MAGNETIC FIELD STRUCTURE OF THE
GALACTIC PLANE FROM DIFFERENTIAL
ANALYSIS OF INTERSTELLAR POLARIZATION

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Abstract

A new method for measuring the global magnetic field structure of the Galactic plane is presented. We have determined the near-infrared polarization of field stars around 52 Cepheids found in recent surveys toward the Galactic plane. The Cepheids are located in the Galactic longitudes −10° ≤ l ≤ +10°5 and latitudes −0°22 ≤ b ≤ +0°45, and their distances are mainly in the range of 10 to 15 kpc from the Sun. Simple classification of the sightlines is made with the polarization behavior vs. \( H - K_S \) color of field stars, and typical examples of three types of them are presented. Then, division of the field stars in each line of sight into a) foreground, b) bulge, and c) background is made with the Gaia DR2 catalog, the peak of the \( H - K_S \) color histogram, and \( H - K_S \) colors consistent to be as distant as the Cepheid in the center,
respectively. The differential analysis between them enables us to examine the magnetic field structure more definitely than just relying on the $H - K_S$ color difference. In one line of sight, the magnetic field is nearly parallel to the Galactic plane and well aligned all the way from the Sun to the Cepheid position in the other side of the Galactic center. Contrary to our preconceived ideas, however, sightlines having such well aligned magnetic fields in the Galactic plane is rather small in number. At least 36 Cepheid fields indicate random magnetic field components are significant. Two Cepheid fields indicate the magnetic field orientation changes more than $45^\circ$ in the line of sight. The polarization increase per color change $\Delta P / \Delta (H - K_S)$ varies from region to region, reflecting the change in the ratio of the magnetic field strength and the turbulence strength.

**Key words:** dust, extinction—Galaxy: center—infrared: ISM—ISM: magnetic fields—stars: distances—techniques: polarimetric

1 Introduction

Interstellar magnetic fields of the Milky Way have been investigated for many years, and they are considered to play important roles in astrophysics and astroparticle physics. The large-scale structure of the Galactic magnetic field has been derived from studies of background starlight polarimetry (Mathewson & Ford 1970; Heiles 1996, 2000), dust emission polarimetry (Planck Collaboration et al. 2015, 2016), Faraday rotation (Han et al. 1997, 2006; Brown et al. 2007; Mao et al. 2010, 2012; Pshirkov et al. 2011; van Eck et al. 2011), and synchrotron emission (Jansson & Farrar 2012a, 2012b). These methods indicate that the large-scale magnetic field is parallel to the Galactic plane.

Interstellar polarization, Faraday rotation and synchrotron emission are integral quantities between the observer and the target along the line of sight, and the observed polarization does not show the magnetic structure at an arbitrary distance from the observer. Therefore, we would like to calculate the polarization as a function of distance, and understand the magnetic structure at a specific distance from the observer. This allows us to examine 3D tomography of large-scale magnetic field structures.

Faraday rotation studies have combined observation of Galactic pulsars estimating distance with observation of polarized extragalactic sources, and detailed models of the Galactic magnetic field have been generated (e.g., Brown et al. 2007; Sun et al. 2008; van Eck et al.
However, Faraday rotation only senses the line of sight component of magnetic field, and does not probe the sky-projected magnetic field. Also, pulsar distances have typical uncertainties of 0.5 kpc or greater, because few pulsars have stellar parallax, and H I kinematic distances typically only give upper or lower distance limits (Frail & Weisberg 1990; Verbiest et al. 2012). In addition, a small number of pulsars are known in the Galactic center region and beyond. For instance, there are only 10 pulsars whose distance is more than 8 kpc toward our observed area ($|l| \leq 10^\circ$, $|b| \leq 0^\circ.2$) in the ATNF Pulsar Catalogue (Manchester et al. 2005). This area suffers from strong confusion of diffuse emission from the Galactic disk at low Galactic latitudes, and Faraday rotation data are more difficult to obtain in the far side of the Galactic center (Han et al. 2017, 2018).

