TESTING GALACTIC MAGNETIC FIELD MODELS USING NEAR-INFRARED POLARIMETRY

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ABSTRACT

This work combines new observations of NIR starlight linear polarimetry with previously simulated observations in order to constrain dynamo models of the Galactic magnetic field. Polarimetric observations were obtained with the Mimir instrument on the Perkins Telescope in Flagstaff, AZ, along a line of constant Galactic longitude ($\ell = 150^\circ$) with 17 pointings of the $10' \times 10'$ field of view between $-75^\circ < b < 10^\circ$, with more frequent pointings toward the Galactic midplane. A total of 10,962 stars were photometrically measured and 1116 had usable polarizations. The observed distribution of polarization position angles with Galactic latitude and the cumulative distribution function of the measured polarizations are compared to predicted values. While the predictions lack the effects of turbulence and are therefore idealized, this comparison allows significant rejection of AO-type magnetic field models. SO and disk-even halo-odd magnetic field geometries are also rejected by the observations, but at lower significance. New predictions of spiral-type, axisymmetric magnetic fields, when combined with these new NIR observations, constrain the Galactic magnetic field spiral pitch angle to $-6^\circ \pm 2^\circ$.

Key words: dust, extinction – ISM: magnetic fields – polarization – radiative transfer

Online-only material: machine-readable table

1. INTRODUCTION

The Galactic magnetic field is an important aspect of the interstellar medium (ISM), but even its large-scale structure is still uncertain. What symmetry properties does the field exhibit? Is the magnetic field axisymmetric, or are there field direction reversals at some radii? How is the magnetic field sustained? As a first step to addressing these questions, this work compares new near-infrared (NIR) starlight polarimetry to predictions of the polarization properties for different magnetic field geometries (Pavel 2011). Through strong observational constraints, the mechanism that sustains the Galactic magnetic field can also be constrained. In addition to the large-scale symmetry of the Galactic magnetic field, these observations are used to constrain the spiral-type magnetic pitch angle of the Galaxy.

Magnetic fields remain one of the most difficult aspects of the nearby universe to probe. Every method for measuring the interstellar magnetic field requires some special circumstance (e.g., a background-polarized source for Faraday rotation, high column density for polarized thermal emission or Zeeman splitting, a background star for interstellar polarization of background starlight). To date, the study of the Galactic magnetic field has been dominated by radio wavelength Faraday rotation studies. However, by combining many different techniques, observational constraints can be placed on the structure of the Galactic magnetic field which will drive, for example, dynamo theories forward.

Over the last few decades, progress has been made in understanding the Galactic magnetic field through, especially, improvements in numerical simulations (Elstner et al. 1992; Brandenburg et al. 1992, 1993; Ferrière & Schmitt 2000; Kleeorin et al. 2002, 2003; Moss & Sokoloff 2008; Hanasz et al. 2009; Moss et al. 2010). However, while our understanding of fundamental dynamo physics grew, there were few observational predictions. Observational constraints of large-scale magnetic field models have almost exclusively relied on Faraday rotation of emission from Galactic pulsars and polarized extragalactic sources (Smith 1968; Manchester 1974; Rand & Kulkarni 1989; Men et al. 2008) that only probe the line-of-sight component of the magnetic field. Heiles (1996) used optical polarimetry to constrain the Galactic magnetic pitch angle (defined as $\rho = \tan^{-1}(B_{r}/B_{\phi})$ for a spiral-like magnetic field pattern), but, beyond this, starlight polarization has not been quantitatively employed as a tool for constraining the large-scale Galactic magnetic field structure.

Polarization of background starlight has been an astrophysical tool since the pioneering works of Hiltner (1949) and Hall (1949), and early theoretical work linked this optical polarization with interstellar magnetic fields (Davis & Greenstein 1951). As currently understood (Lazarian 2007), interstellar polarization arises from dichroic extinction of unpolarized starlight passing through regions of elongated dust grains which are directionally aligned with their long axes preferentially perpendicular to the local magnetic field. Assuming that background stars emit all polarizations equally (i.e., unpolarized), photons polarized parallel to a grain’s long axis see the largest grain cross section and are preferentially extincted. The result is linear polarization whose stronger electric field direction is parallel to the direction of the magnetic field, as projected on the sky.

Much of the previous starlight polarization work has been done at optical wavelengths where the polarization signal is strongest (Serkowski et al. 1975). However, optical wavelengths suffer appreciable dust extinction, especially through the Galactic disk, and typically cannot probe stars farther than 2–3 kpc (Fosalba et al. 2002; Han 2008). At longer wavelengths, starlight is less extincted by dust and polarizations can be measured to stars far beyond optical limits.

In addition to extinction, nearby magnetic structures can dominate the observed optically traced morphology. Loop I is a supernova remnant of 116° diameter on the sky, approximately 130 pc from the Sun, centered at $\ell = 329^\circ$, $b = 17.5$ (Berkhuijsen 1973), and prominently seen in the optical polarization compilation of Heiles (2000). This nearby object obscures the signature
from the large-scale magnetic field structure. Faraday rotation studies of the Galactic magnetic field may also be affected by similar foreground objects (e.g., supernova remnants; Wolleben et al. 2010). By observing in a direction without any obvious disturbances, the quiescent Galactic magnetic field may be reliably probed by NIR starlight polarimetry to distances of several kiloparsecs (Clemens et al. 2012b).

