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THE MAGNETIC FIELD OF L1544. I. NEAR-INFRARED POLARIMETRY AND THE NON-UNIFORM ENVELOPE

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ABSTRACT

The magnetic field (B-field) of the starless dark cloud L1544 has been studied using near-infrared (NIR) background stellar polarization (BSP) and archival data in order to characterize the properties of the plane-of-sky B-field. NIR linear polarization measurements of over 1700 stars were obtained in the H band and 201 of these were also measured in the K band. The NIR BSP properties are correlated with reddening, as traced using the Rayleigh–Jeans color excess (H–M) method, and with thermal dust emission from the L1544 cloud and envelope seen in Herschel maps. The NIR polarization position angles change at the location of the cloud and exhibit their lowest dispersion there, offering strong evidence that NIR polarization traces the plane-of-sky B-field of L1544. In this paper, the uniformity of the plane-of-sky B-field in the envelope region of L1544 is quantitatively assessed. This allows evaluation of the approach of assuming uniform field geometry when measuring relative mass-to-flux ratios in the cloud envelope and core based on averaging of the radio Zeeman observations in the envelope, as done by Crutcher et al. In L1544, the NIR BSP shows the envelope B-field to be significantly non-uniform and likely not suitable for averaging Zeeman properties without treating intrinsic variations. Deeper analyses of the NIR BSP and related data sets, including estimates of the B-field strength and testing how it varies with position and gas density, are the subjects of later papers in this series.

Key words: Galaxy: disk – ISM: individual objects (L1544) – ISM: magnetic fields – magnetic fields – polarization – techniques: polarimetric

Supporting material: machine-readable table

1. INTRODUCTION

Magnetic fields (B-fields) are present in the diffuse interstellar material from which dark, molecular clouds form. B-fields are also present in the cores of those clouds, some of which form new stars. Theoretical modeling of cloud and star formation in the presence of magnetic fields has a long, rich history (Mestel & Spitzer 1956), which continues through recent work (e.g., Mouschovias 1991; Galli & Shu 1993; Basu & Mouschovias 1994; Padoan & Nordlund 1999; Mouschovias et al. 2006; Hennebelle & Fromang 2008; Li et al. 2015) and comprehensive reviews (e.g., Mouschovias 1996a, 1996b). Observational tests of such theories have been rarer (e.g., Goodman et al. 1989, 1995; Crutcher 1999; Crutcher et al. 2009; Zhang et al. 2014; Pillai et al. 2015), but are now advancing at an accelerated pace (see review by Li et al. 2014, p. 101). A key quantity used to assess cloud stability and predict future outcomes is the ratio of mass, in the form of gas and dust, to the flux of the B-field threading that material. This “mass-to-flux” ratio (e.g., Mestel & Spitzer 1956; Mouschovias 1976a, 1976b; Fiedler & Mouschovias 1992; Crutcher 2012) is normally indexed by its critical ratio, the value at which the gravitational and magnetic energy densities are equal, yielding a M/Φ ratio of unity. If M/Φ is less than unity, then B-fields dominate and the region is classified as subcritical. If M/Φ exceeds unity, the region is supercritical, with B-fields overwhelmed by gravity, leading to contraction or collapse. The differential M/Φ of a cloud core relative to its envelope is a key indicator of the role of B-fields in star formation (Mouschovias 1976a).

However, measuring M/Φ is challenging. Assessing the numerator involves sensing atomic or molecular gas densities, temperatures, and columns. This is made especially difficult when depletion onto dust grains robs the gas of the already rare species used as proxy tracers for the dominant H2 gas. Tracing gas by using dust, as revealed through the reddening and extinction of starlight (or background diffuse emission) or via thermal emission from the dust grains, is less affected by depletion, though not fully immune. And, depending on the collision rate of gas and dust, the dust temperature may not closely reflect the gas temperature. Well-sampled, large-area maps of gas spectral lines, sensitive multi-wavelength maps of dust, and multi-species, multi-line analyses over cloud envelope and core regions, where properties change rapidly with location, are necessary to address these difficulties.

Computing the denominator in M/Φ is even more difficult. The B-field is a three-dimensional vector field, yet current best methods can only probe either the line-of-sight component, BLOS, employing the Zeeman effect for radio spectral line observations, or the plane-of-sky component, BP, using background starlight polarization (BSP) or linear polarization of the thermal dust emission. An alternative spectral line method, exploiting the effect of Goldreich & Kylafis (1981), may return more than single-dimension information, but only in special anisotropic settings (e.g., Girart et al. 1999).

Radio Zeeman observations need significant gas column densities and relatively quiescent conditions to yield detectable signals within reasonable integration times. Hence, the number of targets observed using the Zeeman effect for the OH molecule, which is best for the typical conditions in molecular
L1544 represents a nearly ideal laboratory for comparing the Zeeman and BSP methods. It is a molecular cloud with a starless dense cloud core (Snell 1981; Myers et al. 1983; Høyer et al. 1987) in Taurus, at a distance of about 140 pc (Elias 1978; Kenyon et al. 1994; Torres et al. 2012). Detection of ammonia by Myers & Benson (1983) and N$_2$H$^+$, C$_2$H$_2$, and CCS by Benson et al. (1998) began a long history of interstellar chemistry and kinematic studies of L1544, because it supports an unusual chemical richness (e.g., Caselli et al. 2002b; Lee et al. 2003; van der Tak et al. 2005; Vastel et al. 2006; Bizzocchi et al. 2014), strong depletion of many species onto cold dust grains (Tafalla et al. 2002; Kato & Caselli 2010), and rotation plus infall motions (Tafalla et al. 1998; Williams et al. 1999, 2006; Kato et al. 2015). L1544 was the first dark cloud core to be detected in the fundamental ortho-water transition using Herschel (Caselli et al. 2010) and continues to serve as a key laboratory for modeling water in dark clouds (Keto et al. 2014). Detailed modeling of the physical conditions, stability, ionization state, and magnetic properties of L1544 has been pursued in several studies (e.g., Ciolek & Basu 2000; Li & Nakamura 2002; Li et al. 2002; Tafalla et al. 2002; Crapsi et al. 2005; Kato & Caselli 2008). The strong depletion of CO isotopologues and the resultant uncertainty regarding the abundances of these species have favored observations of optically thin dust continuum emission for revealing the physical nature of the L1544 core and envelope regions. Studies include 1.3 mm mapping at IRAM by Ward-Thompson et al. (1999), 850 $\mu$m mapping by Shirley et al. (2000) and Ward-Thompson et al. (2000), and 450 $\mu$m mapping (Shirley et al. 2000; Doty et al. 2005). The Herschel satellite was used to map L1544 at wavelengths of 70, 100, 160, 250, 350, and 500 $\mu$m in programs by O. Krause and P. André (obs. IDs 134219303/4 and 1342204841/2, respectively). These sensitive images reveal the L1544 cloud core and envelope with fine detail. Figure 1 shows the 250 $\mu$m Herschel/SPIRE map as the background image, with black contours stepped linearly with 250 $\mu$m intensity.

The dust found in the dense cores of dark clouds like L1544 is optically thick at optical and NIR wavelengths and optically thin in the mid-infrared (Bacmann et al. 2000). The optically thin core of L1544 is easily seen as resolved, faint absorption in W3 (12 $\mu$m) and W4 (22 $\mu$m) maps of the region from the Wide-field Infrared Survey Explorer (WISE) (Wright et al. 2010), which show the same orientation and structure exhibited by the bright FIR emission core of Figure 1.

