# Chapter IV

# INTERSTELLAR AND GALACTIC DYNAMOS

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# Magnetic fields in our Milky Way Galaxy and nearby galaxies

**JinLin Han**

National Astronomical Observatories, Chinese Academy of Sciences,
DaTun Road 20A, ChaoYang District, Beijing 100012, China

**Abstract.** Magnetic fields in our Galaxy and nearby galaxies have been revealed by starlight polarization, polarized emission from dust grains and clouds at millimeter and submillimeter wavelength, the Zeeman effect of spectral lines or maser lines from clouds or clumps, diffuse radio synchrotron emission from relativistic electrons in interstellar magnetic fields, and the Faraday rotation of background radio sources as well as pulsars for our Milky Way. It is easy to get a global structure for magnetic fields in nearby galaxies, while we have observed many details of magnetic fields in our Milky Way, especially by using pulsar rotation measure data. In general, magnetic fields in spiral galaxies probably have a large-scale structure. The fields follow the spiral arms with or without the field direction reversals. In the halo of spiral galaxies magnetic fields exist and probably also have a large-scale structure as toroidal and poloidal fields, but seem to be slightly weaker than those in the disk. In the central region of some galaxies, poloidal fields have been detected as vertical components. Magnetic field directions in galaxies seem to have been preserved during cloud formation and star formation, from large-scale diffuse interstellar medium to molecular clouds and then to the cloud cores in star formation regions or clumps for the maser spots. Magnetic fields in galaxies are passive to dynamics.

**Keywords.** ISM: magnetic fields, galaxies: magnetic fields, Galaxy: structure, galaxies: ISM

## 1. Introduction

Magnetic fields are frozen in the interstellar medium. Their effects are easily detectable together with the interstellar gas. Elliptical galaxies do not have much interstellar gas, and the magnetic fields of elliptical galaxies appear only in the jets originating from the central blackhole. Therefore, when talking about magnetic fields in nearby galaxies, we most probably mean those in spiral galaxies.

Magnetic fields exist on all scales in the interstellar medium of spiral galaxies, from the stellar scale of AU size, especially in the star formation regions, to the galactic scale of tens of kpc along the spiral arms.

There are many probes for interstellar magnetic fields. The most widely used are the starlight polarization, polarized emission from dust grains and clouds at millimeter and submillimeter wavelengths, the Zeeman effect of spectral lines or maser lines from clouds or clumps, diffuse radio synchrotron emission from relativistic electrons in interstellar magnetic fields, and the Faraday rotation of background radio sources as well as pulsars for our Milky Way. The first three are related to magnetic fields in clouds, and the later two are related to the fields in the diffuse medium. All these methods have been used to detect the magnetic fields in the Milky Way and nearby galaxies. Note that any of these types of magnetic probes can only reveal information of one of the three dimensional components of magnetic fields, except for Zeeman splitting. Therefore, when we look at the observational results, it is important to understand in which part of a galaxy the magnetic fields have been measured, and how the results are related to the magnetic field properties in a galaxy.

In analogy to the situation for Solar and stellar magnetic field studies, we have observed many more details of magnetic fields in our Milky Way galaxy than those in nearby galaxies. We often see a lot of "trees" for magnetic fields in our own Milky Way, while we see "the forest" in nearby galaxies. I will first review and comment on the observational results of magnetic fields in nearby galaxies, and then review the main results of the magnetic structure in our Milky Way. To save space for more context and references, no figures are included in this review. Readers are encouraged to look at PPT file at web-page: http://zmtt.bao.ac.cn/hjl/IAU294Han.ppt

## 2. Magnetic fields in nearby galaxies

Nearby galaxies can be spiral galaxies, elliptical galaxies, or irregular galaxies. Spiral galaxies could be face-on or edge-on or inclined. Magnetic fields in spiral galaxies in general should have similar properties to the fields in our Milky Way. Magnetic fields in nearby galaxies have been detected by using the five types of probes we mentioned above. Let us review one by one.

### 2.1. *Optical polarization*

Starlight polarization is caused by the absorption of dust grains which are preferentially oriented by interstellar magnetic fields. Optical polarimetry has been used for the images of nearby galaxies since 1970 (eg. Mathewson & Ford 1970b for the Large Magellanic Cloud (LMC); Scarrott *et al.* 1987 for M51; Scarrott *et al.* 1991 for NGC 1068). Polarization images show that the polarization vectors and hence the magnetic fields are oriented along the spiral arms.

