New knowledge of the Galactic magnetic fields

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1. Introduction

Our home Galaxy, the Milky way, is very special in the universe. Supernova explosions in our Galaxy are main accelerators for the middle (TeV) or high (EeV) energy cosmic rays. On the other hand, our Galaxy is a large deflector for cosmic rays because of the magnetic fields in interstellar space.

The first idea about the Galactic magnetic fields was proposed by Fermi [14] when he suggested the origin of cosmic rays from interstellar space and the acceleration by interstellar magnetic fields. Richtmyer & Teller found that magnetic field of $10^{-6}$G is needed to confine the cosmic rays with energy $E \sim 10^{14}$ ev in a scale of $r \sim 3 \times 10^{17}$ cm [50]. Though Alfvén [1] insisted for the solar origin of cosmic rays, he first estimated the strength of Galactic fields amplified by the motion of interstellar medium should be a few $\mu$G, which is correct, using the equipartition of magnetic field energy with motion of gas in the form of $B^2/8\pi \sim \rho v^2/2$ and adopting interstellar gas density $\rho \sim 10^{-24}$ g cm$^{-3}$ and typical gas velocity of 10 km s$^{-1}$. These were only very basic ideas on the extent and strength of Galactic magnetic fields, which are quite right even according to recent analysis [7]. When the extremely high energy cosmic rays ($> 10^{18}$eV) were detected or even imagined, much advanced ideas on the extragalactic magnetic fields were very first proposed, e.g. [9,8]. Nowadays, cosmic ray experts have modeled the magnetic fields of, even outside, our Galaxy and try to simulate the propagation and deflection of cosmic rays as well as their anisotropy, e.g. [55,63,43,58]. It seems that cosmic ray experts often have many advanced ideas about magnetic fields, while observational measuring of the magnetic fields is apparently rather difficult.

The Galactic magnetic field can be detected through observations of Zeeman splitting of spectral lines, of polarized thermal emission from dust at mm, sub-mm or infrared wavelengths, of optical starlight polarization due to anisotropic scattering by magnetically-aligned dust grains, of radio synchrotron emission, and of Faraday rotation of polarized radio sources [18]. The first two approaches have been used to detect respectively the line-of-sight strength and the transverse orientation of magnetic fields in molecular clouds [42,27]. Starlight polarization can be used to delineate the orientation of the transverse magnetic field in the interstellar medium within 2 or 3 kpc of the Sun. Careful analysis of such data shows that the local field is mainly parallel to the Galactic plane and follows local spiral arms [25]. Since we live near the edge of the Galactic disk, we cannot have a face-on view of the global magnetic field structure in our Galaxy through the polarized synchrotron emission, which is possible for nearby spiral galaxies [5]. Polarization observations of synchrotron continuum radiation from the Galactic disk give the transverse direction of the field in the emission region and some indication of its strength. Large-
angular-scale features are seen emerging from the Galactic disk, for example, the North Polar Spur \cite{49}, and the vertical filaments near the Galactic center \cite{13}. There are also many small-angular-scale structures resulting from the diffuse polarized emission at different distances which are modified by foreground Faraday screens. Faraday rotation of linearly polarized radiation from pulsars and extragalactic radio sources is a powerful probe of the diffuse magnetic field in the Galaxy \cite{52,53,31,46,17,20,28}. Faraday rotation gives a measure of the line-of-sight component of the magnetic field. Extragalactic sources have the advantage of large numbers but pulsars have the advantage of being spread through the Galaxy at approximately known distances, allowing direct three-dimensional mapping of the field. Pulsars also give a very direct estimate of the strength of the field through normalization by the dispersion measure (DM).

A diffuse magnetic field exists on all scales in our Galaxy. In fact, only if the magnetic field \( \vec{B}(x, y, z) \) in all positions in our Galaxy is known, one can say that we have a complete picture of the Galactic magnetic fields. Here, \( x, y \) are in the Galactic plane, and \( z \) is normal to that. In practice, we only have “partial” measurements in some regions, so we never get a complete picture. However, if we “connect” the available measurements of different locations, then we may outline some basic features of the Galactic magnetic fields. When one tries to look at the large-scale field structure, the small-scale fields act as “random” fields, “interfering” with your measurements to an extent that depends on the strength of random fields. The large-scale magnetic fields appear as a kind of smooth background at small scales, and exist in a coherent manner at different locations inside our Galaxy. To describe the Galactic magnetic fields, we need to clarify following items:

- **Field structure**
  - Disk field: local structure in the Solar vicinity (3 kpc)?
  - Disk field: large scale structure and reversed directions in arm and interarm regions?
  - Field structure in the Galactic halo?
  - Field structure near the Galactic Center?

