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Antisymmetric rotation measures in our Galaxy: evidence for an A0 dynamo

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Abstract. Rotation measures for extragalactic sources, after selection to emphasize the large-scale structure of the Galactic magnetic field, reveal a striking antisymmetric pattern about the Galactic plane and the meridian through the Galactic Centre. This pattern is also observed in the rotation measures of pulsars with $|b| > 8°$. The symmetry of the pattern, the magnitude of the rotation measures and the distance dependence of the pulsar rotation measures show that this pattern is not the result of local perturbations, but is on a large and possibly Galactic scale. This antisymmetric pattern and the existence of magnetic fields perpendicular to the plane in the Galactic Centre region, indicate that a dynamo mode of odd symmetry, possibly of A0 type, makes a substantial contribution to the magnetic fields in the thick disk and halo of our Galaxy, at least inside the Solar circle.

Key words: ISM: magnetic fields – Galaxy: structure – pulsars – polarization

1. Introduction

Despite many investigations over the past several decades, the large-scale structure of the interstellar magnetic field in our Galaxy remains poorly understood. Studies of starlight polarization (e.g., Mathewson & Ford 1970) showed that the field within a few kiloparsec of the Sun had a high degree of uniformity. At low Galactic latitudes the field is largely parallel to the Galactic plane, with extensive perturbations such as the North Polar Spur at high latitudes. Studies of the polarization of the Galactic synchrotron emission (e.g. Berkhuijsen & Brouw 1963; Spoelstra 1972) led to similar conclusions. More recent observations by Yusef-Zadeh & Morris (1987) and Haynes et al. (1992) show polarized structures perpendicular to the Galactic plane near the Galactic Centre.

Extensive studies of the rotation measures (RMs) of extragalactic radio sources (e.g. Gardner, Morris & Whiteoak 1969; Simard-Normandin & Kronberg 1980; Sofue & Fujimoto 1983) showed that the Galactic field is uniform on large scales and, in the local region, directed either azimuthally (towards $l \sim 90°$) or with a pitch angle similar to that of the local spiral arms. Evidence was found for a reversal in direction of the field between the Orion (local) arm and the Sagittarius arm, suggesting that the disk field has a bisymmetric structure. Positive RMs at latitudes $b > 0°$ between $l = 0°$ and 90° were attributed to a perturbation associated with the North Polar Spur (Gardner et al. 1969; Vallée & Kronberg 1975).

Studies of pulsar rotation measures have complemented and added to these findings. Pulsars have several advantages in rotation measure studies. They are distributed through the Galaxy, allowing the three-dimensional structure of the field to be probed. They appear to have no intrinsic Faraday rotation and hence their observed RM occurs entirely along the path to the observer. Their dispersion measure gives an estimate of the distance to the pulsar and, with the RM, a direct estimate of the mean magnetic field strength in the path. Manchester (1974) found that the uniform component of the field within a few kpc of the Sun is directed toward about $l = 94°$ and that the mean field strength is 2.2μG. More recent studies (e.g. Rand & Kulkarni 1989; Rand & Lyne 1994) found a similar orientation and strength for the field and evidence for a reversal in the direction at about 0.4 kpc inside the Solar circle. Weaker evidence is seen for another reversal at about 5.5 kpc from the Galactic Centre, that is, about 3 kpc from the Sun. Han & Qiao (1994) analysed both RMs from pulsars at distances less than 3.5 kpc and from extragalactic sources and concluded that the observations are best fitted by a bisymmetric spiral field (dynamo mode of azimuthal symmetry $m = 1$) in the thin disk. As pointed out by Vallée (1996), an axisymmetric spiral field ($m = 0$) with reversals may also explain the data. From a re-analysis of starlight polarization data, Heiles (1996) concluded that the local magnetic structure is spiral in form, with a pitch angle of $7\overset{\circ}{.}2 \pm 4\overset{\circ}{.}1$, probably smaller than the pitch angle of the optical spiral arms.

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Recent studies of polarized radio emission from spiral galaxies (Beck et al. 1996) show galactic-scale magnetic fields, usually with a pitch angle similar to that of the spiral arms. Remarkable observations by Beck & Hoernes (1996) show that, in the galaxy NGC 6946, the magnetic spiral structure lies in the inter-arm region, but is not confined by the matter arms. Halo magnetic fields may be either poloidal in form (e.g. NGC 4631 – Hummel, Beck & Dahlem 1991), parallel to the galactic disk (e.g. NGC 253 – Beck et al. 1994) or show a filamentary structure which may be connected with outflows from the disk (e.g. NGC 4666 – Dahlem et al. 1996).

