Abstract This chapter presents a review of observational studies to determine the magnetic field in the Milky Way, both in the disk and in the halo, focused on recent developments and on magnetic fields in the diffuse interstellar medium. I discuss some terminology which is confusingly or inconsistently used and try to summarize current status of our knowledge on magnetic field configurations and strengths in the Milky Way. Although many open questions still exist, more and more conclusions can be drawn on the large-scale and small-scale components of the Galactic magnetic field. The chapter is concluded with a brief outlook to observational projects in the near future.

1 Introduction

The Milky Way is a dynamic environment, much of which (partially) consists of plasma: stars, jets, objects such as H II regions or supernova remnants, and the general interstellar medium (ISM). No wonder that magnetic fields are ubiquitous throughout the Galaxy, in almost all astrophysical objects from strong fields in pulsar atmospheres to weak fields on scales of many kiloparsecs, threading the whole Galaxy. The importance of these magnetic fields is manifold: in the energy balance of the Milky Way, transport of angular momentum, acceleration and propagation of charged particles, gas dynamics, etc. All interstellar matter but the densest, coldest clouds is sufficiently ionized (even with an ionization degree of only $10^{-4} - 10^{-3}$) for the neutral gas component to remain coupled to the ionized gas, and therefore be efficiently frozen into the magnetic field [1]. Equipartition of magnetic and turbu-
lent gas density [2] indicates that dynamical feedback of the magnetic field on the gas plays an important role.

Fully characterizing the strength, direction, and structure of the extended Galactic magnetic field threading the entire Milky Way is an extremely daunting task. This field can be regarded as a combination of a large-scale field threading the Galaxy, probably maintained by the Galactic dynamo, and a small-scale field. The small-scale field is caused by and interacts with interstellar turbulence, supernova explosions and remnants and other shock waves, and is altered by gas dynamics, magnetic reconnection, turbulence effects etc. In addition, the available observational methods detect either one component of the magnetic field (strength or direction, parallel or perpendicular to the line of sight) and/or in one particular tracer (ionized gas, dense cold gas, dense dust, diffuse dust). Lastly, some of the difficulty of determining the Galactic magnetic field stems from our vantage point inside the Milky Way. Creating a three-dimensional picture from mostly two-dimensional tracers necessitates many assumptions about the magnetic field, as well as about the thermal and cosmic ray electron distributions, and about the (local) interstellar objects and processes influencing these.

Despite the difficulties, attempts to detect and determine the Galactic magnetic field have been many in recent (and not so recent) years. This is not only because magnetic fields influence so many physical processes in the ISM, but also because of its importance to other fields in astronomy and astrophysics. For instance, the Cosmic Microwave Background (CMB) community has shown a keen interest in the Galactic magnetic field, since it produces Galactic polarized synchrotron emission which acts as a strong foreground for CMB polarization. Also, astroparticle physicists studying sources and propagation of Galactic and extragalactic cosmic rays profit from detailed magnetic field models, which predict distributions of arrival directions of (high energy) cosmic rays. In addition, high-precision cosmological studies of the Epoch of Reionization need a detailed understanding of Galactic polarization to be able to understand and subtract any polarization leaking into their extremely sensitive measurements of highly redshifted H I.

It is not possible to cover all observations of magnetic fields in the Milky Way in this review. Fortunately, I can refer to a number of complementing reviews. For observations of magnetic fields in dense clouds and their relation to star formation, see various chapters in this Volume. For a historical review on magnetic field observations in the Milky Way, see [3] or [4], and [5] provides an excellent treatise on magnetic fields in the Galactic Center. I refer to e.g. [6] for a review on the very local ISM, including magnetic fields, and to [7] for a recent review on Galactic magnetic fields from Faraday rotation of pulsars and extragalactic sources. [8] published a recent review about magnetic fields in galactic haloes. I will focus here on work mostly in the last decade. For earlier reviews, see [9, 3, 7, 2].

This chapter starts with a brief description of some terminology used in literature in Section 2. Sections 3, 4 and 5 describe current knowledge of magnetic field observations in the Galactic disk, in the Galactic halo and in the combined disk-halo system, respectively. A short summary and conclusions are stated in Section 6.
and finally, Section 7 describes some recent, progressing and future observational projects which are important for the investigation of Galactic magnetic fields.

2 Terminology

2.1 Large-scale vs small-scale fields

The description of large-scale and small-scale galactic magnetic fields in the literature is often confusing, with different authors using different terminology for the same magnetic field configurations or the same words for different field structure. Here I give an overview over these different magnetic field configurations and ways to describe them.

Traditionally, galactic magnetic fields have been divided up in small-scale and large-scale fields. The term “large-scale” fields (also called regular, uniform or coherent fields) indicates the component of magnetic field that is coherent on length scales of the order of a galaxy, usually assumed to follow the spiral arms or to be ring-shaped. “Small-scale magnetic fields” (also called random, tangled, or turbulent) describe the magnetic field component connected to the turbulent ISM. The small-scale field is usually simply assumed to follow a power law with a certain outer scale, where energy is injected, which then cascades down to smaller turbulent scales until energy dissipates at the dissipation scale. Small-scale magnetic field fluctuations connected to discrete objects such as H II regions or supernova remnants warrant their own review paper and are usually treated separately from the “Galactic magnetic field”, although interaction between these fields and the general Galactic magnetic field is of course pervasive.

