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OBSERVING THE GALACTIC MAGNETIC FIELD[1,2]

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History

Some highlights of the subject in my opinion are: the symposium on cosmical aerodynamics in Paris 1949, where, owing to the surprise discovery of optical interstellar polarization by Hall and Hiltner a few months earlier, magnetic fields formed a main theme in the discussion. Then the exciting year 1955 in which optical polarization measurements of the Crab Nebula sparked from the USSR through Leiden to Mount Palomar and provided good proof that at least in one object the synchrotron emission is at work and the magnetic field can be mapped. From that time on, measuring the polarization and thus mapping the magnetic field became a prime desideratum in galactic radio astronomy. The first trustworthy results were available by the time of the Princeton symposium in the spring of 1961, where champions of strong fields ($\sim 2\times 10^{-5}$ G) and of weak fields ($\sim 0.2\times 10^{-5}$ G) waged a heavy theoretical battle. At the present symposium[2] the theoretical problems seem to have been somewhat eased but not solved. On the other hand, the amount and the quality of observational data already available is surprising. Some of them are very recent and should await a more thorough discussion by the authors themselves.

Traditionally, polarization phenomena have been discovered too late. There was a delay of about 200 years between the presence of adequate instruments (a wine glass and a birefringent crystal) and the discovery of polarization by reflection. For the optical interstellar polarization the delay was about 40 years. But for the radiopolarization of the galactic synchrotron emission it was something like minus 1 or 2 years; so keen was everybody to get this phenomenon established.

Review of "Other Methods"

Table I presents a list of observed effects from which we may infer something about the magnitude of the magnetic field, or its direction or topology, or both. The comments are conservative and, like many other statements in this review, subjective. I shall first review the "other methods," then the radio methods given in the last two lines.

Optical interstellar polarization.—Active programs of observation in the years after the discovery of the effect led to maps showing the direction and degree of polarization for over 3000 stars (Hall 1958, Behr 1959). There is no

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[1] The survey of literature for this review was concluded in September 1966.

[2] Review paper, with minor additions, presented at the Symposium on Radio Astronomy of the Galactic System, organized by the International Astronomical Union, Noordwijk, August 25 to September 1, 1966.

reasonable doubt that a magnetic field is the basic reason for the partial alignment of the interstellar grains that gives rise to the optical polarization. The mechanism probably is the one first proposed by Davis and Greenstein, which means that the predominant electric vector of the observed starlight is parallel to the magnetic field projected on the sky. Hence the maps give some idea of the topology of the magnetic field. The alignment parallel to the galactic equator is most perfect near $l = 140°$ and completely lacking near $l = 80°$ (all longitudes in this paper are on the new scale). This led Chandrasekhar and Fermi to propose that these are the respective directions where we look across and along the local spiral arms. The conclusion is approximately correct, but the picture of the arm as a continuous tube of force with wiggles does not necessarily follow. An arbitrary magnetic configuration stretched by differential rotation would give much the same observed effect.

TABLE I

OBSERVATIONAL DATA ABOUT THE GALACTIC MAGNETIC FIELD

	Magnitude	Direction topology
Optical interstellar polarization	*q*	*f*
Shapes of filamentary nebulae	—	*q*
Cosmic-ray energy density and confinement	*q*	*q*
Cosmic-ray anisotropy	—	*q*
Cosmic-ray electrons plus nonthermal radio emission	*f*	—
Zeeman effect, H	*q*	—
Zeeman effect, OH	—	—
Polarization of nonthermal radio emission	—	*f*
Faraday effect	*f*	*f*

Key: — no data or don't believe,
q questionable or marginal,
f fair or fine.

Further detailed studies can give a great deal more information. The study of nearby stars (Behr 1959), for which very small degrees of polarization have to be measured, is of special interest. Hiltner's new rotating telescope will offer possibilities for continuing this work with great precision. Many further statistical studies can be made, to find the field topology or to determine scale parameters, which can then be used in a theoretical discussion, or to examine correlation with other properties of stars and nearby nebulae. Many papers have been devoted to these topics in the past ten years.[3] We note, in particular, correlation studies of polarization in clusters,

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[3] Where no detailed references are given, we suggest the triannual Reports on Astronomy of the International Astronomical Union for fairly complete but not necessarily critical reviews.

from which Serkowski (1965 and unpublished work) determines a microscale in the magnetic field of the order of 1 pc.

The magnitude of the field needed to produce enough alignment of the interstellar grains to explain the observed polarization was initially a worry. Thanks to the work of Greenberg (Greenberg & Shah 1966) on the extinction by nonspherical grains, it is now possible to compute the polarization for a given field strength and for a given shape and composition of the grains (including their complex paramagnetic permeability coefficients). Reasonable assumptions, given a reasonable field. Unfortunately our poor knowledge of the grains still leaves this a questionable method for determining the field strength.

Shapes of filamentary nebulae.—Field-aligned irregularities occur in the solar corona (where the polar plumes were the first evidence for a general solar magnetic field), in the Earth's magnetosphere, in aurorae, and in laboratory plasmas, so there is good reason to expect them also in interstellar space. At the Noordwijk Symposium Pikelner sketched a mechanism that could lead to a gaseous nebula stretched along a magnetic-field line. Shajn argued many years ago that many filamentary emission nebulae are oriented along the magnetic field. My problem is only: which nebulae? For it is clear that filaments could also be curtains or shells or shock fronts seen edgewise and that many such features could be explained by nonmagnetic gas dynamics. For this reason it may be difficult to make much progress with this method.