Starlight polarization is sensitive to the sky-projected magnetic field, but arises as an integral quantity of the line of sight between the Sun and the background stars. To examine changes in the sky-projected magnetic field with distance, we need reliable stellar distance markers. Nishiyama et al. (2009) attempted to measure magnetic fields in the Galactic center with near-infrared polarimetry by subtracting the polarization of “bluer” field stars at the near side in the Galactic bulge from the polarization of “redder” stars at the far side in the bulge. This work was followed by Nishiyama et al. (2010) who used the same method to examine a transition from toroidal to poloidal magnetic field above and below the Galactic plane. However, these works simply used $H - K_S$ colors instead of actual distances, and kiloparsec-scale details of the morphology of the magnetic field remain unclear. Pavel (2014) attempted to decompose the line of sight structure of the Galactic magnetic field and provided photometrically identified red clump stars with the polarization data of the Galactic Plane Infrared Polarization Survey (Clemens et al. 2012). For real decomposition, however, spectroscopic follow-up to identify red clump stars is needed, as the author admitted in the paper.

We present a new method for examining the large-scale magnetic field geometry with distance by using classical Cepheids and Gaia data in the Galactic plane. Classical Cepheids are pulsating supergiants with the period luminosity relation (PLR) which enables us to estimate their distances with reasonable accuracy, if we can assume an appropriate extinction law (e.g., Nishiyama et al. 2006). Matsunaga et al. (2016) discovered 29 classical Cepheids between $-10^\circ$ and $+10^\circ$ in the Galactic longitude along the Galactic plane, using the Infrared Survey Facility (IRSF). Dékány et al. (2015a, 2015b) reported dozens of new Cepheids found in the VISTA Variables in the Vía Láctea (VVV) survey (Minniti et al. 2010). Their new Cepheids are located in the far side of the Galactic center. On the other hand, the Gaia astrometric mission (Gaia Collaboration 2018) is to produce a three-dimensional map of unprecedented precision, using
parallaxes for billions of stars. Combining polarization with parallaxes is a powerful tool to probe the 3D topography of the interstellar medium and magnetic field. Visual-wavelength polarimetric studies have tried to resolve magnetic field structure in the diffuse ISM or dark globule using the Gaia DR2 parallax (Panopoulou et al. 2019 and Eswaraiah et al. 2019), and have made some success in detecting the change of magnetic field orientation with distance.

In this paper, we divide field stars into three regions, a) foreground, b) bulge, and c) background, using the Gaia parallax data and near-infrared colors with the Cepheid distances. These three regions are then used as distance markers along a line of sight to probe the magnetic field structure among them via near-infrared starlight polarimetry.

In section 3, we classify 52 Cepheid fields into three types simply from polarization behavior vs. $H - K_S$ color of field stars, choose a field of view from each of the three types, and discuss their polarimetric characteristics. Our new method for measuring the Galactic magnetic field structure with distance is presented in Section 4.

2 Observation

We conducted near-infrared polarimetric observations of 52 classical Cepheids and the stars around them in 2016 and 2017 with the SIRPOL instrument. The 52 classical Cepheids are identified by Dékány et al. (2015a, 2015b) and Matsunaga et al. (2016). Among them, 50 Cepheids are located very close to the Galactic plane ($-10^\circ \leq l \leq +10^\circ;5 -0^\circ;2 \leq b \leq +0^\circ;2$), and the other two Cepheids are in $0^\circ;2 \leq |b| \leq 0^\circ;5$.

SIRPOL consists of a single-beam polarimeter (a half-wave plate rotator unit and a fixed wire-grid polarizer; Kandori et al. 2006) and the near-infrared imaging camera SIRIUS (Simultaneous Infrared Imager for Unbiased Survey; Nagashima et al. 1999; Nagayama et al. 2003), and is attached to the 1.4 m telescope IRSF. The camera is equipped with three 1024 pixel $\times$ 1024 pixel HAWAII arrays. SIRPOL provides images of a 7\,\arcmin\,7 $\times$ 7\,\arcmin\,7 area of sky, in the $J$ ($\lambda_J = 1.25$ $\mu$m), $H$ ($\lambda_H = 1.63$ $\mu$m), and $K_S$ ($\lambda_{K_S} = 2.14$ $\mu$m) bands, simultaneously. The image scale of the arrays is 0\,\arcsec\,45 pixel$^{-1}$. We obtained 10 dithered exposures, each 10 s or 20 s, at four wave-plate angles (0°, 22°5, 45°, and 67°5 in the instrumental coordinate system) as one set of observations. The total exposure time was 400 s for most of the Cepheid fields, and 800 s or more for some fields. The typical seeing was $\sim$ 1\,\arcsec\,2 in the $K_S$ band during the observations. Twilight flat-field images were obtained at the beginning and end of the observations.