Pavel (2011) used existing dynamo-driven Galactic magnetic field models and empirical dust distributions to predict the NIR observational signatures of different magnetic field models: S0 (even), A0 (odd), disk-even halo-odd (DEHO), and simple analytic axisymmetric. From these predictions, the shape of the curve of polarization Galactic position angle (hereafter GPA) with Galactic latitude (b) and cumulative distribution functions (CDFs) of the normalized degree of polarization (P) were proposed as tools for testing predictions of the large-scale structure of the Galactic magnetic field against observations.

Here, the predictions of Pavel (2011) are tested against observations of NIR starlight polarimetry with the goal of constraining possible large-scale magnetic field geometries. In Section 2, the observations and data reduction are described. A summary of the simulated polarization measurements from existing Galactic dynamo and dust models is presented in Section 3, along with a comparison between the predicted and observed polarimetric properties. The results of this analysis are discussed in Section 4, and conclusions are presented in Section 5.

2. OBSERVATIONS AND DATA REDUCTION

Observations were made with the Mimir instrument (Clemens et al. 2007) in H-band (1.6 μm) linear imaging polarimetry mode on the 1.8 m Perkins Telescope outside Flagstaff, AZ, on several nights from 2007 through 2009. Mimir uses a cold, stepping half-wave plate (HWP) and a cold, fixed wire grid to analyze starlight polarization across a 10′ × 10′ field of view. The detector is a 1024 × 1024 InSb Aladdin III array.

The observations were taken along a line of constant Galactic longitude, $\ell = 150^\circ$, for $-75^\circ < b < 10^\circ$ in steps of $\Delta b = 5^\circ$ to enable comparison with the Pavel (2011) predictions. Observations taken at $b = -5^\circ$ were not used because the bright star HD 23049 contaminated the images, instead the neighboring $b = -6^\circ$ field was substituted. Galactic latitudes $b = 0^\circ$, $-35^\circ$, $-50^\circ$, and $-55^\circ$ were not observed because of poor weather, and the Perkins telescope is not able to observe north of $b = 10^\circ$ or south of $b = -75^\circ$ at this Galactic longitude due to telescope mount limits. Supplemental measurements were obtained near the Galactic midplane at $b = \pm 1^\circ:25$ and $\pm 2:5$ to provide higher latitude resolution there.

For each pointing, the HWP is rotated to 16 different P.A.s, equivalent to five measurements at an instrument position angle (IPA) of 0° and four IPA measurements each at 45°, 90°, and 135°. This is done toward six different sky dither positions, following a rotated hexagon pattern on the sky, for a total of 102 images per pointing. Each target field consisted of four sets of observations with 10 s integrations per HWP position for a total of 68 minutes of integration time per field. Integration times were set to ensure that the polarimetric uncertainty at $H \leq 14$ was less than 1%. The dates of each Galactic latitude observation are shown in Column 2 of Table 1. Most of the stars found have complementary NIR photometry from Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006).

| Galactic Latitude (1) | UT Date Observed (2) | Significant Detections (3) | Marginal Detections (4) | Upper Limits (5) |
|-----------------------|----------------------|---------------------------|------------------------|-----------------|
| $-75^\circ$           | 2009 Nov 27          | 0                         | 7                      | 4               |
| $-65^\circ$           | 2009 Dec 1           | 1                         | 5                      | 1               |
| $60^\circ$            | 2009 Nov 27          | 0                         | 14                     | 6               |
| $45^\circ$            | 2009 Nov 27          | 1                         | 14                     | 5               |
| $40^\circ$            | 2009 Dec 1           | 1                         | 10                     | 7               |
| $30^\circ$            | 2009 Dec 1           | 4                         | 13                     | 6               |
| $25^\circ$            | 2009 Nov 27          | 2                         | 12                     | 7               |
| $20^\circ$            | 2007 Nov 24          | 4                         | 29                     | 12              |
| $15^\circ$            | 2007 Nov 24          | 6                         | 46                     | 28              |
| $10^\circ$            | 2007 Nov 24          | 8                         | 57                     | 24              |
| $6^\circ$             | 2009 Dec 1           | 34                        | 54                     | 14              |
| $2:5$                 | 2007 Nov 25          | 76                        | 108                    | 8               |
| $1:25$                | 2007 Nov 25          | 60                        | 117                    | 12              |
| $1:25$                | 2008 Mar 23          | 37                        | 97                     | 23              |
| $2.5$                 | 2007 Nov 25          | 51                        | 93                     | 16              |
| $5'$                  | 2008 Mar 23          | 19                        | 52                     | 5               |
| $10'$                 | 2007 Nov 25          | 28                        | 56                     | 16              |

Total 332 784 194

Notes.

- Significant detections defined as $P/\sigma_P > 3$.
- Marginal detections defined as $1.25 \leq P/\sigma_P < 3$.
- Upper limits defined as $P/\sigma_P < 1.25$ and $\sigma_P < 1.0\%$.

2 http://people.bu.edu/clemens/mimir/software.html

1 Throughout this work, polarization position angles will be measured in the Galactic coordinate system, measured east (+e) from Galactic north (+b).
Stokes $Q$, and associated uncertainties) with Mimir $H$-band photometry and 2MASS $JHK_s$ photometry, where available. The 16 master HWP images were also coadded to create deep photometric images for each field.