However, lately, a third component of the magnetic field starts to be included in Galactic magnetic field studies, as it has for some time in magnetic field studies of external galaxies (see R. Beck’s Chapter in this Volume). This component is a field of which the direction varies on small scales, but the orientation does not. Such a field can arise when a turbulent field structure is compressed into a two-dimensional structure by e.g. supernova remnant shocks, spiral arm density waves, or galactic shear. This field component is often referred to as anisotropic random, but is also called ordered random or striated. A clear explanation of these components is given in Fig 1 reproduced from [12]. The cartoons illustrate the morphology of the three components and indicate the differences between the tracers total intensity I, polarized intensity PI and rotation measures RM for different lines of sight towards these three components. Combination of these tracers makes it possible to distinguish between the three field components.

As Fig 1 shows, studies using RMs alone cannot distinguish between ordered random and isotropic random field components, which are often grouped together in a “random” field. Similarly, investigations using synchrotron emission cannot

\[\text{\footnotesize Note that [12] refer to this component as 'ordered'}\]
distinguish between coherent and ordered random field, due to which these two components are often assembled into one “ordered” component.

![Fig. 1 Sketch illustrating the three components of galactic magnetic fields. For consistency in the literature, the component labeled “ordered” here should be called “ordered random” and the component labeled “random” should be “isotropic random”. The three observables for these magnetic fields are total intensity $I$, polarized intensity $PI$ and rotation measure $RM$. Image reproduced from [12].](image-url)
2.2 Configurations of large-scale Galactic magnetic fields

A number of fairly simple configurations have been explored for the coherent magnetic field in the Milky Way. These configurations are based on rotational symmetry around the Galactic Center, and on mirror symmetry with respect to the Galactic plane.
The two simplest disk configurations are an \textit{axisymmetric}\footnote[2]{sometimes called \textit{disymmetric} \cite{16}.} and \textit{bisymmetric} spiral structure, which denote magnetic fields oriented along the spiral arms. In the axisymmetric situation, magnetic field lines all point inwards or outwards. Bisymmetric fields are antisymmetric with respect to the spin axis of the galaxy. Therefore, the bisymmetric situation includes field reversals in the azimuthal direction (see Fig.\ref{fig:fig2}). Axisymmetric fields are denoted by azimuthal mode $m = 0$, bisymmetric fields are $m = 1$. Higher azimuthal modes $m$ or a mix of modes may be present, e.g. the $m = 2$ or \textit{quadri-symmetric} mode.

The field can also be described in terms of its symmetry with respect to the Galactic plane. A \textit{symmetric} or \textit{even-parity} field has a mirrored magnetic field configuration (see Fig.\ref{fig:fig3}). Note that this indicates a reversal of the vertical magnetic field direction across the Galactic plane, and that the toroidal component of the magnetic field points in the same direction above and below the plane. An \textit{anti-symmetric} or \textit{odd-parity} field has field lines that run through the Galactic plane, and toroidal fields that reverse direction above and below the plane.

This symmetric and anti-symmetric mirror symmetry is often denoted with $S$ and $A$, respectively. This classification is followed by a number which gives the azimuthal mode number $m$. So, e.g., an $A0$ field configuration has an axisymmetric field, the horizontal component of which is directed in opposite directions above and below the Galactic plane.

A slightly more complex field configuration is the Disk-Even-Halo-Odd (DEHO) configuration, consisting of two independent field components for the Galactic disk and halo; as the name indicates, the vertical symmetry of this magnetic field configuration is even in the Galactic disk, but odd in the halo. I mention this morphology here, since it is preferred in several observational studies of all-sky magnetic field configurations, discussed in Section 5.

\textbf{2.3 Pitch angle definition}

The pitch angle of a spiral magnetic field is defined as

\[ p = \tan^{-1} \frac{B_r}{B_\phi} \]  

(1)

where $B_r$ is the radial component of the magnetic field and $B_\phi$ its azimuthal component. For a trailing spiral, $B_r$ and $B_\phi$ have opposite signs, so that the pitch angle is negative, also described in the literature as ‘radially inward’. Note that \cite{15} use a deviating definition of their angle $\psi_0$ as $\psi_0 = \tan^{-1} B_\phi / B_r$. 

\footnote[2]{sometimes called \textit{disymmetric} \cite{16}.}
3 Magnetic fields in the Galactic disk

3.1 Large-scale magnetic field strength

The strength of the local large-scale magnetic field as obtained from Faraday rotation of pulsars and extragalactic sources is typically around $1.5 - 2 \mu G$. These estimates mostly result from RM and Dispersion Measure (DM) data from pulsars [17, 18], from wavelet analysis [19] or fitting RM data to large-scale models of Galactic magnetic fields (as discussed extensively below).

The total field strength in the Solar neighborhood is estimated to be around $6 \mu G$, from observed synchrotron emissivities and assumed equipartition between cosmic rays and magnetic fields [20, 21]. This is in agreement with magnetic field strength estimates in Galactic HI regions from Zeeman splitting ($B \approx 2 - 10 \mu G$, [22]).

Towards the Galactic center, the magnetic field strength increases. Estimates from synchrotron emission give a total field strength of about $10 \mu G$ at a Galactocentric radius of 3 kpc [21], the pulsar study by [23] concludes a regular field strength of $4.4 \pm 0.9 \mu G$ in the Norma arm, and also large-scale magnetic field modeling generally finds stronger total magnetic field strength towards the Galactic center [e.g., [24, 20, 25]]. The extensive study by [26], using various tracers, concludes that $B_{\text{tot}} \approx 7.6 - 11.2 \mu G$ at a Galactocentric radius of 4 kpc.

The magnetic field strength is independent of density for low densities in the diffuse ISM ($n \lesssim 300 \text{ cm}^{-3}$), indicating infall along magnetic field lines [22]. Only for dense clouds and molecular clouds, magnetic field strengths increase roughly as the square root of density.