Now the optical polarimetry and the CCD camera have been well developed. Many new instruments have been constructed for near or far infrared polarization images (e.g. Magalhães *et al.* 2012; Clemens *et al.* 2012), which have already been used for observations of detailed magnetic fields of clouds by using the polarized light of stars behind the clouds (e.g. Marchwinski *et al.* 2012). Probably a new era is coming to use these instruments for revealing the magnetic fields in *inclined* galaxies with enough dust grains, showing magnetic field details in different parts of a galaxy, much more sensitive than previously has been done by e.g. Scarrott and his team (see the review by Scarrott 1996). But at present not many results have been published. Observations for *face-on* galaxies probably cannot obtain images with much significant polarization (e.g. Pavel & Clemens 2012).

### 2.2. *Polarized emission of clouds and dust grains*

Clouds and dust grains have thermal emission with a temperature in a range of a few tens to a few hundred K, and the radiation is peaked at the mm or submm wavelength or far-infrared. The polarized emission from the clouds or dust grains can show the magnetic field orientations in the clouds perpendicular to the line of sight. The technology for polarimetry at these wavelengths has developed very well in the last decades (e.g. Hildebrand *et al.* 2000). Excellent observations have been achieved in Galactic objects and the Galactic plane (e.g. Li *et al.* 2006; Bierman *et al.* 2011). However, the sensitivity and resolution are not good enough for objects in external nearby galaxies. Up to now very few observations have been carried out. The best are observations of 6 giant molecular clouds in M33 by using the SMA (Li & Henning 2011). The fields shown by the polarization vectors in these 6 giant molecular clouds are aligned with the spiral arms, suggesting that the large-scale field in M33 anchors the clouds. In the near future, polarization images of nearby galaxies at mm or submm wavelength can probably be obtained by large telescopes, such as ALMA or larger single dish submm telescopes.

### 2.3. *Maser emission*

Maser emission comes from the dense core or clumps in a cloud. The strong nearby pump sources can be bright stars or galactic nuclei. The line emission or absorption from the clouds or clumps permeated by magnetic fields shows Zeeman splitting. The separation of split lines measures the field strength of the magnetic component parallel to the line of sight, and the sense change of circular polarization of split lines indicates the direction of the field component along the line of sight.

Because of the limited sensitivity, only megamasers in nearby galaxies near their galactic nuclei have been detected. The Zeeman splitting of the megamasers have been detected from 4 and 11 ultra luminous infrared galaxies (Robishaw *et al.* 2008, McBride & Heiles 2013), which indicate the magnetic fields in the star formation regions near the galactic nuclei have a strength of a few mG to 30 mG, similar to the magnetic fields in star formation regions in our Milky Way (see Table 1 in Han & Zhang 2007). Though it is not possible now, in the future, one could use a large telescope array, e.g. SKA, to observe the Zeeman splitting of many normal maser regions in the disk of nearby galaxies and hence to outline the global field directions (not merely orientations), and to check if the magnetic fields in molecular clouds and star formation regions are correlated well with the global spiral and magnetic structures (Han & Zhang 2007).

### 2.4. *Diffuse radio polarized emission*

Synchrotron emission of relativistic electrons gyrating magnetic fields certainly gives information about magnetic fields. The total radiation intensity is related the total strength of fields, and the polarized intensity and polarization angles are related to the strength fraction and the field orientation (not directions) in the sky plane of ordered fields or anisotropic fields. Synchrotron emission produced in random magnetic fields does not show polarization because the polarized emission from all small volume cells within a telescope beam are summed together and hence depolarized.