Dynamo models seem able to explain the main features of galactic magnetic fields (Ruzmaikin, Shukurov & Sokoloff 1988; Beck et al. 1996) but they are not well enough developed to predict the type of field in a given galaxy. Disk fields may be of even (quadrupole) symmetry with respect to the plane and with azimuthal symmetries of either axisymmetric or bisymmetric type (S0 or S1), with S0 fields generally being favoured, whereas A0 type – axisymmetric fields with odd (dipole) symmetry with respect to the plane – are possibly dominant in the central regions (e.g. Sokoloff & Shukurov 1990). Poezd, Shukurov & Sokoloff (1993) and Vallée (1996) showed that field reversals of the type seen in our Galaxy do not necessarily imply a bisymmetric structure. They can arise in axisymmetric fields as relics of the seed field or in axisymmetric dynamo modes with radial reversals.

In this paper, we show that both extragalactic and pulsar RMs at intermediate Galactic latitudes and towards the Galactic Centre have an antisymmetric structure with respect to both the Galactic plane and the meridian through the Galactic Centre. Such a structure suggests that fields within the halo or thick disk in the central part of our Galaxy are generated by a dynamo operating in a mode of odd symmetry, possibly of A0 type.

2. Rotation measure distributions

Measurements of RMs for extragalactic sources are often complicated by Faraday depolarization within the source and their interpretation is made more difficult by possible intrinsic Faraday rotation. However, there are many sources with measured RMs well distributed across the sky, and so they form a valuable probe of the Galactic magnetic field. In their catalogue, Broten, Macleod & Vallée (1988) carefully selected a range of observational wavelength for each source showing Faraday-thin, one-component behaviour to minimize these problems. We have therefore adopted this catalogue, containing 674 RMs, as a data base.

To investigate the large-scale structure of the Galactic magnetic field, we carried out a selection procedure similar to those used by Simard-Normandin & Kronberg (1980) and Oren & Wolfe (1995). Firstly, sources with $|\mathrm{RM}| > 250$ rad m^{-2} were discarded, because such large RMs are unlikely to be produced by even a very ordered Galactic magnetic field with strength $\sim 2\mu$G. This eliminated 66 sources from the sample. Secondly, to smooth over fluctuations in the Galactic field, we compared the RM of each source with those lying within a circle of radius 15° centred on the source. We first computed the mean and rms deviation of the sources within the circle, excluding the central source. If the RM of the central source differed from the mean by more than three times the rms deviation, it was rejected. This procedure eliminated a further 57 sources. Fig. 1 shows the RM distribution of the remaining 551 sources.

In addition to the well-known predominence of negative RMs in the first and second Galactic quadrants, and positive RMs in the third and fourth quadrants, indicating a prevailing local magnetic field directed toward $l \sim 90°$, this figure shows a remarkable antisymmetric structure for RMs in the first and fourth quadrants. In the first quadrant ($l = 0° - 90°$), RMs are positive at positive latitudes and negative at negative latitudes, whereas the reverse is true in the fourth quadrant ($l = 270° - 360°$). That is, for paths inside the Solar circle, the RM distribution is antisymmetric about both the Galactic equator and the meridian through the Galactic Centre.

Recent observations have increased the number of known pulsar rotation measures, particularly in the Southern Hemisphere (Qiao et al. 1995). In Fig. 2, we show the Galactic distribution of RMs for all pulsars with known RMs at latitudes $|b| > 8°$. The latitude selection is made to emphasize the magnetic field structure in the thick disk and halo. It is clear that, with an occasional exception, the same antisymmetric structure is seen in the distribution of pulsar RMs in the first and fourth quadrants.

The remarkable similarity of the pulsar and extragalactic-source RM distributions for $|l| < 90°$ shows that the same field structures are responsible for both. The structures may be either local or more extended. Since the pulsars are at distances up to about 6 kpc, the dominant field structures must be located within this distance. Lines of sight with $|b| > 8°$ pass through the thick Galactic disk on the near side of the Galactic Centre, and so extragalactic sources at these latitudes probe the same region.