Cosmic-ray energy density.—A 20-year-long discussion must here be compressed into a few lines. The argument can best be discussed in the form of an application of the virial theorem (Biermann & Davis 1960)

$$2T + 3P + M = -\Omega$$

All terms are positive. T is the total kinetic energy, P the pressure integrated over the entire volume, M the total magnetic energy, and Ω the (negative) total gravitational energy. If the system is to be maintained, this equality must hold. The large contribution to $2T$ arising from the galactic rotation can be estimated fairly well. Upon subtracting this, it appears already difficult to accommodate the term $3P$, which arises mostly from cosmic-ray pressure. The traditional argument, therefore, is that we cannot accept a value M that is substantially higher than $3P$. On the other hand, if the magnetic fields confine the cosmic rays, it would also be surprising to find M much smaller than than $3P$. Taking the same volume (presumably the halo volume) and precise equality, we would find $3P = 1.6 \times 10^{-12}$ erg cm^{-3}, $B = 7 \times 10^{-6}$ G.

Obviously, this is at most a vague estimate. A questionable point in this argument is that it is not clear yet to what extent the cosmic rays really are confined. Also, as Puppi, Setti, & Woltjer (1966) have pointed out, confinement may be helped by clouds impinging upon the Galaxy from outside.

Cosmic-ray anisotropy—Dozens of positive results have been announced but have not stood up under subsequent examination. This makes us suspicious of further claims. The results announced by Jacklyn (1966) seem above suspicion, however. Data from underground counters in Hobarth, Budapest, and London at depths equivalent to 35–60 m of water gave amplitudes and phases of the diurnal and semidiurnal variation. The errors are typically 0.01 per cent, i.e. about a factor 10 smaller than the maximum variations. The results are consistent with a slight preference for small pitch angles with respect to a field direction to or from $1=62°$, $b=+12°$. The uncertainty is $\pm 5°$. The relatively good agreement with the field direction found in other ways lends support to this determination.

Cosmic-ray electrons combined with nonthermal radio emission.—The principle of this determination is straightforward. Synchrotron emission comes from fast electrons in a magnetic field. If we can measure the emission by observing the nonthermal radio continuum, and the electrons by detecting them as cosmic-ray electrons near the Earth, then we can calculate the field strength.

The theory underlying this determination has been well reviewed by Biermann & Davis (1960) and by Ginzburg & Syrovatskii (1964, 1965) and presents no hazards. But the practical execution involves a number of uncertainties. The main questions are:

(*a*) Can we reliably convert the observed radio brightness into a volume emissivity arising from synchrotron emission?

(*b*) Can we reliably measure the cosmic-ray electrons among the hundred-times-more-abundant protons, other nuclei, and their secondary products?

(*c*) Is the electron density measured near the Earth typical of the density in interstellar space?

With the accumulation of observational data at more frequencies and with better angular resolution, question (*a*) has become more difficult to answer than 10 years ago, when the separation between a relatively smooth disk and smooth halo seemed rather evident. The extreme assumption that most of the nonthermal continuum at low latitudes is due to unresolved sources can pretty well be excluded, so the emissivity in the disk remains about what it was. But the high-latitude distribution shows so many details that some authors prefer to describe it as a collection of shells (Quigley & Haslam 1965). The concept of a large halo with fairly uniform radio emission has almost vanished from the literature. This may be an overcorrection.

Until recently, question (*b*) seemed by far the most difficult one. Several satellite experiments to measure the cosmic-ray electrons near the Earth are in preparation. But the preparatory balloon flights have already given rather convincing results. Figure 1 shows the cosmic-ray electron spectrum as we know it (Tanaka 1966). In the interpretation of these data, naturally, question (*c*) arises. Several arguments are in favor of blaming the change of slope near 1 GeV in Figure 1 on solar modulation. Electrons of higher energy would be unaffected by such modulation. A more secure answer may have to await observations during a solar cycle.

