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MAGNETIC FIELDS IN THE GALACTIC SPURS

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Summary

The structures of the magnetic fields in the ' spurs ' of non-thermal galactic radio emission are investigated by making use of the observed polarization and brightness distribution of the radio emission and data on the optical interstellar polarization. In at least two cases the magnetic fields are remarkably well aligned over large areas, and in four cases the field is parallel to the ridge of the corresponding spur. Comparison of the magnetic field direction with the planes of optical interstellar polarization yields an estimated distance of 100 ± 20 pc for the principal ridge of the North Galactic Spur. These facts severely restrict possible theories of these objects.

1. *Introduction.* The features of the galactic radio emission in high latitudes known as the ' spurs ' still await a completely satisfactory explanation. The theory which has received the strongest support is that they are remnants of nearby old supernovae. This was originally put forward by Brown *et al.* (1960) on the grounds of the similarity of the radio emission from the North Galactic Spur to that from a shell source such as the Cygnus Loop, although the lack of any corresponding optical feature was, and remains, an obvious difficulty. Measurements by Davies *et al.* (1963) showed, in fact, that the brightness of the spur in Hα is less than 0·3 per cent of that of the Cygnus Loop. Despite this and other problems Davies (1964), Large *et al.* (1966) and Quigley & Large (1966) concluded on the basis of further radio observations that the spur was a shell source and a supernova remnant.

Other explanations which have been advanced include that by Oda & Hasegawa (1962), which is based on the supposition that the magnetic field in the North Galactic Spur is parallel to its length and that radiating relativistic electrons have been introduced into it by the explosion of a supernova on the ridge of the spur and close to the galactic plane. More recently Rougoor (1966) has interpreted the various spurs as part of a single helical feature, which perhaps implies the existence of a tube of magnetic field wrapped around the local spiral arm. Yet another possibility is that the spurs are large scale features of the galactic radio halo.

In the present paper observations of the polarization of the radio emission and of optical interstellar polarization are used to derive both the configuration of the magnetic fields in the spurs and an estimate of the distance of the North Galactic Spur. This is followed by a discussion of the bearing of these results on the current theories.

Paper I refers to observations of the polarized emission at 1407 MHz by Bingham (1966) and Paper II to the immediately preceding paper (Bingham & Shakeshaft 1967) in which the methods of obtaining the field configuration are described.

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2. *The North Galactic Spur*

2.1 *Rotation measures and intrinsic polarization in the spur.* Fig. 5 of Paper I showed the polarized emission at 1407 MHz from the area of the North Galactic Spur superimposed on the contours of total emission at 178 MHz (Turtle & Baldwin 1962). From the general coincidence of the two it is clear that the emission of the spur itself is polarized. Using the results of Paper I in conjunction with the observations of Berkhuijsen *et al.* (1963, 1965) at 408 and 610 MHz, a map of the rotation measures may be drawn (Fig. 1). These are seen to be mostly positive, which is somewhat unexpected since part of the area is only about 50° from the direction $l^{II}=70°$, $b^{II}=0°$ in which the local magnetic field is thought to be directed away from the Sun. It is also clear that close to the north galactic pole the rotation measures are small and tend to alternate in sign, indicating that the magnetic field seen in this direction is roughly perpendicular to the line of sight and parallel to the galactic plane. Away from the polar region the rotation measures increase at lower latitudes. In regions where the rotation measures are greater than 3 rad m^{-2} the rotation at 408 MHz is more than 90° and one can conclude from the very presence of measurable polarization at this frequency that most of the rotation takes place between the source of emission and the Sun. If it took place

