OBSERVING THE INTERSTELLAR MAGNETIC FIELD

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1. A LOOK AT HISTORY

Discoveries in present-day astronomy and radio astronomy come with such a rapid succession that results found five years ago are "old" and those of ten years ago "classical". Yet, sometimes, it is good to look back in order to see the present efforts in a proper perspective.

Exactly 15 years before today's dedication, on 25 March 1951, Ewen made the first positive observation of the 21-cm line in the attick of the Harvard physics laboratory. Two years later, when the first excitement of the discovery was over and the first spiral arms had been mapped, Lovell commented that relatively too much attention had been paid to this "predictable" branch of radio astronomy. The radio continuum might prove far more exciting, just because it was basically not understood. His remark was well taken, for the study of this continuous spectrum has now led us to such exciting studies as the quasars, new problems in cosmology and -closer to home- means to map the galactic magnetic fields. I shall deal in this paper only with the last subject.

Astronomers did not wake up promptly to this opportunity. The theory of radiation of an electron moving in a magnetic field at relativistic speeds had been known for half a century. Suggestions that this "synchrotron mechanism" could be a source of continuum radio waves were in the literature since 1950, but were not pursued. The breakthrough came with Shklovsky's bold suggestion that the white optical spectrum of the Crab nebula, a notorious puzzling object, could arise from this mechanism. Soon this suggestion found a spectacular confirmation by several measurements culminating in Woltjer's map of the optical polarization on plates of the nebula taken by Baade (Woltjer, 1957).

From that moment on, the determination of the polarization of the general galactic radio continuum with the aim of (a) establishing its character as synchrotron emission and (b) mapping the magnetic fields, has been high on the list of desiderata for radio astronomy. The first exploratory survey in the Netherlands was made in 1960. Since that time many improvements have been introduced. Surveys at four wavelengths have been completed and Mr.Brouw at Leiden is preparing a thesis on these topics. Less extensive measurements of the same kind have been performed at Cambridge (England) by Bingham. In Australia Matthewson has completed with a narrower beam a polarization survey of the southern sky at 408 Mc/s and has explored interesting areas at three different frequencies.

2. SEVERAL WAYS TO OBSERVE THE MAGNETIC FIELD

Before coming to a more detailed discussion, let us see what ways exist to establish the presence of a magnetic field in the galaxy at all. (Table 1). We shall briefly review these methods one by one.

TABLE 1

Ways to observe the galactic magnetic field

		Kind of observation		
		optical	radio	other
action of magnetic field =	at source =	(synchrotron emission, only in special objects)	Zeeman effect H Zeeman effect OH Synchrotron emission	
	en route =	interstellar polarization	Faraday effect	
	dynamical =	strange shapes		cosmic ray confinement

a. ZEEMAN EFFECT

This effect would provide the most direct way of measuring the field. The only eligible line is the 1420 Mc/s line of hydrogen. A magnetic field in the line of sight can be observed as a frequency separation of 28 c/s per 10^{-5} gauss between the left-hand and right-hand circular polarization. Measuring this separation obviously requires line components with steep sides. These are present in the absorption profiles seen with the brighter discrete sources as background.

More complete measurements have changed the initially positive results into $(-2\pm5) \times 10^{-6}$ and $(-3\pm3) \times 10^{-6}$ gauss for the best observed clouds (Verschuur and Davies, 1966). Hence so far the data are meagre: only a few HI clouds, for those only the line-of-sight component, and for that only an upper limit. Sharp emission components might be studied in the same way but again are found only in a few places.

An attempt to explain the line-profile and polarization of one OH line by means of Zeeman effect required several clouds with fields of the order of 10^{-3} gauss (Davies et al., 1966). It does not seem that this explanation can be maintained if the other OH lines are also taken into account.

b. INTERSTELLAR POLARIZATION

This effect can be used as a tracer of the magnetic field, but not for a firm measurement of its magnitude. It provides a wealth of data, which have, since the discovery in 1949 formed the most important observational basis for all speculations regarding the topology of the magnetic field near us. The suggestion by Chandrasekhar and Fermi (1953), that spiral arms might be tubes of force, was inspired by these data.