Figure 1 shows the coadded $H$-band intensity image obtained toward $b = -6^\circ$, with measured polarizations shown as vectors. For detected polarizations, the length of the vector represents the degree of starlight polarization and its orientation represents the equatorial polarization position angle. The diagonal light gray line shows a line of constant Galactic latitude at $b = -6^\circ$.

Figure 1. Mimir coadded $H$-band intensity image of the $10' \times 10'$ field toward $b = -6^\circ$ with overlaid significant polarization vectors. The length of each vector represents the degree of polarization relative to the 2% scale in the lower left corner, and the vector orientation shows the equatorial polarization position angle. The diagonal light gray line shows a line of constant Galactic latitude at $b = -6^\circ$.

A total of 10,962 stars were detected in the combined photometric images, of which 332 had significant ($P/\sigma_p > 3$) polarization detections, 784 had “marginal” ($1.25 < P/\sigma_p < 3$) detections, and 194 had significant upper limits ($P/\sigma_p < 1.25$ and $\sigma_p < 1\%$). All of these 1310 polarization “targets” are listed in Table 2 by Galactic coordinates, degrees of polarization, GPAs, and 2MASS $H$- and $K$-band magnitudes. The lowest, median, and highest significant detected polarizations are 0.19%, 1.51%, and 12.13%, respectively. All polarization target coordinates were passed through SIMBAD to search for previous spectral classifications, but only eight out of the 1310 polarization targets had entries. Of these matches, three stars had spectral classifications (A2V, A3V, and M3V) and one was identified as the X-ray source 1RXS J042738.8+555831 (Voges et al. 1999), while the other four were only identified as stars. The SIMBAD search result suggests that this is a quiescent direction in the Galaxy suitable for probing the large-scale Galactic magnetic field.

To aid in determining the completeness of these observations, the distribution of $H$-band magnitudes for all detected stars was examined. From this distribution, the photometric observations appear complete to $H \approx 16.5$ mag and the polarimetric observations appear complete to $H \approx 13$ mag. The integration times were set so that the median polarization uncertainty, $\sigma_p$, would be less than 1% for stars brighter than $H = 14$. As shown in Figure 2, this goal was not quite achieved, with a median polarization uncertainty of 1.3% at $H = 14$. The shape of the curve in Figure 2 indicates that polarimetric uncertainties are limited by photon noise.

The polarization efficiency ($P/A_V$) toward each star carries information about the polarization environment and polarization mechanism (Goodman et al. 1992; Lazarian et al. 1997; Whittet et al. 2008). Because these observations span from the Galactic midplane to $75^\circ$ below the Galactic plane, a change in $P/A_V$ could indicate a change in the polarization or grain alignment mechanism. The extinction toward each star can be estimated from the observed $(H - K)$ 2MASS colors and the intrinsic colors from Bessel & Brett (1988). Assuming that all stars have an intrinsic $(H - K)$ color of 0.1 ± 0.1 mag, $E(H - K)$ values can be converted to extinctions at $V$ band, $A_V$, as:

$$A_V = r' E_{H-K},$$

assuming $r' = 16$ for the diffuse ISM (Whittet et al. 1996). Considering only stars with measured 2MASS ($H - K$) colors, 2MASS photometric S/N $> 3$ for $H$ and $K$, and polarimetric S/N $> 3$, the resulting photometric and polarimetric extinction distributions are shown in Figure 3. The median extinctions of the photometric and polarimetric stars are $A_V = 2.6$ and 1.8, respectively. In Figure 3, the photometric and polarimetric distributions appear to have the same overall shape, indicating that they are drawn from the same parent distribution and that the polarimetric selection criteria does not introduce bias to

Figure 2. Distribution of polarization uncertainty as a function of $H$-band magnitude. The solid line traces the median polarization uncertainty with apparent magnitude. The median polarimetric uncertainty at $H = 14$ is shown by the dashed lines.
Table 2

| ξ (deg) | b (deg) | P (%) | σP (%) | GPA (deg) | σGPA (deg) | H (mag) | σH (mag) | K (mag) | σK (mag) |
|---------|---------|-------|--------|-----------|------------|---------|----------|---------|----------|
| 150.00762 | −75.07904 | 6.22 | 3.21 | 140.53 | 14.77 | 15.360 | 0.102 | 15.121 | 0.136 |
| 149.76181 | −75.05685 | 2.65 | 1.26 | 112.51 | 13.58 | 13.615 | 0.037 | 13.476 | 0.043 |
| 150.10707 | −75.02797 | 0.00 | 0.60 | 0.00 | 180.00 | 13.489 | 0.029 | 13.462 | 0.041 |
| 150.08486 | −74.97565 | 0.63 | 0.62 | 20.77 | 28.06 | 13.087 | 0.026 | 13.057 | 0.032 |
| 149.86210 | −74.96854 | 0.00 | 0.46 | 0.00 | 180.00 | 11.966 | 0.025 | 11.755 | 0.026 |
| 149.90275 | −74.95584 | 4.46 | 2.30 | 118.54 | 14.81 | 15.002 | 0.071 | 14.678 | 0.103 |
| 150.16407 | −74.95899 | 6.51 | 4.18 | 175.15 | 18.41 | 15.318 | 0.106 | 15.436 | 0.169 |
| 150.08958 | −74.93429 | 6.15 | 3.75 | 116.61 | 17.47 | 15.494 | 0.113 | 15.205 | 0.146 |
| 150.10019 | −74.93291 | 0.00 | 0.69 | 0.00 | 180.00 | 13.026 | 0.030 | 12.994 | 0.035 |
| 149.96803 | −74.92756 | 7.92 | 4.36 | 107.68 | 15.78 | 15.593 | 0.113 | 15.430 | 0.187 |

Note. Stars with missing 2MASS photometry are listed as having apparent magnitudes of 0.00 mag and uncertainties of 99.99 mag.