The L1544 B-field strength was first measured via detection of the OH Zeeman effect by Crutcher & Troland (2000), who found $B_{\text{LOS}} = +11 \pm 2 \mu$G using the Arecibo telescope along the direction to the cloud core in an integration of nearly 16 hr. In the Arecibo survey of 34 dark cloud cores using the OH Zeeman effect (Troland & Crutcher 2008), L1544 exhibits the second highest Zeeman signal-to-noise ratio ($S/N$), at 6.4. The fraction of survey targets with $S/N \geq 3$ is only 21% and these used about 38% of the total integration time of the survey, underscoring the difficulty of determining B-field strengths from radio Zeeman observations.

To test predictions of ambipolar diffusion (AD) models (e.g., Ciolek & Mouschovias 1994) for cloud core development leading to star formation, Crutcher et al. (2009) combined OH Zeeman observations from Arecibo (beam size $\sim$2.9 arcmin) of four cloud cores with OH Zeeman observations made with the Green Bank Telescope (GBT) (beam size $\sim$7.8 arcmin) of their associated cloud core envelopes. The latter measurements were performed by sampling four positions located outside the Arecibo beam observation of each cloud core, with offsets along each equatorial cardinal direction of $\pm$6 arcmin. The goal was to test whether the cloud cores and envelopes exhibited relative $M/\Phi$ ratios in excess of unity, as predicted by AD models. Of the four clouds observed, only a single envelope position toward L1544 exhibited a GBT Zeeman detection with $S/N \geq 3$. Crutcher et al. (2009) averaged the four envelope GBT Zeeman values for each cloud to increase the $S/N$ and thereby permit envelope $M/\Phi$ values to be estimated or limited. However, this approach was criticized by Mouschovias & Tassis (2010) on the basis of likely non-uniformity of the envelope B-fields over the angular extent of the regions sampled by the GBT beams, based on the appearance of the Herschel and Spitzer distributions of dust thermal emission on the sky for L1544 and the other three dark clouds.

Submillimeter dust emission polarization at 850 $\mu$m was sought in the L1544 core by Ward-Thompson et al. (2000), who used JCMT with SCUBA and its polarimetry module (Greaves et al. 2003, hereafter “SCUPOL”). They obtained detections toward eight Nyquist-sampled directions, all within the Arecibo core OH Zeeman beam of Crutcher et al. (2009). One star (identified as 2MASS PSC J05041591+251157) just outside the core OH Zeeman beam was measured for K-band polarization by Jones et al. (2015).
Based on the condensed, quiescent, starless nature of its dense core, the presence of a resolved envelope, and the two, independent OH Zeeman detections of B-fields (toward the core and toward one envelope position), L1544 appears to be an ideal laboratory for conducting deep, NIR BSP observations and for the analyses of the resulting B-field orientations. Heretofore, no independent probe of the envelope and for the analyses of the resulting B-field orientations.

1.2. Goals and Methodology

The first project goal was to obtain NIR BSP detections in regions that fully covered the portions of L1544 observed by the Arecibo and GBT OH Zeeman observations, to enable the desired polarization and B-field comparisons. NIR wavelengths (Section 2) offer good sensitivity for polarization detections toward regions of moderate dust extinction (\(A_V \sim 1-2\) mag) up to the much higher values (20–30 mag) characterizing the outer parts of dense cloud cores, through which optical starlight cannot penetrate. This observational goal was met through use of the Mimir NIR imaging polarimeter (Clemens et al. 2007) to deeply probe the L1544 core and to less deeply probe five fields offset from the core, four along the same cardinal directions as those of the GBT OH observations (Crutcher et al. 2009) and one to cover the region examined in recent radio OH Zeeman observations conducted at Effelsberg (K. Tassis 2016, private communication). BSP was performed over all these fields in the NIR H band (1.6 \(\mu\)m) and also toward the center field in the NIR K band (2.2 \(\mu\)m). These observations and the details of the data reduction are described in Section 2, below.

The second project goal was to demonstrate that the NIR polarizations returned by the Mimir observations revealed the B-field associated with L1544 and its core. Such association of BSP and the B-fields of molecular clouds has been challenged by Arce et al. (1998) as being due only to a “skin depth” effect, though Whittet et al. (2008) found little evidence of such an effect. In Section 3, descriptions are presented of two tests that were performed to confirm the association of BSP and the B-field of L1544. The first test showed that NIR BSP is correlated with stellar reddening for the same stars and that this reddening is correlated with the dust thermal emission from L1544. The second test showed that the BSP-traced B-field properties of polarization position angle, PA, and dispersion of polarization position angle, \(\Delta PA\), exhibit strong spatial correspondences with the L1544 dust maps.

Section 4 presents an assessment of the properties of the mean BSP-traced \(R_{POS}\) measured in synthetic beam averages representing the Zeeman radio beams (the same angular sizes
2. OBSERVATIONS AND DATA PROCESSING

NIR imaging polarimetric observations of L1544 were conducted on the UT nights of 2013 January 20, 2015 October 27 and 31, 2015 November 1 and 2, and 2016 January 27 and 31 using the Mimir instrument (Clemens et al. 2007) on the 1.83 m Perkins Telescope, located outside Flagstaff, Arizona. Mimir polarimetry used cold, rotated, compound half-wave plates (HWPs) for modulating the polarization signal for each of the H and K wavebands and a fixed wire-grid analyzer preceding the 1024 × 1024 pixel InSb Aladdin III detector array. All polarization and reimaging optics in Mimir operated at 60–70 K and the detector array was at 33.5 K. The plate scale was 0.58 arcsec per pixel, resulting in a 10 × 10 arcmin field of view (FOV). All observations were conducted through fewer than 1.4 airmasses and the seeing was better than 2 arcsec for all observations.

The observations, in each of the two bands, were performed by obtaining an image through a fixed angular orientation of the HWP then rotating the HWP to other angles and obtaining additional images. A total of 16 HWP angle-images, chosen to permit four independent sets of Stokes U and Q parameters to be formed for each star, were observed at each telescope pointing. The telescope performed a set of six sky pointings (as a rotated hex pattern), with 16 HWP angle-images obtained at each pointing, resulting in 96 images per observation.

Six pointing centers (“fields”) were selected toward a Center direction (α = 05°04′16″, δ = +25°10′48″ [J2000]), the four equatorial NSEW directions offset by 6 arcmin from the Center, and one field to the NW offset mostly diagonally by about 10.9 arcmin. In the H band, the observation sets included one dithered observation, at 2.5 s per exposure, toward each of the five fields. The four NSEW fields were also observed with four longer (15 s per exposure) polarimetric observations in the H band. The NW field had eight H-band polarimetric observations of 15 s per exposure. The Center field had one K-band observation of 2.5 s per exposure, two of 15 s per exposure, an additional H-band observation of 2.5 s per exposure, plus four H-band observations of 10 s per exposure and eight of 15 s per exposure. The total integration times were thus about 1.7 hr in the H band for each NSEW field, 3.6 hr in the NW field in H, 0.9 hr in K toward the Center field, and 4.5 hr in H toward the Center field. The shorter exposures served the purpose of extending the observational dynamic range to stars whose brightness would saturate in the longer exposures. The longer Center and NW integration times partially offset the higher extinctions present in these fields.