The traditional name does not say much, because any galactic field is interstellar and any method to observe it involves polarization. A more correct name would be: optical dichroism of the interstellar medium. In a medium two "modes" of electromagnetic wave propagation, each with a characteristic polarization, may propagate with a different velocity (birefringence) and/or unequal losses (dichroism). In interstellar space the optical modes are linear, or very nearly so; Gehrels (1966) has observed a slight rotation of the plane of polarization, which would mean that the modes have an elliptical component. The losses (interstellar extinction) are generally ascribed to dust grains and the fact that the absorption may be some 5-10 percent higher in one mode than in the other must be due to non-random orientation of these grains in a magnetic field.

A great effort has been expanded by observers and theorists over the past 35 years in order to find the nature of these grains. Yet their physics and chemistry is by no means settled yet. Two recent symposia (Edinborough, 1948; Troy, 1965) may serve for sufficient reference.

Skipping these uncertainties and, consequently also the theories of the orientation mechanism, we can still say that it is almost certain that the linear polarizations thus observed display the average transverse comments of the magnetic fields between the stars observed and us. The distances involved range from 100 pc to 2000 pc. Larger distances require measurements of fainter stars; shorter distances require measurement of weaker polarization. In both directions further progress is being made.

c. FARADAY EFFECT

Faraday effect, or circular birefringence is another propagation effect. A linearly polarized wave passing through the medium suffers a rotation of the plane of polarization due to the presence of free electrons and a longitudinal component of the magnetic field. The rotation is by

$$R\lambda^2 \text{ radians}$$

where λ is the wavelength in meters and R is the, already traditional, rotation measure in radians/m^2:

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

where N_e = number of free electrons per cm^3

$B\cos\theta$ = longitudinal component of magnetic field in microgauss

$d\ell$ = element of pathlength in parsec

Either the general synchrotron continuum, or a discrete (usually extragalactic) source may provide the original, linearly polarized wave.

The interpretation of these data is more secure than that of the optical polarization, because an accurate numerical value of the rotation measure is found. Uncertainties arise, first of all in estimating how much of the rotation occurs in the (extragalactic) source itself. The rotation in the terrestrial ionosphere can be eliminated quite nicely by comparing measurements made in the course of a night. An additional complication is that different values of the rotation measure are lumped in the finite beam and finite bandwidth. The effect is to reduce the amount of polarization and to cause a deviation from the λ^2 law. The initial fear was that these effects might delete all observable polarization. This may still be true in many directions and for most of the distant source regions. Hence, one interpretation of regions of strong observed polarization, is that they simply are local "clearings" in the Faraday cover. One of the most pressing problems now is to find objective criteria for weighing this type of explanation against other explanations in which such reasons are structural features of a galactic arm.

d. DYNAMIC EFFECTS

The possible role of the magnetic field in the dynamics of the interstellar gas had been recognized by Spitzer, Alfvén, Biermann and others, well before direct evidence of the field was ever observed. We do not wish to review the theoretical arguments, which are many (see for instance, Woltjer 1961). Direct observational evidence for a magnetic field could show up by a striking pattern, as it does, e.g. in the "polar plumes" of the sun's corona. The dark and bright nebulae in our galaxy displayed so beautifully in the Palomar sky atlas have indeed many striking features. But I should hesitate to quote any of these as evidence for magnetic fields.

A second undeniable observation is the presence of cosmic rays in our galactic system. This has often been quoted as "proving" the existence of a confining magnetic field. Unfortunately, this argument breaks down at the very highest energies, for the gyration radius of a 10^{20} eV proton in a 3×10^{-6} gauss field is 30000 parsec. The criterion at what energy it would start to be applicable would have to come from the position of a knee in the energy spectrum, which at the high-energy end is still somewhat vague (Malhotra et al, 1966).

3. WHAT CAN WE INFER FROM THE OBSERVED POLARIZATION?

We now return to the synchrotron emission. The observational effort of measuring galactic polarization is wedged between two severe dificulties. At the low-frequency end there is too strong Faraday rotation; at the high frequencies the entire brightness, and hence also its polarized part, becomes extremely faint. Unfortunately, it is also a race against time, because radio astronomy has not even been able to reserve through the International Telecommunications Union its claim for a free band every octave (which is already too widely spaced for Faraday measurements) and television stations are rapidly filling up their assigned frequency bands. Systematic errors, arising largely from ground radiation have been overcome and it not necessary anymore to conclude that "magnetic fields in the galaxy are parallel to the pinetrees in Dwingeloo".