3.2 Large-scale magnetic field structure

The configuration of the large-scale magnetic field in the Milky Way disk is still a matter of hot debate. Some features meet with reasonable or total agreement: the magnetic fields seem to roughly follow the spiral arms, which is in agreement with all external spiral galaxies observed [21], and even ring galaxies [27] (however, see [28]). This conclusion is drawn not only from polarized radio synchrotron and Faraday rotation measurements, but is also supported by starlight polarization measurements [29, 30], submm dust polarization [31] and Zeeman splitting observations in hydroxyl masers [32]. Even young H II regions [33] and molecular clouds [34] seem to have magnetic fields aligned with a large-scale field along the Galactic plane.

Also, one large-scale reversal of the magnetic field near the Sun towards the Galactic Center has been known for decades [35, 36] and is confirmed by the rotation measure studies discussed here, but also by magnetic field directions in massive star-forming regions as probed by Zeeman splitting of OH masers [37]. However, the exact number and location of large-scale reversals, pitch angles, characteristics
of the turbulent magnetic field as a function of location and properties of the magnetic field close to the Galactic Center are still under discussion.

The past decade has seen a surge in studies using ad-hoc Galactic magnetic field models such as axisymmetric, bisymmetric or ring-shaped magnetic fields to fit to observational data. The goal is to determine free fit parameters such as magnetic field configuration, pitch angle and strength. Table 1 shows a brief and necessarily incomplete summary of these models and some of their properties, as an attempt to make the differences between these models insightful, and to draw conclusions from this large body of work by many authors. Many of these models contain complexities that cannot all be captured in a simple table, e.g. models include radially declining magnetic field strengths or use different ways to incorporate large-scale magnetic field reversals. Also, the models use various models of thermal and/or cosmic ray electron densities, which we do not discuss here at all. The range of conclusions in these papers is much wider than noted in the table; here we focus on modeling results about the magnetic field strength and structure only.

It is highly non-trivial to compare the results from these models since they are so heterogeneous: most models use different input configurations for magnetic fields, thermal electron density and cosmic ray density, and use the various magnetic field parameters as either input or output parameters. However, some consensus seems to appear: most models tend to favor axisymmetric magnetic field models with one reversal just inside the Solar circle [24, 38, 16, 12]. These best fit configurations (sometimes with some embellishments) have been taken as fixed input in subsequent papers, in order to determine e.g. out-of-plane magnetic fields [11], or the pitch angle and synchrotron spectral index [39]. However, careful analysis of pulsar RMs by [40] proved that none of the three widely used magnetic field models (axisymmetric, bisymmetric, ring) are consistent with the data. These authors conclude that the magnetic field of the Milky Way must be more complex than one simple dynamo mode, possibly a combination of modes, as observed in some external galaxies (see R. Beck’s Chapter, this Volume).

One notable difference in results can be seen in models based mostly on pulsars and models based mostly on extragalactic sources. RMs of extragalactic sources average magnetic field and density fluctuations over the complete line of sight through the whole Galaxy. Pulsar RMs only probe the line of sight to the individual pulsar, or even the path length between two pulsars in close projected proximity on the sky, which is a shorter distance and much more variable over small coordinate differences. In addition, RMs from extragalactic sources tend to be averaged over some region in the sky in order to diminish contributions from their intrinsic RM and from the turbulent Galactic ISM. Therefore, RMs measured from pulsars tend to show much more influence of the small-scale magnetic field component. Good examples of this are presented in [18], who used RMs from pulsars. They did not use any model but constructed a magnetic field configuration by looking at sign reversals of pulsar RMs in arms or interarms. Their data confirmed a counter-clockwise field in the Carina-Sagittarius spiral arm and suggest a counter-clockwise field in the Perseus. They find an abundance of small-scale structure in RM sign, which they interpret as clockwise magnetic fields in the interarm regions and counter-clockwise
magnetic fields in the spiral arms, indicating large-scale magnetic field reversals at every arm-interarm boundary. Magnetic field modeling by [25] confirm reversals at every arm-interarm boundary, but find results at $> 3\sigma$ only for the Crux and Norma arms and the interarm region in between.

Fig. 4, reproduced from [7], nicely illustrates the intermediate-scale structure in RMs from pulsars, which are interpreted in the literature as reversals along spiral arm directions [18] or as intermediate-scale fluctuations in the field [7]. As an example of the difference with modeling results including extragalactic sources, I mention [41], who analyzed the Milky Way’s magnetic field RM data of pulsars and extragalactic sources combined. They divide up the Galactic disk in three separate longitude ranges and concluded that there is no simple configuration which fits the whole Galactic plane sufficiently well, see Fig. 5. They also conclude that not more than one large-scale field reversal is needed to explain the data.

One way to decrease the influence of small-scale structure on pulsar RM measurements is by averaging these data as well before analysis of the structure. This can be done e.g. by wavelet analysis [42], using pulsar RMs. Using this method, [19] only obtained reliable results a few kpc from the Sun due to sparsity of data beyond. However, these authors found evidence for one magnetic field reversal at a distance of $0.6 - 1$ kpc towards the Galactic center, and an other reversal between the Perseus and (local) Orion arm, in agreement with some earlier studies [43, 44]. However, [45] show that the anomalous RMs interpreted as a large-scale reversal
Fig. 5 Left: Bird’s-eye view of the Milky Way, where the Galactic Center is at \((X, Y) = (0, 0)\) and the Sun is at \((X, Y) = (0, 8.5)\) kpc. The small circles within the Galaxy denote observed pulsar RMs, large circles around the Galaxy show observed extragalactic source RMs in the Galactic plane, boxcar-averaged over 9° in longitude with a step size of 3°. The background color scale presents predicted RMs at each location according to the model in the right hand figure. Right: Model of Galactic magnetic field in which the Galaxy is divided up into three regions. Color denotes magnetic field strength. Outer Galaxy: logarithmic spiral with \(p = -11.5°\); fourth Galactic quadrant: model from [24]; first quadrant: ASS+RING model from [38]. Image reproduced from [41].

towards the Perseus arm can be explained by anomalous RMs due to the influence of H\(_\text{II}\) regions along the line of sight.