Calibration consisted of application of corrections for detector linearity and dark current, in-dome polarization flat-fields in each band, as well as super-sky flat-fielding using the observed images, correction for secondary instrumental polarization across the FOV (determined from observations of mostly unpolarized globular cluster stars located off the Galactic plane), and correction for HWP offset angle (determined from observations of polarization standard stars). Details of the observation methodology, data correction steps, and calibration are described in Clemens et al. (2012b, 2012c).

The long (10 s or 15 s) observations for each band were combined to yield deep photometric images and polarimetric point-source catalogs. The short (2.5 s) observations were also processed to polarimetric point-source catalogs. The short and long polarimetric catalogs were combined by matching star positions and computing variance-weighted mean U and Q values and deriving from them polarization percentages, P, and PA values and uncertainties. (All P values and PA uncertainties, σP, were corrected for the effects of positive bias in P, to become P′, following Wardle & Kronberg (1974)).

The combined H-band polarimetric point-source catalog had 1712 entries, while the K-band catalog had 201 entries. The latter is smaller because of the smaller solid angle observed in the K band (29% of that in the H band), the much shorter net integration time in the K band (20% of that in the H band), the lower mean polarizations in K than in H (∼60%, see below) for normal ISM dust (Serkowski et al. 1975), and the higher net extinction in the Center field compared to the NSEW fields (see Figure 1). The positions of all the K-band stars matched those of H-band stars.

In addition, the AllWISE (Cutri et al. 2013) catalog entries for the field shown in Figure 1 were fetched using DS9 (Joye & Mandel 2003) to query the Centre de Données astronomiques de Strasbourg (CDS), resulting in 3616 stars with a detection in at least the WISE W1 (3.6 μm) band or W2 (4.5 μm) band. These were positionally matched to the H-band catalog, yielding 1262 matches. The properties of the 450 H-band stars without WISE star matches and the WISE stars without H-band star matches were similar in being fainter than the subset of stars with H-to-WISE matches. The fainter stars in the H-band polarimetric catalog were not expected to yield polarization detections providing significant B-field information (Clemens et al. 2012a, 2012c), so this 26% non-match rate among the faint stars should not bias any findings based on the brighter stars.

The combined data set of 1712 stars is listed in Table 1. In the Table, the first column lists the star number and the second column presents the R.A. and decl. on successive lines. Columns 3–7 list the Mimir-based H-band photometric magnitude, (debiased) linear polarization percentage, PH, (equatorial) polarization PAH (in deg E from N), and Stokes QH and UH percentages. Columns 8–12 list the Mimir K-band values of magnitude, PK, PAK, QK, and UK, for the 201 matching stars. Values of 20.000 in the column for K-band magnitude signify the absence of a matching star. For those stars, the corresponding P′ entry was set to zero, σP was set to 99.99%, and PA was set to zero, with σPA set to 180°. Uncertainties are found in the line immediately following a line of values.

For stars matched to 2MASS (Skrutskie et al. 2006; Cutri et al. 2003) point sources, columns 13–15 provide the J-, H-, and K-band magnitudes, with their uncertainties in the same
columns on the following line. Where no magnitude is available, a value of 20.000 and uncertainty of 99.999 are inserted. The 1262 WISE W1- and W2-band magnitudes are provided in columns 16 and 17, also following the convention that a missing magnitude is replaced with a value of 20.000 and uncertainty of 99.999. The final column lists letters linked to notes following the Table.

Stellar polarizations obtained using imaging surveys, as performed here, result in wide ranges of polarimetric uncertainties, due to stellar faintness and sky brightness, as described in Clemens et al. (2012a). Users of Table 1 are cautioned to consider the biases in such data.

| No. | R.A./Decl. | H (mag) | $p_H^0$ (%) | PA$_H$ (deg) | Q$_H$ (%) | U$_H$ (mag) | K (mag) | $p'_K$ (%) |
|-----|------------|---------|-------------|-------------|-----------|-------------|---------|-----------|
| 0001| 75.84865   | 15:615  | 8.053       | 42.6        | 0.797     | 9.684       | 20.000  | 0.000     |
|     | 25.26836   | 0:037   | 5.437       | 19.3        | 5.504     | 5.437       | 99.999  | 100.000   |
| 0002| 75.84951   | 16:313  | 8.781       | 8.2         | 11.058    | 3.262       | 20.000  | 0.000     |
|     | 25.36376   | 0:058   | 7.471       | 24.4        | 7.468     | 7.496       | 99.999  | 100.000   |
| ∼   | 75.98059   | 12:889  | 1.447       | 62.4        | −0.840    | 1.205       | 12.640  | 2.358     |
| 0455| 25.18452   | 0:010   | 0.249       | 4.9         | 0.250     | 0.248       | 0.017   | 1.728     |
| ∼   | 76.00536   | 11:766  | 0.000       | 0.0         | −0.155    | −0.057      | 20.000  | 0.000     |
| 0605| 25.03555   | 0:001   | 0.462       | 180.0       | 0.460     | 0.479       | 99.999  | 100.000   |
| 0606| 76.00553   | 10:350  | 0.142       | 47.3        | −0.015    | 0.188       | 20.000  | 0.000     |
|     | 25.03394   | 0:001   | 0.124       | 25.1        | 0.123     | 0.124       | 99.999  | 100.000   |

2MASS Values/Unc. | WISE Values/Unc. | Notes
|-------------------|------------------|-------|
| PA$_K$ (deg) | $Q_K$ (%) | $U_K$ (%) | J (mag) | H (mag) | K (mag) | W1 (mag) | W2 (mag) |
| (10) | (11) | (12) | (13) | (14) | (15) | (16) | (17) | (18) |
| 0.0 | 0.000 | 0.000 | 16.232 | 15.511 | 15.193 | 15.363 | 15.692 | --- |
| 0.0 | 100.000 | 100.000 | 0.099 | 0.109 | 0.134 | 0.047 | 0.146 | --- |
| 0.0 | 0.000 | 0.000 | 20.000 | 20.000 | 20.000 | 15.796 | 15.857 | --- |
| 27.0 | 1.718 | 2.365 | 13.683 | 13.000 | 12.716 | 12.554 | 12.480 | --- |
| 21.0 | 2.055 | 1.527 | 0.034 | 0.032 | 0.025 | 0.024 | 0.026 | --- |
| 0.0 | 0.000 | 0.000 | 12.444 | 11.815 | 11.658 | 11.448 | 11.488 | --- |
| 0.0 | 0.000 | 0.000 | 0.045 | 0.037 | 0.027 | 0.053 | 0.055 | --- |
| 0.0 | 0.000 | 0.000 | 10.893 | 10.422 | 10.243 | 10.158 | 10.136 | a |
| 0.0 | 0.000 | 0.000 | 0.031 | 0.036 | 0.025 | 0.028 | 0.028 | --- |

Note. This is a shortened version of the full table that is available in electronic form, with the rows shown here containing entries with, and without, K-band polarimetry and WISE photometry.

* Foreground star.

(This table is available in its entirety in machine-readable form.)