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)

3. COMPARISON WITH SIMULATED OBSERVATIONS

Comparisons of these observations with predictions of the large-scale structure of the Galactic magnetic field can constrain the magnetic geometry. Pavel (2011) simulated all-sky NIR starlight polarization observations for several magnetic field geometries. These included: three A0 (disk antisymmetric) and three S0 (disk symmetric) magnetic field geometries (Ferrière & Schmitt 2000); three DEHO geometries (Moss et al. 2010); and three analytic axisymmetric magnetic fields with different pitch angles (α = 0°, −11.5°, and −24°). In a trailing spiral galaxy, since the magnetic field is tied to the gas and not to the spiral density pattern, differential rotation causes the \( B_r \) and \( B_φ \) components to have opposite signs (Krasheninnikova et al. 2012a).
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1989). The pitch angle is defined by \( p = \tan^{-1}(B_r/B_\phi) \), and therefore the pitch angle is negative (Beck et al. 1996). S0 and A0 magnetic fields are two common axisymmetric predictions for the large-scale structure of the Galactic magnetic field. DEHO magnetic fields, predicted by Moss et al. (2010) and possibly observed by Sun et al. (2008), invoke a Galactic wind that connects independent halo and disk dynamos. Analytic axisymmetric magnetic fields (consisting of only \( B_b \) and \( B_\phi \) components) were used by Pavel (2011) to predict the effects of a spiral-based Galactic magnetic pitch angle on the observed polarization distribution, and do not represent a magnetic field geometry with a known physical basis. All of these magnetic field models were combined with two different empirical dust distributions (Spergel et al. 1996; Drimmel & Spergel 2001) yielding a total of 24 sets of predictions, as summarized in the first three columns of Table 3. In addition to an all-sky map for each prediction, an \( \ell = 150^\circ \) GPA with \( b \) plot was shown, all-sky polarization CDFs were plotted, and the 1st, 2nd, and 3rd all-sky CDF quartile values were tabulated for synthetic stellar samples complete to \( H = 14 \).

Pavel (2011) suggested that two tests were most diagnostic for comparing the predictions with observations: (1) comparing the CDFs of the observed and predicted starlight polarizations, and (2) comparing the change in GPA with Galactic latitude between the observations and predictions. Each test is applied and discussed below.

3.1. Cumulative Distribution Functions

The predicted CDFs in Pavel (2011) were normalized in that work by the maximum predicted polarization because of uncertainties in the degree of polarization caused by the unknown magnetic alignment and dust polarization efficiencies. If these factors do not change significantly along or between different lines of sight, then the predicted GPA is unaffected and the normalized CDFs are related to the actual polarization CDFs by a multiplicative factor.

The Pavel (2011) predictions were generated for the whole sky, while the observations presented here cover only a small region of sky. Since the predicted degree of polarization strongly depends on Galactic latitude and longitude, a subsample was drawn from the all-sky predictions which included only those directions corresponding to observations reported here. To account for the observations at \( b = \pm 1^\circ 25, \pm 2^\circ 5, \) and \(-6^\circ\) that have no corresponding Pavel (2011) predictions, new simulations toward these directions were made, following the procedure in Pavel (2011), and included in the subsample.

While the shapes of the variation of GPA with Galactic latitude for all 24 models presented in Pavel (2011) are unchanged, the new subsample-predicted polarization CDFs are, as would be expected, different from the all-sky Pavel (2011) CDF predictions. In Figure 7, the new subsample CDF predictions (solid lines), containing 332 stars, are shown along with modified all-sky CDF predictions (dotted lines) from Pavel (2011). In the original all-sky predictions, a population of distant, high-polarization stars exists toward the Galactic center (\(|\ell| < 20^\circ, b = 0^\circ\)) that are not characteristic of the rest of the sky. The presence of these stars was identified in Pavel (2011) as a discontinuity in the CDFs presented there. These very high polarization stars were removed from the all-sky CDFs shown in Figure 7 (as dotted lines). Significant differences remain between the shapes of the modified original and subsample CDFs. The inclusion of four additional sight lines near the Galactic plane (\( b = \pm 1^\circ 25, \pm 2^\circ 5 \)) to the subsamples preferentially adds higher polarization stars, because of the large dust columns expected in the plane, which increases the cumulative probability at higher polarizations. This results in a lower cumulative probability at small \( P/P_{\text{max}} \) and higher probability at large \( P/P_{\text{max}} \), seen in all of the CDFs as a general flattening of the subsample curves.