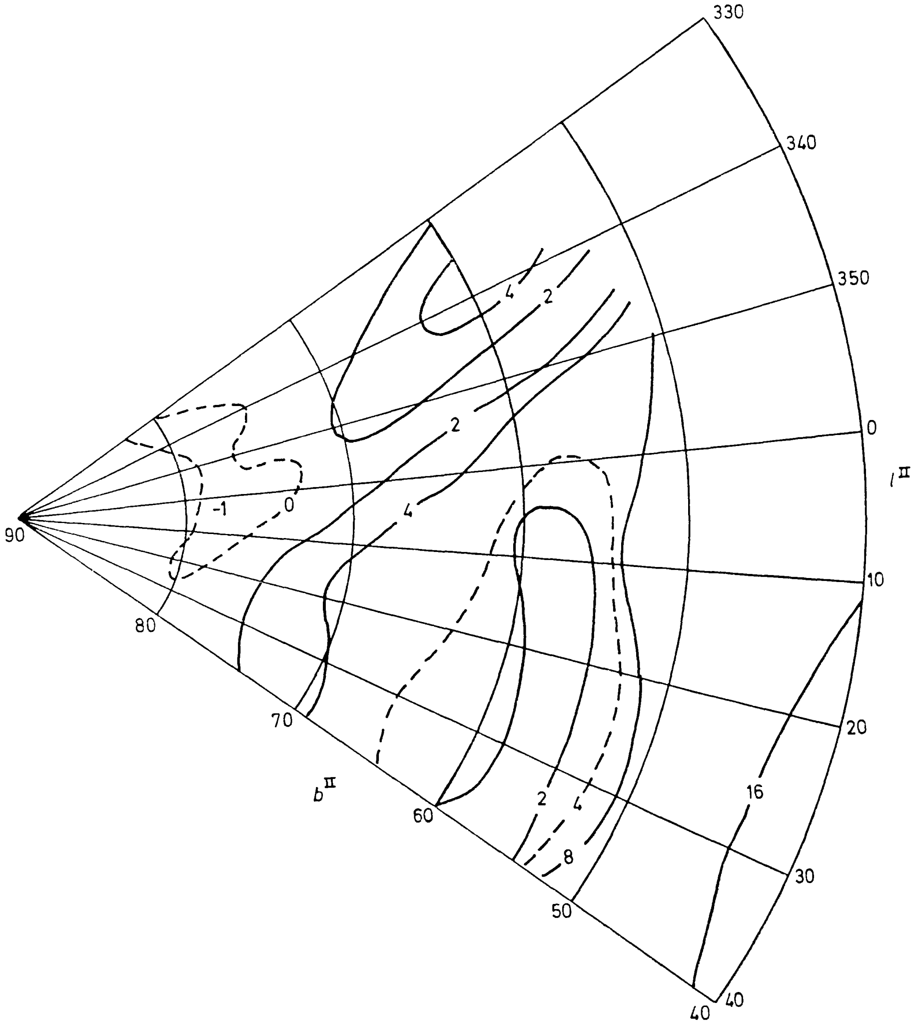

FIG. 1. *Rotation measures (rad m^{-2}) in the North Galactic Spur.*

inside the source the radiation would be expected to be completely depolarized at 408 MHz by the addition of differently oriented components from different parts of the source (see e.g. Burn 1966). Since the maximum internal rotation in the source is ~ 3 rad m^{-2}, a lower limit to the rotation occurring between the polarized source and the Sun may therefore be obtained by subtracting 3 from the values given in Fig. 1.

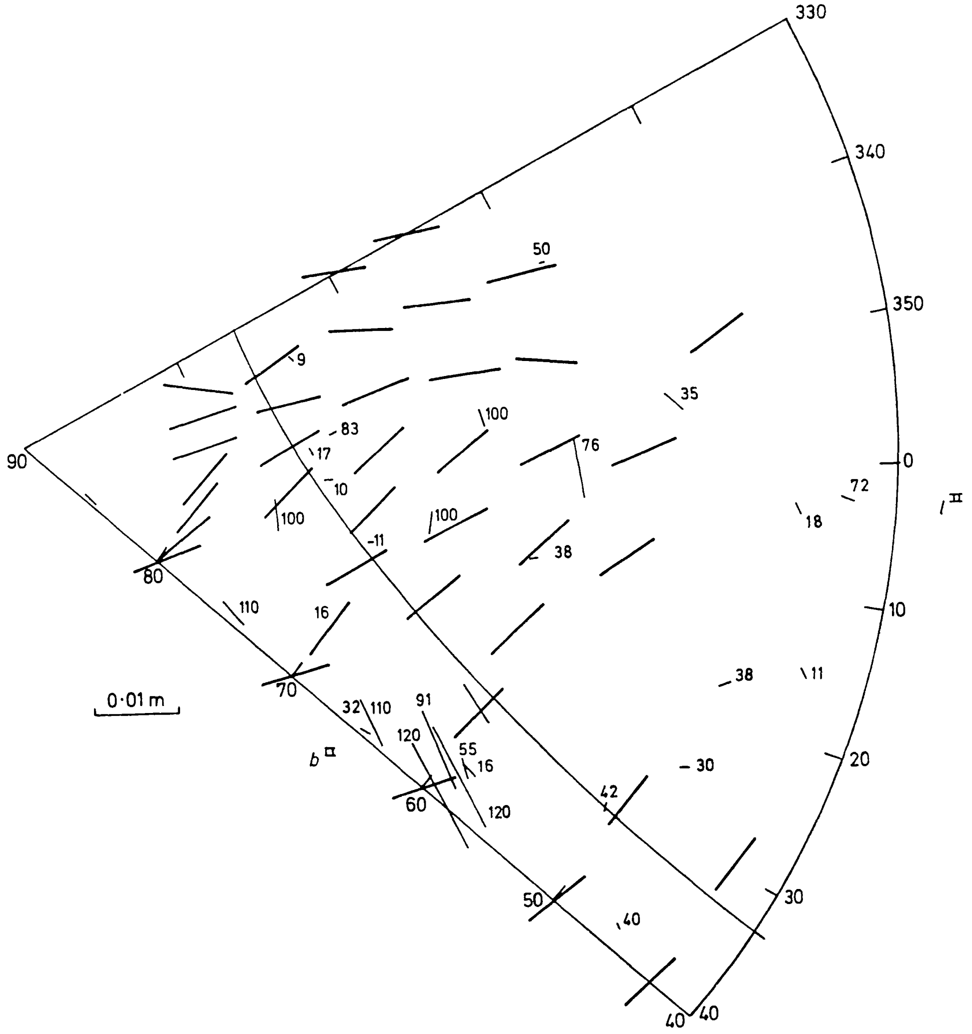

Fig. 2. *Intrinsic radio polarization and optical interstellar polarization in the North Galactic Spur. The thick lines represent the intrinsic radio polarization (electric vectors) and the thin lines the optical polarization (electric vectors). The latter are from Behr* (1959) *and the distance to each star is given in parsecs by the small figures. The circle which fits best the ridge of maximum emission of the spur (Large et al.* 1962) *is also shown.*