3. ANALYSIS

3.1. Do NIR Polarizations Reveal the L1544 B-field?

Establishing the nature of the B-field in L1544 from NIR BSP rests on showing that the lines of sight to the background stars sample dust in the L1544 cloud and core and that the polarizations originate in that dust. In the past, BSP for other Taurus clouds has been argued to be incapable of revealing B-fields within the clouds, but instead reveals only those B-fields residing on the surfaces of the clouds (Arce et al. 1998). In the following, the data set in Table 1 is shown to probe the L1544 envelope and core dust and the B-fields there. This begins by developing a map of stellar reddening and comparing to the Herschel thermal dust emission of the cloud (Figure 1). In the second phase, unique physical characteristics of the cloud are shown to correlate with unique changes in polarization properties—conditions unlikely to obtain unless the B-field of the cloud also participates in those changes and is traced by the BSP up through extinctions as high as $A_V \sim 40$ mag.

3.1.1. Stellar Reddening Map

The Rayleigh–Jeans color excess (RJCE) method of Majewski et al. (2011) reveals the stellar reddening caused by interstellar dust from differences in H-band and M-band (4.5 μm) magnitudes, as compared to intrinsic $(H - M)$ stellar colors. RJCE is superior to similar techniques that do not use M-band, because of the narrower range of intrinsic stellar colors. In the second phase, unique physical characteristics of the cloud are shown to correlate with unique changes in polarization properties—conditions unlikely to obtain.
uncertainties below 0.7 mag. There are another 386 stars in the table without such 2MASS \( H \)-band data, but with good \( W2 \)-band data. Their \( H \)-band magnitudes, which are normally not color-corrected but are matched to 2MASS \( H \) zero points in each field (Clemens et al. 2012c), can be used if color-corrected. This was done by finding the dependences of the zero point \( \left( H_{\text{Mimir}} - H_{\text{2MASS}} \right) \) and the color term \( \left( H_{\text{2MASS}} - W2 \right) \) on \( \left( H_{\text{Mimir}} - W2 \right) \). The final combined set of \( (H - M) \) colors contained 1158 stars, distributed mostly uniformly across the region.

This area of the Mimir survey region of about 420 arcmin\(^2\), sampled by 1158 stars, results in just under three measured stellar reddenings per arcmin\(^2\). Interpolation onto a 10 \( \times \) 10 arcsec grid included weighting each star’s color by its inverse color variance and Gaussian-tapered offset from each grid center. The effective angular resolution of the resulting \( (H - M) \) color map was set by the stellar search radius from each grid center, the Gaussian offset taper, and a final Gaussian smoothing of the gridded interpolation. The effective number of stars used in the calculation of the interpolated reddening at each grid center was also found. At a resolution of 120 arcsec FWHM, no fewer than two stars were used to estimate color at each grid point (this was in the most opaque part of the cloud core) and a mean of 10 to 11 stars characterized the color estimates of the grid centers across the map.

Figure 2 shows the resulting \( (H - M) \) map. The grayscale image fills the Mimir survey region (outlined in black). White contours run from 0.6 through 3.3 mag of \( (H - M) \) color. The blue filled circles show the locations of the 1158 stars. The reddening structure revealed in this map closely follows the location and structure of the \textit{Herschel} 250 \( \mu \)m dust emission shown in Figure 1, including the general location of the dense core, the lower density extension running from the core to the west-northwest (i.e., L1544-W; Tafalla et al. 1998), and the partially detached feature of lower density located east of the core (i.e., L1544-E; Tafalla et al. 1998). Thus, the BSP stellar polarization sample of Table 1 is well suited to probing the dust and gas structure of the L1544 dark cloud.

Interestingly, the region of Figure 2 showing \( (H - M) \) colors bluer than 0.6 mag (i.e., outside the outermost contour) still shows significant color of about 0.4 mag. For an average intrinsic \( (H - M) \) color of 0.08 mag (Majewski et al. 2011), the color excess is 0.32 mag, equivalent to \( A_K = 0.29 \) mag or \( A_V = 2.2 \) to 2.6 mag (depending on the extinction curve chosen, as embodied in different \( R_V \) values), distributed throughout the region surrounding L1544. The greatest reddening contour in Figure 2 is offset from the peak emission in Figure 1 for two reasons. First, the blue dot pattern shows that there are no stars in Table 1 with \( (H - M) \) colors located within 120 arcsec of the direction of the strongest FIR thermal dust emission, leaving the interpolated reddenings there based on the surrounding stars. Second, the star closest to the central contour has the greatest \( (H - M) \) color of the sample, at 5.5 mag (\( A_V \gtrsim 40 \) mag), affecting or biasing the contour locations to some degree. Nevertheless, outside the very core,
the stellar reddenings closely follow the structure of the dust thermal emission, giving high confidence that these stars can probe the B-field in their directions.

### 3.1.2. Foreground Star Censuses

One potential concern involves the possible biasing effects of including polarization values for stars located in the foreground with those for stars behind the cloud. Foreground stars in this field were sought using screening for proper motion and for color plus polarization. Thirteen stars exhibit proper motions in UCAC3 (The Third U.S. Naval Observatory CCD Astrograph Catalog; Zacharias et al. 2010) with S/Ns in either RA or decl. exceeding 2.5. Of these, all but two have \((H - M)\) colors that are redder than the value in the extended region of 0.4 mag, and were thereby judged to be background to the cloud. One of the survivors has \(H = 16.2\) mag (i.e., is quite faint) and \(\sigma_{PA}\) of 60° (i.e., has a poorly constrained polarization PA) and so is unlikely to affect polarization findings no matter how its location is classified. The lone remaining star (number 606 in Table 1) with detectable proper motion (0.42 ± 0.04 arcsec per year) has \(m_H = 10.4\) mag, \((H - M) = 0.22\) mag, and \(P = 0.14 ± 0.12\)% such low reddening and low polarization from a relatively bright star with measurable proper motion make it almost certainly a foreground star.

Other similar stars were sought in the \((H - M)\) subsample of Table 1, through color and polarization selections (stars bluer than some color limit and less polarized than some polarization limit). However, all such cuts returned samples of potential foreground stars that failed to be uniformly distributed across the Mimir survey region. In particular, all selections resulted in trial samples that avoided the high extinction zone of L1544. If there were significant numbers of foreground stars, some fraction of them should be projected against the mostly opaque core. Instead, no stars bluer than \((H - M)\) of 0.6 mag appear within any 0.8 mag contour in the \((H - M)\) image.

Hence, only one foreground star was detected with certainty, no significant population of foreground stars brighter than \(H \sim 14\) can be present, and foreground stars fainter than 14th mag are likely to be few and will offer nearly zero contribution to the polarization maps and interpretations thereof. As a result, corrections for foreground extinction and polarization were deemed unnecessary.

#### 3.1.3. K-band Polarizations

The restricted solid angle observed for K-band polarization and the shorter integration times yielded only 201 stars with Mimir-measured polarizations in this band. Yet they provide important checks of the nature of the B-field and dust grains along these lines of sight. If polarization properties changed significantly as a function of wavelength or dust column density, reflected here in \((H - M)\) reddening, then disentangling changes in dust properties from changes in B-field properties would be more complex. The K-band polarization values were therefore compared to the H-band polarization values to assess their correlation.

