The galactic magnetic field

T. A. Th. Spoelstra

Netherlands Foundation for Radioastronomy, Sterrewacht, Huygens Laboratory, Leiden, The Netherlands
Usp. Fiz. Nauk **121**, 679–692 (April 1977)

Estimates for the scale, geometry and strength of the magnetic field in the galactic system can be derived from observations of polarization properties of radio emission from the Galaxy, extragalactic radio sources and pulsars, and polarization of starlight. Within distances of about 500 parsecs (1 parsec = 3.26 lightyears) from the solar system the magnetic field is directed towards galactic longitude $l \approx 45°$, while at distances extending over a few kiloparsec its average direction is towards $l \approx 90°$. Seen on a large scale the magnetic field in the Galaxy may be directed parallel to the galactic plane and along the spiral arms. The field may consist of a regular component and a random component with small scale variations of about 50 parsec in size. The strength of both components is of the same order of magnitude, about 2×10^{-6} Gauss (this is about 6×10^{-6} times the magnetic field strength of the earth).

PACS numbers: 98.50.Tq

CONTENTS

1. INTRODUCTION

Electromagnetic radiation originating in the extraterrestrial cosmos is observed at a variety of wavelengths from meters in the radio domain to around 10^{-10} m in the domain of x-rays. We know of several radiation mechanisms. Furthermore we distinguish between line and continuum radiation, which can be unpolarized or polarized. Line radiation is observed at a specific wavelength, while continuum radiation is observed at a continuous sequence of wavelengths.

Information about the scale, geometry and strength of the galactic magnetic field can be obtained from polarization properties of radio emission from the Galaxy, extragalactic radio sources and pulsars and polarization of starlight. During the last 30 years these properties have been studied extensively to understand the galactic magnetic field in terms of a simple realistic model.

2. RADIO EMISSION

The relevant radio emission originates from the synchrotron emission[1] mechanism, where continuum radiation is emitted by relativistic electrons spiralling around the lines of force of the magnetic field. The emitted intensity at a certain wavelength is determined by the strength of the magnetic field and the energy distribution of cosmic relativistic electrons. In the case of the interstellar medium, we expect this radiation to be linearly polarized—i.e., its plane of vibration has a preferential orientation in space—at right angles to the direction of the magnetic field with a percentage polarization—i.e., the ratio of the polarized to the total intensity—of about 72%. However, the observed properties are different in reality. This is due to several effects within the interstellar medium, the radio source itself and the properties of the magnetic field. When a linearly polarized signal travels through a medium containing magnetic fields and (slow) thermal electrons, its polarization direction rotates over an angle ψ, an effect known as the Faraday rotation.

This Faraday rotation ψ is proportional to the product of the density of thermal electrons (N), the component of the magnetic field along the line of sight ($B_{\parallel}$), the dimensions along the line of sight (L) of the region in which Faraday rotation occurs and the square of the wavelength (λ). In other words:

$$\psi = KNB_{\parallel}L\lambda^2, \quad (1)$$

where K is a constant. Here the product $KNB_{\parallel}L$ is generally called the rotation measure of the polarized radiation. Since the Faraday rotation is proportional to λ^2, observations at different wavelengths are necessary to derive the rotation measure. When the rotation measures are known the observed polarization direction can be corrected for the effect of the interstellar medium and the intrinsic polarization direction—i.e., as might be observed in the emission region—can be found. In the case of synchrotron radiation this direction is perpendicular to the direction of the magnetic field component at right angles to the line of sight, $B_{\perp}$.

When the observer looks at right angles to the magnetic field it is clear that its component along the line of sight, $B_{\parallel}$, is small. This means that in this case the rotation measures are small. Relative maxima in the emission might be observed in this case too. On the other hand, when the observer looks along the magnetic field, its component $B_{\parallel}$ is large implying a high rotation measure and its component $B_{\perp}$ is small. Additional information about the direction of the field can be obtained from the sign of the rotation measure. If the rotation measure is negative (rotation of the polarization direction is clockwise) the field points away from the observer, while in the case of positive rotation measure it points towards the observer. Thus the rotation measure contains important information about the geometry of the magnetic field.

We mentioned already that the synchrotron radiation is linearly polarized up to about 72%. This is in the ideal case without Faraday rotation. Whenever Faraday rotation is present the degree of polarization diminishes dependent on the wavelength. The degree of polarization will decrease too when the magnetic field within the radio source is not homogeneous, e.g., a random component might be superimposed on a regular component. Therefore, the degree of polarization at different wavelengths implies information about the regularity of the field. And, if the field can be split up into two components, the relative strengths of these components can be found. [2]

As can easily be seen from Eq. (1) the strength of the magnetic field can be derived from the rotation measure if the distance to the source of emission and the density of thermal electrons are known. Since synchrotron radiation contains no distance information it should be derived by other means. This is also the case for the density of thermal electrons.