Altogether it appears that the numbers change very little from those

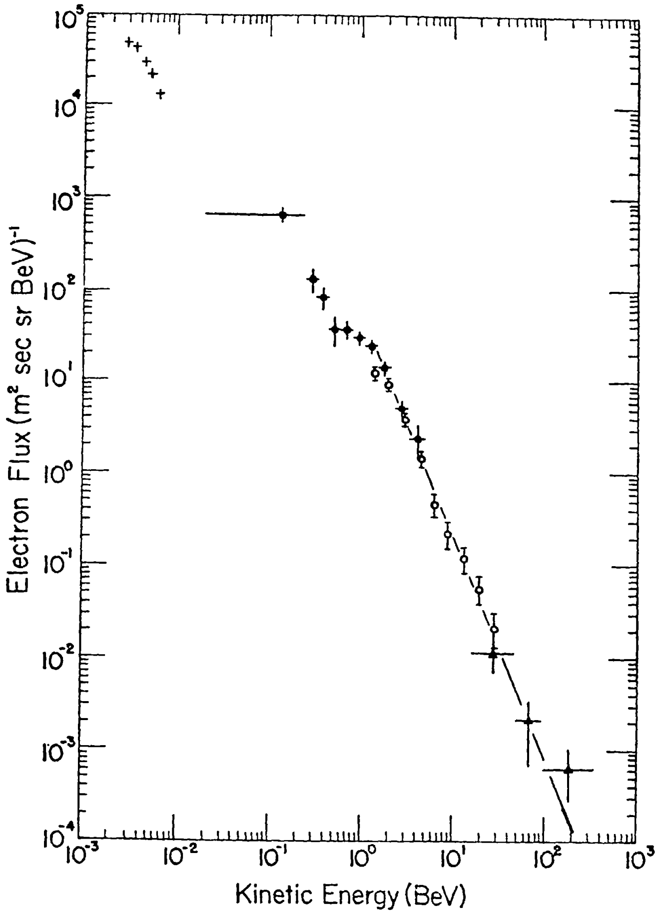

FIG. 1. Energy spectrum of cosmic-ray electrons. This is a composite diagram prepared by Dr. Y. Tanaka (October 1966) from data by Cline et al. (+, 1964), Meyer et al. (●, unpublished), Bleeker et al. (o, unpublished), and Daniel & Stephens (Δ, unpublished).

given by Biermann & Davis (1960), but that their lower limit of the electron density and hence the higher limit of the field strength can now (tentatively) be regarded as actually measured values. This would make the disk field 2×10^{-5} G. An independent estimate by Sironi (1965) gave 0.9×10^{-5} G, by Tanaka (1966) 1.6×10^{-5} G. The slope $\gamma=2.4$ of the observed electron spectrum in the range 2–30 GeV would give a radio spectral index $\alpha=\frac{1}{2}(\gamma-1)=0.7$, well within the range of values determined by direct observation.

Zeeman effect.—The atomic hydrogen line at 21 cm has a Zeeman effect, well established in the laboratory and by theory. The two circularly polarized components in a longitudinal field are separated by 28 c/s per 10^{-5} G. Unfortunately, this separation is so small that the best efforts, devoted to the sharpest absorption peaks available, still give only an upper limit for the field strength. The values quoted for two such clouds are $(-2\pm5)\times10^{-6}$ G and $(-3\pm3)\times10^{-6}$ G (Verschuur 1966). In interpreting these data it should be noted that the field in such a dense cloud may actually be smaller than it generally is in the disk.

Some polarization phenomena in the OH lines have been interpreted as Zeeman effect in fields of the order of 10^{-3} G. As long as the conditions of excitation of these lines remain enigmatic (they probably involve some chance maser effect), it is hard to take this quantitative result seriously. The qualitative argument that circular polarization can be produced only in the presence of a magnetic field may be incorrect. Heer (1966) has shown that circular polarization could result from saturation effects in a maser amplifier with an energy level structure similar to that of the OH molecule.

TABLE II

CONTINUUM POLARIZATION SURVEYS

Observatory	Authors	Year of publication	Frequency	Beam-width
Parkes	Mathewson & Milne	1965	408	48′
Cambridge	Wielebinsky & Shakeshaft	1964	408	8°
Dwingeloo	Westerhout, Seeger, Brouw & Tinbergen	1962	408	2°
Dwingeloo	Brouw, Muller & Tinbergen	1962	408	2°
Dwingeloo	Berkhuijsen & Brouw	1963	408	2°
Dwingeloo	Brouw	Unpublished	465	1°8
Dwingeloo	Berkhuijsen, Brouw, Muller & Tinbergen	1965	610	1°3
Parkes	Mathewson, Broten & Cole	1966	620	32′
Dwingeloo	Brouw	Unpublished	820	1°
Cambridge	Bingham	Unpublished	1407	2°
Dwingeloo	Brouw	Unpublished	1411	30°
Parkes	Mathewson, Broten & Cole	1966	1410	14′
Parkes	Högböm	Unpublished	1410	14′

THE RADIO-POLARIZATION DATA

The effects noted in the last two lines of Table I are: the polarization of synchrotron emission, which shows the existence of a magnetic field at the source of radiation; and the Faraday effect, which shows the existence of a field along the line of sight. The discussion of these topics cannot quite be separated. We shall place the main emphasis on the first one.

Continuum polarization surveys.—By now we have a number of reliable continuum polarization surveys, and have passed from the stage when instrumental corrections formed the main topic to the early stages of astronomical interpretation. Table II lists all surveys available to date.

Since no circular polarization has been found, the quantities measured, in principle, are three Stokes parameters for any point on the sky. They can be separated into a polarized and an unpolarized component as follows

$$\begin{bmatrix} I(l, b, \nu) \\ Q(l, b, \nu) \\ U(l, b, \nu) \end{bmatrix} = \begin{bmatrix} I_u \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} I_p \\ I_p \cos 2\theta \\ I_p \sin 2\theta \end{bmatrix}$$

Here l, b = galactic longitude and latitude, ν = frequency, I_u = unpolarized intensity, I_p = polarized intensity, and θ = position angle. The degree of polarization is $p = I_p/(I_u + I_p)$.

The instrumentation usually is designed to measure the polarized component with great accuracy at one frequency. It is therefore natural to display the results as maps in which each observed point (l, b) shows a dash with length I_p and direction θ. We may call I_p the polarization brightness and convert it in the usual manner into a brightness temperature.