The multiplicative scale factors between each of the new predicted subsample CDFs and the observed CDF must also be calculated. Simple comparison of normalized predicted subsample CDFs to the observed CDF is unreliable because the maximum observed polarization value (used to normalize all other values) was based on a single star in the high-end tail of the polarization probability distribution. A single extreme polarization value would affect all of the normalized starlight polarizations and change the CDF.

For each model comparison, the null hypothesis is that the subsample-predicted and NIR-observed polarization CDFs are drawn from the same parent distribution. If the probability
that they are drawn from the same parent distribution is small, the null hypothesis can be rejected. The Kolmogorov–Smirnov (K-S) test was used to determine both the appropriate scaling factor and to perform the test of the null hypothesis. By scaling the predicted subsample CDFs so that the maximum absolute difference between the observed and predicted CDFs was minimized, the K-S probability that the CDFs are drawn from the same parent distribution is maximized. This introduces a heavily conservative bias that overestimates the likelihood of agreement. If this overestimated probability is a strong, conservatively biased criteria for rejecting the null hypothesis.

For sky locations matching the observations, 866 simulated stars with $H \lesssim 14$ mag make up the predicted subsample CDFs. The 332 observed stars with $H \lesssim 14$ mag and significant polarizations make up the NIR-observed CDF. Many of the simulated stars, however, would actually have polarization values below the NIR observational limit and should be culled. To calculate the stars to ignore, the following procedure was used for each of the 24 subsample predictions. First, the entire predicted subsample polarization CDF was scaled so that the maximum deviation between it and the observed polarization CDF was minimized. Next, model stars with scaled polarizations below the observational polarization threshold (0.19%) were identified and removed. Then, a new predicted polarization CDF was calculated and scaled to the observations again. The resulting (overestimated) K-S probabilities for each model-observation comparison are listed in Column 4 of Table 3. These represent the probabilities that the best-scaled predicted CDFs were drawn from the same population as the observed CDF. The largest probability of all the models is only 0.27 and is too low to identify any obvious good match. The smallest probabilities (strongest model rejections) are approximately $10^{-5}$ for the DEHO models, though further consideration is necessary before rejection and will be discussed below.

### 3.2. GPA versus Galactic Latitude

The second observational test proposed by Pavel (2011) was based on the dependence of the polarization GPA on Galactic latitude. The observational data for this test were shown in Figure 4. Weighted means and uncertainties in the mean for each latitude bin were shown in Figure 5. To facilitate comparison with the observations, the runs of predicted GPAs, for each model at $\ell \leq 150^\circ$, as a function of Galactic latitude (see Figures 4–7 in Pavel 2011), were fit by a third-order polynomial:

$$\text{GPA} = A + B \times \theta + C \times \theta^2 + D \times \theta^3,$$

where GPA is the predicted Galactic polarization position angle; $\theta$ is the Galactic latitude of the prediction; and $A$, $B$, $C$, and $D$ are constants to be fit. The parameters from these fits are listed in Columns 5–8 in Table 3. The choice of a third-order polynomial was based on an $F$-test.

The observed GPAs and two example model polynomial fits are plotted in Figure 8. Model 1 (top panel) is an example of a