3. OPTICAL POLARIZATION

In the case of optical polarization it is assumed that light from stars is scattered on interstellar dust grains. In the presence of interstellar magnetic fields the grains are oriented perpendicular to the field lines. [2] Then due to the properties of light scattering starlight will be polarized parallel to the field pattern. Thus the observed polarization direction on the sky is identical to the direction of the magnetic field projected on the sky.

It is important to note that *if* optical and radio polarization originate in the same volume of space, then their polarization angles are perpendicular to each other: i.e., the radio polarization direction is perpendicular to $B_{\perp}$. This holds if one looks at some angle to the field direction. If on the other hand one looks along the field and the field consists of a regular and a random component the regular component shows small values of $B_{\perp}$ and the random component dominates. This will result in a less pronounced preference for the optical and radio polarization directions to be perpendicular to each other.

4. EXTRAGALACTIC RADIO SOURCES

Polarization studies of extragalactic radio sources have been made by a large number of investigators tors. [3,4,5,6,7,8] The sources in question, e.g., quasars, are smaller than the beam of the telescope, so that from an observation at a certain wavelength the total brightness, we can derive the degree of polarization and the polarization direction integrated over the whole source. The observed polarization characteristics contain some contributions from the source, from our Galaxy, and perhaps from the intergalactic medium, since the radio signal travels from the emitting regions in the extragalactic object through the intergalactic space and the Galaxy to the observer. Compared with the radio source and the Galaxy the contributions from the intergalactic medium can be neglected since here the electron density and the magnetic fields resulting in Faraday rotation and depolarization (Sec. 2) are several orders of magnitude less. The polarization characteristics of the emitted radiation are mainly modified by the influence of the Galaxy. Observations at different wavelengths reveal the influence of the interstellar medium on the polarization angles (Faraday rotation). In principle the rotation measures are due to all contributions along the line of sight, but a systematic distribution of the values with galactic coordinates gives insight in the properties of the galactic magnetic field.

A contour map of these rotation measures is shown in Fig. 1. This figure gives an indication of the distribution of $NB_{\parallel}$ (for the total line of sight in the Galaxy). High rotation measures occur in the direction $l \simeq 80°$, $b = 0°$. The rotation measures are negative here, which means that the average direction of the magnetic field is directed away from the observer. Other maxima are at $l \simeq 240°$ and 310°. Since these values are positive the magnetic field points towards the observer. The extreme values of the rotation measures at $l \simeq 80°$, 240° and 310° are found just in the direction of the Cygnus and Perseus spiral arm complexes, the Orion spiral arm and the Carina spiral arm (Fig. 2). If the distance along which the rotation measures are generated is in the order of kiloparsecs (see below) the average magnetic field may point from the direction of the Orion and Carina spiral arms towards the Cygnus and Perseus arms. The galactic magnetic field may, therefore, be directed along the spiral arms when one looks on a large scale.

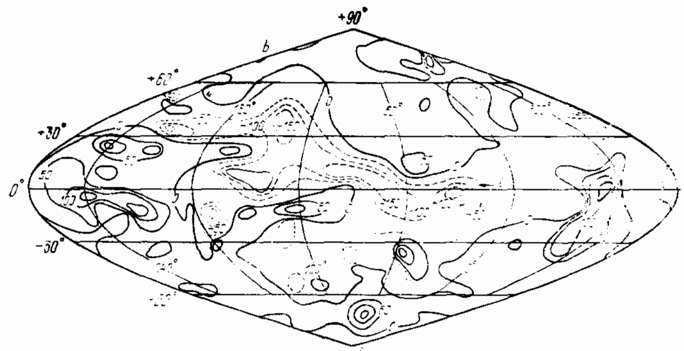

FIG. 1. Rotation measures for extragalactic radio sources. Contours with steps of 50 radians m^{-2} are drawn. Dashed contours indicate negative values. The coordinates are galactic longitude, l, and galactic latitude, b. The galactic plane is at $b = 0°$ and the direction to the galactic center is at $l = 0°$, $b = 0°$.

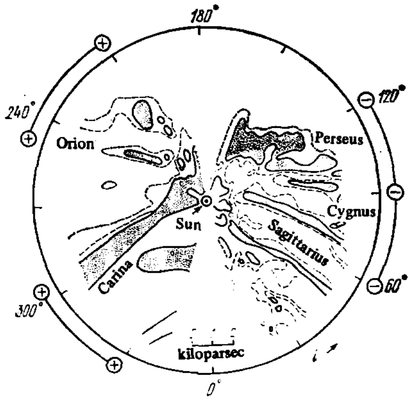

FIG. 2. Part of the pattern of galactic spiral structure. The signs around the edge of the figure indicate the positive and negative domains of rotation measures for extragalactic sources as seen from the sun.