The first polarized emission images of spiral galaxies, M51, M81 and M31, were observed using WSRT (Mathewson *et al.* 1972, Segalovitz *et al.* 1976). The images show the E-vector perpendicular to the arms and optical vectors so that the ordered magnetic fields are indicated to follow the spiral arms. The German MPIfR group led by Prof. R. Wielebinski has been dedicated to the polarization observations of many nearby galaxies at many bands for more than two decades by using the VLA and Effelsberg telescopes (e.g. Beck *et al.* 1978, Krause *et al.* 1989, Neininger *et al.* 1991, Beck & Hoernes 1996, Beck *et al.* 2002, Wielebinski & Krause 1993). I visited the group and was involved in the studies of magnetic fields in NGC 2997 (Han *et al.* 1999a), a beautiful grand-design spiral galaxy as always seen in text books. For spiral galaxies, the observed polarization vectors, and hence the B-vectors after being rotated by 90° at a short wavelength, show that the ordered fields follow the spiral arms. Strong polarized emission is detected in interarm regions (Beck & Hoernes 1996). The most impressive is that the fields follow the arm even when an arm is locally distorted (e.g. Han *et al.* 1999a) or dynamically distorted in the interaction pairs (e.g. Fletcher *et al.* 2011). This means that magnetic fields are dynamically passive, which has been confirmed by polarization observations of bar galaxies (e.g. Beck *et al.* 2002). Polarized emission has also been detected in the halos of some edge-on galaxies (e.g. Hummel *et al.* 1991), indicating an X-shaped field structure as poloidal-like (e.g. NGC 4631) or simply parallel to the mid-plane as being toroidal-like.

A Polish group has joined the efforts for magnetic fields in nearby galaxies and often cooperated with the German group. They have observed many different types of galaxies, e.g. irregular galaxies (e.g. Chyży *et al.* 2000, Chyży *et al.* 2003), merging or interacting galaxies (e.g. Soida *et al.* 2001, Chyży & Beck 2004), ring galaxies (Chyży & Buta 2008), flocculent galaxies (Soida *et al.* 2002). The magnetic fields are revealed to always have a good patten, but again are passive to dynamics. In other words, magnetic fields in galaxies cannot affect dynamics, but dynamics can affect magnetic fields.

Notice that the polarized emission could be produced by either large-scale ordered coherent magnetic fields or anisotropic random fields. To judge if the magnetic fields in the nearby spiral galaxies have large-scale coherent directions, a rotation measure (RM) map is necessary. The images of polarization angles in two or more wavelengths have often been used to derive rotation measure maps and study the magnetic field structure (e.g. Berkhuijsen *et al.* 2003, Fletcher *et al.* 2011). Polarization maps with marginal significance (3-5$\sigma$) in most areas can produce an RM map but only significant in some area, not everywhere (e.g. Han *et al.* 1999a). Note also that the polarized emission of nearby galaxies has different depth limits at different wavelengths. If observations are made at high frequencies, e.g. 5GHz or higher, the polarized emission from all layers in the disk for the whole thickness is transparent and has a peak near the galactic plane. The emission can be added together without much Faraday rotation. If the observations are made at longer wavelengths, e.g. 20 cm or longer, the polarized emission from the far layers suffers from severe and various Faraday rotations and hence is depolarized when emission from these far layers is added together. Only polarized emission from nearer shallow layers of the disk can be observed at a long wavelength band. The observable layer depth depends on the wavelength and the inclination angle of a galactic disk.

The global variation of rotation measures derived from polarization maps at two or more almost transparent frequencies can show the magnetic field configuration of the nearer layers up to a half thickness of the disk. Polarization angle maps of many channels of a very long wavelength band therefore can reveal the field structure in the shallow layers but not the global field configuration in a galactic disk of whole thickness.

In recent years we see the great developments on polarimetry observations of many channels in wide bands, i.e. the spectro-polarimetry. When polarization angles of many frequency channels have been measured, one can get the rotation measure maps or perform rotation measure synthesis (Brentjens & de Bruyn 2005). New observations made with the EVLA for 35 edge-on galaxies (Irwin *et al.* 2012a, Irwin *et al.* 2012b) and with Westbork for 21 nearby galaxies (Heald *et al.* 2009, Braun *et al.* 2010) have achieved the rotation measure maps, from which magnetic field structures in the galactic disk, up to a half thickness, have been derived. Many small-scale field structures emerge in the RM map (e.g. Heald 2012), in addition to the general large-scale RM distribution.

