

The Galactic magnetic fields

JinLin Han

National Astronomical Observatories, Chinese Academy of Sciences,
Jia-20, DaTun Road, Chaoyang District, Beijing 100012, China

E-mail: hjl@bao.ac.cn

Abstract. A good progress has been made on studies of Galactic magnetic fields in last 10 years. I describe what we want to know about the Galactic magnetic fields, and then review we current knowledge about magnetic fields in the Galactic disk, the Galactic halo and the field strengths. I also listed many unsolved problems on this area.

1. Introduction

The first idea about the Galactic magnetic fields[‡] was proposed by Fermi (1949) when he suggested the origin of cosmic rays from interstellar space and the acceleration by interstellar magnetic fields. Though Alfvén (1949) insisted for the solar origin of cosmic rays, he first estimated the strength of Galactic fields amplified by motion of interstellar medium, $B \sim$ a few μG , 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 $\rho \sim 10^{-24}\text{g cm}^{-3}$ and typical gas velocity of 10 km s^{-1} . These are only very basic concepts on the extent and strength of Galactic magnetic fields.

Nowdays, to study the origin, the transportation and the arrival direction and species of cosmic rays, especially in recent computer simulations (e.g. Stanev 1997; Tinyakov & Tkachev 2002; Prouza & Šmída 2003; Torres & Anchordoqui 2004; Yoshiguchi et al. 2004), details of Galactic magnetic fields are appreciated. In short, we like to know $\vec{B}(x, y, z)$ for the whole Galaxy. To fully describe the Galactic magnetic fields, we probably have to know 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**

[‡] Thanks to Peter Biermann for reminding me this important fact, especially for this conference.

- Random field versus ordered field: $\langle \delta B \rangle^2 / B^2$?
- Dependence on the Galacto radius ($R = \sqrt{x^2 + y^2}$): B or δB as a function of R , i.e. $f(R)$?
- Dependence on the height (z) from the Galactic plane: B or $\delta B \sim f(z)$?
- B or δB : difference in arm and interarm regions?
- **Strength versus scales**
 - Spatial B-energy spectrum?
 - Maximum field strength in the energy injection scale?

When we talk about Galactic magnetic fields, we only concern the magnetic fields in diffuse interstellar medium, and do not care much about the fields inside molecular clouds (see Crutcher 2004) except for the cases where the fields are related to the large-scale magnetic fields (e.g. Novak et al. 2003). Though we have already know many basic facts about the Galactic magnetic fields, it is true that we are premature to give a good picture.

2. The Galactic magnetic fields: Knowledge about 10 years ago

When real measurements available are very limited, a good model could be very useful. About the magnetic field in the Galactic disk, there were three models. Vallée (1991) argued for an axisymmetric spiral field model according to Rotation Measures (RMs) of some extragalactic radio sources near tangential direction of spiral arms. Rand & Kulkarni (1989) and Rand & Lyne (2004) analyzed the new RM data of pulsars, and proposed the concentric ring model for the disk field according to pulsar RMs available that time. SIMD-Normandin & Kronberg (1980) and Sofue & Fujimoto (1983) fitted a bisymmetric spiral field model to the (average) RM distribution along the Galactic longitudes, which was later supported by Han & Qiao (1994) using pulsar RM data. These three models have to be verified by more data.

We also got to know from starlight polarization that the local field is parallel to the Galactic plane and follow the local spiral arms (see Andrae & Makarov 1989). The pulsar RM data have shown that the local magnetic field going toward $l \sim 90^\circ$ (Manchester 1974). Another consensus about the field structure is that the fields reverse their direction (i.e. going towards $l \sim 270^\circ$) in about the Carina-Sagittarius arm (Thomson & Nelson 1980; Lyne & Smith 1989).

Near the Galactic center, the vertical filaments were observed (Yusef-Zadeh et al. 1984) and interpreted as illumination of vertical magnetic fields (Yusef-Zadeh & Morris 1987).

These above are the main results about the structure of magnetic fields. The field strengths were measured from pulsar rotation measures and dispersion measures. For the large-scale field, the strength is about $2 \mu\text{G}$ (Rand & Kulkarni 1989; Han & Qiao 1994), but for the random field the strength is about $6 \mu\text{G}$ (Ohno & Shibata 1993).

3. The Galactic magnetic fields: progress in last 10 years

Indeed there are a lot of progress on Galactic magnetic fields, mostly comes from the more RMs of newly discovered pulsars.