The largest values of the rotation measures occur at low latitudes where the line of sight through the Galaxy reaches its largest values. If a typical value for the rotation measure is 50 radians m^{-2} with $N = 0.03$ cm^{-3} [9] and $B = 2\times 10^{-6}$ gauss[10] (see Sec. 2) the distance for the average line of sight is then 1 kiloparsec.

5. PULSAR DATA

The polarization characteristics of pulsars have been studied extensively by Manchester.[10,11] Pulsars are galactic objects emitting radiation in pulses with regular intervals. They are observed both at radio and optical wavelengths. When a pulsed signal travels through the interstellar medium the profile broadens proportionally with the density of thermal electrons and distance. This is expressed by the dispersion measure. With an estimate for the electron density the distance can be derived from the dispersion measure. This is in the order of a few hundred to several thousand parsec. The polarization properties of the emitted radiation are modified by the influence of the interstellar medium. Thus basically the same analysis as for extragalactic radio sources can be made. Although the number of pulsars for which polarization data are available is much smaller, the distribution of the signs of rotation measure on the sky agrees well with that for the extragalactic radio sources (Fig. 1). The rotation measures for pulsars at high latitudes are about a factor of 2 smaller than for extragalactic radio sources. The polarization data of pulsars indicate that the galactic magnetic field runs roughly from the direction $l \simeq 270°$ to $l \simeq 90°$. This agrees with the results for the extragalactic radio sources.

6. GALACTIC CONTINUUM RADIO EMISSION

The galactic continuum radio emission does not originate in discrete sources but in interstellar space. A contour map giving the brightness distribution at 2 m wavelength[12] is presented in Fig. 3. Apart from the broad band of emission associated with the galactic plane (galactic latitude $b = 0°$) large features extend to high latitudes. These features are partly associated with nearby large remnants of very old supernovae (i. e., exploded stars). These supernova remnants are shells expanding into the interstellar medium with its matter and fields.[13] Some of these shells are indicated by deformed loops in Fig. 3. It turns out that the observed brightness distribution for these shells depends on the orientation of the average magnetic field surrounding the shell with respect to the line of sight.[13,14] Although the number of these objects is very small their analysis indicates a magnetic field directed towards about $l = 36°$. However, this field is much closer to the sun than that found from pulsar and extragalactic source data. Indeed it may be found within a few hundred parsec from the sun.

A more detailed investigation of the galactic magnetic field can be made using linear polarization observations at five wavelengths covering about half the sky visible at northern latitudes.[15] These wavelengths are 73.5, 65, 49, 37.5 and 21.2 cm. Smaller sections of the celestial sphere have been observed at even more wavelengths. From these data rotation measures have

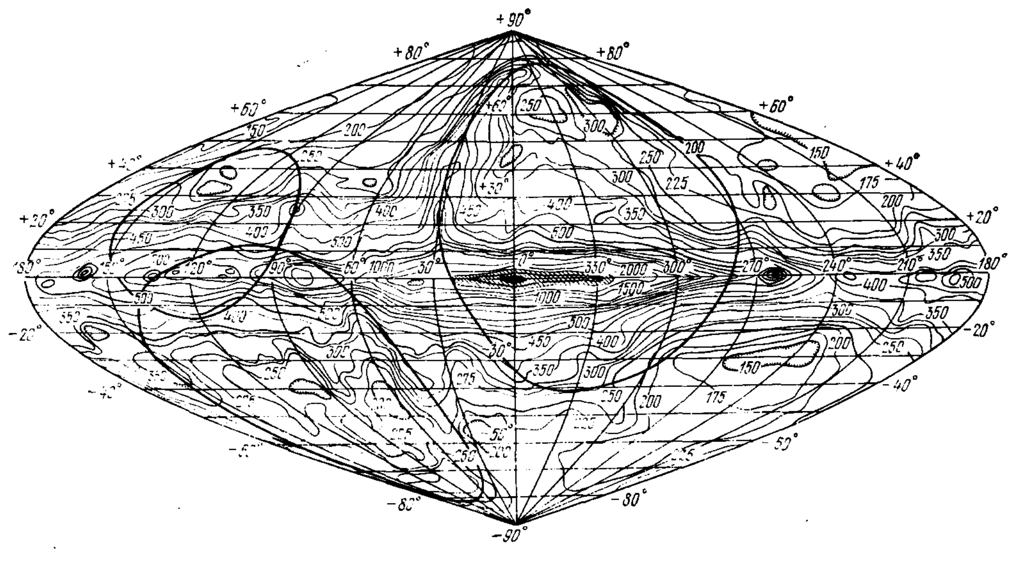

FIG. 3. The total intensity brightness distribution of galactic continuum radiation at 2 m wavelength. The deformed loops indicate the pattern of shell-like features. The intensities are given in units of brightness temperature (Kelvin).