- **Field strength \( B \)**
  - Random field versus ordered field: \( \langle \delta B \rangle^2 \) vs. \( B^2 \)?
  - Variation of field strength with the Galacto-radius \( R = \sqrt{x^2 + y^2} \), i.e. \( B \) or \( \delta B \) varies with \( R \)?
  - Variation of field strength with the Galactic height (\( z \)): \( B \) or \( \delta B \) varies with \( z \)?
  - \( B \) or \( \delta B \): difference in arm and interarm regions?

- **Fluctuations and scales**
  - Spatial B-energy spectrum in large and small scales?
  - Maximum field strength in the energy injection scale?

In this review, the magnetic fields in our Galaxy we talk about are the fields in the diffuse interstellar medium, rather than the fields in molecular clouds which are very extensively reviewed by Heiles & Crutcher \cite{27}.

2. The Galactic magnetic fields: a decade ago

A. Local disk field: there was some consensus.

Starlight polarization data are mostly limited to stars within 2 or 3 kpc but gave the very first evidence for large-scale magnetic fields in our Galaxy \cite{36}. It has been shown that the local field is parallel to the Galactic plane and follows the local spiral arms \cite{22}. The rotation measures (RMs) of small sample of local pulsars showed that the local magnetic field going toward \( l \sim 90^\circ \) \cite{32}, with a strength about 2 \( \mu \)G. The field reversal near the Carina-Sagittarius arm was shown by model-fitting to the pulsar RM data by Thomson & Nelson \cite{57}. All these have been confirmed later by much more pulsar RM data \cite{17,28,21}.

B. Which model for the large-scale disk field

When available measurements are very limited, a good model is needed to connect the measurements and give an idea of the basic features. Simard-Normandin & Kronberg \cite{52} and Sofue & Fujimoto \cite{53} showed that the large-scale magnetic fields in the Galactic disk with a bisymmetric spiral (BSS) structure of a negative pitch angle and field reversals at smaller Galacto-radii can fit the (average) RM distribution of extragalactic radio sources along the Galactic longitudes better than the concentric ring model.
New knowledge of the Galactic magnetic fields

and the axisymmetric spiral (ASS) field model. After the RMs of 185 pulsars were published [15], the field reversals near the Carina-Sagittarius arm and the Perseus arm were confirmed [31]. Rand & Kulkarni [46] failed to fit the BSS to the pulsar RM data and emphasized the validity of the concentric ring model (also [47]). Vallée argued [59] for an axisymmetric spiral field model according to early RM data of extragalactic radio sources near tangential directions of spiral arms. Han & Qiao [17] carefully checked the model and data, and found that the BSS model is the best to fit pulsar RM data.

It seems to be not very clear which structure the Galactic magnetic fields have.

C. Fields in the Galactic halo or the thick disk

Evidence was found for a thick magneto-ionic disk with a scale height of \( \sim 1.2 \text{kpc} \) [52,17]. A thin and thick radio disks were found from modeling the radio structure of our Galaxy at 408 MHz [6]. Large-scale polarized features in sky (see a comprehensive review by Reich [48] and references therein) as well as the outstanding features in the RM sky [52] were all attributed to the disturbed local magnetic fields. No large-scale magnetic fields in the Galactic halo were recognized.

D. Fields near the Galactic center

Near the Galactic center vertical filaments were observed [65] and interpreted as illumination of vertical magnetic fields with mG strength [64].

