Chin. J. Astron. Astrophys. Vol. 6 (2006), **Suppl. 2**, 211–217
(*http://www.chjaa.org*)

Chinese Journal of
Astronomy and
Astrophysics

Magnetic Fields in Our Galaxy: How much do we know?
III. Progress in the Last Decade

J. L. Han ⋆

National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China

Abstract A decade ago, there was very limited knowledge of magnetic fields of our Galaxy. The local fields in the Solar vicinity were known to be directed towards a Galactic longitude $l \sim 90°$ with reversed directions at smaller Galacto-radii. The regular field strength was found to be about 2 μG. The filaments near the Galactic Center show the possible poloidal fields there. There was no information about the magnetic fields in the Galactic halo. In last decade, there has been significant progress on measurements of the Galactic magnetic fields. In the Galactic disk, from the RMs of a large number of newly observed pulsars, large-scale magnetic fields along the spiral arms have been delineated in a much larger region then ever before, with alternating directions in the arm and interarm regions. The toroidal fields in the Galactic halo have been revealed to have opposite directions below and above the Galactic plane, which is an indication of an A0 mode dynamo operating in the halo. The strength of large-scale fields also has been found from pulsar RM data to exponentially increase at smaller Galacto-radii. Compared to the steep Kolmogorov spectrum of magnetic energy at small scales, the large-scale magnetic fields show a shallow broken spatial magnetic energy spectrum.

Key words: Pulsars: general — ISM: magnetic fields — Galaxy: structure

1 INTRODUCTION

Magnetic fields in our Galaxy: How much do we know? When I first asked myself this question, I discussed the magnetic fields in local Galactic disk in Han (2001). The magnetic fields in the Galactic halo and the global field structure picture with maximum likelihood were discussed in Han (2002) as being the second part of the answer. Now, in this third one, I will talk about progress in the last decade, and also show how much we should know.

Only if the magnetic field $\boldsymbol{B}(x, y, z)$ 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.

Magnetic fields exist on all scales in our Galaxy, the Milky Way. 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. 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 (2005).

To describe the Galactic magnetic fields, we need to clarify following items:

⋆ E-mail: `hjl@bao.ac.cn`

- **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 δB varies with R?
  - Variation of field strength with the Galactic height (z): B or δB varies with z?
  - B or δB: 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?

There are five observational tracers for the Galactic magnetic fields: Zeeman splitting, polarized thermal emission from the dusts in clouds, polarization of starlight, synchrotron radio emission, Faraday rotation of polarized sources. All knowledge of the Galactic magnetic fields comes from observations of these tracers, but some show the local fields and some show the large-scale fields. Compared to the knowledge a decade ago about the above terms, significant progress has been made on many aspects as we describe below.

2 THE GALACTIC MAGNETIC FIELDS: STATUS 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. It has been shown that the local field is parallel to the Galactic plane and follows the local spiral arms (e.g. Andreasyan & Makarov 1989). The rotation measures (RMs) of small sample of local pulsars showed that the local magnetic field going toward $l \sim 90°$ (Manchester 1974), with a strength about 2 μG. The field reversal near the Carina-Sagittarius arm was shown by model-fitting to the pulsar RM data by Thomson & Nelson (1980). All these have been confirmed later by much more pulsar RM data.

B. Which model for the large-scale disk field? Not clear.

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 (1980, SK80) and Sofue & Fujimoto (1983) show 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 and the axisymmetric spiral (ASS) field model. After Hamilton & Lyne (1987) published the RMs of 185 pulsars, the field reversals near the Carina-Sagittarius arm and the Perseus arm were confirmed by Lyne & Smith (1989). Rand & Kulkarni (1989: RK89) failed to fit the BSS to the pulsar RM data and emphasized the validity of the concentric ring model (also in Rand & Lyne 1994). Vallée (1996) argued for an axisymmetric spiral field model according to early RM data of extragalactic radio sources near tangential directions of spiral arms. Han & Qiao (1994: HQ94) carefully checked the model and data, and found that the BSS model is the best to fit pulsar RM data.

C. Fields in halo or thick disk? Did not know much.

SK80 and HQ94 found evidence for a thick magneto-ionic disk with a scale height of ~1.2 kpc. A thin and thick radio disk was found from modeling the radio structure of our Galaxy at 408 MHz (Beuermann et al. 1985). Large-scale polarized features in sky (see a comprehensive review by Reich 2006 and references therein) as well as the outstanding features in the RM sky (e.g. SK80) 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? Yes.