| Model | Magnetic | Dust | K-S Test | Fitting Constants | $\Delta$GPA |
|-------|----------|------|----------|------------------|------------|
| Number | Field | Model | Probability | $A$ | $B$ | $C \times 10^{-4}$ | $D \times 10^{-5}$ | (deg) |
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
| 1 | S0 reference run | DS2001 | 0.195 | 90.1 | -0.72 | -1.53 | 4.00 | 7.14 ± 0.94 |
| 2 | S0 reference run | SMB96 | 0.079 | 90.1 | -0.71 | -0.98 | 3.95 | 6.99 ± 0.94 |
| 3 | S0 reference with alpha quenching | DS2001 | 0.252 | 90.0 | -0.58 | 2.19 | 3.35 | 3.69 ± 0.94 |
| 4 | S0 reference with alpha quenching | SMB96 | 0.094 | 90.0 | -0.58 | 2.67 | 3.36 | 3.60 ± 0.94 |
| 5 | S0 with vacuum BC | DS2001 | 0.270 | 90.0 | -0.57 | 1.60 | 3.22 | 4.54 ± 0.94 |
| 6 | S0 with vacuum BC | SMB96 | 0.105 | 90.0 | -0.57 | 2.08 | 3.24 | 4.46 ± 0.94 |
| 7 | A0 reference run | DS2001 | 0.241 | -0.20 | 0.043 | 43.4 | 9.76 | 78.12 ± 1.03 |
| 8 | A0 reference run | SMB96 | 0.055 | -0.03 | 0.060 | 13.0 | 7.63 | 77.04 ± 1.50 |
| 9 | A0 reference with alpha quenching | DS2001 | 0.241 | -0.24 | 0.039 | 41.5 | 9.58 | 77.72 ± 1.08 |
| 10 | A0 reference with alpha quenching | SMB96 | 0.084 | -0.12 | 0.043 | 4.19 | 6.74 | 75.91 ± 1.71 |
| 11 | A0 with vacuum BC | DS2001 | 0.241 | -0.07 | 0.047 | 46.0 | 10.14 | 77.75 ± 1.08 |
| 12 | A0 with vacuum BC | SMB96 | 0.063 | -0.19 | 0.061 | 12.6 | 7.69 | 75.94 ± 1.71 |
| 13 | DEHO $C_{\text{wind}} = 0$, $R_{\text{halo}} = 300^b$ | DS2001 | 7.42 ± 10^{-5} | 90.1 | -0.80 | -14.2 | 3.31 | 8.66 ± 1.15 |
| 14 | DEHO $C_{\text{wind}} = 0$, $R_{\text{halo}} = 300^b$ | SMB96 | 2.70 ± 10^{-5} | 90.1 | -0.80 | -14.7 | 3.24 | 8.68 ± 1.17 |
| 15 | DEHO $C_{\text{wind}} = 100$, $R_{\text{halo}} = 300^b$ | DS2001 | 8.91 ± 10^{-5} | 90.1 | -0.77 | 3.87 | 5.36 | 8.69 ± 1.37 |
| 16 | DEHO $C_{\text{wind}} = 100$, $R_{\text{halo}} = 300^b$ | SMB96 | 4.31 ± 10^{-5} | 90.1 | -0.78 | 3.11 | 5.35 | 8.66 ± 1.39 |
| 17 | DEHO $C_{\text{wind}} = 200$, $R_{\text{halo}} = 300^b$ | DS2001 | 7.25 ± 10^{-5} | 89.5 | -1.13 | -61.1 | 0.64 | 14.37 ± 1.28 |
| 18 | DEHO $C_{\text{wind}} = 200$, $R_{\text{halo}} = 300^b$ | SMB96 | 3.32 ± 10^{-5} | 89.5 | -1.13 | -61.8 | 0.56 | 14.34 ± 1.30 |
| 19 | Ring, $\theta = 0^\circ$ | DS2001 | 0.270 | 90.0 | -0.54 | 0.71 | 2.95 | 2.56 ± 0.93 |
| 20 | Ring, $\theta = 0^\circ$ | SMB96 | 0.167 | 90.0 | -0.54 | 1.23 | 2.95 | 2.49 ± 0.94 |
| 21 | Ring, $\theta = 11.5^\circ$ | DS2001 | 0.265 | 90.0 | -0.31 | 4.86 | 1.89 | -3.58 ± 0.93 |
| 22 | Ring, $\theta = 11.5^\circ$ | SMB96 | 0.222 | 90.0 | -0.30 | 5.25 | 1.89 | -3.64 ± 0.94 |
| 23 | Ring, $\theta = 24^\circ$ | DS2001 | 0.270 | 90.0 | -0.080 | 6.01 | 0.86 | -9.66 ± 0.93 |
| 24 | Ring, $\theta = 24^\circ$ | SMB96 | 0.156 | 90.0 | -0.076 | 6.34 | 0.86 | -9.72 ± 0.94 |

Notes.

a DS2001: Drimmel & Spergel (2001); SMB96: Spergel et al. (1996).

b The fit is of the form GPA = $A + B \times \theta + C \times \theta^2 + D \times \theta^3$.

c Ferrière & Schmitt (2000).

d Moss et al. (2010).
Figure 7. Predicted starlight polarization CDFs for the subset of directions corresponding to the observations reported here (solid lines). These curves are different from the all-sky curves presented in Pavel (2011, dotted lines; modified as described in the text), especially at low and high polarizations because of the limited sampling of the sky by the new observations and the latitude and longitude dependence of the polarizations.

Figure 8. Two example model polynomial fits (dashed lines) plotted over the observed GPAs (points) as a function of Galactic latitude. For clarity, only the significantly detected (P/σP > 3) polarizations are plotted, and are identical in both panels. The S0-type Model 1 (top) is an example of fair agreement between the predictions and observations. The A0-type Model 7 (bottom) is an example of poor agreement, with an approximately 90° difference between the predictions and observations.

For each latitude bin having observations, the difference between the predicted mean GPA and observed mean GPA was calculated. These are shown in Figure 9 for all models. The weighted observational mean GPA uncertainties and the predicted subsample GPA dispersions are combined in quadrature to estimate the uncertainties for these differences. In Figure 9, Models 1–6 and 13–24 show fair agreement between predictions and observations. Models 7–12 (A0 magnetic field geometries), however, do not agree with the observations, with most latitude bins having discrepancies of ΔGPA > 80°, essentially orthogonal to the predicted GPAs, and therefore are not shown.

To reject specific models, it is necessary to quantify these differences. For each model, a weighted average of the differences between the model’s predicted GPA and observed GPA in each latitude bin, as shown in Figure 9, was calculated and the weighted uncertainty in this average difference was obtained by propagation. These values and uncertainties are listed in Column 9 in Table 3. While all S0, A0, and DEHO models can be rejected at the 3σ level, the A0 models are particularly discrepant (>40σ) since they predict polarizations essentially perpendicular to the Galactic plane.