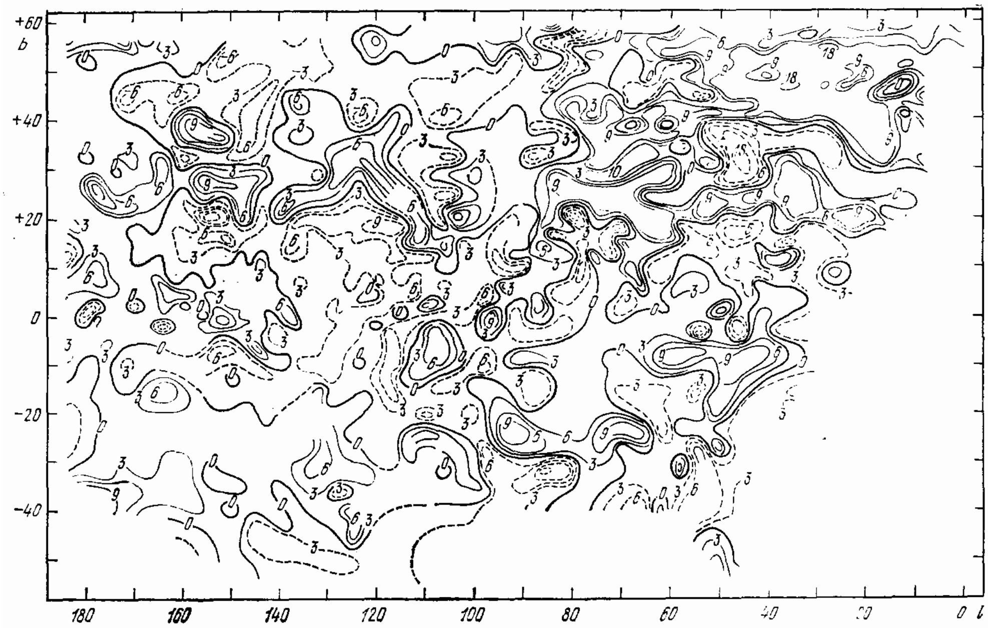

FIG. 4. Rotation measures for galactic continuum radio emission. Contours with steps of 3 radians m^{-2} are drawn. Dashed contours indicate negative values.

been calculated. They are shown in Fig. 4 for a part of the sky. The distribution of the observed rotation measures is very complex: no relation seems to exist with the features shown in the total intensity distribution of Fig. 3. The values for these rotation measures are lower than those found for extragalactic radio sources and pulsars. If a typical value is 8 radians m^{-2} with $N = 0.03$ cm^{-3} and $B = 2\times10^{-6}$ gauss the magnetic field with which the polarization observations are related lies at about 300 parsec from the sun. Thus the complex pattern of the rotation measures indicates the *local* variations of the product of $B_{\parallel}$ and N. If a typical scale of the variations in the results of Figure 4 is 5° it suggests a typical cell size of 30 parsec for the variations of the magnetic field and electron density in the interstellar medium.

When rotation measures are known, the direction of the intrinsic polarization angle in the emitting region, can be found. From this information the distribution of the projected direction of the magnetic field on the sky $B_{\perp}$ can be derived using the known properties of the synchrotron radiation (Sec. 2). This is shown in Fig. 5. The contours indicate the distribution of the total intensity at 37.5 cm wavelength.[16] The most striking regions in Fig. 5 are the regions at $b \gtrsim +60°$ and at $l \simeq 140°$, $b \simeq +8°$ where the direction of $B_{\perp}$ is very regular. In the region $90° \lesssim l \lesssim 180°$, $b \gtrsim +60°$ where the pattern is more irregular the polarization intensity is low (see below). In the remarkable region at $l \simeq 140°$, $b \simeq +8°$ the rotation measures are very low (Fig. 4) indicating low values of $B_{\parallel}$, the component of the magnetic field along the line of sight. This suggests that in the direction of $l \simeq 140°$ one looks perpendicular to the local galactic magnetic field.[17] It shows, furthermore, that the magnetic field is nicely aligned with the Milky Way, the projection of the galactic plane on the sky, indicating that the field may be directed parallel to the plane. The regular distribution of $B_{\perp}$ at $b \gtrsim +60°$ fits in this result too. However, at high latitudes the influence of the large features (old supernova remnants) mentioned in Fig. 3 still plays an important role. This makes it difficult to specify strict numbers on the basis of the available data and theoretical understanding. It should be noted that the direction of the magnetic field agrees with the result derived for the galactic shells