Using the rotation measures in Fig. 1, the 1407 MHz polarization angles were converted to their intrinsic values which are shown in Fig. 2. Also shown are the circle given by Large *et al.* (1962) as the best fit to the ridge of maximum emission in the spur and optical polarization data from Behr (1959). The distance of each star is given in parsecs by the small figures. It is apparent that the magnetic field in the spur is approximately parallel to Large's circle.

2 . 2 *An estimate of the distance of the spur.* Examination of the optical polarization data which is given in Fig. 2, and comparison of Fig. 5 of Paper I with Fig. 6

of Behr (1959), shows that the curvature of the magnetic field in the radio spur is apparent in the polarization of all stars at 90–120 pc at $\delta > 10°$ and in two stars at about 75 pc at $\delta < 10°$, one of which is in Fig. 2 at $l^{\mathrm{II}} = 2°$, $b^{\mathrm{II}} = 58°$. Stars closer than 70 pc show little polarization and do not reflect the structure of the spur. On the reasonable supposition that the very similar magnetic field structures revealed in this way are one and the same, the distance is therefore fairly closely defined as 100 ± 20 pc in the region $\alpha = 13^{\mathrm{h}}$ to 17^{h}, $\delta = +10°$ to $+20°$. Other parts of the object may be more distant, but there are no observations of stars at distance > 120 pc for comparison. There is some evidence that the distance decreases towards the centre of curvature of the spur, which would be consistent with a spherical structure, but this conclusion depends on a small number of stars at $\delta = 5°$ and so cannot be given great weight. It is also interesting that Behr (1959) finds a rapid increase in polarization with distance in the range 50–120 pc, which he attributes to an increased density of absorbing and polarizing dust. If the spur is to be interpreted as a spherical shell source of angular diameter 113° (Quigley & Haslam 1965) and if the length of the tangent from the Sun is 100 pc, it follows that the linear diameter is about 300 pc, an order of magnitude larger than the known supernova remnants. The centre of this sphere is about 55 pc north of the galactic plane and 180 pc from the Sun.

Previously (Davies 1964) the presence of radio polarization at 408 MHz has been taken to indicate a distance considerably less than 100 pc. The more complete data now available are, however, in no way incompatible with the larger distance in view of the uncertainty in our knowledge of the magnitudes of the magnetic field and electron density, and the fact that the highest polarization temperatures at 408 MHz correspond to the exceptional region around $b^{\mathrm{II}} = 75°$ where the rotation measures are small, probably due to a reduced line-of-sight magnetic field component. The rotation measures of 10 rad m^{-2} found at lower latitudes are consistent with a distance of 100 pc if the product of the line-of-sight magnetic field and the electron density is $1 \cdot 5 \times 10^{-7}$ G cm^{-3}. This is to be considered a lower limit, as there is an indication of reversal of the line-of-sight magnetic field somewhere along the path (as mentioned in Section 2·5 of Paper II). Taking the mean electron density as 0·08 cm^{-3} (Ellis & Hamilton 1964), and combining this with the limit given above, the lower limit to the line of sight magnetic field component is $1 \cdot 9 \times 10^{-6}$ G. It is uncertain to what extent the electrons are concentrated in clouds; if they are, then the magnetic field limit is raised by a factor $\sqrt{x}$ where x is the ratio of the cloud density to the mean density.

2.3 *Degree of polarization of the spur.* In order to estimate the degree of polarization of the spur, it is necessary to decide what proportion of the total radiation from this direction is due to the spur rather than to other sources. To perform this separation, the 1407 MHz polarization temperatures were plotted (Fig. 3) against the background brightness at 400 MHz (Seeger *et al.* 1965). Since the spur extends over a large area we cannot assume that the background is uniform, and it is also not clear that the internal Faraday depolarization is small except at high galactic latitudes (Fig. 1). Hence the plot is given for a limited section of the spur defined by $\alpha = 14^{\mathrm{h}}$ to 15^{h} and $\delta = -1°$ to $30°$. There is seen to be approximately a linear relationship, which suggests a feature with a uniform degree of polarization superimposed on an unpolarized background of about 20°K at 400 MHz. Assuming a temperature spectral index of 2·8 between 400 MHz and 1407 MHz, the gradient of the line indicates a degree of polarization of 62 per cent, or 48 per cent if a spectral index of 2·6 is used. These are remarkably high values and imply that the magnetic field in the source must be well aligned in depth, to within about 20° of its preferred direction. We may note that Fig. 5 of Paper I shows a similar good alignment of the polarization vectors across the source.