There is some evidence to suggest that the one well-determined large-scale reversal in the disk magnetic field does not follow the Sagittarius-Carina arm exactly, but slices through it [24, 41], see also Fig. 5, a phenomenon that has been seen in the nearby spiral galaxy M51 as well [46, 47]. In addition, the magnetic field towards the outer Galaxy \(l \sim 180°\) may be closer to circular rather than spiral [48, 41].

Also, many studies provide evidence for a dominant even symmetry of the local regular field in the disk with respect to the Galactic plane [19, 16, 49, 50].

### 3.3 The pitch angle of the magnetic spiral arms

Estimates of the pitch angle of the Milky Way’s magnetic spiral arms are widely varying, depending on the tracer used to determine this angle. [51, 52] collected pitch angle estimates from 1980 to 2001, obtained from H\(_\text{I}\) and H\(_\text{II}\) gas, pulsars, dust, CO, rotation measures and O stars, which vary from \(-5°\) to \(-21°\). His weighted average is \(p = -12° \pm 1°\). Polarized starlight indicates a pitch angle of \(p = -7.2° \pm 4.1°\) [29], consistent with the other estimates.
Table 1: Table summarizing models comparing Milky Way magnetic field configurations to various observational tracers. Note the incredible range of possible data, models, fixed parameters and output parameters. Column 1 gives the reference to the paper, column 2 details the used tracers and column 3 notes whether the model pertains to the Galactic disk, the halo, or both (‘all’). Column 4 summarizes the ad-hoc models used for each paper, and Column 6 (some of) the main results. Column 7 gives the pitch angle of the disk field, where ‘IN’ is added if this pitch angle was a fixed input value. Symbols are as defined in the text.

| ref | TRACER \(^a\) | D/H | MODELS \(^b\) | MODEL RESULTS | \(p\) |
|-----|---------------|-----|-------------|---------------|-----|
| [24] | 149 EGS RMs | Q4\(^d\) | spiral | one reversal | \(-11.5^\circ\) |
| [39] | 120 pulsar RMs | | | | |
| [12] | WMAP5 \(P\) 23GHz | all | modified log spiral | \(B_z = 0.4\ \mu G\) | \(-30^\circ\) |
| [16] | WMAP5 PI 23GHz | disk | ASS, log spiral, compression | \(B_{\text{reg}}: B_{\text{sun}}: B_{\text{ani}} = 1:5:4\) | \(-11.5^\circ\) IN |
| [11] | WMAP7 PI 23GHz | all | spiral, \(B_{\text{sun}}, B_{\text{ani}}\), one reversal \(B_{\text{ani}} = 1.7B_{\text{reg}}\) | \(-11.5^\circ\) IN |
| [40] | 482 pulsar RMs | disk | ASS, BSS, ring | no good models, slight preference for ASS | |
| [25] | WMAP5 PI 23GHz | halo | BSS, \(B_{\text{sun}}\) | \(B_{\text{sun}} = 0.57B_{\text{reg}}\) | \(-8.5^\circ\) |
| [15] | 133 pulsar RMs | Q4\(^d\) | log spirals | QSS/many reversals preferred | |
| [10] | WMAP3 PI 23GHz | halo | log spirals, \(B_z\), \(B_z\) at 25\(^\circ\) tilt | \(-55^\circ\) \(^d\) |
| [49] | \(\geq37000\) EGS RMs | all | ASS, BSS, ring | ASS best in disk; odd in halo | \(-5^\circ\) |
| [54] | WMAP5 PI 23GHz | halo | ASS, BSS, ring, bi-toroidal, \(B_z\) | ASS preferred, \(B_z = 1/\mu G\) | \(-24^\circ\) \(^e\) |
| [38] | WMAP5 PI 23GHz | all | ASS, BSS, ring | ASS best in disk, odd in halo | \(-12^\circ\) IN |
| [55] | 354 pulsar RMs | disk | rings with \(p\) | one reversal only | \(-12^\circ\) IN |
| [39] | \(\geq37000\) EGS RMs | | | | |
| [11] | 1373 EGS RMs | disk | ASS, BSS, ring combinations | no single model | 0\(^e\) or |
| [57] | 557 pulsar RMs | | | for complete Galaxy | \(-11.5^\circ\) IN |

\(^a\) I = total intensity; \(PI =\) polarized intensity; EGS = extragalactic sources; WMAP\(i =\) Wilkinson Microwave Anisotropy Probe data over \(i\) years.

\(^b\) ASS = axisymmetric spiral; BSS = bisymmetric spiral; QSS = quadrisymmetric spiral; -A/-S = (anti-)symmetric with respect to Galactic plane.

\(^c\) \(Qi = i\)th quadrant of the Milky Way; GC = Galactic Center.

\(^d\) taking into account their deviating definition of pitch angle, see Section 2.3

\(^e\) actually given as \(p = +24^\circ\) in the paper, but with the opposite definition of azimuth direction.
The magnetic field models in Table 1 based on RM data give pitch angles in the range $p \sim -5^\circ$ to $-15^\circ$, while models fitting to high-frequency (mostly WMAP) polarized synchrotron emission data tend to find much higher pitch angles $p \sim -25^\circ$ to $-30^\circ$ (except for [53], who find $p = -8.5^\circ$ based on the WMAP degree of polarization, modeling a BSS spiral field and adding a turbulent component to match the observed depolarization). As a notable exception, [16] finds a high (and oppositely directed!) pitch angle $p = +35^\circ$, based on RMs, but warns that this result is “highly model dependent”. Indeed, they describe that fixing the pitch angle at $p = -12^\circ$ in their best-fit model only decreases the fitting quality slightly.