E. Strength of regular and random fields

The strength of large-scale regular field is about 2 \( \mu \text{G} \) [17,46], and the total field is about 6\( \mu \text{G} \). Therefore, random field is stronger than regular field. By adopting a single-cell-size model for the turbulent field, Rand & Kulkarni obtained a turbulent field strength of 5 \( \mu \text{G} \) with a cell size of 55 pc [46], and Ohno & Shibata got 4 - 6 \( \mu \text{G} \) for the random field with an assumed cell size in the range 10 - 100 pc [43]. Extensive discussions on the strength and energy of the random field and regular field can be found in [6]. Rand & Lyne found evidence for stronger fields towards the Galactic center [47].

F. Other Unknowns

There was no information about the variation of field strength with Galactocentric radius or Galactic height, although there were some hints for such variations [6]. It is understandable that the fields in the arm region could be more tangled than these in the interarm regions [17,26], but not much more information was available. There was no consideration of the spatial energy spectrum, i.e., the magnetic field strength on different scales, although turbulence in interstellar medium was known already to follow the Kolmogorov spectrum on small scales.

3. The Galactic magnetic fields: progress in the last decade

Compared to the knowledge a decade ago about the above terms, significant progress has been made on many aspects as we describe below. Pulsars have unique advantages as probes of the large-scale Galactic magnetic field. Their distribution throughout the Galaxy at approximately known distances allows a true three-dimensional mapping of the large-scale field structure. Furthermore, combined with the measured DMs, pulsar RMs give us a direct measure of the mean line-of-sight field strength along the path, weighted by the local electron density. In last decade, a large number of pulsars have been discovered by Parkes pulsar surveys [34,35,38], and many of them are distributed over more than half of the Galactic disk. The RMs of these pulsars provide a unique opportunity for investigation of the magnetic field structure in the inner Galaxy. Compared with about 200 pulsars RMs available in 1993 [56], now in total, the RMs of 550 pulsars have been observed [13], and about 300 of them by our group [45,21,23].

3.1. The magnetic field structure versus the spiral arms: new consensus

A bisymmetric spiral model for magnetic fields in local area (< a few kpc) has been established by using pulsar RM data [17,28,21]. The pitch angle of the magnetic fields is about \(-8^\circ\), with reversals of magnetic field directions. The new analysis of starlight polarization data [25] also gives a pitch angle of large-scale magnetic fields about \(-8^\circ\), coincident with that from pulsar data. We therefore conclude that the large-scale magnetic fields in our Galaxy, at least in the local region, follow the spiral structure and probably have the same pitch angle of spiral arms.

3.2. Discrimination of Models

The limited pulsar RM data and only measurements in local Galactic regions give room for three models
Figure 1. The RM distribution of 374 pulsars with $|b| < 8^\circ$, projected onto the Galactic Plane. The linear sizes of the symbols are proportional to the square root of the RM values, with limits of 9 and 900 rad m$^{-2}$. The crosses represent positive RMs, and the open circles represent negative RMs. The approximate locations of four spiral arms are indicated. The large-scale structure of magnetic fields derived from pulsar RMs are indicated by thick arrows. See reference [23] for details.

3.3. Field structure in the Galactic disk: new measurements

We observed more than 300 pulsar RMs [45,21,23], most of which lie in the fourth and first Galactic quadrants and are relatively distant. These new measurements enable us to investigate the structure of the Galactic magnetic field over a much larger region than was previously possible. We even detected counterclockwise magnetic fields in the most inner arm, the Norma arm [22]. A more complete analysis [23] gives such a picture for the coherent large-scale fields aligned with the spiral-arm structure in the Galactic disk, as shown in Fig.1: magnetic fields in all inner spiral arms are counterclockwise when viewed from the North Galactic pole. On the other hand, at least in the local region and in the inner Galaxy in the fourth quadrant, there is good evidence that the fields in interarm regions are similarly coherent, but clockwise in orientation. There are at least two or three reversals in the inner Galaxy, occurring near the boundary of the spiral arms [21,23]. The magnetic field in the Perseus arm can not be determined well, although Brown et al. argued for no reversal [10], using the negative RMs for distant pulsars and extragalactic sources which in fact suggest the interarm fields both...
Figure 2. The antisymmetric rotation measure sky, derived from RMs of extragalactic radio sources after filtering out the outliers of anomalous RM values, should correspond to the magnetic field structure in the Galactic halo as illustrated on the right [20,21].

between the Sagittarius and Perseus arms and beyond the Perseus arm are predominantly clockwise.