### 2.5. *Rotation measures of background polarized sources*

If observational sensitivity is good enough, many background radio sources behind a large galaxy can be detected. If they are polarized, and their RMs can be measured, then the RMs can be used to diagnose the magnetic fields in the galaxy for the whole thickness of the disk. Magnetic fields of an odd mode or even mode cause different spacial RM distributions of background sources (Han *et al.* 1998). The more RMs of background sources are observed, the better the field configuration in the galaxy can be diagnosed. In this aspect, our Milky Way galaxy has the major advantage that all the polarized radio sources in the sky can be used as the probes for the magnetic field configuration in both the disk and the halo (see next section). For external galaxies, at present the sensitivity for radio polarization observations is very limited, so only a limited number of radio sources behind a few large objects have been observed.

The first one is M31 (Han *et al.* 1998). In a field of view of a few square degrees, the rotation measures of 21 polarized radio sources have been observed. Using these rotation measures, together with the rotation measures derived from the diffuse polarized radio emission from the galactic disk at 6cm and 11cm, Han *et al.* (1998) showed that the magnetic fields in M31 may have an even mode field configurations.

Two of the largest objects are in the southern sky. One is the LMC. By using ATCA, Gaensler *et al.* (2005) have observed RMs of 240 sources behind or around the LMC, and figured out the magnetic field configuration in the LMC as being axisymmetric fields. Another one is Cen A. Feain *et al.* (2009, 2011) have used the ATCA to observe it for 1200 hours, and got 281 RMs behind or around Cen A. By comparing the 121 RMs behind the lobes and 160 sources outside the lobes, they found that the lobes contribute very small RMs of a few rad $\mathrm{m}^{-2}$, but the lobes cause RM fluctuations of 20-30 rad $\mathrm{m}^{-2}$. Note that this is the best magnetic field measurements for the jets from an elliptical galaxy.

In the future, because of excellent sensitivity, the SKA may observe RMs of many background sources for a few hundred galaxies (Gaensler 2006), and can probe magnetic field configurations in these galaxies.

### 2.6. *Summaries for external galaxies*

Many kinds of observations for magnetic fields in nearby galaxies have been made. Optical starlight polarization can be used to trace magnetic field orientations in gas-rich properly-inclined galaxies. The polarization observations and the Zeeman splitting observations for magnetic fields in clouds or cloud cores or clumps in nearby galaxies are still very premature because of currently poor sensitivity and resolution. The most extensive measurements are radio continuum polarization observations. The polarization vectors show that magnetic field orientations follow the spiral arms and are evidently dynamically passive. The rotation measure maps of polarized diffuse emission can be used to probe the magnetic field directions in the galactic disk of the nearer half thickness. Rotation measure synthesis for the multichannel polarization observations in a very wide band has been used to diagnose the magnetic configurations. The rotation measures of background radio sources behind a galaxy can be used to probe the magnetic configurations in a galactic disk of the full thickness.

## 3. Magnetic fields in our Milky Way galaxy

The Milky Way can be divided into three parts: the central region, the halo and the disk. Many details of magnetic fields in our Milky Way have been revealed by using the five probes mentioned above. Because of our location at the disk edge of our Galaxy, the best probes for the *large-scale structure* of the Galactic magnetic fields have to be able to detect the magnetic component parallel to the line of sight. For this reason, three probes, which show the orientation of the transverse field component: starlight polarization, the polarized emission of dust grains and clouds and the diffuse radio synchrotron emission, are good at revealing magnetic field details ("trees") but not at getting the large-scale structure ("the forest"). The two kinds of excellent probes for the large-scale magnetic structure are 1) the Zeeman effect of spectral lines or maser lines from clouds or clumps, if magnetic fields in clouds are closely related to large-scale magnetic structure, and 2) the Faraday rotation of extragalactic radio sources and pulsars.

Now I review the observational results as well as new progress for the measurements of magnetic fields in the three parts of the Milky Way, by using all kinds of probes. Note that when we try to understand the properties of magnetic fields in our Milky Way, we have to "connect" all measurements in different regions to get the most probable structure of the Galactic magnetic fields.

### 3.1. *Magnetic fields in the Galactic central region*

In the central region of a few hundred pc of our Milky Way, the poloidal magnetic fields are indicated by the polarized radio filaments, and the toroidal magnetic fields have been detected by using the polarized emission of the central cloud zone. Recently the near-infrared polarimetry of stars in the central region shows the smooth transition from the toroidal to poloidal fields. The Faraday rotation measures of a good number of background radio sources behind the central region have also been observed and used for the modelling the field structure near the central bar.