Using the straightforward method of comparing longitude-dependences of RMs of extragalactic sources in the first and fourth quadrants, [56] conclude that the Milky Way has a bisymmetric structure towards the inner disk and an axisymmetric pattern towards the outer disk with an “inward spiral pitch angle” of $5.5^\circ \pm 1^\circ$. However, their pitch angle calculation assumes that the sign changes in RM in the first and fourth quadrant are due to the same spiral arm, which would actually indicate a pitch angle of $p = +5.5^\circ$, i.e. a trailing instead of a leading spiral. The longitudes of the changes in RM sign in the first and fourth quadrants are more plausibly due to the Local Arm in the first quadrant and the Carina arm in the fourth, in which case their pitch angle estimate is based on an incorrect assumption.

### 3.4 Turbulent magnetic fields in the disk

The strength of the random, turbulent magnetic field component can be estimated from RM fluctuations, combined with an estimate of thermal electron density [57]. [58] performed this analysis in a small region in the Galactic plane in the 4th quadrant and found a random field strength of $B_{\text{ran}} \gtrsim 1.3 \mu G$. Large-scale magnetic field models that include the turbulent magnetic field as a free parameter find $B_{\text{ran}} \sim 3 - 4 \mu G$ [e.g., 12, 38]. However, the estimates for the regular and total magnetic field strengths would suggest a slightly larger value for the turbulent component, i.e. $B_{\text{ran}} = \sqrt{B_{\text{tot}}^2 - B_{\text{reg}}^2} \approx 5.5 \mu G$.

Under the assumption of a Faraday screen, [58] find that $B_{\text{ran}}/B_{\text{reg}} \lesssim 2$ in a relatively small field of view at the anti-center at Galactic latitude $b = 20^\circ$, based on synchrotron depolarization. In two other relatively small fields out of the Galactic plane, [59] find $B_{\text{run}} \approx 1 - 3 \mu G$ and an unusually low ratio of random to regular magnetic field components $B_{\text{ran}}/B_{\text{reg}} = 0.7 \pm 0.5$. However, both these regions are located in the extended, high-polarization Fan region, which is thought to have a higher contribution of the regular magnetic field than the average ISM [60]. This unusually low value of magnetic field ratio agrees with the higher-frequency synchrotron polarization study of [53], which however includes the anisotropic random

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3 Since RM fluctuations and synchrotron depolarization trace the isotropic random field and the parallel component of the ordered random field (see Fig. 1), the strengths cited are a combination of these two components.
field component in their regular field strength calculation, plausibly explaining the low random-to-regular magnetic field ratio.

The power spectrum of magnetic field is difficult to measure directly, but information about the field can be derived from power spectra or structure functions of RM, assuming some distribution of thermal electron density fluctuations. RM fluctuations follow a power law, although the slope tends to be flatter than Kolmogorov [61,44]. Early studies covering large parts of the sky conclude that the outer scale of the turbulent magnetic field, connected to the energy injection scale of the dominant source, is \( \sim 100 \) pc [62,63]. However, when distinguishing spiral arms and interarm regions explicitly, the turbulent outer scale in spiral arms seems to be much smaller, only a few parsecs [64,65,66]. Small outer scale estimates like this are also found from anisotropies in TeV cosmic ray nuclei [67], and from analysis of fluctuations in radio synchrotron emission in the Fan region [68].

Finally, there is evidence for an anti-correlation between small-scale magnetic field structure and density, at least in the denser ISM: denser components display more disordered magnetic field structure in submm BICEP data in the Galactic plane [31].

4 Magnetic fields in the Galactic Halo

The strength of the magnetic field in the Galactic halo\(^4\) is estimated to be between 2 – 12 \( \mu G \) from the best-fit models in Table 1. The field in the halo is thought to be fairly uniform: the average line of sight component of the magnetic field at high latitudes (where the \( \sin(b) \) dependence has been taken into account) has a standard deviation \( \sigma_B \lesssim 0.4 \) \( \mu G \) [69]. Using equipartition arguments, [70] derived \( B_{\text{ran}} \approx 1 \) \( \mu G \) in the halo, indeed smaller than in the disk.

The scale height derived from synchrotron emissivity under the assumption of equipartition between cosmic rays and magnetic fields is about 5 – 6 kpc [71]. Using hydrostatic balance, including kinetic, magnetic and cosmic-ray pressures, [72] find an almost linearly decreasing field strength from about 5 \( \mu G \) in the plane to 1 – 2.5 \( \mu G \) at 3 kpc height above the disk. [73] used pulsar RMs to derive a magnetic field scale height of 1.5 kpc - the discrepancy with earlier estimates may be due to the fact that pulsar RMs only sample the large-scale, regular component of the field while equipartition estimates also take into account the turbulent component.

The northern and southern hemisphere have different properties. The RM variance is a factor of 2 higher toward the South Galactic Pole than toward the North Galactic Pole [74]. RM data also show a north-south asymmetry in RMs [19], emphasized by [50], who studied extragalactic source RMs in two distinct parts of the sky towards the outer Galaxy (100° < \( l < 117° \) and \( |b| > 15° \)). They concluded that

\(^4\) Two separate definitions of the Galactic halo with respect to the thick disk cause some confusion: The Galactic halo is regularly referred to as the region above the thick disk. However, in a second common use of the term Galactic halo it is equal to the thick disk. We use here the second definition, where the halo is equal to the thick disk.
the observations cannot be reproduced by symmetric exponential or double-toroidal Galactic halo fields as used in the literature. They find a higher halo field strength in the south \( (B_H ≈ 7 \, \mu G) \) than in the north \( (B_H ≈ 2 \, \mu G) \), and suggest that magnetic spiral arms might exist in the halo as well.