3. Discussion

Figs. 1 and 2 show the antisymmetric structure in the RM distributions in the inner Galactic quadrants much more clearly than any previous work. Many authors have noted the tendency for RMs in the inner Galactic quadrants (1 and 4) to have opposite signs above and below the plane (e.g. Gardner et al. 1969; Vallée & Kronberg 1975; Simard-Normandin & Kronberg 1980; Andreasyan 1980, 1982) and this effect is clearly visible in Fig. 3 of Oren & Wolfe (1995). These deviations from a simple bilateral symmetry have usually been attributed to the effects of relatively local perturbations; for example, those associated with the North Polar Spur and Loop I. However, Andreasyan (1980) attributed them to a reversed disk field above and below the plane. We argue that the field structures giving rise to the antisymmetric RM distributions are not local perturbations, but are major features of the Galactic magnetic field.

Sofue (1994) argues that Loop I originates in a very large bubble near the Galactic Centre, but most authors accept the interpretation originally proposed by Brown, Davies & Hazard

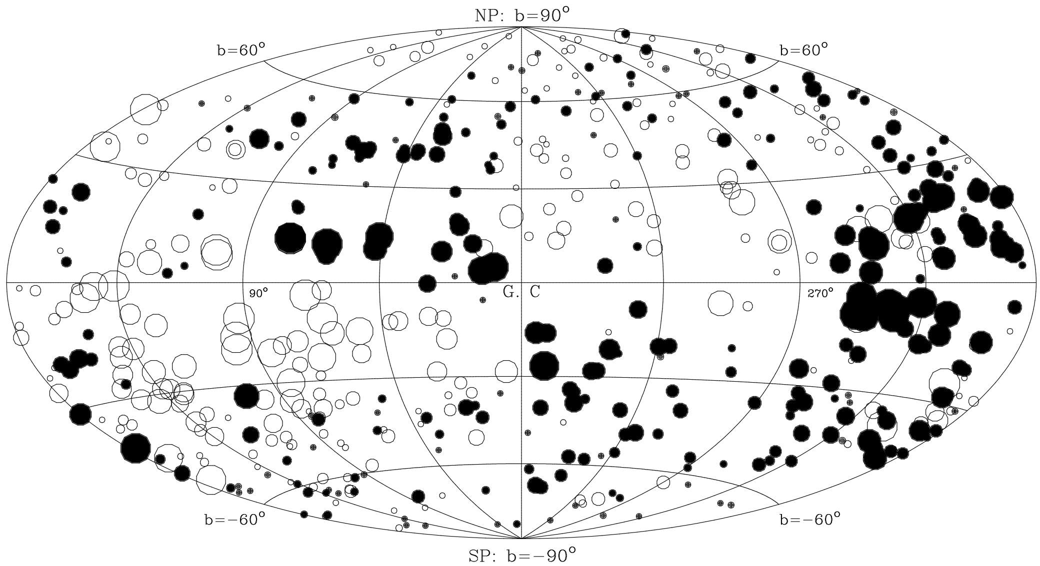

Fig. 1. Galactic distribution of RMs of extragalactic radio sources from the Broten et al. (1988) catalogue, selected as described in the text to show the large-scale structure of the Galactic magnetic field. Filled circles represent positive RMs (magnetic field directed toward the observer) and the area of the circle is proportional to |RM| within limits of 5 and 150 rad m^{-2}.