Figures 3 and 4 show such maps for two regions in the sky that have attracted special interest. The complete maps would require too much space to be included in this review. Taking the 408 Mc/s as an example, we observe that in most points of the sky the polarization brightness rises just above the instrumental errors. The amount and direction in adjacent points usually are similar and sometimes create a coherent pattern over 10° or more on the sky. This shows at once that there is no typical magnetoturbulence with fields tangled on a small scale. If 200 pc is adopted as a representative distance, the coherence scale is about 40 pc.

Spectra, depolarization.—Before entering into a more detailed discussion of these maps, it should be noted that this presentation misses some important points: the maps do not show the unpolarized component or the degree of polarization, nor do they give ready information about the spectrum. Figure 2 provides this information in the form of a sketch of some typical spectra.

This illustration, made from eye estimates on the preliminary maps of Brouw, will need revision in detail, but suffices to show the general trend. The ordinate is proportional to brightness I_p for the polarized part, and to $I_p + I_u$ for the total brightness. Since temperature units are more important in the discussion than brightness units, the lines of constant brightness temperature have been drawn in for reference. The polarization temperatures in the four regions shown are low, but remain well above the internal mean errors shown by crosses. The total brightness is rather similar in these four regions and is shown in the top part of the figure by one solid line with adopted slope -0.65. In this Figure the published polarization temperatures at 408 Mc/s and 620 Mc/s have been revised upwards by the factors 1.4 and 1.5, respectively, on the basis of a new calibration by Brouw.

The most striking feature of these spectra is the existence of a strong depolarization. The theoretical synchrotron radiation of electrons with isotropic velocities in a homogeneous magnetic field has the degree of polarization

$$p = (\gamma + 1) \Big/ \left(\gamma + \frac{7}{3}\right)$$

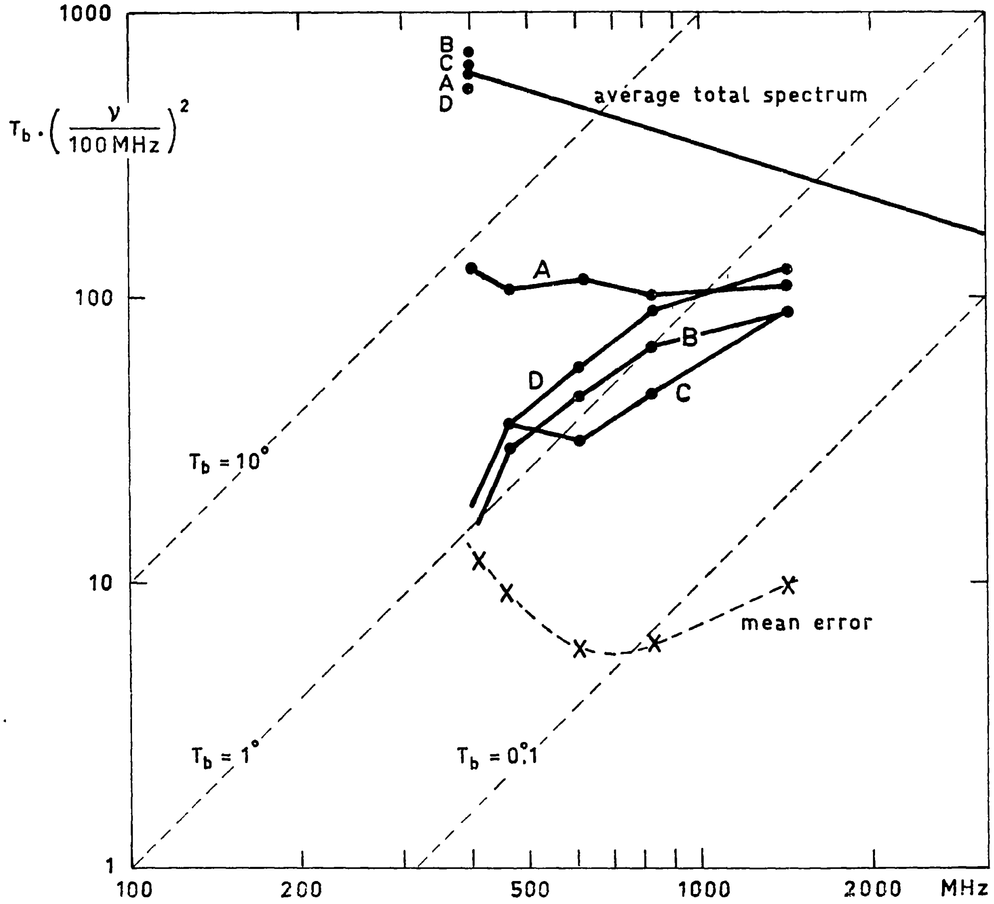

FIG. 2. Spectra of polarized and unpolarized radiation in four regions of the sky (rough sketch based on unpublished data by Brouw). Region A:$l=140°$, $b=5°$; Region B:$l=125°$, $b=5°$; Region C:$l=30°$, $b=30°$; Region D:$l=30°$, $b=50°$.

where γ is the exponent of the electron energy spectrum. The value $\gamma=2.4$ gives $p=0.72$. The regions shown in Figure 2, however, have degrees of polarization from 3 to 50 per cent, much lower than the theoretical 72 per cent. In most regions of the sky the polarization is even weaker.