3.1. Pitch angle

After Han & Qiao (1994) and Indrani & Deshpande (1998) as well as Han et al. (1999), the bisymmetric spiral model for magnetic fields in local area ($<$ a few kpc) have been established. The new analysis of starlight polarization data of Heiles (1996) also gives a pitch angle of large-scale magnetic fields about -8° . Therefore we can conclude that the large-scale magnetic field in our Galaxy follow the spiral structure, at least in the local regions for sure.

3.2. Field structure in the Galactic disk

Pulsar RMs are unique probes for the 3-D magnetic field in the Galactic disk. Thanks for the newly discovered pulsars, mostly by Parkes pulsar surveys (e.g. Manchester et al. 1996; Manchester et al. 2001), which spread in about half of the Galactic disk and enable us to detect the magnetic field in about one third of the disk.

The limited RM data and other measurements in a small local area gives the space for all three models to survive. From pulsar RM data available now, it becomes clear now that the fields in the inner Galaxy have two or three reversals, which always occur near the boundary of the spiral arms (Han et al. 1999, 2005). This, together with the pitch angle, strongly favors the bisymmetric spiral model. The newly observed pulsar RMs in the much extended area of the Galactic disk are not consistent with the concentric ring model and the axisymmetric model.

Using a large number of pulsar RMs, we even detected the counter-clockwise magnetic fields in the most inner arm, the Norma arm (Han et al. 2002). A more complete analysis by Han et al. (2005) gives such a primary picture for the large-scale magnetic field structure in the Galactic disk as shown in Fig.1: magnetic fields in all inner spiral arms are going counterclockwise when viewed from the North Galactic pole, and fields in all interarm regions evidently going clockwise. More RM data, especially in the interarm regions, are needed to confirm this global picture.

3.3. Field structure in the Galactic halo

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

From the RM distribution, we identified the antisymmetric RM sky 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 the A0 dynamo (Han et al. 1997). The observed filaments near the Galactic center

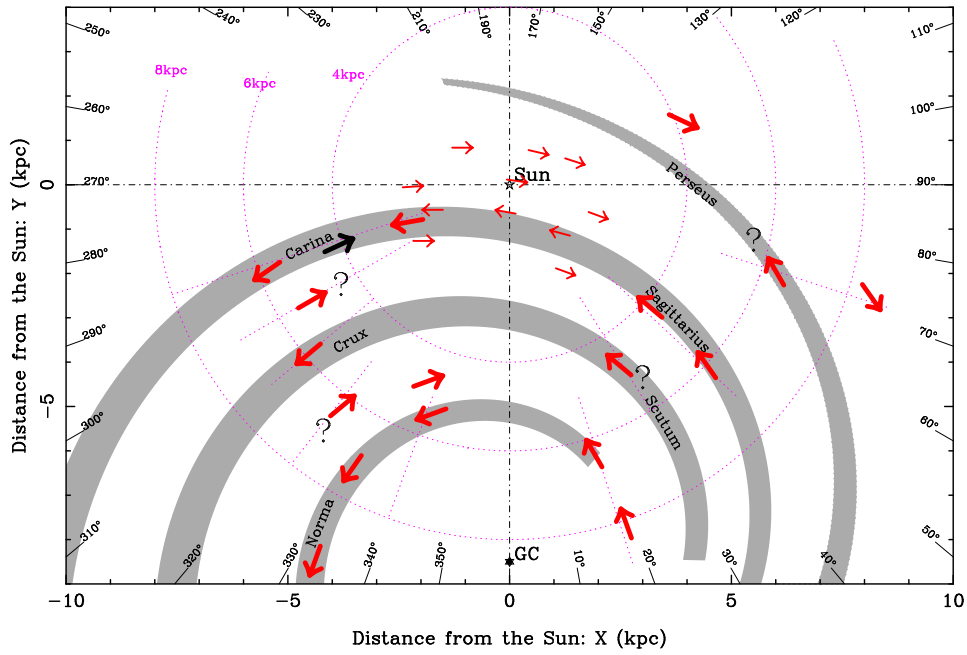


Figure 1. The observed large-scale structure of magnetic fields in the Galactic disk. See Han et al. (2005) for details.

should come from the dipole field in this frame. The local vertical field component of $\sim 0.2 \mu\text{G}$, as shown by Han & Qiao (1994) and Han et al. (1999), may be related to the dipole field in the solar vicinity.