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

E. Strength of regular and random fields? There were estimates.

The strength of large-scale regular field is about 2 μG (HQ94, RK89), and the total field is about 6 μG. Therefore, random field is stronger than the regular fields. By adopting a single-cell-size model for the turbulent field, RK89 obtained a turbulent field strength of 5 μG with a cell size of 55 pc, and Ohno & Shibata (1993) got $4-6$ μG for the random fields with an assumed cell size in the range $10-100$ pc. Heiles (1996b) discussed the strength and energy of the random fields and regular fields.

Rand & Lyne (1994) found evidence for stronger fields towards the Galactic center.

F. Others: Unknown.

There was no information about the variation of field strength with Galactocentric radius or Galactic height, although there was some hints for such variations (e.g. Beuermann et al. 1985). It is understandable that the fields in the arm region could be more tangled than these in the interarm regions (see HQ94), but not much more information is 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.

3 THE GALACTIC MAGNETIC FIELDS: PROGRESS LAST DECADE

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 (e.g., Manchester et al. 2001), 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, now in total, the RMs of 550 pulsars have been observed, and about 300 of them by Qiao et al. (1995) and Han et al. (1999, 2006).

3.1 The Magnetic Field Structure Versus the Spiral Arms: New Consensus

After Han & Qiao (1994) and Indrani & Deshpande (1998) as well as Han et al. (1999), a bisymmetric spiral model for magnetic fields in local area ($<$ a few kpc) has been established. The new analysis of starlight polarization data of Heiles (1996a) also gives a pitch angle of large-scale magnetic fields about $-8°$. We can also 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 gives room for three models to survive. Discrimination between different models is complicated by small-scale irregularities of field structure and sparse measurements. However, the measured pitch angle of the magnetic fields using different approaches, as we have seen above, is hard evidence to rule out the concentric ring model of RK89 and Rand & Lyne (1994) which has zero pitch angle. See detailed analysis of Indrani & Deshpande (1998) and discussions in Han et al. (1999, 2006). The axisymmetric model of Vallée (1996) suggests that the field near the Norma arm is clockwise, which has been disapproved by Han et al. (2002, 2006). New measurements of the large-scale fields in the Galactic disk (Han et al. 2006) suggest a tighter BSS field structure.

3.3 Field Structure in the Galactic Disk: New Measurements

We observed more than 300 pulsar RMs (Qiao et al. 1995; Han et al. 1999, 2006), 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 counter-clockwise magnetic fields in the most inner arm, the Norma arm (Han et al. 2002). A more complete analysis by Han et al. (2006) gives such a picture for the coherent large-scale fields aligned with the spiral-arm structure in the Galactic disk, as shown in Figure 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 (Han et al. 1999, 2006). The magnetic field in the Perseus arm can not be determined well, though Brown et al. (2003) argued for

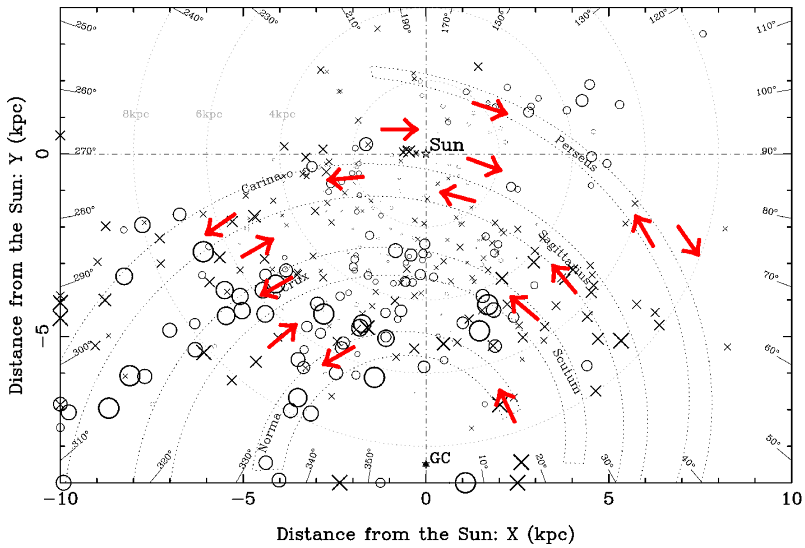

Fig. 1 The RM distribution of 374 pulsars with $|b| < 8^\circ$, projected onto the Galactic Plane. The linear sizes of the symbols are proportional to the square root of the RM values, with limits of 9 and 900 rad m^{-2}. The crosses represent positive RMs, and the open circles represent negative RMs. 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 Han et al. (2006) for details.