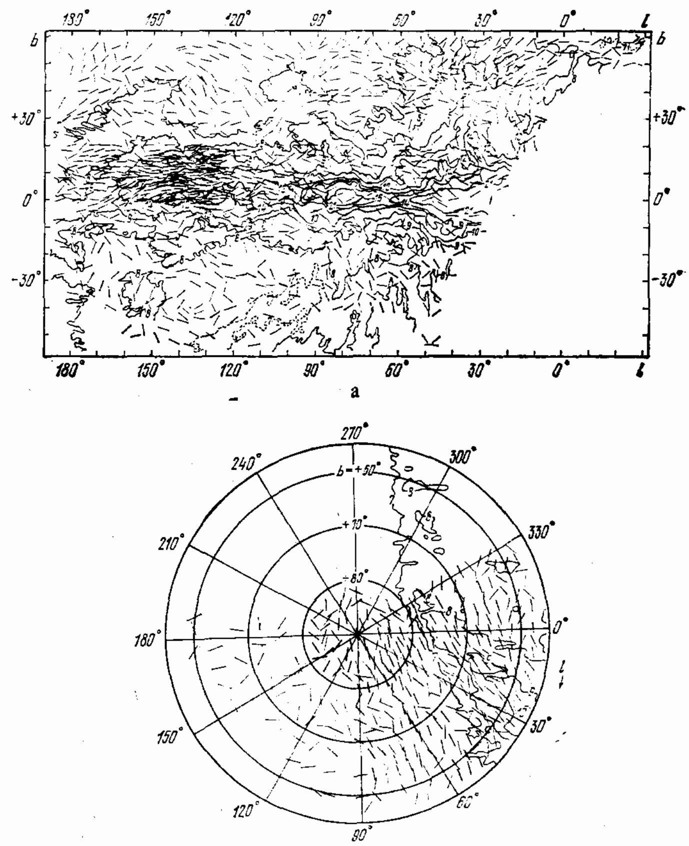

FIG. 5. a) Direction of $B_{\perp}$ as a function of coordinates. The contours indicate the total intensity brightness distribution at 37.5 cm wavelength. Contour units are given in Kelvin (cf. Fig. 3). b) Same as Fig. 5(a) but for $b \gtrsim 60°$.

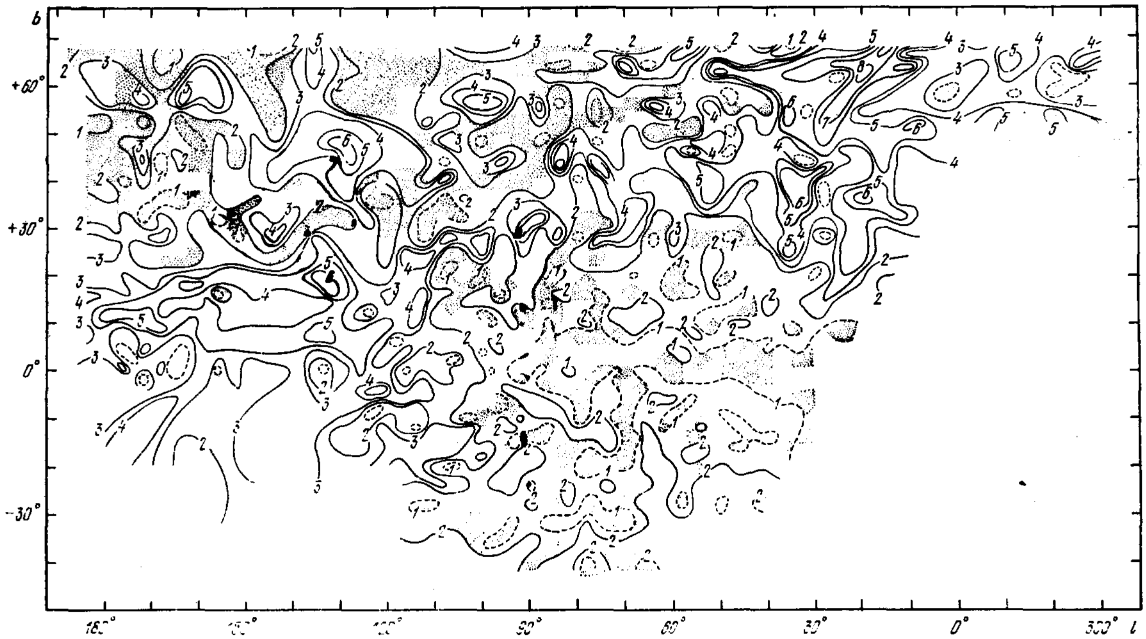

FIG. 6. Degrees of polarization at 21.2 cm wavelength. Contour steps of 6%. Shaded areas indicate regions where the linear polarization intensities were at about the detection limit.