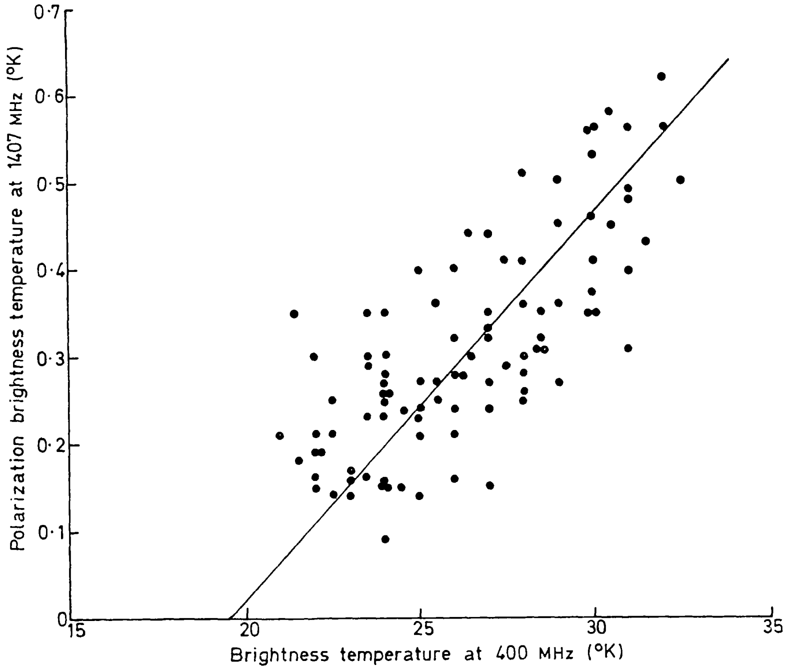

FIG. 3. *Polarization brightness temperatures at* 1407 *MHz* (*Paper I*) *plotted against background temperatures at* 400 *MHz* (*Seeger et al.* 1965) *in the North Galactic Spur.*

Although the very highest degree of polarization occurs almost on the ridge of maximum emission, it is also very high at $\alpha = 15^{\mathrm{h}}$, $\delta = -1^{\circ}$, which is well away from the ridge. This suggests that the field lines in the spur have a large-scale parallelism and that the alignment is not simply that of an arbitrary magnetic field compressed into a spherical shell.

The frequency dependence of the polarization can provide further information on the magnetic field structure and the distribution of the material causing Faraday

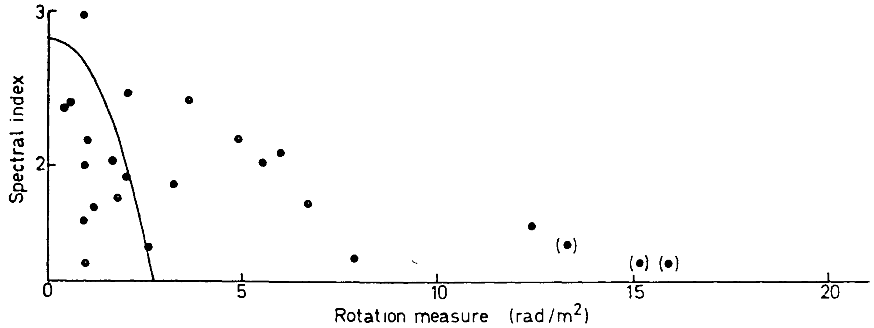

FIG. 4. *Polarization temperature spectral index between* 408 *and* 1407 *MHz plotted against rotation measure at the same points, in the North Galactic Spur. The full curve is explained in the text. The rotation measures at the points marked* (•) *were derived from measurements at two frequencies only and were taken to be positive by comparison with neighbouring points.*

rotation. As a measure of this we shall make use of the polarization temperature spectral index, defined by Berkhuijsen *et al.* (1965) to be exactly analogous to that used for unpolarized radiation. Fig. 4 shows the polarization temperature spectral indices determined between 408 MHz and 1407 MHz for different directions in the region $b^{\mathrm{II}} > 40°$, $330° < l^{\mathrm{II}} < 30°$, plotted against the rotation measures for the same directions. As already noted, there is evidence that much of the rotation occurs between the spur and the Sun. We may test this deduction by comparing the plotted points with the spectral indices and rotation measures expected if the source were uniform, with a spectral index of 2·8 for unpolarized radiation, but with no rotation between the source and the Sun. The smooth curve of Fig. 4 shows the relationship this would produce. The interpretation of this diagram is as follows:

(i) Points with a spectral index steeper than, say, 2·8 are few; they would correspond to complex structure in the beams of the polarimeters.

(ii) Points on the curve would be consistent with a simple uniform source.

(iii) Points to the right of the curve must suffer rotation between the source and the Sun (as explained in Section 2 . 1).

(iv) Points to the left of the curve show a fall in the degree of polarization at low frequencies with little corresponding rotation. The explanation of these points is probably that there are small scale irregularities in Faraday rotation which appear at lower frequencies and increase the apparent depolarization.