no reversal, using the negative RMs for distant pulsars and extragalactic sources which in fact suggest the interarm fields both between the Sagitarius 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. (1997, 1999) identified the striking antisymmetry in the inner Galaxy respect to the Galactic coordinates, as being a result from the azimuth magnetic fields in the Galactic halo with reversed field directions below and above the Galactic plane (see Figure 2). Such a field

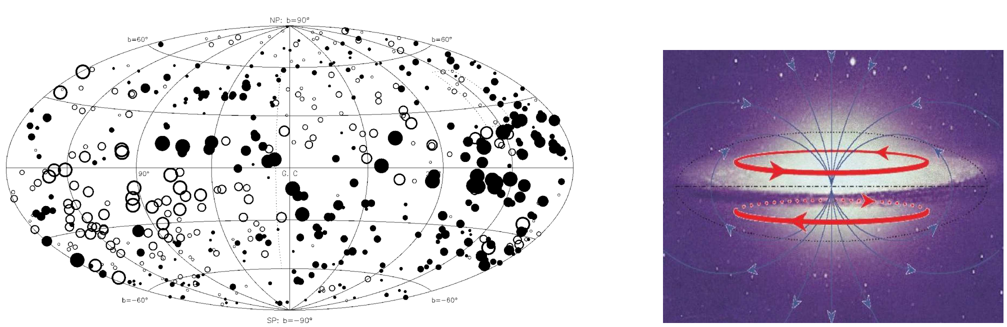

Fig. 2 The antisymmetric rotation measure sky, derived from RMs of extragalactic radio sources after filtering out the outliers of anomalous RM values, should correspond to the magnetic field structure in the Galactic halo as illustrated on the right. See Han et al. (1997) for details.

can be naturally produced by an A0 mode of dynamo (see Wielebinski & Krause 1993 and Beck et al. 1996 for reviews). The observed filaments near the Galactic center should be result from the dipole field in this scenario. The local vertical field component of $\sim$0.2 μG (HQ94 and Han et al. 1999) may be related to the dipole field in the solar vicinity.

Han (2004) has shown 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.

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 (e.g. Balsara & Kim 2005).

Estimation of the large-scale field strength (e.g. HQ94, Han et al. 2006) and a turbulent field strength at a scale of tens of pc by RK89 and Ohno & Shibata (1993) 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. Armstrong et al. (1995) showed that the spatial power spectrum of electron density fluctuations from small scales up to a few pc could be approximated by a single power law with a 3D spectral index -3.7, very close to the Kolmogorov spectrum. Minter & Spangler (1996) found 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. Haverkorn et al. (2006) found the RM fluctuations are much enhanced in the Galactic spiral arms than in interarm regions.

Pulsar RMs are the integration of field strength times electron density over the path from a pulsar to us. Therefore, RM data of pulsars with different distances should reflect the fluctuations on different scales. Han et al. (2004) took RM differences and obtained the spatial energy spectrum of the Galactic magnetic field in scales between $0.5 < \lambda < 15$ kpc, which is a 1D power-law as $E_B(k) \sim k^{-0.37\pm0.10}$, with $k = 1/\lambda$. The rms field strength is approximately 6 μG 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 (see Figure 3).

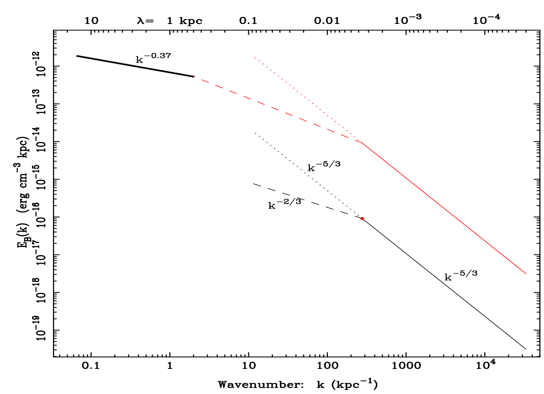

Fig. 3 Composite magnetic-energy spectrum in our Galaxy. The large-scale spectrum was derived from pulsar RM data. The thin solid and dashed/dotted lines at smaller scales are the Kolmogorov and 2D-turbulence spectra inferred from the results of Minter & Spangler (1996), and the upper one is from new measurements of Minter (2004, private email). See Han et al. (2004) for details.