Since no physical effect will destroy the polarization, its weakness must be attributed to superposition of some kind. Many possibilities are open: superposition of thermal emission, which is unpolarized; superposition of different intrinsic directions of polarization within the beam; different intrinsic directions of polarization along the line of sight. Further, the Faraday effect may rotate by different amounts the radiation emitted at different distances along the line of sight, or at different directions within the beam, or even at different frequencies within the band. The positive slope of the spectra in Figure 2, i.e. the rapid (but perhaps not quite smooth) decrease of polarization with increasing frequency, points very clearly to the Faraday effect. The currently popular explanation is that only the relatively nearby regions contribute to the observed polarization. The emission at greater distances arrives with so many different angles of rotation that it is virtually unpolarized. It is, so to say, covered by a "Faraday fog." This fog gradually lifts when we go to higher frequencies. We may recall that the Faraday rotation turns the plane by $R\lambda^2$ radians where R, the rotation measure, is

$$R = 0.81\int N_e(B\cos\theta)dl$$

with N_e = electron density in cm^{-3}, $B\cos\theta$ = longitudinal component of field strength in 10^{-6} G, dl = element of line of sight in parsecs.

Mathewson's belt.—Among the details shown by the polarization maps, the "fan region" in the northern sky near $l = 140°$ is most striking. Figure 3 shows maps of the region at two frequencies. This region is in no other way peculiar, and it seems likely that it is just a rather prominent hole in the Faraday fog. It fans out more widely at 465 Mc/s than at 1411 Mc/s. If the rotation is taken out by its proportionality to ν^{-2}, the dashes become vertical, showing a magnetic field parallel to the galactic plane. The rotation is 0 at $l = 140°$, showing that at that longitude the field is perpendicular to the line of sight, which fixes its direction (including the sign) in space.

An analysis of this type is permissible if a strict separation between a fully depolarized background and a polarized but rotated foreground emission can be made. Consistent with this extreme assumption would be a polarization spectrum with the same slope as the normal synchrotron spectrum. We see in Figure 2 that the fan region (region A) indeed comes closest to this assumption. And only with this assumption is it possible to define a unique rotation measure for the continuum polarization.

Closer examination shows that the simple picture just sketched does not explain all details of the fan region. For one thing, a second zero in the rotation occurs near $l = 160°$. Both Hornby (1966) and Bingham (unpublished) have fitted more complicated field models to this region. More generally, models computed by Komesaroff (unpublished) for emission along the line of sight, with various values of the rotation measure, have shown that the direction of polarization may suggest a unique rotation measure, but when the degree of polarization is plotted against frequency, prominent fluctuations show that this simple interpretation is incorrect.

Polarization maps of the entire sky reveal the existence of a large-scale feature sometimes called "Mathewson's belt." Mathewson & Milne (1965) marked all places where, as in the fan region, the observed polarization is relatively strong. With hardly any exceptions these fall in a belt, about 60° wide, cutting the galactic equator at $l = 320°$-$20°$ and at $l = 120°$-$180°$, and perpendicular to it. This belt contains the fan region just described, and Mathewson's explanation is similar to the one given above: the belt is the locus of directions perpendicular to the local magnetic field, where Faraday rotation is smallest and synchrotron polarization strongest. The deviation by about 10° of the belt from a great circle may be due to the magnetic-field lines expanding outwards in the direction of $l = 250°$.