3. *Other spurs*

3 . 1 *The polarized feature at* $l^{\mathrm{II}}=90°$, $b^{\mathrm{II}}=+30°$ (*Loop III*). Some radio polarization appears to be associated with another ' spur ' of the galactic emission which has been discussed by Seeger *et al.* (1965) and Quigley & Haslam (1965). In Fig. 5 the 1407 MHz polarization vectors are shown with the contours of the 400 MHz unpolarized emission from Seeger *et al.* superimposed. The small circle, determined by Quigley & Haslam, which fits best the ridge of emission of this object is also marked. The dotted lines show the intrinsic direction of the radio polarization (electric vectors); the 408 MHz polarization is rather weak but indicates the least Faraday rotation consistent with the measurements at 1407 and 610 MHz (≈ 6 rad m^{-2}). The tentative deduction may be made that the magnetic field is roughly parallel to Quigley & Haslam's circle, a situation similar to that in the North Galactic Spur. In this connection it is of interest that there is some indication from the optical polarization observations (Hall 1958, Behr 1959, Lodén 1961), and from the shapes of elongated nebulae (Behr 1954), of magnetic fields in a similar direction at latitudes $b^{\mathrm{II}}=-1°$ to $20°$; this is an unusual region where the magnetic field is almost perpendicular to the galactic equator. It seems clear that the region with magnetic field in this direction is more extensive than the radio emission feature; the situation is similar to that around the North Galactic Spur where the magnetic field both inside and outside the spur is parallel to the ridge of maximum emission. The distance is uncertain, but the field in this direction certainly exists within 500 pc of the Sun (see Behr 1959).

Fig. 6 shows the 1407 MHz polarization temperatures plotted against the 400 MHz unpolarized emission. The correlation indicates that the degree of polarization is very similar to that in the major spur, and that the background level (extrapolating to zero polarization temperature) is 18°K at 400 MHz. Clearly this object

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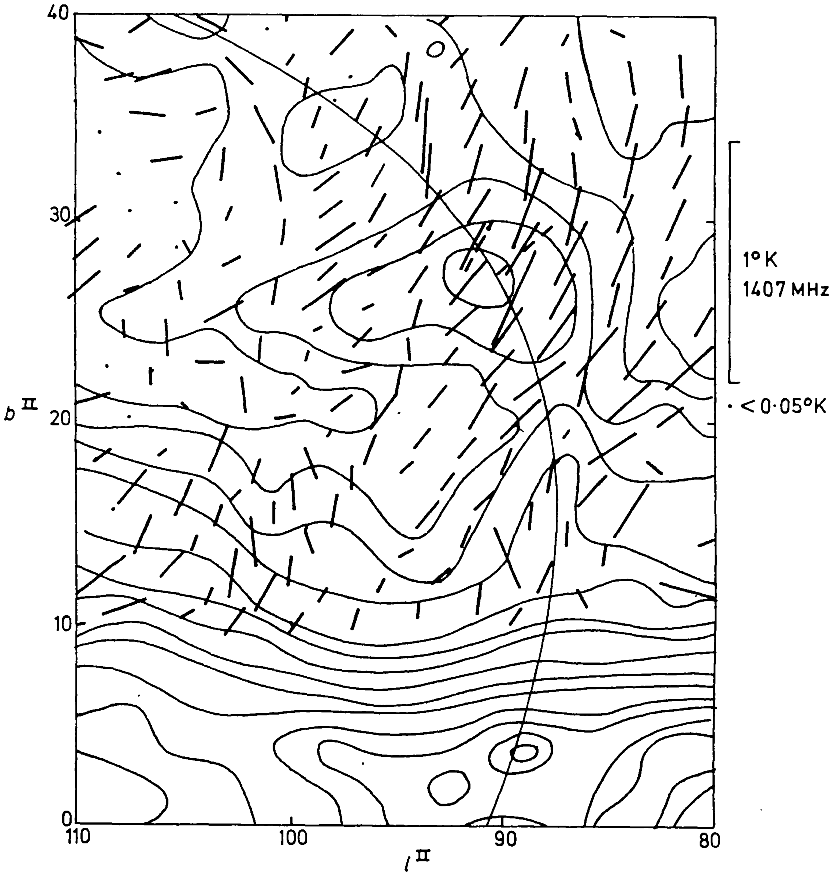

Fig. 5. *Loop III. The* 1407 *MHz polarization* (*Paper I*) *is shown by the full lines* (*electric vectors*) *and the intrinsic planes of polarization by the dashed lines. The circle which fits best the ridge of emission of this object is also shown.*