(see before): both results indicate a direction towards $l \simeq 45°$.

More information can be derived from the variation of the degree of polarization with wavelength. Although in the ideal case it is about 72%, it is observed to be lower even at the shortest wavelength (21.2 cm) at which observations are available (Sec. 2, Eq. (1)]. At longer wavelengths the degrees of polarization are lower (and the Faraday rotation related with this depolarization is higher). The degree of polarization at 21.2 cm is presented in Fig. 6 for a part of the sky. The complex distribution of polarization percentages seems largely unrelated to the structures in the total emission (Fig. 3). The lowest values are reached near the galactic plane. This is quite natural, since most influence of the interstellar medium on the radiation occurs in the galactic disk. Thus there the largest depolarization is to be expected. The highest degrees of polarization are expected where the observer looks perpendicular to the local magnetic field, i.e., where $B_{\parallel}$ reaches minimum values. Near the galactic plane this happens at $l \simeq 140°$ where values up to 20% are reached. Detailed analysis indicated that at high latitudes the distribution of the polarization percentage is closely related with the large scale shells mentioned in Fig. 3.[13,18] In the direction of these shells maxima are observed in the distribution of the degree of polarization. Sometimes these maxima show a somewhat different profile when plotted as intensity versus galactic coordinates but that can easily be explained in terms of depolarization within the shell (Fig. 7).[13]

The radiation observed originates from a medium in which both emission and depolarization occur. The observed degree is always lower than the maximum degree of polarization which is theoretically possible. This discrepancy suggests that, superimposed on a regular

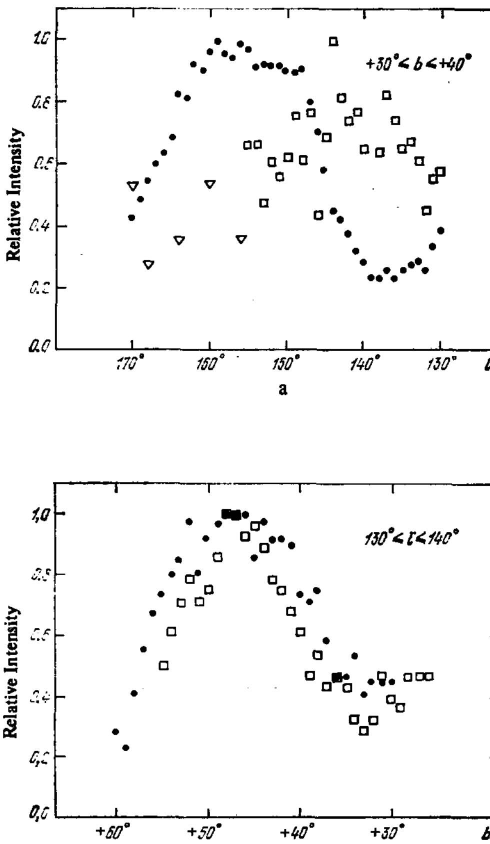

FIG. 7. Relation between total intensities at 37.5 cm wavelength (dots) and polarization intensities at 21.2 cm wavelength as a function of galactic coordinates. The vertical scale (squares and triangles) is arbitrary: the maximum is given unit intensity. The triangles indicate data for which the uncertainty is about 3 times larger than for the squares. In Fig. a the data at each longitude have been averaged over the indicated latitude interval.

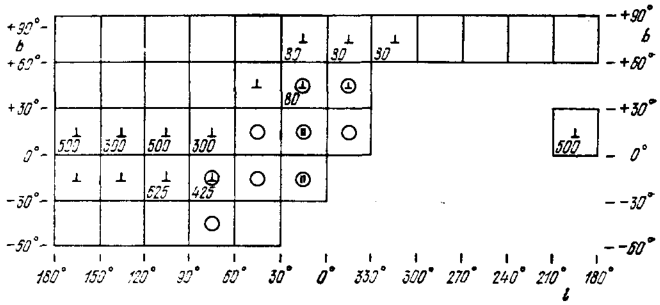

FIG. 8. Relation between the directions of optical polarization and linear polarization of galactic radio emission. For an explanation of the symbols see text. The numbers in the boxes indicate the distance within which the galactic magnetic field mainly determined the results.

field there is a random field of the same order of magnitude or somewhat stronger or that the distribution of thermal electrons is patchy, or both. From an analysis of the wavelength dependence of polarization it has been found that the scale of the variations of the random component of the magnetic field is 10 to 100 parsec. This agrees well with the estimate of 30 parsec derived above. A reasonable value may then be of the order of 50 parsec. [19,20]

7. POLARIZATION OF STARLIGHT

The polarization of starlight has been investigated in relation with the results discussed in the preceding section. For intervals of $30° \times 30°$ in galactic coordinates the difference between the optical and intrinsic radio polarization angles (see Sec. 3) has been studied. [19,20] The results are schematically represented in Fig. 8. Here the region of the sky for which the observations discussed in Sec. 6 are available are available is divided into boxes of $30° \times 30°$ in l and b. In each box the relation between the radio and optical polarization directions is given (empty boxes indicate that not enough observations are available). For this relation the ⊥-sign indicates preference to 90° differences, the ‖-sign indicates that both directions are parallel and the o-sign says that no preference exists. A combination of two signs indicates that a tendency to perpendicular or parallel exists. A thick sign is shown for the region where this relation is extremely well defined.