3.4. Field structure in the Galactic halo

The magnetic field structure in halos of other galaxies is difficult to observe. Our Galaxy is a unique case for detailed studies, since polarized radio sources all over the sky can be used as probes for the magnetic fields in the Galactic halo.

From the RM distribution in the sky, Han et al. identified the striking antisymmetry in the inner Galaxy respect to the Galactic coordinates [20,21], as being a result from the azimuth magnetic fields in the Galactic halo with reversed field directions below and above the Galactic plane (see Fig.2). Such a field can be naturally produced by an A0 mode of dynamo (see reference [62] for a review). The observed filaments near the Galactic center should result from the dipole field in this scenario. The local vertical field component of $\sim 0.2 \mu G$ [17,21] may be related to the dipole field in the solar vicinity.

I have shown [16] that the RM amplitudes of extragalactic radio sources in the mid-latitudes of the inner Galaxy are systematically larger than those of pulsars, indicating that the antisymmetric magnetic fields are not local but are extended towards the Galactic center, far beyond the pulsars. We are observing more RMs of extragalactic radio sources and modeling the RM sky with a various magnetic field structure in the Galactic halo. The azimuthal halo fields with reversed directions above and below the Galactic plane could simply result from a shearing of the dipole fields by differentially rotating layers of the ISM.

3.5. Field strength on different scales

Interstellar magnetic fields exist over a broad range of spatial scales, from the large Galactic scales to the very small dissipative scales, but with different field strength. Knowledge of the complete magnetic energy spectrum can offer a solid observational test for dynamo and other theories for the origin of Galactic magnetic fields [4].

Estimation of the large-scale field strength [17,23] and a turbulent field strength at a scale of tens of pc [46,43] is only the first step. It is also possible to get more hints from electron density fluctuations in interstellar medium, since magnetic fields are also always frozen in the interstellar gas. The spatial power spectrum of electron density fluctuations from small scales up to a few pc [3] could be approximated by a single power law with a 3D spectral index $-3.7$, very close to the Kolmogorov spectrum, which gives us a hint that the magnetic energy on the small scales to a few pc should have the Kolmogorov spectrum as well. This was confirmed by Minter & Spangler who found [37] that structure functions of RM and emission measure were consistent with a 3D-turbulence Kolmogorov spectra of magnetic fields up to 4 pc, but with a 2D turbulence between 4 pc and 80 pc. The RM fluctuations, due to both the magnetic fields and electron density, are much enhanced in the Galactic spiral arms than in interarm regions [24].

Pulsar RMs are the integration of field strength times electron density over the path from a pulsar
Figure 3. Composite magnetic-energy spectrum in our Galaxy. The large-scale spectrum was derived from pulsar RM data [19]. The thin solid and dashed/dotted lines at smaller scales are the Kolmogorov and 2D-turbulence spectra given by Minter & Spangler [37], and the upper one is from new measurements of Minter (2004, private email). Therefore, RM data of pulsars with different distances should reflect the fluctuations on different scales. Han et al. investigated the RM differences at different scales and obtained the spatial energy spectrum of the Galactic magnetic field in scales between $0.5 < \lambda < 15$ kpc [19], which is a 1D power-law as $E_B(k) \sim k^{-0.37 \pm 0.10}$, with $k = 1/\lambda$. The rms field strength is approximately 6 $\mu$G over the relevant scales and the spectrum is much flatter than the Kolmogorov spectrum for the interstellar electron density and magnetic energy at scales less than a few pc.

3.6. Variation of the field strength with Galactocentric radius

Stronger regular magnetic fields in the Galactic disk towards the Galactic Center have been suggested in references [53,46,26]. Such a radial variation of total field strength has been derived from modeling of the Galactic synchrotron emission (E. Berkhuijsen, Fig.14 in [61]) and the Galactic $\gamma$-ray background [54]. Measurements of the regular field strength in solar vicinity give values of $1.5 \pm 0.4$ $\mu$G [46,17,28], but near the Norma arm it is $4.4 \pm 0.9$ $\mu$G [22].