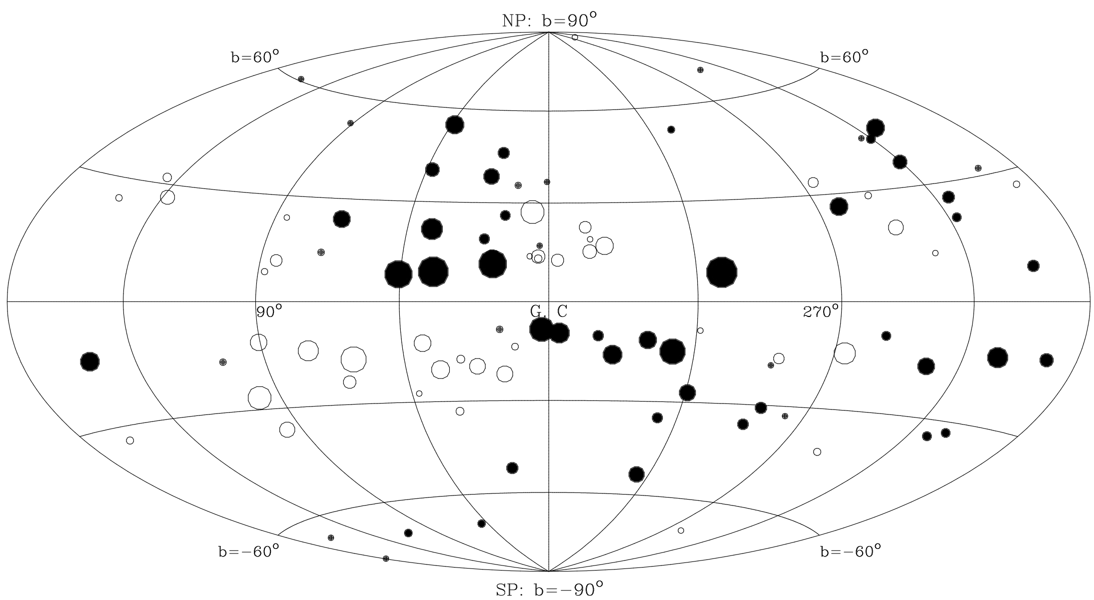

Fig. 2. Galactic distribution of RMs for pulsars with $|b| > 8°$ from Taylor, Manchester & Lyne (1993), Rand & Lyne (1994), Qiao et al. (1995) and Manchester & Johnston (1995). Filled circles represent positive RMs and the area of the circle is proportional to |RM| within limits of 5 and 150 rad m^{-2}.

(1960), that Loop I is an old supernova remnant shell or bubble located 100 – 150 pc from the Sun. This interpretation is strongly supported by the distance dependence of starlight polarization in the region (Mathewson & Ford 1970), radio continuum and HI observations (Berkhuijsen, Haslam & Salter 1971), radio polarization observations (Spoelstra 1972) and X-ray observations (Egger & Aschenbach 1995).

Although Loop I has weak emission extending to about $l = 60°$ at $b > 10°$, the strongest parts of the loop are confined to $l < 35°$ (Berkhuijsen 1971; Sofue 1994). In contrast, the region of positive RMs in the first quadrant extends to about $l = 80°$. Furthermore, if Loop I is caused by a nearby expanding bubble compressing the prevailing local field, at least at latitudes less than $\sim 50°$, we would expect negative RMs around $l = 30°$ rather than the positive RMs observed. We conclude therefore that Loop I does not contribute significantly to the observed RMs in this region.

Loop II and Loop III in quadrant 3 appear to be similar structures (Berkhuijsen 1971), but there are no obvious corresponding features in the RM maps, which also argues that the RM structure in quadrant 1 is not due to fields associated with Loop I.

The negative RMs in quadrant 4, $b > 0°$, also cover essentially the whole octant (Fig. 1). This striking inverse symmetry with the positive RMs in quadrant 1 argues for a more global explanation. Furthermore, within the uncertainties arising from the finite number of measured RMs, the longitude transition in sign, both above and below the plane, occurs on the meridian through the Galactic Centre. Similarly, the latitude transition occurs on the Galactic plane. If these reversals were caused by local perturbations, there would be no reason for this high degree of symmetry about these major Galactic axes.

Another reason to favour large-scale fields is that the RMs are too large to be accounted for by a local perturbation. In particular, the RM from the North Polar Spur is likely to be only a few rad m^{-2} (Simard-Normandin & Kronberg 1980; Broten et al. 1988) over most of its area. As an extreme case, we take the peak of the emission near l = 30°, where the path through the shell may be as much as 200 pc (Berkhuijsen 1973). Even if we assume a line-of-sight field strength of four times the ambient value, or about 10 μG, the RM contribution is only $\sim$ 50 rad m^{-2} for n_e = 0.03 cm^{-3}. This value is a maximum possible contribution from the North Polar Spur and should be seen only along the main ridge where magnetic fields are strongest. In fact, rotation measures larger than this are seen over the whole region (at least l = 10° – 80°), so it is impossible that they are due to Loop I.

Fig. 3 shows the dependence of |RM| on distance for pulsars in the first and fourth quadrants with $8° < |b| < 30°$. While there is considerable scatter in this plot, the average magnitude of |RM| grows with increasing distance, at least to 3 or 4 kpc from the Sun. The scatter may result from random fluctuations in the magneto-ionic medium or from the changing orientation of the large-scale field relative to the line of sight. Large RMs are seen only at distances greater than about 1.5 kpc. This shows that the fields that give rise to the antisymmetric structure are not local, but are extended over at least 3 or 4 kpc. Furthermore, at a latitude of 30°, a distance of 4 kpc corresponds to a Galactic z-distance of 2 kpc. These fields are therefore well out of the thin Galactic disk, and instead lie in the thick disk (Beuermann, Kanbach & Berkhuijsen 1985) or halo of the Galaxy.