In trying to review the interpretation of these valuable data and to assess the already heated arguments in the literature let us first look at the degree of polarization.

The synchrotron emission process by itself gives 50 to 100 per cent polarization. More precisely, if the electron velocities are isotropic and have an energy spectrum proportional to $E^{-\gamma}$ dE, the brightness is proportional to $\nu^{-\alpha}$ where $\alpha = \frac{1}{2}(\gamma - 1)$ and the degree of polarization is $p = (\gamma+1)/(\gamma+7/3)$ (see, for instance Ginzburg and Syrovatski, 1965). Inserting, the values $\gamma = 2.3$, $\alpha = 0.65$ we get p = 71 per cent.

Typical observed figures at 408 Mc/s are 2 °K polarization temperature on 30 °K total brightness temperature (Seeger et al, 1965), which makes 6 per cent polarization. Why is this so much lower than the theoretical value? There is no physical depolarization effect. Only incoherent superposition of radiation with different directions of polarization can produce this effect. We may think of superposition of:

a. unpolarized radiation from a different mechanism (e.g. thermal);
b. different intrinsic polarization along the line of sight;
c. different Faraday rotation because sources are spread slong the line of sight
d. different Faraday rotation or intrinsic polarization side by side in the beam;
e. different Faraday rotation side by side in the bandwidth.

We can exclude a because thermal radiation is weak and no other mechanism is known. Likewise, d cannot be the major cause because of the fairly regular pattern shown by the maps and e because it would be felt only at rotation measures larger than 100. Hence b and c, both of which are line-of-sight effects, remain. In integrating over the line of sight no bias in favour of the nearer or farther portions exists, which would again make the regularity of the maps hard to understand. However, effect d clearly is stronger at larger distance because the beam covers a larger domain of space. So the conclusion seems warranted that we see mainly the polarization produced in the regions of space near us and that ninety percent of the observed intensity arises at larger distances where a combination of effects b, c, and d causes virtually complete depolarization.

This conclusion is consistent with the values of the rotation measure. Only 11 out of 49 discrete (extragalactic) sources listed by Gardner and Davies (1966) have $R < 5$ and many come as high as

40 or 50. Yet the majority of the galactic fields with measurable polarization at two frequencies have $R < 2$ (Mathewson et al,(1966) Brouw, priv. comm.)

The next task is to look for structural details. The main "local" structure in optical astronomy and in hydrogen line studies is formed by the spiral arms. The main features in radio continuum studies in meter waves are three arcs, each part of a circle: the north galactic spur, the Cetus arc, and "loop 3" (Quigley and Haslam, 1965). Rougoor (1966) wishes to string them all together. The most striking feature on the polarization maps so far is Mathewson's ring, a band 60° wide perpendicular to the galactic plane and cutting it at $\ell^{II} = 350°$ and 150°. (Mathewson and Milne, 1965). This band contains all areas of locally high polarization. One of these near $\ell^{II} = 140°$, $b^{II} = 3°$, has been discussed in detail by Berkhuysen et.al. (1965).

How are these features, observed by different techniques, interrelated? In my opinion it is still too early to decide on a precise model. Much will depend on what the surveys at 1400 Mc/s, now in progress, will show us.

The most convincing suggestion, so far, is that the ring of relatively high-polarization features is perpendicular to the local direction of the spiral arm (Mathewson and Milne, 1965; Mathewson, Broten and Cole, 1966). The magnetic field in the arm then runs from $\ell^{II} = 250°$ to $\ell^{II} = 70°$. To interpret the map of rotation measures presented by Gardner and Davies (1966) in a similar manner seems more questionable, because the values are so large and because Maltby (1966) finds absence of correlation between the degree of polarization and the galactic latitude. Probably the Faraday rotation in the sources themselves can assume higher values than Gardner and Davies admit.