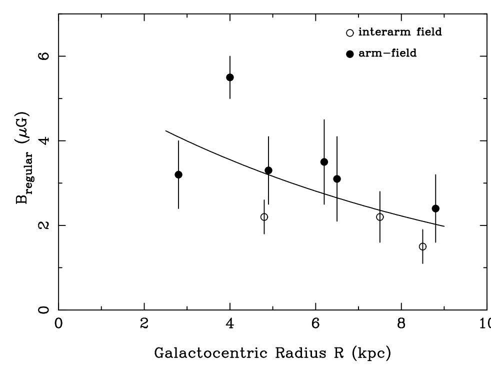

Fig. 4 Variation of the large-scale regular field strength with the Galactocentric radius. Filled dots are for arm regions and small open circles are for interarm regions. The curved line is a fit of an exponential model. See Han et al. (2006) for details.

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 by Sofue & Fujimoto (1983), RK89 and Heiles (1996b). Such a radial variation of total field strength has been derived from modeling of the Galactic synchrotron emission (E. Berkhuijsen, Figure 14 in Wielebinski 2005) and the Galactic $\gamma-$ray background by Strong et al. (2000). Measurements of the regular field strength in solar vicinity give values of $1.5 \pm 0.4\,\mu$G (HQ94, Indrani & Deshpande 1998), but near the Norma arm it is $4.4 \pm 0.9\,\mu$G (Han et al. 2002).

With the much more pulsar RM data now available, Han et al. (2006) were able to measure the regular field strength near the tangential points in the 1st and 4th Galactic quadrants, and then plot the dependence of regular field strength on the Galactoradii (see Figure 4). Although uncertainties which reflect the random fields in ISM are large, there is clear tendency for the regular 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 χ^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, $B_{\rm reg}(R) = B_0\ \exp\left[\frac{-(R-R_\odot)}{R_{\rm B}}\right]$, 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 $R_{\rm B} = 8.5 \pm 4.7$ kpc.

3.7 Field Structure and Strength Near the Galactic Center

Progress has been made in two aspects for the region within tens to hundreds pc of the Galactic Center (see Novak 2005 for a review), both for poloidal field and for toroidal fields.

Poloidal fields: More non-thermal filaments near the Galactic center have been discovered (e.g. LaRosa et al. 2004; Nord et al. 2004; Yusef-Zadeh 2004). The majority of the brighter non-thermal filaments are perpendicular to the Galactic plane, indicating a predominantly 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.(2005) detected the diffuse radio emission and argued for a weak pervasive field of tens of μG near the Galactic Center. The new discovery of an infrared 'double helix' nebula by Morris et al. (2006) reinforces the conclusion of strong 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, the toroidal fields have been observed near the Galactic center (Novak et al. 2003; Chuss et al. 2003), complimenting the poloidal fields shown by the vertical filaments. Analysis of the much enhanced RMs of radio sources near the Galactic Center (e.g. Roy et al. 2005) may indicate the toroidal field structure.

4 CONCLUDING REMARKS

In the last decade, there has been significant progress in studies of the 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/or in the first Galactic quadrant, would be 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.

Acknowledgements I am very grateful to colleagues who have collaborated with me for many years to make the progress described in this review: Dr. R.N. Manchester from Australia Telescope National Facility, CSIRO, Prof. G.J. Qiao from Peking University (China), Prof. Andrew Lyne from Jodrell Bank Observatory (UK), and Dr. Katia Ferriére from Observatory of Midi-Pyrénées (France). I also thank R.N. Manchester, E. Berkhuijsen, R. Beck, Xiaohui Sun and Wolfgang Reich for reading the draft carefully. The author is supported by the National Natural Science Foundation of China (10521001 and 10473015).