Rotation measures from extragalactic sources.—At this point a comparison

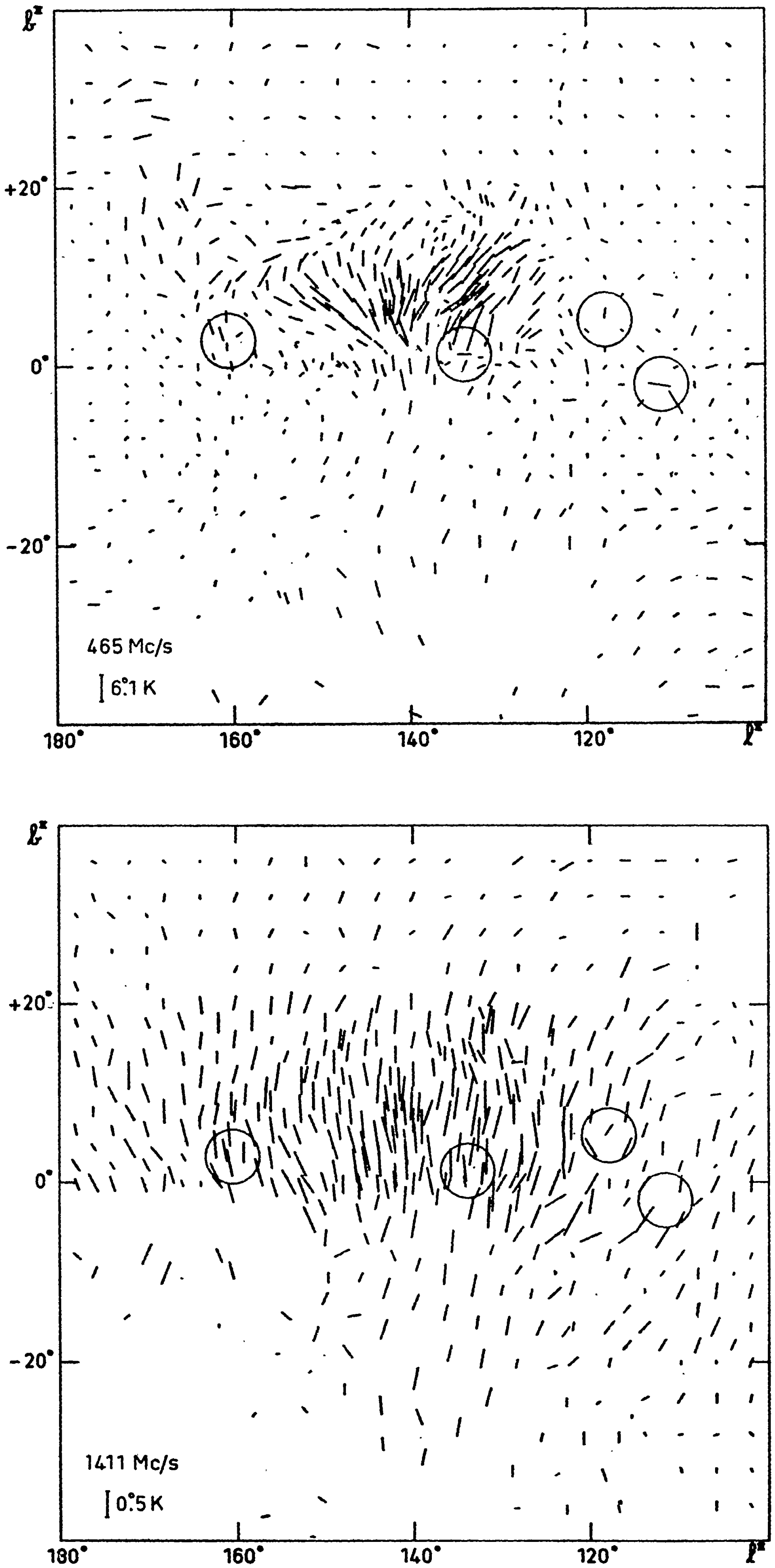

FIG. 3. Polarization maps of the "fan" region near $l=140°$ at two frequencie showing different Faraday effect (Brouw, unpublished).

with rotation measures derived from the observation of extragalactic radio sources suggests itself. This has been a very active field of research in the past few years, including many sets of observations and statistical and theoretical studies (e.g. Bologna et al. 1965, Maltby & Seielstad 1965, Gardner & Davies 1966a, Gardner & Whiteoak 1966).

We shall not review this entire field. Rotation measures thus found typically are 10–100, or even larger, whereas the galactic polarization studies just discussed give typical values 0–5. At least three independent arguments for such a difference can be advanced: Faraday rotation in the extragalactic source; Faraday rotation in the more distant parts of the Galaxy, which are virtually depolarized in the continuum studies; the fact that determinations from the observed continuum polarization constitute a selection of regions where the rotation measure is small. Different authors assess these explanations with different weights. Probably further model calculations and statistical studies will be necessary before a conclusion can be reached. That is why we are not quite ready to discuss this important subject in full in the present review.

A few results may be noted. Gardner & Davies (1966b) have constructed a map in which the rotation measures of extragalactic sources, with their proper sign, are plotted as a function of galactic coordinates. They have tentatively drawn iso-R contours, which presumably give information about the large-scale field of the Galaxy. The sign changes not only with longitude, at about 200° and 340°, but also with latitude, thus requiring rather complicated field models for its explanation. Seymour (unpublished) has made model studies using Legendre expansion. Mathewson & Milne, disregarding the signs, note from the same map that large rotation measures systematically occur outside Mathewson's belt, which is understandable if this belt is more than a local phenomenon. Most statistical studies correlating the rotation measure with other parameters have been disappointing (Maltby 1966). However, Bologna, McClain & Sloanaker (unpublished) find a significant absence of high degrees of polarization at low latitudes only in the longitude quadrants towards the center, where we look through much galactic gas. The explanation would be that the solid angle subtended by the source is wide enough to permit different values of R, thus leading to partial depolarization. With source diameters of the order of 1′ and reasonable distances of the gas this would point to a fine structure in the magnetic field of the order of 1 pc.

The north-galactic spur.—In all continuum surveys the north-galactic spur forms the most prominent feature outside the galactic plane. It was already visible on Reber's old maps. The spur can be traced from the galactic equator near $l=40°$ to the galactic pole and beyond; according to some authors it extends all around a great circle. Nobody knows what it is, although there are plenty of speculations. There are a few fainter arcs which may have a similar character (Quigley & Haslam 1965).