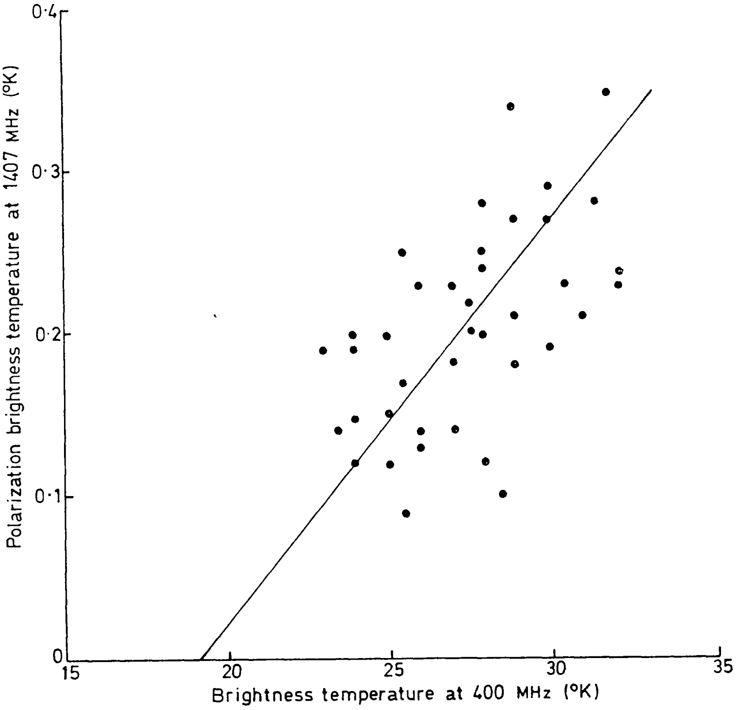

Fig. 6. *Loop III. Polarization brightness temperatures at* 1407 *MHz* (*Paper I*) *plotted against background temperatures at* 400 *MHz* (*Seeger et al.* 1965).

is physically similar to the spur; in addition to the properties mentioned, the narrow ' neck ' of the North Galactic Spur described by Haslam *et al.* (1964) has a counterpart which may be seen at $l^{\mathrm{II}}=87°$, $b^{\mathrm{II}}=+18°$ in Fig. 5.

3 . 2 *The Cetus Arc.* Mathewson *et al.* (1966) found polarization at 408 and 620 MHz in the spur referred to as the Cetus Arc (Quigley & Haslam 1965). They noted that the magnetic field was parallel to the ridge of emission. The polarization temperatures at 1410 MHz were $<0{\cdot}3\,°\mathrm{K}$ except at one point. The 1407 MHz survey shows three points with brightness of about $0{\cdot}15\,°\mathrm{K}$ (barely significant) near $l^{\mathrm{II}}=155°$, $b^{\mathrm{II}}=-48°$. Another region with polarization temperature approximately $0{\cdot}2\,°\mathrm{K}$ near $l^{\mathrm{II}}=150°$, $b^{\mathrm{II}}=-39°$ seems to be associated with structure closer to the galactic plane; see Fig. 3 of Paper I. As pointed out by Mathewson *et al.*, the spectral index of the polarized emission from this region is comparatively steep. Using temperatures given by Mathewson at 408 and 620 MHz and from Paper I at 1407 MHz a temperature spectral index of $\geqslant 3{\cdot}0$ is obtained. To find out whether this is due to peculiar depolarization or to an unusual emission spectrum, measurements of the unpolarized emission from the Cetus Arc are needed over a range of frequency.

3 . 3 *The spurs at* $l^{\mathrm{II}}=80°$, $b^{\mathrm{II}}=-40°$ *and* $l^{\mathrm{II}}=150°$, $b^{\mathrm{II}}=+40°$. Examination of the results given in Paper I shows that although polarization is present in the regions of other spurs at $l^{\mathrm{II}}=80°$, $b^{\mathrm{II}}=-40°$, and $l^{\mathrm{II}}=150°$, $b^{\mathrm{II}}=+40°$, it is also present in much larger surrounding areas and cannot be attributed definitely to these features. However, the observations of Lodén (1961) in *SA* 11 ($l^{\mathrm{II}}=157°$, $b^{\mathrm{II}}=+26°$) show that there is optical polarization occurring at a distance of 100 pc in this region again indicating a magnetic field parallel to a radio spur; the radio feature was described by Quigley & Haslam (1965) as an extension of that shown in Fig. 5 (Loop III).

4. *Discussion.* It was shown in Section 2 that the major Northern spur has a well-aligned magnetic field parallel to its length, and that the field is also parallel to the same direction for at least 15° on each side of the ridge of maximum emission. Evidence was presented in Section 3 that the magnetic field has a similar relationship in three other spurs.

Given the general direction of the magnetic field in the spur, other information on the magnetic field structure may be obtained from the distribution of non-thermal emission; for example, the low brightness and absence of a sharp ridge of emission close to the North galactic pole is simply explained if the magnetic field has gradually diverged and is weaker here, which would not be unexpected if the distance of the object at this point is 100 pc, a distance which is comparable with the half-thickness of the gaseous galactic disk. To investigate this point further, the brightness of the ridge of the major spur was determined as a function of b^{II}, using the survey at 178 MHz by Turtle & Baldwin (1962) and subtracting an estimate of the radiation outside the spur at similar latitudes. The result of this is shown in Fig. 7, where it can be seen that the brightness has a maximum at $b^{\mathrm{II}}=20$ to 25°. Plots are also given for the four other recognised spurs in the Northern hemisphere, and all show similar maxima. Using the variation of brightness shown in Fig. 7, it is possible to construct models of the magnetic field structure; in one example field lines on a spherical shell may converge at low latitudes down to the point at which the maximum brightness occurs, then branch out from the shell leaving the filamentary neck (Haslam *et al.* 1964) apparently displaced from the central line of the spur, as illustrated in Fig. 8.