4. DISCUSSION

4.1. Large-scale Magnetic Field Symmetry

Using the two tests proposed by Pavel (2011) and the observations reported here, all of the magnetic field models taken from the literature can be formally rejected as deviating by more than 3σ from the observations. The K-S analysis of CDF values was inconclusive about rejection of the predicted polarization values. None of the probabilities was high enough to suggest one set of models was the best choice, and (except...
Figure 9. Differences between the observed mean GPAs and predicted subsample mean GPAs in each latitude bin for Models 1–6 and 13–24. Models 7–12 are not shown because the differences for all latitude bins are greater than 60°. The error bars show the ±1σ uncertainties for each difference. The effect of magnetic pitch angle on ΔGPA for |b| > 10° is seen in Models 19–24 where the pitch angle (listed to the right of each plot) is varied.

for the DEHO models) the probabilities were not small enough to definitively reject classes of models outright. The differences between the predicted and observed polarization GPAs as a function of Galactic latitude are significant enough to reject all of the magnetic field models. However, the full interpretation of these results requires a more careful analysis.

The initial results should not be completely surprising, since the actual Galactic magnetic field is unlikely to be as simply represented as the simulated magnetic field models. The dynamo-driven magnetic field models have a resolution of ~200 pc (Moss et al. 2010) or ~400 pc (Ferrière & Schmitt 2000), so any turbulence or magnetic disturbances on smaller scales could not be included. The analytic axisymmetric models, with effectively infinite resolution, also lack turbulence. If turbulence creates random magnetic field components, then along a line of sight the starlight is expected to suffer some depolarization as it passes through multiple randomly oriented cells (Jones 1989). Ohno & Shibata (1993) calculated a coherent magnetic cell size of 10–100 pc using Galactic pulsar rotation and dispersion measures, implying that starlight from distant stars will generally pass through many cells. Pavel (2011) also discussed uncertainties in the predicted degree of polarization arising from changes in the polarization efficiency, though they are less likely to affect the GPAs. This, combined with uncertainties from the calculated scale factors, creates uncertainty in the absolute probability returned by the K-S test, though the relative probabilities may still provide insight into ranked likelihoods.

Considering the relative K-S probabilities in Table 3, the S0, A0, and analytic axisymmetric models using the Drimmel & Spergel (2001) dust distributions have the highest probability (>0.20) of being drawn from the same parent distribution as the observations. The DEHO models all produce polarization CDFs that are poor matches to the observed polarization CDF. The choice of dust model causes a significant difference in the probabilities for all models. The S0, A0, and analytic axisymmetric models using the Drimmel & Spergel (2001) dust distribution have larger (i.e., more similar to the observations) probabilities than the models using the Spergel et al. (1996) dust distribution. This is not surprising given that the Drimmel & Spergel (2001) dust model accounts for more details (e.g., spiral arms, local arm, Galactic warp) than the axisymmetric Spergel et al. (1996) dust model. The DEHO models, as shown by their K-S probabilities, are unable to reproduce the observed polarizations.

The amount of polarization increases as starlight passes through the regular (uniform) magnetic field, but depolarizes as it passes through cells of randomly oriented magnetic field. The interplay between regular and random magnetic fields is strongly dependent on the nature of turbulence, and beyond the scope of this paper. Because of the lack of depolarization in the simulations, all simulated stars will show larger polarizations than would actual stars. The exact effect on the simulated degrees of polarization requires a detailed study of the ratio of power in the random and regular magnetic fields in the diffuse ISM,
analogous to the studies that have been conducted in higher density molecular clouds (Falceta-Gonçalves et al. 2008; Hildebrand et al. 2009; Houde et al. 2009). The changes to the degree of polarization caused by depolarization may be large enough to change the predicted polarization CDF and account for the significant differences measured by the K–S test.

Given the uncertainties associated with the predicted degree of starlight polarization, the distribution of GPA versus Galactic latitude may serve as a better test for constraining the large-scale structure of the Galactic magnetic field.

The A0 (disk-odd) Galactic magnetic fields, Models 7–12, show huge differences between the observed and predicted GPs toward $\ell = 150^\circ$ and are therefore not shown in Figure 9. In typical A0 magnetic field models, the poloidal magnetic field has a dipolar configuration and the toroidal magnetic field consists of antisymmetric tori of magnetic flux above and below the Galactic disk with opposite field directions. To sustain this structure, there must be a toroidal null point approximately in the Galactic plane where the toroidal magnetic field goes to zero. At this point, only the poloidal magnetic field is expressed, which is oriented roughly in the Galactic north–south direction, orthogonal to the Galactic plane as seen in the simulations. Also, most of the toroidal magnetic flux in the specific A0 magnetic field geometries used for these simulations (e.g., Figure 10 in Ferrière & Schmitt 2000, for Model 7) is contained within the solar circle and would not be probed when looking toward the outer Galaxy. Based solely on the GPA discrepancies, these A0 models can be rejected.

The rejection of A0 magnetic field geometries is at odds with previous work utilizing rotation measure studies (e.g., Andreasyan & Makarov 1988; Han et al. 1997, 2003; Sun et al. 2008), which probe the Galactic magnetic field over kiloparsec length lines of sight. Evidence for an antisymmetric magnetic field is seen in antisymmetric rotation measures above and below the Galactic plane toward the Galactic center. This implies that the dominant toroidal magnetic field direction is reversed above and below the Galactic plane. Wolleben et al. (2010), however, have recently shown that this observed asymmetry may be dominated by a nearby (100 pc), northern-sky, H I bubble and that the observed asymmetry may not reflect the actual large-scale Galactic magnetic field. By using a different method (starlight polarimetry instead of Faraday rotation) away from known magnetic disturbances, the rejection of the A0 magnetic field is robust.