Naturally, when polarization methods became feasible, the spur was one

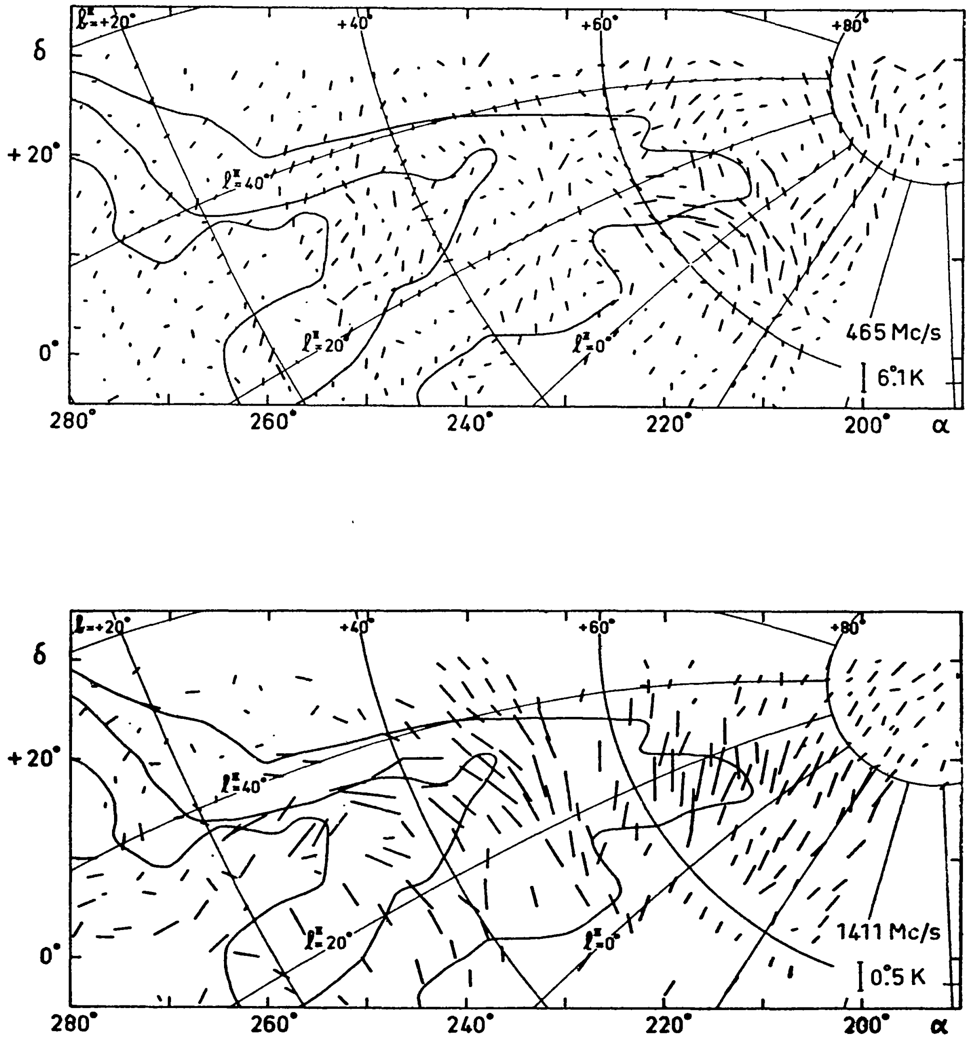

FIG. 4. Polarization maps of the north-galactic spur at two frequencies, from data obtained at Dwingeloo (Brouw, unpublished).

of the first objects to be studied. Figure 4 shows its polarization maps at two frequencies with the Dwingeloo 25-m telescope. A full discussion of these data is not yet available. Measurable polarization gradually appears at lower latitudes as we let the frequency increase. This fact, which is also shown by the strong positive slopes of curves *C* and *D* in Figure 2, points to a distant object that gradually becomes more visible through the Faraday fog. If the peculiar convergence of optical polarization towards the point $l=37°$, $b=0°$ noted by Hall (1958) has anything to do with the spur, this also would indicate that it cannot be very near. On the other hand, Bingham (unpublished), in correlating his polarization measurements with the optical polarization data of Behr (1959), finds a fair correlation with stars at a distance of only 100 pc and suggests that the spur may be at a distance of that order. Finally, the few polarization scans made by Högböm (unpublished) with a beam of

11′ show examples of marked changes of direction, which would have been obliterated by a larger beam (Figure 5). The obvious conclusion is that any explanation based on low-resolution maps may be subject to drastic revision when better data become available.

CONCLUSIONS

The review in this paper has been conservative, dealing mostly with the observations and adding only relatively unassailable theoretical interpretations. This attitude can be justified by the fact that I have been permitted to use much unpublished observational material that has not yet been fully discussed by the authors themselves.

For a full understanding of the galactic magnetic field a more aggressive theoretical approach, exploring not only the geometry but also the dynamics and stability of all kinds of configurations, is certainly necessary. Important facts entering into such an approach are the existence of differential galactic rotation and that of spiral arms. Recent studies of these subjects have been presented by Wentzel (1963), Woltjer (1965), and Parker (1966).