References

Andreasyan, R. R., Makarov, A. N., 1989, Afz, 31, 247
Armstrong, J. W., Rickett, B. J., Spangler, S. R., 1995, ApJ, 443, 209
Balsara, D., Kim, J., 2005, ApJ 634, 390
Beck R., Brandenburg A., Moss D., Shukurov A. M., Sokoloff D. D., 1996, ARA&A, 34, 155
Beuermann, K., Kanbach, G., Berkhuijsen, E. M., 1985, A&A, 153, 17
Brown, J. C., Taylor, A. R., Wielebinski, R., Mueller, P., 2003, ApJ, 592, L29
Chuss, D. T., Davidson, J. A., Dotson, J. L. et al., 2003, ApJ, 599, 1116
Hamilton, P. A., Lyne, A. G., 1987, MNRAS, 224, 1073
Han, J. L., 2001, Ap&SS, 278, 181
Han, J. L., 2002, in: Astrophysical Polarized Backgrounds, AIP 609, p.98
Han, J. L., 2004, In: The Magnetized Interstellar Medium, Copernicus GmbH, p.3
Han, J. L., Qiao, G. J., 1993, IAU Symp.157, 279
Han, J. L., Qiao, G. J., 1994, A&A, 288, 759 (HQ94)
Han, J. L., Ferriere, K., Manchester, R. N., 2004, ApJ, 610, 820
Han, J. L., Manchester, R. N., Berkhuijsen, E. M., Beck, R., 1997, A&A, 322, 98
Han, J. L., Manchester, R. N., Qiao, G. J., 1999, MNRAS, 306, 371
Han, J. L., Manchester, R. N., Lyne, A. G., Qiao, G. J., 2002, ApJ, 570, L17
Han, J. L., Manchester, R. N., Lyne, A. G., Qiao, G. J., van Straten, W., 2006, ApJ, 642, 868
Haverkorn, M., Gaensler, B. M., Brown, J. C. et al., 2006, ApJ 637, L33
Heiles, C., 1996a, ApJ, 462, 316
Heiles, C., 1996b, in ASP Conf. Ser. 97: Polarimetry of the Interstellar Medium, 457
Heiles, C., Crutcher, R., 2005, In: Cosmic Magnetic Fields, LNP 664, 137
Indrani, C., Deshpande, A. A., 1998, New Astronomy, 4, 33
LaRosa, T. N., Nord, M. E., Lazio, T. J. W., Kassim N.E., 2004, ApJ, 607, 302
LaRosa, T. N., Brogan C.L., Shore S.N. et al., 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., D'Amico N. et al., 1996, MNRAS, 279, 1235
Manchester, R. N., Lyne, A. G., Camilo, F. et al., 2001, MNRAS, 328, 17
Minter, A. H., Spangler, S. R., 1996, ApJ, 458, 194
Morris, M., Uchida, K., Do, T., 2006, Nature, 440, 308
Nord, M. E., Lazio, T. J. W., Kassim, N. E. et al., 2004, AJ, 128, 1646
Novak, G., 2005, AIP Conf. Proc. Vol. 784, p.329
Novak, G., Chuss, D. T., Renbarger, T. and et al., 2003, ApJ, 583, L83
Ohno, H., Shibata, S., 1993, MNRAS, 262, 953
Qiao, G. J., Manchester, R. N., Lyne, A. G., Gould, D. M., 1995, MNRAS, 274, 572
Rand, R. J., Kulkarni, S. R., 1989, ApJ, 343, 760 (RK89)
Rand, R. J., Lyne, A. G., 1994, MNRAS, 268, 497
Reich, W., 2006, in: Cosmic Polarization, (astro-ph/0603465), in press
Roy, S., Rao, A. P., Subrahmanyan, R., 2005, MNRAS 360, 1305
Simard-Normandin, M., Kronberg, P. P., 1980, ApJ, 242, 74 (SK80)
Sofue, Y., Fujimoto, M., 1983, ApJ, 265, 722
Strong, A. W., Moskalenko, I. V., Reimer, O., 2000, ApJ, 537, 763
Thomson, R. C., Nelson, A. H., 1980, MNRAS, 191, 863
Vallée, J. P., 1996, A&A, 308, 433
Wielebinski, R., 2005, in: Cosmic Magnetic Fields, LNP 664, 89
Wielebinski, R., Krause F., 1993, A&AR, 4, 449
Yusef-Zadeh, F., Morris, M., 1987, ApJ, 320, 545
Yusef-Zadeh, F., Morris, M., Chance, D., 1984, Nature, 310, 557
Yusef-Zadeh, F., Hewitt, J.M., Cotton, W., 2004, ApJS, 155, 421