A subsample of the 201 K-band stars was selected based on the requirement that \(\sigma_{PA}\) in both \(H\) and \(K\) be below 30°, to select good, or better quality, data. This yielded 39 stars. For these, the variance-weighted (from propagated uncertainties) mean band ratio of polarization percentage and the mean band difference in position angles were found to be \(P_K/P_H = 0.62 ± 0.04\) and \(\sigma_{PA_H} - \sigma_{PA_K} = 8°9 ± 1°7\), respectively. The polarization ratio is higher than values expected for dust grains obeying the Serkowski law of polarization versus wavelength (Serkowski et al. 1975; Wilking et al. 1980) and having \(\lambda_{MAX}\) (the wavelength of maximum polarization) in the range 0.3–0.8 \(\mu\)m that is typically found (Wilking et al. 1980). Instead, values of \(\lambda_{MAX}\) in the range 1.0–1.2 \(\mu\)m would be needed. Hence, the elevated \(P_K/P_H\) ratio signifies that grain growth has taken place. This agrees with the strong depletion of gas-phase molecules known to occur in L1544 (Caselli et al. 2002c).

The position angle offset is rather less revealing. The small offset from zero could be reflective of remnant K-band HWP zero-angle calibration, which was based on far fewer observations of many fewer standard stars than for the extensive H-band calibration performed to support the GPIPS project (Clemens et al. 2012b). Alternatively, it could signify small changes in B-field and dust properties along the line of sight (Messinger et al. 1997).

Dependence on reddening, a proxy for dust column density, was examined via polynomial trial fits of \(P_K/P_H\) versus \((H - M)\) color, and the same polynomial trial fits for \(\sigma_{PA_H} - \sigma_{PA_K}\) versus that color. F-tests showed that no significant linear or higher terms were detectable in the stellar subsample of 39 members, and are thereby unlikely in the remainder of the sample. Interestingly, there is no difference in the \(P_K/P_H\) ratio when the stars are split into a sample with high reddening \((H - M) > 0.9\) mag) and one with low reddening. This implies that grain growth must have also occurred in the cloud envelope or periphery, as well as in the dense core.

The overall conclusion is that dust properties along the lines of sight probed by both H-band and K-band polarization are similar. There is no evidence of major changes in dust properties that would prevent B-field interpretations of the measured values of polarization position angle, despite the evidence for larger than normal grains. The uncertainties in the K-band polarization data are significantly larger than the corresponding uncertainties in the H-band polarization data for the same stars. Thus, mean PAs computed from the PAs measured in the two bands, when weighted by their inverse variances, are indistinguishable from the H-band PAs. Hence, for most of the remainder of the analyses, only the H-band polarization properties are analyzed and reported (though the K-band values remain in Table 1 to support other studies). The K-band data are included in the final test of \(B_{POS}\) properties across the GBT Zeeman beams, in Section 4.2.

#### 3.1.4. Stellar PA Map

Figure 3 displays the H-band polarization position angles for the 396 stars in Table 1 having \(\sigma_{PA} \leq 2°\). These are grouped by \(\sigma_{PA}\) value and coded into groups by color, thickness, and length of line segment (“vector”) to better identify the highest quality values. The 123 stars with \(\sigma_{PA} \leq 1°\) have longer, thicker, red vectors. The middle 122 stars, with \(\sigma_{PA}\) between 1° and 15°, have magenta vectors of average length and average thickness. The 151 stars with \(\sigma_{PA}\) between 15° and 20° have shorter, thinner, blue vectors. Together, these 396 stars represent the 23% of the full sample that have the lowest \(\sigma_{PA}\) values. In addition to the colored vectors, the Herschel contours of 250 \(\mu\)m dust emission from Figure 1 are reproduced here to begin the association of the properties of
NIR polarization vector with the properties of dust emission in L1544.

The large number of vectors reveals several clear trends in the polarization properties. First, there is a high degree of correlation of PA orientations among neighboring stars. This basic uniformity is one of the best indicators that a large-scale B-field is being revealed across many parsecs of cloud extent. Second, there is an apparent change in mean PA across the surveyed region. In the western zone, the PAs are more nearly horizontal ($\sim 65^\circ$ PA), while in the eastern zone, they are more nearly vertical ($\sim 25^\circ$ PA). Hence, the mean field direction, as projected onto the plane of the sky, is seen to change in the region of the L1544 cloud and core. Third, the PAs seen for stars projected behind the zones of strongest dust emission are not greatly different in orientation than those seen just outside those zones. Fourth, the dispersion in PA values among local vectors varies with position across the map. The eastern zone shows a high degree of star-to-star PA agreement, and thus a small PA dispersion, while the southern and northern zones show stronger local variations of PAs.

3.1.5. NIR BSP Smoothed Images of $P$, $PA$, and $\Delta PA$

Spatial means of the NIR BSP values were developed to allow detailed comparison of the L1544 B-field properties with the gas and dust distribution. As was done for the $(H - M)$ map, weighted mean properties were computed on grid centers spaced 10 arcsec apart, including all stars out to 2.3 arcmin away from each center, and using inverse variance weighting and Gaussian tapering by each star's offset from the grid centers. This width of the Gaussian taper ($\sigma$) was set to 1 arcmin, to favor values for stars located closest to the grid centers. The values computed at each grid center were created from as few as seven stars (at the opaque cloud core) to as many as 34 stars. The mean number of stars per grid center was 16.6. The grid was smoothed with a second Gaussian ($s = 50$ arcsec), yielding images with a resolution of 3 arcmin FWHM, comparable to the Arecibo Zeeman beam size used by Crutcher et al. (2009), and much smaller than the GBT Zeeman beam size.

Figure 4 displays an image of the distribution of the mean NIR $H$-band polarization percentage ($P_H'$), and includes contours of the 250 $\mu$m dust emission traced by Herschel. Though there are some small differences (the NIR BSP is too extincted to probe the brightest 250 $\mu$m core emission), overall the NIR BSP polarization percentage is significantly enhanced where L1544 dust emission is strongest. Thus the NIR polarizations are tracing the B-field embedded in the same dust that is emitting at submillimeter wavelengths. There appear to be three spatial peaks in the $P_H'$ map: a strong peak at the center of dust emission, a weaker peak offset by 8 arcmin to

Figure 3. Grayscale $H$-band image mosaic of the region surveyed by Mimir. Black contours indicate the Herschel 250 $\mu$m dust emission of Figure 1. Colored line segments (“vectors”) display the $H$-band PAs and $\sigma_{PA}$, for subsets drawn from Table 1. Thicker, longer, red vectors display PA orientations for the 123 stars having $\sigma_{PA} \leq 10^\circ$. Medium thick, medium length, magenta vectors are for the 122 stars with $\sigma_{PA}$ between 10$^\circ$ and 15$^\circ$. Thinner, shorter, blue vectors are for the 151 stars with $\sigma_{PA}$ between 15$^\circ$ and 20$^\circ$. The PAs show significant star-to-star correlation while also revealing large-scale variation in overall PA orientations across the survey region.
the NW (south of L1544-W), and another weaker peak offset by 5.5 arcmin to the ENE (L1544-E).