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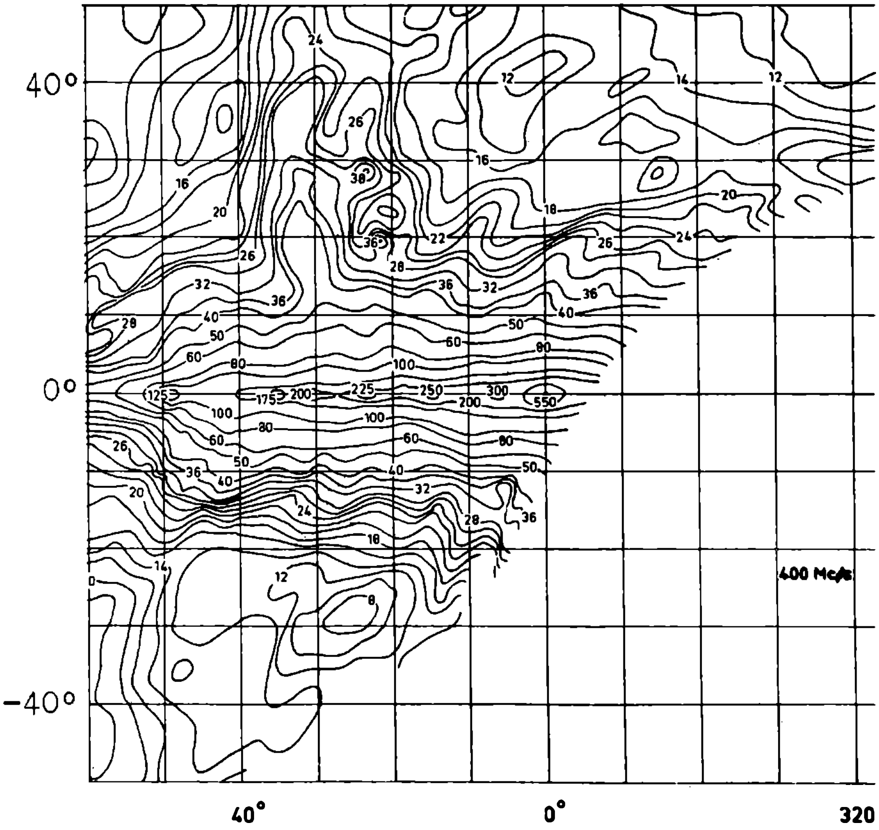
LEGENDS TO FIGURES

Fig. 1 Part of Continuum survey at 400 Mc/s (Seeger et. al. 1965) showing galactic center and base of north galactic spur.

Fig. 2 Part of polarization survey at 820 Mc/s (Brown, unpublished) showing approximately the same area of the sky as Figure 1. Depolarization appears to become less effective toward higher latitudes in the spur.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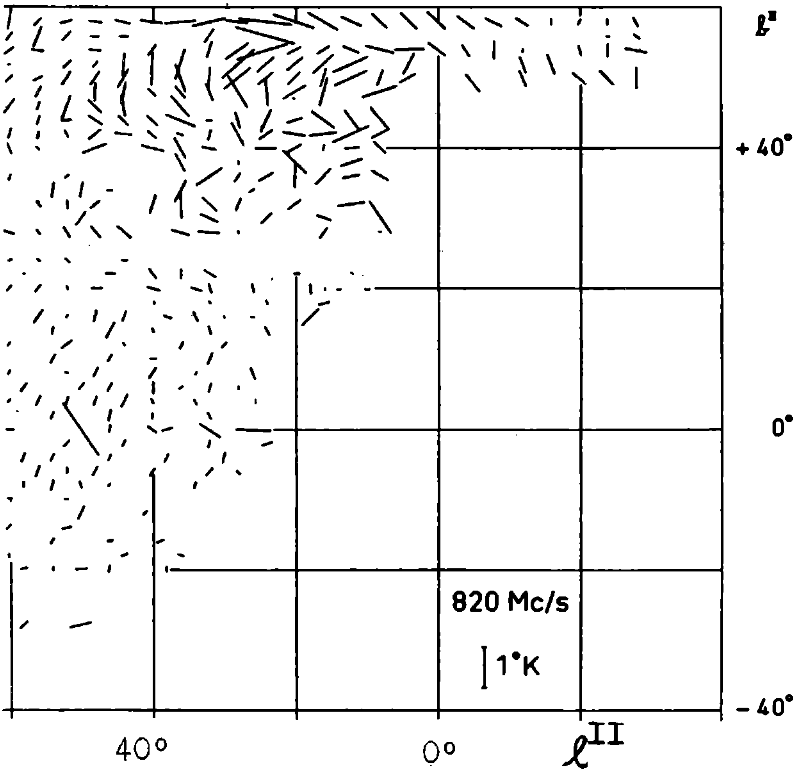
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