The analytic axisymmetric models (Models 19–24) show the best overall matches, both in degree of polarization and GPA. The difference between the observed and predicted GPs suggests that $-24^\circ$ is too large to match the observations. Based on the quality of these matches, a magnetic pitch angle between $0^\circ$ and $-11^\circ$ provides the best fit to the data.

4.2. Magnetic Pitch Angle

To place tighter constraints on the magnetic pitch angle, additional analytic axisymmetric model polarization sub-sample predictions were generated for pitch angles of $\theta = 0^\circ$ to $-24^\circ$ in steps of $0.5^\circ$. The average discrepancies between the observed and predicted GPs were calculated for the data in the zone $-60^\circ \leq b \leq -15^\circ$, shown by the dashed box in Figure 5 (all latitudes were used in the earlier analysis). Latitude bins close to the Galactic plane were not used for two non-independent reasons: the average predicted GPs for $|b| \leq 10^\circ$ are not significantly affected by the changing pitch angle (as seen in the rightmost column of Figure 9), and the uncertainties on the GPA differences near the midplane are much smaller than those at larger latitudes. For a properly weighted mean, the change in uncertainty with latitude will cause the non-diagnostic, low-latitude bins to dominate the average while the diagnostic, large-latitude bins carry little weight. Also, the observations at $b = -65^\circ$ and $-75^\circ$ were not used because their GPs were not consistent with any of the models and include only one significant starlight polarization measurement (see Table 1).

The average difference between the predicted and observed GPs, and $\pm 1\sigma$ uncertainties, as a function of magnetic field pitch angle, are shown in Figure 10. In this figure, the six models whose error bars enclose $\Delta \mathrm{GPA} = 0^\circ$ (horizontal dashed line) are shown. The models not shown follow the same trend away from $\Delta \mathrm{GPA} = 0^\circ$, with larger and smaller model magnetic pitch angles. The diagonal dotted lines trace the $\pm 1\sigma$ error bars for all of the models. The best-fit magnetic pitch angle is between $\theta = -5\degree:5$ and $-6\degree:0$, shown by the vertical solid line in Figure 10. To estimate the uncertainty on this magnetic pitch angle, the upper and lower $1\sigma$ uncertainty limits for all analytic axisymmetric models were each fit with second-order polynomials (shown as the diagonal dotted lines in Figure 10).

The pitch angles enclosed by these fits are shown by the gray region in Figure 10. Based on these new observations and predictions, the Galactic magnetic pitch angle is $\theta = -6\degree \pm 2\degree$ toward $\ell = 150^\circ$.

Previous estimates of the Galactic magnetic pitch angle have returned similar results: $-6\degree$ (Vallee 1988), $-8\degree:2 \pm 0\degree:5$ (Han & Qiao 1994), $-7\degree:2 \pm 4\degree:1$ (Heiles 1996), and $-8\degree \pm 1\degree$ (Beck 2007). Unlike these previous estimates, which typically use data from large areas of the sky, this result was obtained from one Galactic longitude. Additional measurements in the outer Galaxy may show pitch angle variations with Galactic longitude that are missed when averaging over large areas.

5. CONCLUSIONS

New NIR starlight polarimetry observations were obtained toward the outer Galaxy that trace the orientation of the Galactic
magnetic field. These observations, combined with predictions from Pavel (2011) and new simulations presented here, constrain important aspects of the geometry of the large-scale Galactic magnetic field. The K-S test probabilities of the CDFs of the polarization percentages and the GPA differences can be used to formally (3σ) reject all of the models tested here, though relative rankings may also be useful. Key results from this study include the following.

1. The A0 model predictions are strongly inconsistent with the observed distribution of NIR starlight GPAs and are thereby rejected. While here limited to a set of sample A0 models from Ferrière & Schmitt (2000), the ability of any A0-type magnetic field model to reproduce the observed GPA distribution in the outer Galaxy is doubtful.

2. The GPA distributions of the S0, DEHO, and analytic axisymmetric models typically differ from the NIR starlight observations by only a few degrees. Since the model magnetic fields do not include any turbulence or systematic motions, such differences are to be expected. The general agreement shows that disk-even (S0, DEHO, and analytic axisymmetric) magnetic fields better represent the Galactic magnetic field than A0 models.

3. Based on the CDFs of observed and predicted degrees of starlight polarization and their K-S probabilities (see Table 3), the DEHO magnetic field models (Moss et al. 2010) are especially discrepant. This result, and all of the K-S probabilities, may be affected by uncertainties in predicting the degree of starlight polarization.

4. Even if the predicted DEHO polarization CDF was not discrepant, the observed distribution of GPAs would still be inconsistent, though at a similar level as for the S0 and analytic axisymmetric models.

5. New simulations presented here, with different spiral-type magnetic pitch angles, when matched to the new observations, constrain the Galactic magnetic pitch angle to −6°±2°. This estimate is for a single Galactic longitude and agrees well with previous estimates of optical starlight polarization (Heiles 1996) and radio Faraday rotation (Vallee 1988; Han & Qiao 1994; Beck 2007) that each average over large areas of the sky.

This work highlights the utility of NIR polarimetry and its ability to place strong constraints on the Galactic magnetic field. Future application of NIR polarimetry to larger areas of the sky will provide additional constraints for Galactic dynamo theory on large scales and star formation on small scales.

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