With the much more pulsar RM data now available, Han et al. were able to measure the regular field strength near the tangential points in the 1st and 4th Galactic quadrants [23], and then plot the dependence of regular field strength on the Galactoradii (see Fig. 4). Although uncertainties are large, there are clear tendencies for fields to be stronger at smaller Galactocentric radii and weaker in interarm regions. To parameterize the radial variation, an exponential function was used as following, which not only gives the smallest $\chi^2$ value but also avoids the singularity at $R = 0$ (for $1/R$) and unphysical values at large R (for the linear gradient). That is, $B_{\text{reg}}(R) = B_0 \exp \left[ -\frac{(R-R_\odot)}{R_B} \right]$, with the strength of the large-scale or regular field at the Sun, $B_0 = 2.1 \pm 0.3$ $\mu$G and the scale radius $R_B = 8.5 \pm 4.7$ kpc.

3.7. Magnetic fields near the Galactic center

Progress has been made in two aspects for the region within tens to hundreds pc of the Galactic Center, both for poloidal fields and for toroidal fields [41].

Poloidal fields: More non-thermal filaments near the Galactic center have been discovered [29,40,66]. The majority of the brighter non-thermal filaments are perpendicular to the Galactic plane, indicating a predom-
New knowledge of the Galactic magnetic fields

Dominantly poloidal fields of $\sim$\,mG strength, but some filaments are not, indicating a more complicated field structure than just the poloidal field. LaRosa et al. detected the diffuse radio emission \[30\] and argued for a weak pervasive field of tens of $\mu$G near the Galactic Center. The new discovery of an infrared ‘double helix’ nebula \[39\] reinforces the conclusion of strong poloidal magnetic fields merging from the rotated circumnuclear gas disk near the Galactic center.

**Toroidal fields**: With the development of polarimetry at mm, submm or infrared wavelengths, toroidal fields have been observed near the Galactic center \[42,11\], complimenting the poloidal fields shown by the vertical filaments. Analysis of the much enhanced RMs \[51\] of radio sources near the Galactic Center may indicate toroidal field structure.

4. The Galactic magnetic fields: work to do

We have known a lot about the Galactic magnetic fields, but it is far away to have a full picture of Galactic magnetic fields. Here I list some questions which might be answered in next years.

1. Large-scale field structure in the Galactic disk: The RM data of extragalactic radio sources in the outer Galaxy show no field reversal in the Perseus arm \[10\], while the weak evidence for the reversal comes from pulsar RMs about $l \sim 70^\circ$ \[21,60\]. RMs of newly discovered pulsars from Arecibo pulsar survey \[12\] would become available in or exterior to the Perseus arm, which can settle down this controversy. The field structure in the 1st Galactic quadrant can be, but not yet, revealed by more pulsar RM data.

2. Detailed field structure and field strength in the Galactic halo. We need much more RM data over the all sky. We have observed 1700 RMs using Effelsberg telescope and will try our best for the model of the halo field.

3. It is important to know the magnetic energy spectrum from scales of 1 pc to 0.5 kpc, which has not been well determined at the moment. The strongest field should be the energy-injection-scale, which should be a few pc from supernova remnants. We have very little measurements of the fields on scales around 10 pc, which is extremely important for the discrimination of mechanisms for the maintenance or generation of magnetic fields. It is also necessary to determine the spectrum at small scales in different parts of the Galactic disk.

4. We have to understand the magnetic field near the Galactic center. There is consensus on the field structure \[66,39\] but not the field strength \[30,64\]. More data and physical analysis are desired to make a coherent picture.

5. The field strength must vary with the Galactic height and the Galactocentric radius. At present, we haven’t had a good measure on $B \sim B(z)$ yet. We should be able to model it according to currently available data.

5. Concluding remarks

In the last decade, there has been significant progress in studies of Galactic magnetic fields, mainly due to the availability of a large number of newly observed RMs of pulsars. Further pulsar rotation measure observations, especially for interarm regions and especially in the first Galactic quadrant, would be especially valuable to confirm the large-scale magnetic field structure in the Galactic disk. An improved RM database for the whole sky will enable us to probe details of the magnetic fields in the Galactic halo. Future detailed modeling of the global magnetic field structure of our Galaxy should match all measurements of the fields in different directions or locations, including the field near the Galactic center.

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