Figure 8 shows that for the region $120° < l < 150°$, $-30° < b < +30°$ the optical and radio polarization angles are nicely perpendicular to each other. This is just the region where we look perpendicular to the local galactic magnetic field (Sec. 6). This perpendicularity is somewhat less pronounced in the adjacent regions. The results are different for the region $330° < l < 90°$, $-60° < b < +60°$ where hardly any relation is present. This may indicate that the line of sight is at small angles with the local regular magnetic field component and the random component dominates.

As has already been mentioned that the distance estimates for the galactic magnetic field is rather uncertain and difficult. However, the optical and radio polarization directions should be perpendicular to each other if the origin of polarization is spatially the same. For a large number of the stars used distance information is available. Then the difference between optical and radio polarization directions as a function with distance gives some indication of the spatial parameters of the local galactic magnetic field. These distance estimates are presented in the appropriate boxes of Fig. 8.

8. THE GALACTIC MAGNETIC FIELD

The observations described seem to indicate a longitudinal magnetic field while a random component might be added to the regular one (Sec. 6). The direction of this field as seen on a large scale (orders of kiloparsecs) might be along the galactic spiral arms. Near the sun a field has been observed running roughly from $l = 270°$ to 90° and parallel to the galactic plane. This result is based on data of several hundreds extragalactic radio sources and a few tens of pulsars (which are at much less distances from the observer). Studies of the galactic continuum radio emission and optical polarization indicate a field directed to $l \simeq 40°$. This field is clearly reflected in the distribution of the optical polarization angle as given in Fig. 9[20] where also the pattern is drawn as projected on the sky. The direction of the field given in Fig. 9 as found by calculation from the pattern of optical polarization[19] angles is towards $l = 39.1°$. This field is embedded in the interstellar medium over distances up to about 500 parsec from the sun. Thus nearer to us than the field found from extragalactic source and pulsar data. The transition between the two regions and the details of galactic structure for this part of the Galaxy which is so close to the sun are not clear. However, the spatial distribution of pulsars, outside the local region of 500 parsec and within the Galaxy, justifies the outlook that if much more data are available *that* information may possibly reveal more details of the relation between galactic structure and the galactic magnetic field. The results from the present investigation are summarized in Table I.

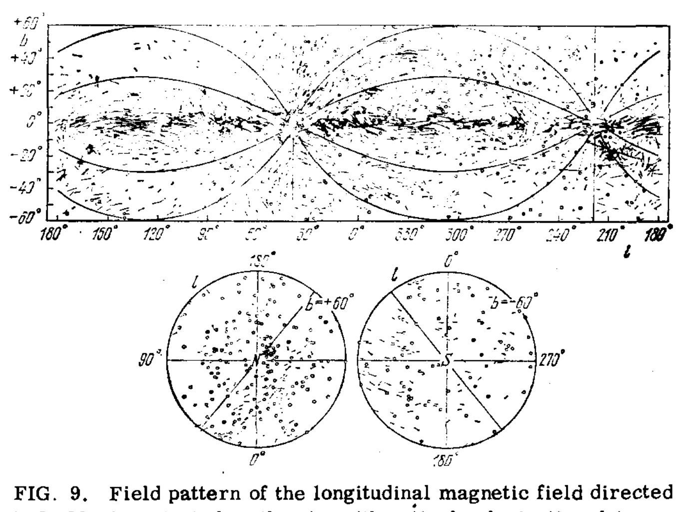

FIG. 9. Field pattern of the longitudinal magnetic field directed to $l = 39°.1$ projected on the sky with optical polarization data. The direction of each "vector" indicates the polarization angle, while its length indicates the optical degree of polarization.

TABLE I. Parameters of the galactic magnetic field.