From the evidence given in this paper, some conclusions may be drawn concerning the various theories of these objects. As pointed out in Section 2 . 2, if the distance estimate of 100 ± 20 pc for the ridge of the North Galactic Spur is correct the physical size of this feature is very much greater than that of a supernova remnant such as the Cygnus Loop. Although compression of the interstellar medium by the expanding shell of a supernova remnant might well lead in the early stages to magnetic field alignment such as that revealed by the polarization observations, such alignment could not be expected to persist to a radius of 150 pc. To find the velocity as such an object develops, we note that the conservation of momentum implies that the velocity of expansion is inversely proportional to the swept volume, in uniform density (Minkowski 1958); in this case the velocity would be about 0·5 km s^{-1} at 150 pc radius. Even this is to be considered an upper limit, as the original density in the vicinity of the Cygnus Loop was probably exceptionally low (Minkowski 1958) and it seems unlikely that it would remain low and uniform to a large radius. Hence the velocity would have been lower than the turbulence velocities of the interstellar medium (e.g. Dieter & Goss 1966) for the greater part of the age of the object and would also have been subsonic, in

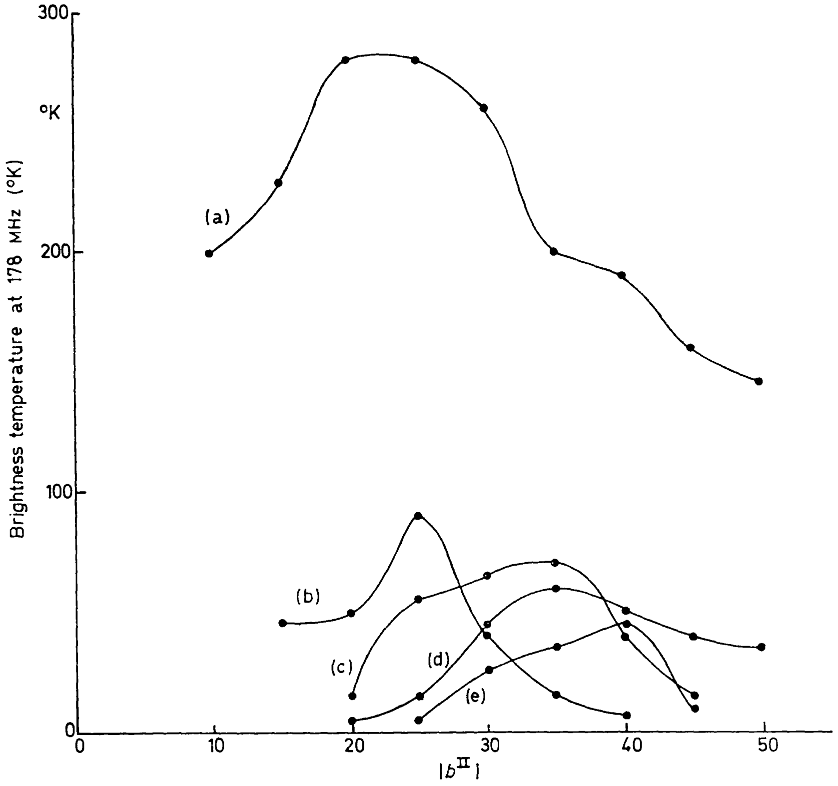

FIG. 7. *Brightness temperatures at* 178 *MHz along the ridges of the spurs as functions of galactic latitude, subtracting estimates of the emission from regions outside the spurs at similar latitudes. The survey used was that of Turtle & Baldwin* (1962). *The different spurs may be identified as follows:* (*a*) *North Galactic Spur;* (*b*) *Loop III at* $l^{\text{II}} = 90°$; (*c*) *Feature at* $l^{\text{II}} = 90°$, $b^{\text{II}} = -30°$; (*d*) *Cetus Arc at* $l^{\text{II}} = 155°$; (*e*) *Loop III at* $l^{\text{II}} = 155°$.

which case the whole concept of shock compression fails to apply. The regularity of the structure would also have been destroyed by collisions of the shell with at least 45 individual clouds in the volume concerned (e.g. van de Hulst 1958).

Consideration of this argument together with the other difficulties (listed below) in the interpretation of the spurs as supernova remnants similar to the Cygnus Loop makes this interpretation now hard to maintain. These other difficulties are:

(i) The special relationship of the spurs to the galactic equator, in that (a) their radio brightness becomes less at high latitudes; (b) the spurs intersect the galactic equator approximately at right angles, but do not definitely cross it; (c) there are maxima of brightness at similar latitudes in each spur (Fig. 7) and (d) the rotation measures in the North Galactic Spur are least at the highest latitudes (Fig. 1).

(ii) The improbability of so many supernovae occurring within a small region (cf. Oort 1966).

(iii) The lack of any definitely associated optical features (though see Meaburn 1967).