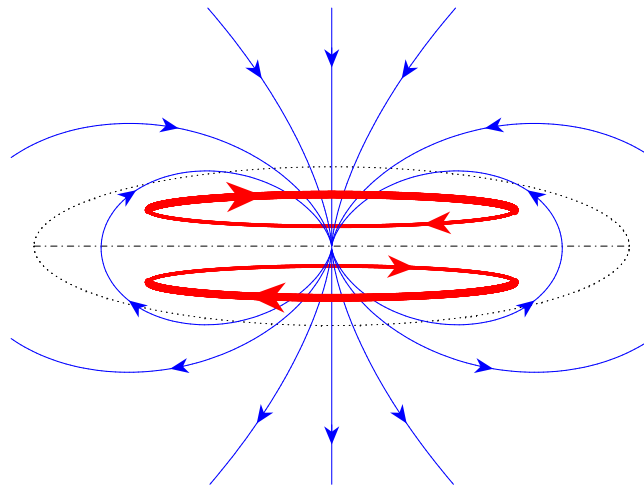


Figure 2. The magnetic field structure in the Galactic halo and near the Galactic center, according to the rotation measure sky and filaments near the Galactic center. See Han et al. (1997) for details.

Near the Galactic center, the toroidal fields have been observed in the molecular clouds (Novak et al. 2003). This is very new and compliment to the poloidal fields

shown by the vertical filaments.

However, these are very qualitative results. We do need more data to reveal the details and determine the strength of the halo field.

3.4. Field strength on different scales

Previous estimates about random field strength was about $B \sim 6\mu\text{G}$ at scales about 10-100 pc (Rand & Kulkarni 1989; Ohno & Shibata 1993). This rough value is a result from simulations with a single cell-size. Field strength at scales larger than a few kpc is about 1 or 2 μG (e.g. Han & Qiao 1994).

It is very difficult to figure out the field strength on different scales. Han et al. (2004) have obtained the spacial energy spectrum of the Galactic magnetic field from pulsar RM data. The basic result shows that the fields is about 1 μG on a scale of 10 kpc, but increase to $\sim 2\mu\text{G}$ on about 1 kpc. and increase exponentially for smaller scales. The magnetic energy $E_B(k) \sim k^{-0.37 \pm 0.10}$ in scales between $0.5 < \lambda < 15$ kpc, with $k = 1/\lambda$. This is much flatter spectrum than the Kolmogorov spectrum for the interstellar electron density and magnetic energy at scales less than a few pc.

Using pulsar RM data, Han et al. (2005) also figured out that the regular magnetic fields get stronger towards the smaller Galactocentric radius.

3.5. Unresolved problems

If one compares what we knew with the list for what we want to know, it is true that we know very little. We are far away to have a full picture of Galactic magnetic fields. Here are some problems which should be solved in next years.

1. Large-scale field in the Perseus arm: Brown et al. (2003) argued for non-field reversal in the arm using the RM data of extragalactic radio sources in the outer Galaxy. While the weak evidence for the reversal is the pulsar RMs about $l \sim 70^\circ$ (Han et al. 1999; Weisberg et al. 2004). We expect more polarization observations for pulsars in or exterior to the Perseus arm, which will be discovered by the Arecibo ALFA survey (Cordes et al. 2005), can settle down this controversy.

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 is not 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 do not know the field strength near the Galactic center. Recent LaRosa et al. (2005) argued that the field is not as strong as mG but only several μG . More data

seems necessary to make a coherent picture.

5. The field strength must vary with the Galactic height and the Galactocentric radius. At present, we do not have a good measure on $B \sim B(z)$ yet.

4. Concluding remarks

In the last decade, there have been a great progress in this research area. In next decade the new development of instruments, such as the EVLA, will enable us to probe details of the magnetic fields in the Galactic halo.

It is also interesting to note that the propagation of cosmic ray protons in the energy range 10^{18} to 10^{19} eV, such data are being collected now, may help to diagnose parity of the Galactic magnetic fields in future (see Alvarez-Muñiz & Stanev, 2005).

For further reading, I would like to point to my recent reviews. Han (2004) § briefly reviewed the methods to reveal magnetic fields in our Galaxy, and current understanding about magnetic fields in the Galactic halo, in the Galactic disk. The structure of magnetic fields in the Galactic disk is now updated in a recent paper by Han et al. (2005).

Acknowledgments

I sincerely thank Dr. R.N. Manchester from Australian Telescope National Facility (Australia) and Prof. G.J. Qiao from Peking University (China) for working together with me in last 10 years to improve the knowledge on the magnetic fields of our Galaxy, and also Prof. Andrew Lyne from Jodrell Bank Observatory (UK) and Dr. Katia Ferriere from Observatory of Midi-Pyrénées (France) for recent cooperations on the topic. My research in China is supported by the National Natural Science Foundation of China (1025313 and 10473015) and the National Key Basic Research Science Foundation of China (G19990756).