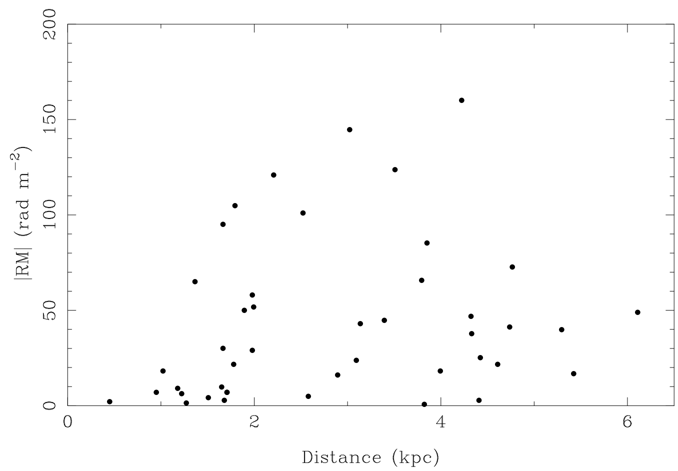

Fig. 3. |RM| versus distance for pulsars with $0° < |l| < 90°$ and $8° < |b| < 30°$.

4. Interpretation and Conclusions

Field structures which are Galactic in scale are believed to have a dynamo origin (Ruzmaikin et al. 1988; Beck et al. 1996). The antisymmetric structure between l = 270° and 90°seen in Figs. 1 and 2 is exactly that expected from an axisymmetric dynamo mode with odd vertical symmetry (A0 mode) operating in the thick disk or halo of the Galaxy. Such a dynamo creates toroidal fields of opposite sign above and below the Galactic plane and poloidal fields of dipole structure perpendicular to the plane in the Galactic Centre region (cf. Fig. 19 of Wielebinski & Krause 1993). Lines of sight with $|l| \lesssim 80°$ will be tangential to the toroidal fields at distances of a few kpc, giving the RM distribution observed. However, it is clear that the antisymmetric structure is not seen in the second and third quadrants and hence that the vertically reversed field structure is not present outside the Solar circle. Fields of odd type are likely to be weaker at large radial distances (Elstner, Meinel & Beck 1992; Poezd et al. 1993) allowing other sources of field to dominate in this region.

Magnetic field structures perpendicular to the Galactic plane in the vicinity of the Galactic Centre have been observed by Yusef-Zadeh & Morris (1987), Haynes et al. (1992) and others. With present sensitivities, these structures appear to have a perpendicular scale of 250 pc or so, and hence are smaller than expected from an odd-mode dynamo. However, the associated fields possibly extend to much greater z-distances. Although not of large scale, these vertical magnetic structures are consistent with the perpendicular fields expected from an odd dynamo in the central region of the Galaxy.

An A0 dynamo is likely to be dominant in quasi-spherical or halo regions of spiral galaxies (Sokoloff & Shukurov 1990). Numerical simulations (Donner & Brandenburg 1990; Brandenburg et al. 1992) showed that the A0 modes are favoured in a thick disk or halo, although these modes might take of order a Hubble time to develop.

However, the existence of radial field reversals in the thin disk indicates that other dynamo modes dominate in this region, for example, A0 with radial reversals, or a mixture with higher-order modes (e.g. A1, S1). It is not known whether the reversals extend into the thick disk. The observations presented here, though, are consistent with a dominant A0 mode. Nonlinear dynamo models are needed to investigate the relationship between dynamo modes in the thick and thin disks.

In face-on external spiral galaxies, odd field structures are difficult to observe because the average line-of-sight RMs differ by only a factor of two between S0 and A0 fields. The polarized emission from the halos of edge-on galaxies is too weak to measure RMs with sufficient accuracy (Beck et al. 1994). Hence our own Galaxy is much better suited to search for odd fields.

We conclude that the observed antisymmetric distribution of RMs in the first and fourth Galactic quadrants and the observed vertical field structures near the Galactic Centre favour the idea that a large-scale, odd dynamo, possibly an A0 mode, operates in the thick disk or halo inside the Solar circle. This conclusion is supported by numerical simulations of linear dynamo modes in thick disks. However, magnetic field structures in the thin disk are more complicated and may result from other dynamo modes.

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