The highly polarized non-thermal radio filaments (e.g. Yusef-Zadeh *et al.* 1984, Lang *et al.* 1999, Yusef-Zadeh *et al.* 2004, LaRosa *et al.* 2004) have been detected within 1° from the Galactic center. They are almost perpendicular to the Galactic plane, although some of the newly found filaments are not (LaRosa *et al.* 2004). After Faraday rotation correction, polarization observations show that the magnetic fields are aligned along the filaments (Lang *et al.* 1999). These filaments are probably radio-illuminated flux tubes, with a field strength of about 1 mG (Morris & Serabyn 1996), which indicate poloidal magnetic fields within a few hundred parsecs from the Galactic center. The diffuse radio emission detected in an extent of about 400 pc (LaRosa *et al.* 2005) implies a weak pervasive field of tens of $\mu$G. However, this could be the volume-averaged field strength in such a region. The observed “double helix” nebula (Morris *et al.* 2006) with an estimated field strength on order of 100 $\mu$G reinforces the presence of strong poloidal magnetic fields in the form of tubes merging from the rotating circumnuclear gas disk near the Galactic center.

Polarized thermal dust emission has been detected in the ring-like central molecular cloud zone of a size of a few hundred pc at sub-mm wavelength (Novak *et al.* 2003, Chuss *et al.* 2003), which indicates the orientations of toroidal fields in the clouds parallel to the Galactic plane. The Zeeman splitting measurements the OH maser emission (Yusef-Zadeh *et al.* 1999) or absorption (Uchida & Guesten 1995) in the central region give a line-of-sight field strength of 0.1 to a few mG in the clouds. It is possible that toroidal fields in the clouds are sheared from the poloidal fields.

Recently, new near-infrared observations have been made of the stars in a sky area of $2° \times 2°$ around the Galactic center (Nishiyama *et al.* 2010). Differential polarization between the objects behind the center and the objects in the front of the center shows that the magnetic fields are toroidal near the Galactic plane and smoothly transition to poloidal fields at latitudes of $|b| > 0.4°$.

Within a few hundred pc to a few kpc from the center, stellar and gas distributions and the magnetic structure are all mysterious. There probably is a bar. If so, the large-scale magnetic fields should be closely related to the material structure but have not been observationally revealed yet. The RMs of background radio sources within $|l| < 6°$ of the Galactic center (Roy *et al.* 2005) are consistent with either the large-scale magnetic fields of a bisymmetric spiral configuration or the large-scale fields oriented along the Galactic bar (Roy *et al.* 2008).

### 3.2. *Magnetic fields in the Galactic halo*

Our edge-on Milky Way has a tenuous extended component beyond the obvious disk, which is shown in radio emission and the space distribution of stars and gas. We call it the halo or the thick disk, which should probably be defined as the component outside a given height from the Galactic plane. However, it is difficult at present to define the scale radius and scale height for the extension of such a halo. In reality, the local emission features are always mixed with the weak background halo component. Observationally the halo is always visible at Galactic latitudes higher than a few degrees.

Magnetic fields in the Galactic halo have been shown by the starlight polarization, synchrotron emission, the polarized emission of dust grains and clouds and the sky distribution of rotation measures of extragalactic radio sources and pulsars. The measurements of starlight polarization of a few thousand stars (Mathewson & Ford 1970a; Heiles 2000) within a few kpc from the Sun show not only the field orientations mostly parallel to the Galactic plane in the disk but also the fields in the local halo of a few kpc (Heiles 1996). The most prominent feature is the polarization vectors following the north Galactic spur, which in fact is a very localized feature.