The dispersion in polarization position angle, $\Delta_{PA}$, is a measure of the degree to which background starlight reveals variations in the plane-of-sky $B$-field PAs. Figure 5 displays the spatial distribution of $\Delta_{PA}$, compared to the *Herschel* 250 μm dust emission. The map was computed similarly to the $P'_H$ map, measuring PA dispersions with the same resolution of 3 arcmin FWHM. This effectively removes the effects of any changes in PA orientation on angular scales larger than this, but includes in the computed dispersions any changes on scales smaller than 3 arcmin. Also, the biasing effects of the individual stellar angular uncertainties in the overall PA dispersions were removed in quadrature, using a procedure similar to that used for SCUPOL data by Crutcher et al. (2004).

In the figure, note that the false-color scale is inverted to highlight where $\Delta_{PA}$ values are small, which might indicate higher $B$-field strengths according to the Chandrasekhar–Fermi (1953; hereafter “C-F”) method.

The minimum $\Delta_{PA}$ value is just under 10° in the cloud core, and minima of 13° are seen very near the locations of $P'_H$ maxima to the ENE and NW. Thus, $P'_H$ maxima and $\Delta_{PA}$ minima arise in the same material, likely signifying where conditions are quiescent and the $B$-field is more uniform and perhaps stronger. The NIR BSP features in $\Delta_{PA}$ are correlated with the *Herschel* 250 μm emission, though there does appear to be a small offset along the “spine” of the cloud. The sense of the displacement is that the minimum in $\Delta_{PA}$ is located about 2 arcmin to the NE of the similar ridge of 250 μm dust emission. One possible cause of this offset is revealed in the map of mean PA, below.

Figure 6 displays the mean PA, computed over the same region as for the previous two figures. Rather than forming the mean PA directly from the BSP values, which introduces significant aliasing, images of the mean Stokes $U$ and $Q$ were computed from the individual stellar values, and these images were used to generate the mean PA map. The most striking finding is the strong gradient in mean PA coincident with the spine of L1544 infrared *Herschel* 250 μm emission, extending from the cloud core to the NW. Along this spine, the polarization PA changes abruptly from about 60°–65° to 30° over a physical size smaller than the resolution of this map (∼0.1 pc). This swing in PA is made more interesting by comparing it to the direction of the spine (PA ∼ −40°; the white, dashed line in the figure). Along the spine, the polarization PA changes from being roughly perpendicular to the cloud for directions in the west (an 80° difference; the yellow, solid line in the figure) to being similarly perpendicular, but with a somewhat smaller acute angle difference (70°; the cyan, solid line in the figure) for positions north and east of the ridge.

One possible explanation is that the cloud ridge is located at a boundary, or collision, between two distinct magnetic media, with different $B_{POS}$ PAs. Another explanation is that the $B$-field changes close to the dust ridge because the $B$-field has significant helical pitch (Fiege & Pudritz 2000) and manifests different $B_{POS}$ PAs on the two “sides” of the cloud ridge.
3.1.6. Gas Kinematics and B-fields

The steep PA gradient associated with the elongated ridge of gas and dust in L1544 might be expected to be associated with a similar gradient in the radial velocity of the gas, possibly generated through rotation of the L1544 cloud or envelope. Interestingly, while some velocity gradients have been detected in spectroscopic maps of various gas tracers, there is no clear indication of rotation.

A velocity gradient, mostly along the major axis of the cloud complex, is present when comparing the radial velocity of L1544-W (10 arcmin offset), L1544, and L1544-E (5 arcmin offset). Heyer et al. (1987) found an offset of about 0.4 km s$^{-1}$ across 37–40 arcmin in $^{13}$CO, yielding a gradient of 0.3 km s$^{-1}$ pc$^{-1}$. Similarly, Tafalla et al. (1998) used C$_{18}$O to reveal a somewhat larger gradient of 1.1 km s$^{-1}$ pc$^{-1}$ along the major axis. Their channel maps also reveal that the L1544 core exhibits another velocity gradient, of about 3.4 km s$^{-1}$ pc$^{-1}$, along the decl. direction. Using N$_2$H$^+$, Williams et al. (1999, 2006) and Caselli et al. (2002a) found core velocity gradients of 3.8, 4.1, and 1.0 km s$^{-1}$ pc$^{-1}$, respectively, with the latter two values mostly along the decl. axis.

However, neither the large-scale velocity gradient along the major cloud axis nor the smaller scale decl. velocity gradient across the L1544 core exhibits a strong correlation with the polarization PA gradient shown in Figure 6. It may be that a weak shear due to the large-scale velocity gradient is bending the plane-of-sky $B$-field lines from PA 60° to PA 30° at the location of the cloud’s major axis, but why this would affect BSP PAs on only one side of the cloud (W) and not the other is unclear. There appears to be no evidence of strong cloud or core rotation, and neither of the observed weak velocity gradients appears to explain the change in BSP PA across L1544.

3.2. Polarization of SCUBA 850 µm Dust Emission in the L1544 Core

The SCUPOL instrument combination was used on the JCMT by Ward-Thompson et al. (2000) to probe the L1544 core for linear polarization of the thermal dust emission at 850 µm. These data were also used by Crutcher et al. (2004) to estimate the $B_{\text{POS}}$ field strength in the core, using the C-F method. Matthews et al. (2009) reprocessed all SCUPOL data taken on the JCMT to produce an improved and uniformly calibrated legacy data archive. This included refined gain calibration for all pixels and yielded improved maps of Stokes $I$, $Q$, $U$, and their uncertainties. These reprocessed SCUPOL data for L1544 were obtained from the legacy archive and post-processed for this current study using techniques similar to those described above.

The polarization S/Ns at the native pixel sizes of 10 × 10 arcsec (the diffraction-limited beam size was 14 arcsec) in the archive data are too low to yield adequate constraints on the polarization position angles for more than a couple of positions. This relates to the small number of positions (eight) showing polarization S/N > 2 selected by Ward-Thompson et al. (2000) for plotting and used by Crutcher et al. (2004) for analysis by the C-F method. However, post-
processing options are available that utilize more of the submillimeter information and can increase the number of independent positions with detectable submillimeter polarization. Here, to boost the S/N (though at the expense of angular resolution), the maps of Stokes $Q$ and $U$ from the archive were smoothed, using weighting by both the archive maps of $Q$ and $U$ variance and a Gaussian taper, of FWHM 35 arcsec, and resampled onto 25 arcsec pixels. From these smoothed maps of Stokes parameters, maps of $P$ and its uncertainty $\sigma_P$ were developed and debiased to yield $P'$ values. A mask image was generated that selected all (smoothed, resampled) map pixels having $P'/\sigma_P \geq 1.9$, corresponding to $\sigma_{PA} \leq 15^\circ$, and which had Stokes $I$ values more than 25% of the peak, smoothed value. A polarization PA map was computed from the smoothed Stokes maps and masked, and the PA values were rotated by $90^\circ$ to represent $B_{POS}$ orientations.