Direction:

Method	Field direction	Distance from Sun
Polarization of galactic radio emission	$l \simeq 50°$	
Polarization of starlight	$l \simeq 39°.1$	$\leqslant 500$ pc
Orientation of very old nearby supernova remnants	$l \simeq 36°$	
Rotation measures of extragalactic radio sources	$l \simeq 94°$	kiloparsecs
Rotation measures of pulsars	$l \simeq 94°$	

Strength of the regular component $\simeq 2\times10^{-6}$ gauss
Strength of the random component $\simeq 2\times10^{-6}$ gauss
Scale of the variations of the random component $\simeq 50$ parsec

9. CONCLUDING REMARKS

It is evident that the longitudinal model described in this paper is not the first one and will not be the last one. As the amount and quality of the observational material increases the parameters of the models may change. For the first time it has been tried to combine all observational data which contain enough information to derive insight in the overall galactic magnetic field. For small parts of the sky additional data are available: i.e., polarization of line emission in dense clouds (Zeeman effect). But at present this is insufficient for a study of the large scale properties. On the other hand the existing longitudinal models do fit in the present results while models of a helical kind (e.g., magnetic field lines sound around the spiral arms) do conflict with various observations[10,11,13,19] and can therefore be excluded from further analysis.

The difference in the direction of the galactic magnetic field for the local region and the more distant regions will be studied further. It is not excluded that the galactic magnetic field running along the spiral arms is deformed by the occurrence of nearby supernova explosions of which the remnants are seen as large loops (Sec. 6, Fig. 3).[22]

Note: The English version of this article was supplied to the American Institute of Physics by the author.

[1]V. L. Ginzburg and S. I. Surovatskii, Ann. Rev. Astron. and Astrophys. **3**, 297 (1965); the same, Usp. Fiz. Nauk **87**, 65 (1965) [Sov. Phys. Usp. **87**, 65 (1965)].
[2]B. J. Burn, Mon. Not. Roy. Astron. Soc. **133**, 67 (1966).
[3]a) L. Davis, Jr. and J. L. Greenstein, Astrophys. J. **114**, 206 (1951). b) R. C. Bignell, Astron. J. **78**, 1058 (1973).
[4]F. F. Gardner, D. Morris, and J. B. Whiteoak, Austr. J. Phys. **22**, 813 (1969).
[5]S. Mitton, Mon. Not. Roy. Astron. Soc. **155**, 373 (1972).
[6]D. Morris and H. Tabara, Publ. Astron. Soc. Japan **25**, 295 (1973).
[7]J. P. Vallée and P. P. Kronberg, Astron. and Astrophys. **43**, 233 (1975).
[8]W. E. Wright, Ph.D. Thesis (California Institute of Technology, 1973).
[9]G. Goméz-Gonzâlez and M. Guélin, Astron. and Astrophys. **32**, 441 (1974).
[10]R. N. Manchester, Astrophys. J. **172**, 43 (1972).
[11]R. N. Manchester, *ibid.* **188**, 637 (1974).
[12]T. L. Landecker and R. Wielebinski, Austr. J. Phys. Suppl. **16** (1970).
[13]T. A. Th. Spoelstra, Astron. and Astrophys. **21**, 61 (1972).
[14]T. A. Th. Spoelstra, *ibid.* **24**, 149 (1973).
[15]W. N. Brouw and T. A. Th. Spoelstra, Astron. and Astrophys., Suppl. Ser. (1976) (in press).
[16]E. M. Berkhuijsen, Astron. and Astrophys. **14**, 359 (1971).
[17]E. M. Berkhuijsen, W. N. Brouw, C. A. Muller, and J. Tinbergen, Bull. Astron. Inst. Netherlands **17**, 465 (1965).
[18]T. A. Th. Spoelstra, Astron. and Astrophys. **13**, 237 (1974).
[19]T. A. Th. Spoelstra and W. N. Brouw, *ibid.* (1976) (submitted to editor).
[20]T. A. Th. Spoelstra, Paper at Symposium on "Problems of Magnetic Fields in Space" (Crimea, April 6–11, 1976).
[21]J. P. Vallée and P. P. Kronberg, Nature **246**, 49 (1973).

Supplement to the translation

A. A. Ruzmaikin

Usp. Fiz. Nauk **121**, 693–694 (April 1977)

PACS numbers: 98.50.Tq

The magnetic field undoubtedly plays a most important role in phenomena that take place in the Galaxy. It suffices to mention the problem of containment of cosmic rays[1] and the formation of stars.[2] Although the very existence of the Galaxy's magnetic field is universally accepted, real observational proof that makes it possible to assess the magnitude and the geometry of the field appeared only 10–15 years ago. Recently the number and depth of the investigations of the Galaxy's magnetic field has greatly increased because of the great advances in radioastronomy. Foremost among them are polarization investigations of nonthermal (synchrotron) radio emission of the Galaxy, a great contribution to the understanding of which was made by Soviet scientists.[3,4] The most valuable information on the magnetic field is obtained by studying the Faraday rotation of the emission of extragalactic radio sources and quasars. Finally, pulsars turned out to be a splendid magnetometric tool. The ratio of the measure of the Faraday rotation of a pulsar, which is pro-