The best evidence for the existence of magnetic fields in such a halo is the radio continuum emission, much extended away from the disk (Beuermann *et al.* 1985), as seen in the early days at 408 MHz (Haslam *et al.* 1982) and later at 1420 MHz (Reich & Reich 1986, Reich *et al.* 2001). The polarized diffuse emission at a few hundred MHz mainly comes from regions within a few hundred parsecs from the Sun while the polarized emission at higher frequencies from more distant regions. In the all sky polarization map at 1.4 GHz (Wolleben *et al.* 2006, Testori *et al.* 2008), strong polarization is seen in the outer Galaxy and high Galatic latitutes. Obvious depolarization is seen in the inner Galaxy near the Galactic plane. Recent development of spectro-polarimetry technique has been applied for the diffuse halo emission, and the sky has been mapped in many polarization channels in a few hundred MHz (Wolleben *et al.* 2010). Synthesized rotation measure maps† can be constructed. Some features emerged in some rotation measure channels are coincident or anti-coincident with some known objects. The best polarization maps which suffer less depolarization come from the WMAP measurements (Page *et al.* 2007, Jarosik *et al.* 2011), which show the well-ordered distribution of E-vectors. In the disk near the Galactic plane, the indicated magnetic fields are parallel to the Galactic plane, while beyond the plane, the B vectors are indicators of the local halo fields, showing the transition from the horizontal to vertical field components. In other words, these vectors at hight latitudes are very useful for constraining the local halo fields.

Because of the geometry of the Galactic halo and our location at the disk edge, the Faraday rotation measures in the middle latitude regions of the inner Galaxy ($|l| < 90°$) contain the information of the magnetic field component along the line of sight and hence are the best probes for the magnetic fields in the halo. The rotation measure distribution as well as other polarization measurements in the outer Galaxy (Mao *et al.* 2012) cannot be used to show the halo fields because the observed RMs of background sources contain various intrinsic RMs and probably different RM contributions from intergalactic space, in addition to the common RM foreground from our Milky Way. The outliers of RM data have to be filtered out and then the average or the median of the RM data can be the representative for the RM foreground. The antisymmetry of the RM sky so found by Han *et al.* (1997) in the inner Galaxy has been interpreted as the toroidal magnetic fields in the halo with reversed field directions below and above the Galactic plane (see also Han *et al.* 1999b), which are very consistent with the magnetic field configuration of the A0 dynamo. The vertical fields in the Galactic center naturally act as the poloidal fields in such a field configuration. Although the scale radius and scale height for such halo toroidal fields are not yet known, and more seriously little is known about the electron density distribution in the halo, this qualitative toroidal halo field model derived from the antisymmetric RM sky (Han *et al.* 1997, Han *et al.* 1999b) has now widely been adopted in many quantitative models (e.g. Sun *et al.* 2008) since the first parametrization by Prouza

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† Rotation measure synthesis is probably not a good tool to separate the diffuse emission from different regions along a sightline at different distances with different polarization properties and different foreground Faraday rotations.

& Smída (2003). As more and more RM data have become available (Taylor *et al.* 2009), the antisymmetric RM sky has been confirmed, no matter how data are analyzed and presented (e.g. Oppermann *et al.* 2012). Certainly the much enhanced density of the RM data distribution can show the details of magnetic fields (Stil et al. 2011) especially in large objects (Harvey-Smith *et al.* 2011), in addition to the large-scale RM distribution for the halo fields.

Using the rotation measure distribution in the two Galactic poles, the local vertical field component can be estimated, which could be taken as a part of the halo field or the dipole field. In the early days, using a few tens of RMs, we found $B_z \sim 0.2\mu$G (Han & Qiao 1994, Han *et al.* 1999b). Recent extensive observations have resulted in a much improved RM dataset (Mao *et al.* 2010) which more or less confirmed the existence and the strength of such a vertical field.

### 3.3. *Magnetic fields in the Galactic disk*

The stellar disk of the Milky Way is very thin, only a few tens of pc in thickness. The diffuse interstellar medium in the disk has a larger thickness of at least a hundred pc. In the disk, there are spiral arms which can be traced well by molecular clouds and HII regions (Hou *et al.* 2009). But we do not know how many arms exist in our Milky Way and how they are connected.

Magnetic fields in the Galactic disk have been measured by all five probes (see discussion on advantages of these probes in Han 2013). Some of these results have been mentioned above. Three probes, starlight polarization, polarized emission from dust grains and clouds at millimeter and submillimeter wavelengths, and diffuse radio synchrotron emission from relativistic electrons in interstellar magnetic fields, give the magnetic field orientation projected onto the sky plane. Because of our location in the Milky Way, they are not very good probes for *large-scale magnetic structure* in the Galactic disk.

