperatures (Fig. 3) in the stronger regions of 408 Mc/s polarization vary from about 5°K to 8°K, which gives a percentage polarization of about 30%. This is quite large, particularly as the maximum percentage polarization to be expected under ideal conditions is about 70% (LeRoux 1961). The polarized radiation must therefore come from a fair proportion of the whole spiral arm and is not an extremely local feature. Taking into account the evidence from the rotation measure studies given above, a very tentative distance of 150 pc is suggested for the 408 Mc/s polarized regions, assuming as before that the mean radius of the local spiral arm is 400 pc.

A knowledge of the distance makes it possible to make a rough calculation of the magnetic field strength in the 408 Mc/s polarized regions. The assumptions involved in this calculation are that

(1) the distance to the polarized region is 150 pc,

(2) the radio emission is confined to filaments of circular cross section of diameter 25 pc,

(3) the spectral index of the radiation is $-0\cdot6$,

(4) the high and low frequency cut-offs for the synchrotron emission are 10^{10} and 10^{7} c/s respectively, and

(5) there is equipartition between the energy in the relativistic particles and the magnetic field, and that the protons have 100 times the energy of the electrons (Burbidge and Burbidge 1959).

A field strength of 5×10^{-5} G was obtained. This is high compared with 7×10^{-6} G measured in the Zeeman experiment (Davies *et al.* 1964). It is quite possible that the radio emitting regions in the spiral arms have higher magnetic field strengths than the dense HI regions. A field of this strength is in accord with that predicted on the basis of the total intensity of the non-thermal radio emission from the galactic disk.

VI. Conclusions

Summing up, the large-scale distribution of linear polarization at 408 Mc/s may be explained on the basis of synchrotron radiation theory if the Sun lies almost at the centre of a spiral arm that has a magnetic field directed along it towards $l^{\mathrm{II}} = 70°$ and 250°. The concentrations of relativistic electrons may be confined to regions of higher than average magnetic field strength (5×10^{-5} G) elongated in the direction of the arm. The observations show that the magnetic fields in these synchrotron regions are very ordered. The distance to the polarized regions may be about 150 pc.

Evidence from other observations such as the rotation measures of sources, polarization of starlight, and the H-line Zeeman experiment suggests that the magnetic fields in HII regions, dust clouds, and concentrations of neutral hydrogen are ordered and lie in approximately (within 20°) the same direction as the magnetic fields in the synchrotron regions. It appears that the local synchrotron regions are manifestations of a larger-scale field extending throughout the spiral arms.

These polarization studies enable the near emission to be separated from the more distant emission. Past continuum surveys reveal clearly the existence of the local band of radio emission and the positions of the three observed minima agree well with those predicted on the basis of the proposed model. This local emission should be removed before estimates are made of any coronal or extragalactic component.

At high latitudes, close correlation is observed between features of the distribution of background polarization and Faraday rotation of extragalactic sources.

It will be of great interest to compare the fine detail of these distributions when rotation measures are available for a much greater number of sources.

Multifrequency measurements of the background polarization are also required to give the Faraday rotation of the radiating regions and the intervening medium. These will provide data on field directions and strengths and, in combination with rotation measures for radio sources, estimates of the distances to the synchrotron regions.

VII. Acknowledgments

The authors wish to thank Mr. J. R. Healy and Mr. M. James for their assistance in part of the observations and reduction of the records, Miss J. E. Leveleky for her help in the preparation of the Tables and Figure 4, Miss V. Rowntree for the preparation of the diagrams, and Mr. J. G. Bolton for his critical reading of the manuscript and many helpful comments.

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