A large-scale vertical magnetic field at the Solar radius is small, if it exists at all. \cite{70} find from extragalactic source RMs towards the northern and southern Galactic pole at \(|b| > 70°\) that there is no evidence for a large-scale vertical magnetic field component at the Solar radius in the northern hemisphere, while \( \langle B_z \rangle ≈ 0.3 \, \mu G \) in the south. This is not necessarily due to an asymmetry in the large-scale vertical field, but can be due to differences in nearby structure in the two hemispheres. \cite{75} evaluated the vertical magnetic field from RMs from all NVSS sources. Their conclusion that \( \langle B_z \rangle = 0.3 ± 0.03 \, \mu G \) agrees with \cite{70} in the southern hemisphere, but they also find a small vertical magnetic field of \( \langle B_z \rangle = −0.14 ± 0.02 \, \mu G \) in the northern hemisphere. \cite{70} attribute this difference to the North Polar Spur, which they removed from their data and \cite{75} did not. \cite{73} found a vertical magnetic field \( B_z = 0.2 − 0.3 \, \mu G \) from south to north; however, they forced the direction of the field to be south-north or north-south and only fitted the field strength. Therefore, it is not possible to say whether their data would agree with the above conclusions. Small and varying vertical magnetic field strengths found in a field of view at \( l = 153°, \ 0.5° < b < 18° \) by \cite{77} and at high Galactic latitudes \( b = 70° \) \cite{78} probably reflect smaller-scale magnetic field fluctuations and not the large-scale field.

5 Magnetic fields in the entire disk+halo system

Most models in Table 1 do not only discuss the Galactic disk or halo but simultaneously fit both the disk and the halo, allowing for different configurations in disk and halo magnetic fields. \cite{16} tried to unify models of the Galactic disk and halo, using a number of different models from the literature. They concluded that the magnetic field structure in the Galactic disk and halo were different and cannot be captured by scaled-up versions of the same magnetic field configuration. Their best-fit model is a disk-even halo-odd (DEHO) field, which was shown to be theoretically possible if one attributes an important role to the Galactic wind in the dynamo process \cite{79}. The conclusion of a best-fit DEHO field was also reached by \cite{38}. These authors fitted 22.8 GHz synchrotron data from the Wilkinson Microwave Anisotropy Probe [WMAP, \cite{80}] and rotation measures from 1090 extragalactic point sources to their models and argued that none of the available models were a good fit to the data. However, they could conclude that a disk magnetic field which was symmetric with respect to the Galactic plane was strongly favored. For the halo, a toroidal field which is anti-symmetric with respect to the plane was preferred. Indeed, this anti-symmetric structure in the rotation measure sky with respect to the Galactic Center (“butterfly pattern”), only existent in the inner Galaxy, was already noticed decades

\footnote{NRAO VLA Sky Survey \cite{76}.}
ago \cite{36}. This has been interpreted as an A0 dynamo \cite{18}, i.e. a dynamo causing an A0 field configuration (see Section 2.1), but has also been attributed to local structure \cite{81,74}. A0 dynamo models are also strongly inconsistent with modeling comparing near-infrared starlight polarization measurements, based on discrepancies in the Galactic disk. However, adding an even disk-component to these models (DEHO field) makes them inconsistent with observed degrees of polarization of near-infrared starlight \cite{82}.

\cite{12} included an ordered (anisotropic random) component to the regular (coherent) and random Galactic magnetic field components in their model. Due to the large number of free parameters (22), some of which are degenerate, they choose to constrain some parameters using one observational data set only, and keeping these fixed while constraining other parameters. Due to these degeneracies and the large number of unknowns, the authors caution to not attach too much value to the absolute numbers they find for field strengths. They do argue that their ratio of the three field components regular:random:anisotropic random, of 1:5:3, is relatively robust. So they conclude that the anisotropic random field is stronger than the regular field component. In \cite{83}, these authors use a more realistic cosmic ray distribution in the Galaxy and find that the random component is even larger with respect to the coherent component.

At the moment, the latest all-inclusive modeling attempt is presented in \cite{11,84}. \cite{11} include two new components for the magnetic field: a vertical, out-of-plane component similar to the X-shaped fields seen in external galaxies \cite[e.g., 8]; and a contribution by anisotropic random magnetic fields. The latter is degenerate with an increased intensity of cosmic ray electrons over the usually quoted values \cite{85}, but generally comparable in strength to the regular field. A random component for the magnetic field is added in \cite{84}, which is allowed to vary in strength in 8 spiral regions. This complex magnetic field model now has 36 free parameters, making it exceedingly difficult to be confident that the true minimum in 36-dimensional parameter space has been found.

The set of papers which fit magnetic field models to radio polarization data at high frequencies (≥ 22 GHz WMAP data) \cite{54,39} tend to find a higher pitch angle than rotation measure studies of ∼ 24° – 30°. Planck all-sky maps will provide additional observational constraints, which simulations show suggest the same high pitch angles \cite{86}. A non-negligible vertical magnetic field component is needed in these models as well, currently at odds with conclusions from rotation measure analyses (Section 4).

It may be possible in the near future to derive Galactic magnetic field structure from observations of arrival directions of Ultra-High Energy Cosmic Rays (UHE-CRs), but currently the sources and composition of UHECRs are too uncertain to constrain any Galactic magnetic field models \cite{87}. 