Starlight polarization data near the Galactic plane show that the orientation of magnetic fields in clouds, traced by the accumulated polarization due to absorption of dust grains preferentially oriented by the fields, are always parallel to the Galactic plane, except for high Galactic latitude data for very local features (Mathewson & Ford 1970a, Heiles 1996, Nishiyama *et al.* 2010). Deep observations (Clemens *et al.* 2012) will probably reach the same conclusion with much more and new data. A similar situation occurs for polarization measurements of thermal emission from molecular clouds at mm, submm or infrared wavelengths. Observed magnetic fields in most clouds are parallel to the Galactic plane (Novak *et al.* 2003, Li *et al.* 2006, Bierman *et al.* 2011), no matter how far away or where the clouds are located in the disk, except that the large-scale fields are distorted locally. From such orientation measurements of cloud fields, it is impossible to derive the large-scale magnetic fields in the disk. Nevertheless the results suggest that the fields in clouds have their orientations well preserved during cloud formation probably from the similarly oriented magnetic fields frozen in very diffuse interstellar gas.

The diffuse synchrotron emission comes from everywhere in the disk. The observed emission is very depolarized in the low latitudes at low frequencies because the emission from different distances suffers different Faraday rotations and then is added together for the observed values. Therefore it is not possible to derive the large-scale magnetic field structure in the disk from the observed polarized synchrotron emission at low frequencies. At a frequency of a few GHz, the depolarization occurs in the inner Galaxy (Sun *et al.* 2011, Xiao *et al.* 2011) but not the outer Galaxy (Gao *et al.* 2010) where many magnetic field details can be seen around various objects, such as SNRs and HII regions. At very high frequencies above 20 GHz, no severe depolarization occurs even in the inner Galaxy. Polarization measurements simply indicate that the magnetic fields are parallel to the

Galactic plane (Page *et al.* 2007). It is not possible to derive the large-scale magnetic field structure in the disk from the polarization measurements of diffuse synchrotron emission at low latitudes, though some models which include the magnetic field structure can fit well the variations of total synchrotron emission intensity along the Galactic longitude, which result from the enhanced field strength in spiral arms.

Two kinds of measurements for the field component along the line of sight can be used for the large-scale field structure. One is the Zeeman splitting of line emission or absorption, the other is the Faraday rotation of background sources and pulsars. The Zeeman splitting can be used to measure the fields (both strength and directioon) in clouds or clumps of a scale of pc or even AU. Surprisingly, the distribution of available magnetic field measurements from maser lines around a large number of HII regions is very coherent with the large-scale spiral structure and large-scale magnetic fields (Han & Zhang 2007). This is strong evidence that magnetic fields have preserved their directions from the kpc scale to AU scale during cloud formation and star formation processes. A big project for extensive observations of many HII regions for the coherent large-scale magnetic structure of the Milky Way is in progress (Green *et al.* 2012).

Faraday rotation measures of background radio sources behind the Galactic disk can be very powerful probes for the field structure. Many authors have tried to figure out the disk field structure from the RM variation as a function of Galactic longitude (Simard-Normandin & Kronberg 1980, Sofue & Fujimoto 1980, Pshirkov *et al.* 2011). The median or average RMs of background sources behind the disk are the integrated measurement of polarization angle rotations over the whole path in the disk and therefore are not sensitive to the possible magnetic field reversals inside the disk between arms and interarm regions along the path. The dominant contribution to RMs of background sources comes from tangential regions of spiral arms, where the magnetic fields have the smallest angle with the line of sight if the large-scale magnetic fields follow spiral arms. In recent years extensive efforts have been made to enlarge the RM samples of background sources at low Galactic latitudes (e.g. Brown *et al.* 2007, Van Eck *et al.* 2011). The RM data behind the Galactic disk (see Fig.1 of Han 2013) are much denser in the outer Galaxy than in the inner Galaxy. Closer to the Galactic center, the RM data become more scarce, because the diffuse emission is stronger and because the polarization observations are more difficult to carry out. The RM data in the outer Galaxy cannot constrain the magnetic field structure in the Galactic disk, because such large-scale fields become more and more perpendicular to the line of sight. When a set of RMs of background sources is fitted with a magnetic structure model, the electron density model is a necessary input. The disk magnetic field models derived mainly from the RMs of background sources along Galactic longitude should be treated with cautions because the field reversals in the disk cannot be constrained.