Figure 7 displays the 20 map pixels that passed the mask operation, with $B_{POS}$ PA values coded into the color of each 25 arcsec pixel and the orientations of the black line segments. The yellow contours show the Stokes $I$ distribution for the 850 $\mu$m dust emission. The pixel $P'$ and $B_{POS}$ PA values are listed in Table 2. The variance-weighted mean PA of all 20 points is $9.9^\circ \pm 1.7^\circ$ and the $\Delta_{PA}(\text{raw})$ is $20.4^\circ$. Following Crutcher et al. (2004), $\Delta_{PA}(\text{raw})$ was debiased by the mean $\sigma_{PA} = 8.3^\circ$ to yield $\Delta_{PA}(\text{corrected})$ of $18.6^\circ$. This value is larger than found by Crutcher et al. (2004) for the eight positions reported by Ward-Thompson et al. (2000) for the SCUPOL data, but prior to the reprocessing by Matthews et al. (2009). However, examination of Figure 7 reveals that the reprocessing of Matthews et al. (2009) plus post-processing reveals complexity not seen in the older works. The figure shows that the vectors closest to the intensity peak have a nearly vertical orientation, PA = $0^\circ$, while the vectors farther from the peak have PAs closer to $30^\circ$–$40^\circ$. This distinction can be seen post facto in the map of Ward-Thompson et al. (2000), though the number of central pixels is only two or three, and the number of outer pixels is similarly small. The impression from the reprocessed data is that the central $B_{POS}$ orientation is closer to being parallel to the major axis of the dust structure of the L1544 dense core, while the outer regions show $B_{POS}$ orientations more in agreement with the NIR values. Indeed, if the eight new positions located closest to the intensity peak are considered as a subset, their mean $B_{POS}$ PA is $177.4^\circ \pm 2.5^\circ$ and their $\Delta_{PA}(\text{corrected})$ is $15.9^\circ$, compared to PA = $22.5^\circ \pm 2.2^\circ$ and $\Delta_{PA}(\text{corrected})$ of $23.9^\circ$ for the 12 positions surrounding the core. The mean PAs for the two subsets differ by $8\sigma$, indicating significant changes in $B_{POS}$ within the Arecibo Zeeman beam size.

A comparison between reprocessed SCUPOL and NIR BSP values of $B_{POS}$ PA is shown in Figure 8. This $8 \times 8$ arcmin central region of the Mimir survey shows $H$-band PA vectors in blue, $K$-band PA vectors in red, and (90° rotated) SCUPOL vectors in black. Together, they reveal a twist in $B_{POS}$ orientations in going from the dense core out to the larger, lower density region that starts approximately at the circle.
Figure 7. False-color and black vector representations of the $B_{\text{POS}}$ PA (in deg and rotated $90^\circ$ from the polarization PA of the electric field due to dust emission) measured by SCUPOL at 850 $\mu$m, after smoothing the maps of Stokes parameters to 35 arcsec FWHM and sampling on a 25 arcsec grid. The color look-up table on the right shows how colors map to PA (in deg). Pixels shown have $\sigma_{\text{PA}} \leq 15^\circ$. Yellow contours show Stokes $I$ surface brightness at 850 $\mu$m, starting at 43 kJy sr$^{-1}$ and increasing in steps of half of that value.

Table 2
SCUPOL 850 $\mu$m Polarizations

| Pixel | R.A. (deg) | Decl. (deg) | $\rho^{\text{a}}$ (%) | $B_{\text{POS}}$ PA (deg) |
|-------|------------|-------------|-----------------------|---------------------------|
| 1     | 76.05390   | 25.18405    | 3.80 (1.21)           | 173.1 (9.1)               |
| 2     | 76.05390   | 25.19095    | 3.70 (1.20)           | 28.8 (9.3)                |
| 3     | 76.05390   | 25.19785    | 4.70 (1.92)           | 179.7 (11.8)              |
| 4     | 76.06152   | 25.17026    | 9.72 (1.56)           | 175.2 (4.6)               |
| 5     | 76.06152   | 25.17176    | 2.97 (0.74)           | 3.0 (7.1)                 |
| 6     | 76.06152   | 25.18405    | 2.52 (0.61)           | 162.6 (7.0)               |
| 7     | 76.06152   | 25.19095    | 3.07 (0.75)           | 19.2 (7.0)                |
| 8     | 76.06152   | 25.19785    | 5.95 (1.38)           | 15.6 (6.6)                |
| 9     | 76.06914   | 25.17026    | 2.24 (0.75)           | 22.0 (9.5)                |
| 10    | 76.06914   | 25.17176    | 2.04 (0.45)           | 2.24 (6.3)                |
| 11    | 76.06914   | 25.18405    | 3.30 (0.46)           | 168.3 (4.0)               |
| 12    | 76.06914   | 25.19095    | 1.36 (0.70)           | 9.8 (14.8)                |
| 13    | 76.06914   | 25.19785    | 4.78 (1.53)           | 51.8 (9.2)                |
| 14    | 76.07676   | 25.16337    | 3.61 (1.15)           | 53.8 (9.1)                |
| 15    | 76.07676   | 25.17026    | 3.27 (0.73)           | 48.0 (6.4)                |
| 16    | 76.07676   | 25.17176    | 2.09 (0.54)           | 5.4 (7.4)                 |
| 17    | 76.07676   | 25.18405    | 3.60 (0.66)           | 5.0 (5.3)                 |
| 18    | 76.08438   | 25.17026    | 2.33 (1.16)           | 35.2 (14.3)               |
| 19    | 76.08438   | 25.17176    | 3.09 (1.18)           | 44.5 (11.0)               |
| 20    | 76.08438   | 25.18405    | 6.88 (1.43)           | 25.2 (6.0)                |

Note.
$^a$ Pixel values are followed by uncertainties in parentheses.

denoting the Arecibo beam size, where the SCUPOL vectors begin to match the NIR vectors.

4. DISCUSSION

4.1. NIR BSP Traces B-fields in L1544

The evidence presented above shows that the L1544 cloud, as revealed in the Herschel 250 $\mu$m thermal dust emission (Figure 1), is well traced by NIR reddening using the RJCE $E(H - M)$ colors (Figure 2). That same dust is responsible for both BSP in the NIR (Figures 3 and 4) and polarization of thermal emission in the submillimeter (Figure 7).

The changes in the polarization properties with direction on the sky, especially changes in the mean PA orientation (Figure 6) and changes in $\Delta_{\text{PA}}$ (Figure 5), correlate strongly with location relative to the “spine” of the L1544 cloud and its dense core. That the PAs change so dramatically at the location of the cloud and yet $\Delta_{\text{PA}}$ reaches its lowest minimum there argues for close coupling of the $B$-field and the gas and dust within L1544.

The strong decrease in the NIR $\Delta_{\text{PA}}$ associated with the spine of the cloud and in the core, and the overall outer-core agreement of the NIR and SCUBA B-field orientations (Figure 8), points to increases in the $B$-field strength with gas density in L1544. To quantify this increase, and indeed to perform a close comparison of $B_{\text{POS}}$ to $B_{\text{LOS}}$ (radio Zeeman)...
amplitudes, requires establishing the mean gas density and velocity dispersion across the NIR survey zone and invocation of the C-F method. These are outside the scope of this current paper, but are the subjects of later papers in this series.

4.2. The Non-uniform B-Field in the L1544 Cloud Envelope

The analysis by Crutcher et al. (2009) of the Zeeman properties of their clouds’ envelopes assumed that each of the GBT pointings sampled the same uniform, regular B-field and thus measured a single, representative value of $B_{\text{LOS}}$ for each cloud envelope. Assessing the validity of this assumption requires examining whether the GBT beams covered regions of similar or non-similar B-fields for each cloud. No quantitative measure of B-field uniformity exists to easily address when B-fields are uniform enough to return unbiased results when samples are averaged as per Crutcher et al. (2009). Instead, a statistical assessment of key polarization properties was performed for L1544 using the $B_{\text{POS}}$ NIR BSP data of Table 1.