References

- Alfvén, H. 1949, *Phys. Rev.* **75**, 1732
 Alvarez-Muñiz, J., Stanev, T. 2005, *astro-ph/0507273*.
 Andriasyan, R. R., Makarov, A. N. 1989, *Afz.* **31(2)**, 247
 Brown, J. C., Taylor, A. R., Wielebinski, R., Mueller, P. 2003, *ApJ.* **592**, 29
 Cordes, J.M., et al. 2005, *ApJ.* **submitted**
 Crutcher, R.M., 2004, in *The Magnetized Interstellar Medium*, Proceedings of the conference, held in Antalya, Turkey, September 8 - 12, 2003, Eds: B. Uyaniker, W. Reich, and R. Wielebinski, Copernicus GmbH, Katlenburg-Lindau., p. 123-132,
 Fermi, E. 1949, *Phys. Rev.* **75**, 1169
 Heiles, C. 1996a, *ApJ.* **462**, 316

§ <http://www.mpifr-bonn.mpg.de/div/konti/antalya/Session-I.pdf>

- Han, J. L. 2004, in *The Magnetized Interstellar Medium*, Proceedings of the conference, held in Antalya, Turkey, September 8 - 12, 2003, Eds: B. Uyaniker, W. Reich, and R. Wielebinski, Copernicus GmbH, Katlenburg-Lindau., p.3
- Han, J. L., Manchester, R. N., Berkhuijsen, E. M., Beck, R. 1997, *A&A*. **322**, 98
- Han, J. L., Manchester, R. N., Lyne, A. G., Qiao, G. J. 2005, *ApJ*. **submitted**.
- Han, J. L., Manchester, R. N., Lyne, A. G., Qiao, G. J. 2002, *ApJ*. **570**, 17
- Han, J. L., Manchester, R. N., Qiao, G. J. 1999, *MNRAS*. **306**, 371
- Han, J. L., Qiao, G. J. 1994, *A&A*. **288**, 759
- Indrani, C., Deshpande, A. A. 1998, *New Astron.* **4**, 33
- LaRosa, T. N., Brogan, C. L., Shore, S. N., Lazio, T. J., Kassim, N. E., Nord, M. E. 2005, *ApJ*. **626**, L23
- Lyne, A. G., Smith, F. G. 1989, *MNRAS*. **237**, 533
- Manchester, R. N. 1974, *ApJ*. **188**, 637
- Manchester, R. N., Lyne, A. G., Camilo, F. et al. 2001, *MNRAS*. **328**, 17
- Manchester, R. N., Lyne, A. G., D'Amico, N., Bailes, M., Johnston, S., Lorimer, D. R., Harrison, P. A., Nicastro, L., Bell, J. F. 1996, *MNRAS*. **279**, 1235
- Novak G., Chuss, D. T., Renbarger, T., Griffin, G. S., Newcomb, M. G., Peterson, J. B., Loewenstein, R. F., Pernic, D., Dotson, J. L. 2003, *ApJ*. **583**, 83
- Ohno, H., Shibata, S. 1993, *MNRAS*. **262**, 953
- Prouza, M., Šmída, R. 2003, *A&A*. **410**, 1
- Rand, R. L. & Kulkarni, S. R. 1989, *ApJ*. **343**, 760
- Rand, R. L. & Lyne, A. G. 2004, *MNRAS*. **268**, 497
- Simard-Normandin, M., Kronberg, P. P. 1980, *ApJ*. **242**, 74
- Sofue, Y., Fujimoto, M. 1983, *ApJ*. **265**, 722
- Stanev, T. 1997, *ApJ*. **479**, 290
- Thomson, R. C., Nelson, A. H. 1980, *MNRAS*. **191**, 863
- Tinyakov, P. G., Tkachev, I. I. 2002, *AstroPart. Phys.* **18**, 165
- Torres, D. F., Anchordoqui, L. A. 2004, *Rep. Prog. Phys.* **67**, 1663
- Vallée J. P. 1991, *ApJ*. **366**, 450
- Weisberg, J. M., Cordes, J. M., Kuan, B., Devine, K. E., Green, J. T., Backer, D. C. 2004, *ApJS*. **150**, 317
- Yoshiguchi, H., Nagataki, S., Sato, K. 2004, *ApJ*. **607**, 840
- Yusef-Zadeh, F., Morris, M. 1987, *ApJ*. **320**, 545
- Yusef-Zadeh, F., Morris, M., Chance, D. 1984, *Nature*. **310**, 557