Pulsars are excellent probes of the magnetic fields in our Milky Way. They are located inside our Galaxy. The observed RMs of pulsars come only from the interstellar medium between pulsars and us, because there is no intrinsic Faraday rotation from the emission region and pulsar magnetosphere. For a pulsar at distance $D$ (in pc), the RM is given by $\mathrm{RM} = 0.810 \int_0^D n_e \mathbf{B} \cdot d\mathbf{l}$. With the pulsar dispersion measure, $\mathrm{DM} = \int_0^D n_e dl$, we obtain a direct estimate of the field strength weighted by the local free electron density

$$\langle B_{||} \rangle = \frac{\int_0^D n_e \mathbf{B} \cdot d\mathbf{l}}{\int_0^D n_e dl} = 1.232\,\frac{\mathrm{RM}}{\mathrm{DM}}. \tag{3.1}$$

If pulsar RM data are model-fitted with the magnetic field structures with the electron density model (Han & Qiao 1994, Indrani & Deshpande 1999, Noutsos *et al.* 2008, Nota &

Katgert 2010), then the pulsars and EGRs are more or less equivalently good as probes for the magnetic structure. However, pulsars are spread through the Galaxy at approximately known distances, allowing three-dimensional mapping of the magnetic fields. When RM and DM data are available for many pulsars in a given region with similar lines of sight, e.g. one pulsar at $d0$ and one at $d1$, the RM change against distance or DM can indicate the direction and magnitude of the large-scale field in particular regions of the Galaxy (Han *et al.* 1999b, Han *et al.* 2002, Han *et al.* 2006, Noutsos *et al.* 2008). Field strengths in the region can be directly derived by using $\langle B_{||}\rangle_{d1-d0} = 1.232\frac{\Delta\mathrm{RM}}{\Delta\mathrm{DM}}$, where $\langle B_{||}\rangle_{d1-d0}$ is the mean line-of-sight field component in $\mu$G for the region between distances $d0$ and $d1$, $\Delta\mathrm{RM} = \mathrm{RM}_{d1} - \mathrm{RM}_{d0}$ and $\Delta\mathrm{DM} = \mathrm{DM}_{d1} - \mathrm{DM}_{d0}$. Notice that this derived field is not dependent on the electron density model.

Using pulsar data, Han *et al.* (2006) show that magnetic fields in the spiral arms (i.e. the Norma arm, the Scutum and Crux arm, and the Sagittarius and Carina arm) are always counterclockwise in both the first and fourth quadrants, though some disordered fields appear in some segments of some arms. At least in the local region and in the fourth quadrant, there is good evidence that the fields in interarm regions are similarly coherent, but reversed to be clockwise. The strengths of regular azimuthal fields near the tangential regions in the 1st and 4th Galactic quadrants show a clear tendency that the fields get stronger at smaller Galactocentric radius. It has been found from pulsar RMs that the random field has a strength of $B_r \sim 4-6$ $\mu$G independent of cell-size in the scale range of $10-100$ pc (e.g. Ohno & Shibata 1993). From pulsar RMs in a very large region of the Galactic disk, Han *et al.* (2004) obtained a power law distribution for magnetic field fluctuations of $E_B(k) = C\ (k/\mathrm{kpc}^{-1})^{-0.37\pm0.10}$ at scales from $1/k =$ 0.5 kpc to 15 kpc, with $C = (6.8 \pm 0.8)\ 10^{-13}$erg cm$^{-3}$ kpc, corresponding to an rms field of $\sim 6$ $\mu$G in the scale range.

## 4. Conclusions

Magnetic fields in our Milky Way and nearby galaxies have been probed by using five types of observations, each only giving partial information of one of the 3D field components. Magnetic field structure and field strength have been derived from these measurements. The magnetic fields in spiral galaxies follow the spiral structure and are passive to dynamics. Magnetic field directions are evidently preserved during the cloud formation from diffuse interstellar gas and the star formation regions. Magnetic fields in our Milky Way show field direction reversals in the halo and in the disk between arms. Such reversals have not yet been detected in nearby galaxies. We know more details about magnetic fields in our Milky Way than in nearby galaxies. Obviously more sensitive observations are needed for the field strength and field structure in nearby galaxies, via diffuse polarization observations in multi-frequency channels, Zeeman splitting observations of clouds and masers, and the polarized thermal emission of clouds. Such observations will be possible in the near future using ALMA and in distant future using the SKA.

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