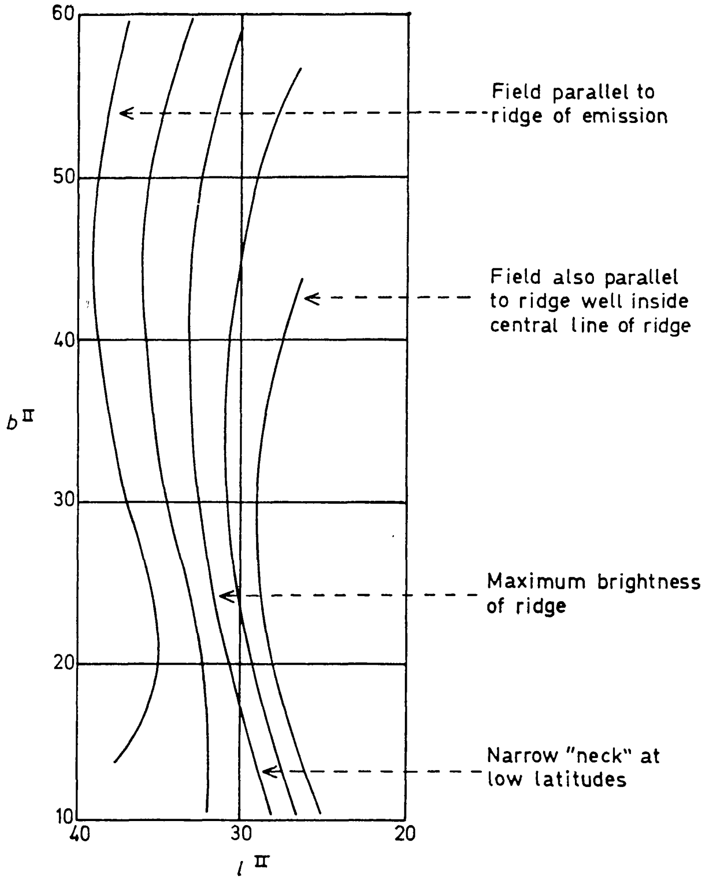

FIG. 8. *An illustration of the possible magnetic field structure in the North Galactic Spur.*

Hence it is necessary to consider whether any alternative theory is more readily tenable. If we are to retain the shell source model to account for the circular form of the spurs (Quigley & Haslam 1965) it will be necessary to find either a cause of more energetic expansion or a mechanism which keeps the whole structure in equilibrium. Parker (1966) has recently deduced that the interstellar magnetic field is unstable to cosmic-ray pressure with the result that bubbles or loops would be expected to appear in the magnetic field on one side of the galactic plane, expanding with a velocity of 100 km s^{-1}. These might produce a magnetic field configuration similar to that in the spurs. The theory of their formation is not in an advanced state and it seems that special conditions would be required for a hollow shell source of emission to be produced. Another possible source of very high velocities of expansion would be the occurrence of a super-supernova of unusual energy or the occurrence of multiple explosions (e.g. Oort 1966). Evidence for such events has been found in external galaxies in the form of rings of OB stars by Hayward (1964), Westerlund & Mathewson (1966) and Hodge (1967). Although it seems unlikely at present that they could be the cause of the spurs, both on account of the lack of associated optical features and also on the grounds that if several super-explosions can occur within a radius of 200 pc they would dominate the interstellar medium, this possibility cannot be discarded. It also seems necessary to reconsider other theories of the spurs and in particular to investigate the possibility of a static configuration. We may note that the geometry of the magnetic field parallel to the spur involved in the theory of Oda & Hasegawa is consistent with the observations, and that the helix discussed by Rougoor (1966) could be taken to imply the existence of a magnetic field parallel to the spurs. Neither of these theories, however, includes a physical explanation of the origin of the magnetic field structure. Tunmer's theory (1958) is inconsistent with the polarization observations, as it requires a magnetic field perpendicular to the length of the spur.

We require a mechanism which would produce an equilibrium configuration of the magnetic field in the form of a shell of radius 150 pc. The existence of a strong magnetic field might explain why the structure was not distorted by random motions of the gas clouds; if the configuration were static, the magnetic forces would have to be balanced by the existence of a lower gaseous pressure in the region of high magnetic field, to prevent its lateral expansion, or, in the case of a shell source, by the existence of an excess pressure inside the shell.

We may note that there is some evidence for the existence of excess interstellar matter near the centres of the North Galactic Spur and Loop III, in that there are bulges in the zone of avoidance at low latitudes (Hubble 1934). Neither of these bulges, however, has more than half the radius of the surrounding spur, and it would be necessary to assume that the associated gaseous matter is more extensive. The most valuable approaches to the solution of these problems will be to continue the determination of the magnetic structure of the spurs, from optical and radio polarization measurements, to investigate the possibility of an excess density inside the circles which apparently fit them, and to attempt to detect and measure the velocity of optical nebulosity associated with the spurs.

5. *Summary of conclusions.* It has been deduced that the magnetic field in the galactic spurs is remarkably well aligned and an estimate of the linear scale of the North Galactic Spur has been made. Considering also the low optical emission of the spurs and their special relationship to the galactic equator, it is apparent that they differ from supernova remnants such as the Cygnus Loop. It seems possible that the features could be produced by some more energetic expansion in the interstellar medium, but unless some independent manifestation of this expansion can be found it seems more probable that the spurs have a static configuration than that they are due to a shock compression of the interstellar medium.

6. *Acknowledgments.* It is a pleasure to acknowledge frequent helpful discussion with Dr J. R. Shakeshaft, and to thank him and Dr J. E. Baldwin and Dr D. Lynden-Bell for comments on the manuscript.

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