For each of the Arecibo and GBT beams, the data sets from the $H$ band, $K$ band, and SCUPOL were sampled. A suitable Gaussian taper was computed for each star or SCUBA position, with respect to the center of each Arecibo or GBT beam, with the FWHM width of each Gaussian taper set to the corresponding FWHM width of the beam size. Additional weighting was by the variance of the quantity being “observed” using these synthetic beams. The data were selected to be of good quality, by applying cuts in $P'$ and PA uncertainty ($\sigma_P < 3\%$; $\sigma_{\text{PA}} < 45^\circ$). Very low uncertainties (associated with the brightest stars) were restricted to being no less than the lowest quartile uncertainties in order to prevent a few values from dominating the weighted means.

Most of the stellar values used were based on the $H$-band, which yielded 329 entries after applying the criteria above. Similarly, the $K$ band provided 29 stars and SCUPOL provided all 20 positions. The means and uncertainties for polarization PA, $\Delta_{\text{PA}}$, and $P'$ were computed for the different combination of $H$-band and $K$-band samples, as well as the sample combinations $H+K$ bands, SCUPOL, and SCUPOL+$H+K$. Note that SCUPOL points cover only the central, Arecibo beam.

Figure 9 shows, and Table 3 lists, the beam-based comparisons of plane-of-sky means of PA, $\Delta_{\text{PA}}$, and $P'$ values. In the figure, the x-axis displays “Orientation PA,” which was defined as the projected PA from the center of the Arecibo beam to each of the regions covered by a GBT beam (with the usual east-from-north angle increment). Thus, the “GBT-N” (north) beam is centered at Orientation PA $= 0^\circ$, but spans about $\pm 40^\circ$ of Orientation PA. In this plot, a uniform B-field in the envelope of L1544 would show the same polarization PA (or other property) for all Orientation PAs. The table presents the NIR-weighted means and uncertainties, using $H$- and $K$-band stellar data for PA and $\Delta_{\text{PA}}$ and $H$-band data alone for $P'$.

For the Arecibo beam average, the first line in the table presents...
the $H$ and $K$ values, while the second line includes the effects of the (weighted) SCUPOL points.

In the top panel of Figure 9, the red points show the averages and uncertainties of the polarization PA from the Arecibo beam. The numbers below each GBT beam identifier list the effective number of stars used in the $H$- and $K$-band averages. These are effective numbers because of the Gaussian tapers—all of the individual stars contribute, but only in summed Gaussian weights equivalent to the listed numbers. The violet line and hatching show the same polarization PA and uncertainty for the $H$ and $K$ stars in the Arecibo beam (much smaller than the GBT beams and centered on the opaque cloud core). The blue line and hatching add the SCUPOL values to the $H$ and $K$ ones. The Orientation PA of the Arecibo beam spans $0^\circ$–$360^\circ$, hence the use of the hatched regions to render its values.

This panel displays just how different the polarization properties are in the different GBT and Effelsberg beams. While the polarization PAs of two of the beams (GBT-N and GBT-E) are partially consistent with each other (differing by 5\(\sigma\)) and also with one or another of the Arecibo beam estimates, the other two beams’ polarization PAs are quite different (6.5\(\sigma\) for GBT-S and 23\(\sigma\) for GBT-W, both compared to GBT-N). These differences from position to position indicate that the $B$-field is unlikely to be uniform in the envelope surrounding the L1544 core.

The middle panel is the same type of comparison for $\Delta_{PA}$ values. The differences, compared to the values for the central Arecibo beam, are less significant here, though large differences between the values in the GBT beams remain. This is especially true when comparing the values for the GBT-N and -E beams to those for the GBT-S and -W beams.

The bottom panel compares $P'$ values for the $H$ band only, because no other similar comparison covers all of the beams. The GBT beams would not be expected to contain background stars exhibiting polarizations as high as those seen in the

Figure 9. Comparison of $H$, $K$, and SCUPOL polarizations in the Arecibo and GBT beams of Crutcher et al. (2009) (as well as in the Effelsberg beam). The horizontal axis is Orientation PA of the GBT beams, seen from the center of the Arecibo beam. Red and green diamonds with error bars are beam-averaged values, uncertainties, and Orientation PAs. Top panel (A) shows polarization PA from $H$ and $K$. Beam designations and effective stellar numbers by band (see text) run along the top of the panel. PAs for Arecibo are the violet horizontal line and hatching for $H$ and $K$, and the blue line and hatching when also including SCUPOL data. The middle panel (B) compares $\Delta_{PA}$. The bottom panel (C) compares $H$-band $P'$ with the Arecibo value and uncertainty shown by the green line and hatching. Strong beam-to-beam variations in PA and $P'$ and weaker variations in $\Delta_{PA}$ indicate that $B_{POS}$ is unlikely to be highly uniform in the GBT-sampled L1544 envelope.
Arecibo, but a uniform B-field in the L1544 envelope might be expected to yield better uniformity of Pa across the GBT beams. This is not what is seen here: the GBT-N and GBT-S beams show Pa values by Crutcher et al. (2009) are likely to be biased. Detailed conclusions regarding the applicability of AD models to dense core formation and evolution, which rest on relative core-envelope estimates of M/Φ, must be revisited using more robust observational approaches, including deeper analyses of the current NIR BSP data.

5. SUMMARY

Accurately characterizing B-fields is challenging, but is vital to understanding how molecular clouds form, evolve, and produce new stars. Testing leading B-field models that address these phases is equally important, and must be performed using a variety of techniques and tools. Here, new NIR imaging background starlight polarimetry, and post-processing of the archived re-reduced SCUPOL data, were used to survey the full extent of the L1544 dark cloud, which has the best radio detections of the OH Zeeman effect (of its core and one envelope position) of any dark cloud.

The first goal of this study was to show that NIR starlight polarimetry is able to reveal B-fields across the L1544 cloud at high angular sampling and precision. This goal was met by revealing that the positional changes in plane-of-sky B-field PA orientations and in dispersions of those orientations correlate strongly with the location and structure of the thermal emission from L1544 dust.

The second goal was to test whether the plane-of-sky polarization properties were uniform throughout the envelope of L1544 or whether these properties vary significantly. A key assumption of the analysis of OH Zeeman observations, performed by Crutcher et al. (2009) and leading to relative mass-to-flux ratios of the L1544 core and envelope, was that the B-field was uniform in the envelope, permitting averaging of the Zeeman observations across the four GBT beam pointings without accounting for possible beam-to-beam intrinsic variations.

The NIR BSP, averaged over each of the different GBT Zeeman beam sizes and positions observed, instead showed strong beam-to-beam variations in the plane-of-sky polarization properties. The reprocessed SCUPOL data showed a similar strong change in PA directions within the much smaller Arecibo beam size used for the initial Zeeman detection of the core B-field.

Averaging low-signal Zeeman observations from different pointings without treating intrinsic variations would be effective if the B-field were uniform across the pointings. For L1544, the NIR polarimetry results are at odds with this assumption of uniformity and thereby the conclusions that rest upon it.

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