Returning to the data directly inferred from observation, we find, in summary, that a fair measure of agreement exists about the direction of the magnetic field in our neighborhood. The points 90° or 270° away from the directions where we look perpendicularly to the field, or the points 0° or 180° away from the directions where we look along it, are:

from optical polarization $l = 50°–80°$
from cosmic-ray anisotropy $l = 62°$
from the polarization "fan" $l = 50°$
from Mathewson's belt $l = 70°$
from rotation measures of extragalactic sources $l = 70°–110°$

For comparison, the direction of the local spiral arm (Sharpless 1965) is

as outlined by O associations $l = 50°$
as outlined by H II regions $l = 60°$
as outlined by H I gas $l = 70°$

These values deserve to be more than quoted and averaged. Each of them is uncertain by at least 10°, not only in determination but also in definition. Much depends on the definition of "local" in this context. The spiral-arm studies refer to objects at distances up to several kiloparsecs, the radio continuum polarization surveys effectively to objects at several hundred pc, and the cosmic-ray anisotropy to a minute fraction of 1 pc. The best this comparison does is to relieve us somewhat from the worry that the astronomical studies of magnetic fields might not be relevant at all on the small scale covered by cosmic-ray studies.

The question of topology, whether the direction just quoted is the direction of a wiggly but continuous tube of force, or just the predominant direc-

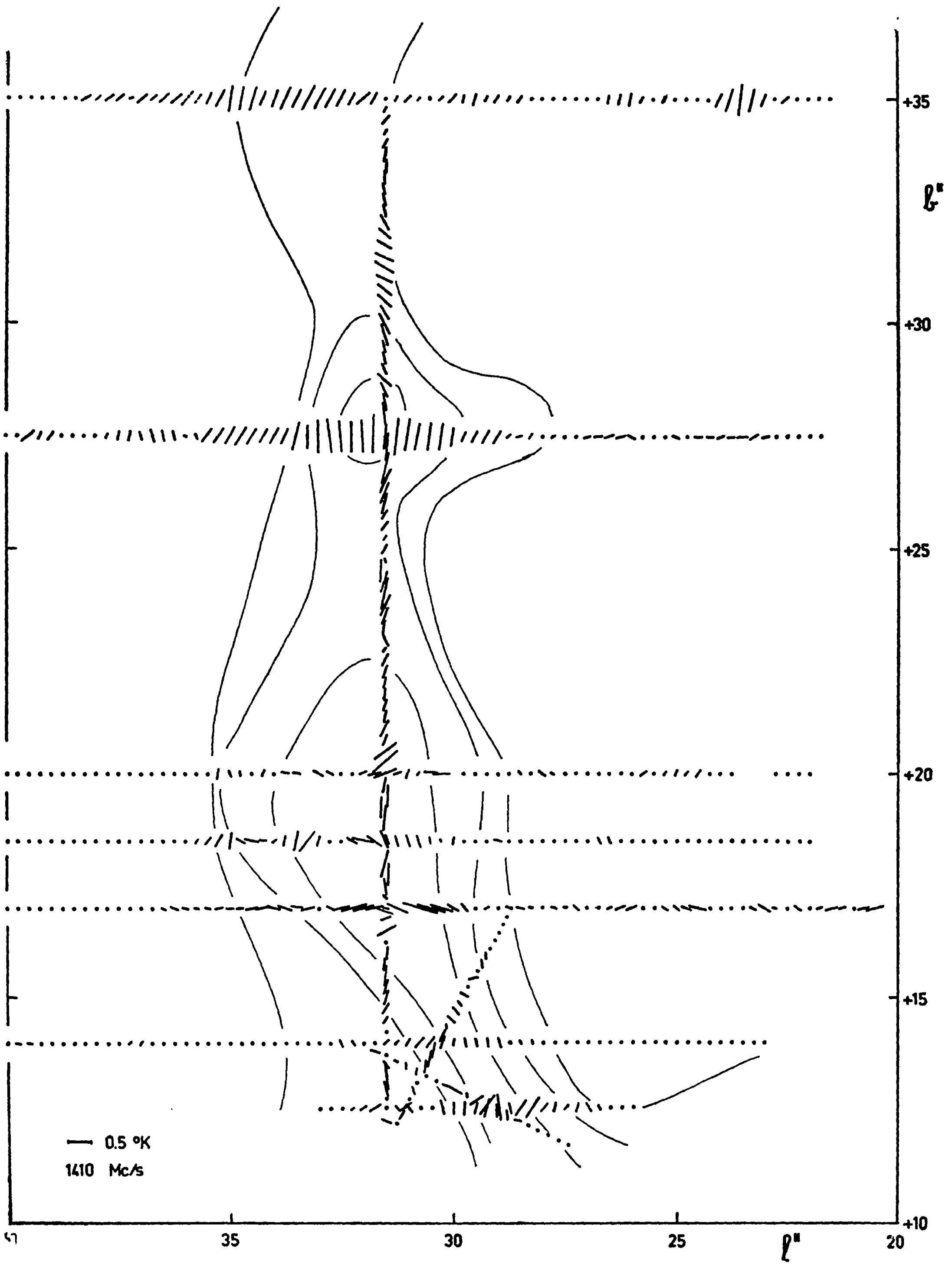

FIG. 5. Polarization scans through the north-galactic spur made with an angular resolution of 14′ with the Parkes telescope (Högböm, unpublished). This Figure covers about $\frac{1}{8}$ of the area of Figure 4.

tion of a more tangled field, remains open. The microscales of the order of 1 pc suggested by some optical and radio studies should warn us not to take the simplest picture for granted. The question of magnitude remains very much up in the air. The estimate "of the order of 10^{-5} G" seems all right. But factors of the order of 3 in the field, and hence 10 in the pressure—which would make an enormous difference to the dynamical picture—cannot yet be firmly decided by direct observation.

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