6 Summary and conclusions

In this Section, I present a short summary of observational knowledge of magnetic fields in the Milky Way, neglecting all subtleties discussed above. I will also try to draw some conclusions.

The strength of the magnetic field in the Solar neighborhood is fairly well determined. The regular, large-scale component $B_{\text{reg}} \approx 2 \mu G$, while the total magnetic field is $B_{\text{tot}} \approx 6 \mu G$. Estimates of the isotropic random magnetic field from magnetic field modeling of $B_{\text{ran}} \approx 3 - 4 \mu G$ suggest that there exists also an anisotropic random field component of comparable strength to the random component. The magnetic field strength increases towards the inner Galaxy, and is independent of density for the diffuse interstellar gas.

The magnetic field direction in the Galactic disk most likely roughly follows the spiral arms. This is not always the case, since pitch angle estimates from modeling still vary, and there are concrete indications at several locations in the Galactic disk that the magnetic field direction does not coincide with the stellar or gaseous arms. The disk magnetic field is symmetric (even) with respect to the Galactic plane.

There is one large-scale magnetic reversal close to the Sun towards the inner Galaxy, but the existence and location(s) of more reversals is still under debate. The studies that rely mostly or totally on pulsar data indicate magnetic fields with more intermediate-scale structure (reversals) than studies (also) including extragalactic source RMs. This difference is likely due to the intrinsic differences in the data: extragalactic source RMs are averaged over the entire line of sight through the Galaxy and often over a patch of the plane of the sky as well, which washes out smaller scale structure partially. Fitting pulsar data would retrieve this smaller scale structure. However, pulsars with known RMs are concentrated in a few kpc from the Sun and their distances can be quite uncertain. Therefore, it is quite possible that what is interpreted as reversals along spiral arms are actually other intermediate scale structures caused by e.g. superbubbles.

The pitch angle of the magnetic field is roughly $p \approx -5^\circ$ to $-15^\circ$, depending on tracer (rotation measure, starlight polarization, gas, CO, etc). A notable exception is modeling of high-frequency (i.e. Planck/WMAP frequencies and higher) synchrotron emission, studies of which consistently show higher pitch angles of $p \approx -25^\circ$ to $-30^\circ$. The random magnetic field component shows a turbulent power spectrum with an outer scale of turbulence that is a few parsecs in the disk, possibly only the spiral arms, and up to $\sim 100$ pc in the Galactic halo.

The magnetic field strength in the gaseous halo, or thick disk, is comparable to that in the disk, with an uncertainty of a factor $2 - 3$. The scale height is many kiloparsecs ($\sim 5 - 6$ kpc), possibly smaller for the regular field component. There is a pronounced north-south asymmetry across the Galactic disk: the magnetic field variance is higher in the south. There is a small large-scale vertical magnetic field component towards the south $B_z \approx 0.3 \mu G$, while a small vertical magnetic field component towards the north could be attributed to the North Polar Spur.

The complete disk-halo system has been extensively modeled in the past decade, using a wide variety of observational tracers, magnetic field configurations and com-
ponents, thermal and cosmic ray density models, and input and output parameters. One property that all models share is that none of them gives a satisfactory fit to all the data. This is not surprising, seeing the immense complexity of the magnetic and gaseous structures observed in the Milky Way. Large loops of radio emission such as the North Polar Spur or Loop I to IV [88] show influence of magnetic fields [89, 74], created by supernovae blowing bubbles in the ionized interstellar gas, dragging the magnetic field with them. The named Loops are giant structures in the sky because they are located very close to the Sun and are therefore conspicuous on the sky. However, hundreds or even thousands more of these structures should exist in the rest of the Milky Way, all affecting the large-scale structure of the magnetic field. These and other local structures are virtually impossible to include in modeling and therefore often omitted. This is especially clear towards the Galactic anti-center, where the regular magnetic field is directed almost perpendicular to the line of sight and therefore has a negligible RM contribution in this direction. As [49] note, any regular magnetic field model with a small pitch angle severely underestimates the amount of RM fluctuations observed in this direction. These local structures, combined with the location-dependent turbulent nature of the magneto-ionized medium, make this modeling a daunting enterprise.

The variety in conclusions from Galactic magnetic field models using different tracers and methods, indicates a large role of small-scale position-dependent turbulence, discrete structures, significant changes in pitch angle along a spiral arm, or – most likely – all of these. Variable pitch angles are also suggested by simulations of density waves including magnetic fields [90]. This explanation does make it more plausible why a ring-like magnetic field model gives fit results of comparable quality as the spiral arm models, or why deviations of magnetic field directions from gaseous and stellar pitch angles are found.

7 Epilogue

A number of recent technological and computational developments make a large expansion in parameter space related to studies of cosmic magnetic fields possible: Phased Array Feeds allow deep surveys of large parts of the sky in reasonable observing times; low frequency polarimetry is becoming possible thanks to sufficient computer power and technological expertise to build software telescopes, and finally large-scale galactic (but also extragalactic, intracluster) magnetic fields can be probed in (almost) three dimensions using Rotation Measure Synthesis [91].

This has sparked renewed interest in the field of cosmic magnetism, as evidenced by the Cosmic Magnetism Key Science Project [MKSP, 92] for the LOw-Frequency ARray LOFAR; the Polarisation Sky Survey of the Universe’s Magnetism [POSUM, 93] for the Australian Square Kilometre Array Pathfinder (ASKAP), and cosmic magnetism studies as part of the WODAN project [94] using the APERTIF Phased Array Feeds on the Westerbork Synthesis Radio Telescope (WSRT). These are all exciting innovative telescopes and/or instruments currently under construc-
tion. For details on magnetism studies with LOFAR, SKA, Planck and ALMA see the Chapters by R. Beck and W. Vlemmings in this Volume. I will discuss other important future and ongoing initiatives below.

### 7.1 Galactic magnetism with existing instrumentation

A number of large radio polarimetric surveys have recently been done or are in progress, with the aim of studying the magnetized ISM of the Milky Way, at a variety of frequencies.

Several surveys with the ALFA seven feed array on the Arecibo telescope are being performed, among which the Galactic ALFA Continuum Transit Survey [GALFACTS, 95]. GALFACTS will survey the whole Arecibo sky ($-1.33^\circ < \delta < 38.03^\circ$) in the frequency range $1225 - 1525$ MHz down to a sensitivity of $90$ $\mu$Jy. Its main science goals are exploration of the Milky Way's magnetic field and the properties of the magnetized ISM. Observations have been progressing for four years and will be completed in 2013.

The lower Faraday rotation (and therefore more distant polarization horizon) at higher frequencies was the reason for the 6-cm Sino-German survey of the Galactic plane ($10^\circ < l < 230^\circ$, $|b| < 5^\circ$) with the Urumqi 25-m single dish [96, 97, 98, 99]. This survey is mostly focused on the detection of discrete magnetized objects such as H II regions, supernova remnants and Faraday screens. At even higher frequencies of 5 GHz, the C-Band All-Sky Survey (C-BASS) will provide an all-sky polarimetric survey. Although its main science goal is providing characterization of foregrounds for Cosmic Microwave Background (CMB) polarization studies, it will also explore Galactic magnetic fields. Data acquisition is ongoing.

The S-Band Polarization All-Sky Survey (S-PASS) is a radio polarimetric study of the entire southern sky at $2307$ MHz in a $184$ MHz bandwidth, performed with the Parkes 64-m single dish telescope with a polarization sensitivity better than $1$ mJy/beam. The science goals of the survey are two-fold: characterizing polarized foregrounds for measurements of the B-mode of CMB Polarization, and exploration of Galactic magnetic fields. The survey observations are completed and first science results are being published [100, 101, 102]. The Southern Twenty-centimeter All-sky Polarization Survey (STAPS) was observed commensally with S-PASS and data processing is ongoing.

The largest ongoing project to map Galactic magnetism using existing instrumentation is the Global Magneto-Ionic Medium Survey [GMIMS, 103]. This project consists of a series of polarimetric surveys in the northern and southern hemispheres, from $\sim 300$ MHz to $\sim 1800$ MHz. Data acquisition for the southern-sky survey spanning $287 - 870$ MHz with the Parkes telescope is completed and data processing in progress, while the STAPS survey described above will function as the high-band ($1300 - 1800$ MHz) southern-sky survey for GMIMS. For the high-band survey in the north ($1277 - 1740$ MHz), performed with the DRAO 26-m single dish [104], observations have finished and data reduction is nearing completion, with first sci-
ence results discussed in [81]. Options for observing the remaining GMIMS surveys are being considered.

With an angular resolution of $30^\circ - 60^\circ$ and a frequency resolution of at least 1 MHz, GMIMS will provide the first spectro-polarimetric data set of the large-scale polarized emission over the entire sky, observed with single-dish telescopes. The broad frequency coverage is of great importance for high resolution and broad sensitivity of Rotation Measure Synthesis. Therefore, the combined surveys with a 1.5 GHz bandwidth will give unprecedented maps of Faraday depth over the whole sky, revolutionizing studies of the magneto-ionized ISM in the Galaxy using this method.

### 7.2 Galactic magnetism with next-generation instrumentation

The WSRT is being upgraded with phased array feeds named APERture Tile In Focus [APERTIF, 105] with a 300 MHz bandwidth in the range of 1.0 GHz to 1.7 GHz. This upgrade will increase Westerbork’s field of view with a factor 25 to about 8 square degrees, making it a wonderful survey instrument.

One of the key surveys to be performed with APERTIF is the Westerbork Observations of the Deep APERTIF Northern-Sky [WODAN, 94]. WODAN aims to image the whole northern sky down to 10 μJy rms with a broad bandwidth around 1400 MHz, and part of the sky a factor two deeper. It is mostly geared towards cosmology and other extragalactic science, with an observational aim to detect 30 million radio sources including 100,000 clusters, 10 million starbursting galaxies at $z > 1$ and virtually all radio loud AGN in the Universe. However, many of these sources will emit polarized emission at this wavelength, which will be Faraday rotated by the Galactic magnetized ISM. This will provide an observational data set for Galactic magnetism studies far surpassing the currently available NVSS rotation measure data base [75].

Similarly to WODAN in the northern sky, the southern sky will be surveyed by several projects on the Australian SKA Pathfinder [ASKAP, 106]. WODAN’s sister survey is called Evolutionary Map of the Universe [EMU, 107], but the data obtained is shared between EMU and a project dedicated to cosmic magnetism, named Polarization Sky Survey of the Universe’s Magnetism [POSSUM, 93]. POSSUM aims to measure the Faraday rotation of 3 million extragalactic radio sources over 30,000 square degrees, which will allow major steps in characterizing the large-scale and turbulent components of the Galactic magnetic field, but also test (dynamo) theories for the origin and evolution of the Milky Way’s magnetic field.

Finally, the Murchison Widefield Array [MWA, 108], under development in Western Australia at the moment is a low-frequency radio interferometer at 80 – 300 MHz - analogous to LOFAR in the north but smaller; however, with an excellent uv-coverage on small baselines. Although its main science goals are the Epoch of Reionization, solar and ionospheric science and transients, it can also be used to
provide detailed rotation measure synthesis maps of low-magnetic-field areas in the southern sky.

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