Standard procedures, dark subtraction, flat-fielding with twilight-flats, bad pixel subtraction, sky subtraction, and averaging of dithered images were applied with IRAF. In this
paper, we discuss the result of $K_S$-band polarimetry only. The Stokes parameters, $I$, $Q$, and $U$ for Cepheids and the field stars are determined from aperture photometry of combined images as follows. $Q = I_0 - I_{45}$, $U = I_{22.5} - I_{67.5}$, and $I = (I_0 + I_{22.5} + I_{45} + I_{67.5})/2$, where $I_0$, $I_{22.5}$, $I_{45}$, and $I_{67.5}$ are intensities at four wave-plate angles. DAOFIND and PHOT tasks were used for point source identification and the aperture photometry at each wave-plate angle ($I_0$, $I_{22.5}$, $I_{45}$, and $I_{67.5}$). Since the aperture photometry gives a better result than PSF fitting photometry (Hatano et al. 2013), aperture photometry was applied in the following procedure. Photometry measurements are greatly affected by the choice of aperture size. If the aperture radius is too large the obtained value suffers from background contamination in the Galactic plane and the signal to noise ratio is decreased. If the aperture radius is too small, however, only a fraction of total flux is measured and the fraction inevitably changes, resulting in artificial polarization. The aperture size was chosen after a search from 1.0 to 2.0 × FWHM at intervals of 0.1. We mostly adopted the aperture size of 2 × FWHM measured, but we adopted the aperture size of 1.5 or 1.0 × FWHM if the Cepheid was faint or the seeing was bad. The Two Micron All Sky Survey catalog (Skrutskie et al. 2006) was used for absolute photometric calibration of the field stars.

The raw polarization degree $P_{raw}$ and the position angle $PA$ were calculated from

$$P_{raw} = \sqrt{\left(\frac{Q}{I}\right)^2 + \left(\frac{U}{I}\right)^2}, \quad PA = \frac{1}{2} \arctan \frac{U}{Q}.$$ 

The debiased $P$ (Wardle & Kronberg 1974) was finally derived from $P = \sqrt{P_{raw}^2 - \delta P_{raw}^2}$ where $\delta P_{raw}$ is the error of $P_{raw}$, calculated from the propagation of errors in the four intensities at four wave-plate angles. The typical error is $\delta P_{raw} = 0.5\%$ for $K_S = 11.5$ mag.

In this paper, we use the Galactic coordinate system, and furthermore the position angle $PA_{GP}$ is measured anti-clockwise from the longitude-increasing direction of the Galactic plane (i.e., the usual position angle in the Galactic coordinate system (e.g., Appenzeller 1968), which is measured from the north Galactic pole, minus 90°). Lowercase $q_{GP}$ and $u_{GP}$ stand for $(Q/I)_{GP}$ and $(U/I)_{GP}$ in this system, respectively. Our zero-point of the $PA$ is estimated to be determined better than $\sim 3°$ (Kusune et al. 2015).

We have checked our polarimetry by observing the unpolarized standard star WD 2539-434 from the VLT list (Fossati et al. 2007) in order to estimate instrumentally induced polarization. We have confirmed that the instrumental polarization is small enough to neglect within the errors of our polarimetry precision. Although it was found to vary with a period of 2.6950 hours and semiamplitude of 4 mmag in the $R$ band (Gary et al. 2013), variations at such a level do not affect our polarimetry because the average time difference is only about 30
s between the intensity measurements of different wave-plate angles.

We have also examined how the measured polarization of WD 2539-434 changes as a function of aperture size from 1.0 to 4.0 × FWHM to check whether our chosen aperture is too small and introduces artificial polarization. Its debiased polarization stays zero between 1.5 and 2.4 × FWHM; its calculated δP_{raw} stays below 0.28% between 1.0 and 2.2 × FWHM, but it increases to 4.0 × FWHM at a rate of nearly 0.01% per 0.1 × FWHM, probably due to too much background contamination. We have examined several field stars of different magnitude as a function of aperture size also, and many of them tend to be stable near 2 × FWHM although some stars fainter than 11 mag have a variety of fluctuations.

In a similar vein, we have examined the polarization of all the stars that are brighter than $K_S = 11$ mag and bluer than $H - K_S = 0.2$ mag in the 52 fields, to check the level of instrument polarization. We have observations of only a few fields which suffer interstellar extinction small enough, so polarimetry of such blue stars less affected by extinction in the 52 fields can serve to estimate the level of instrument polarization of our observation system. The mean of $q$, its standard deviation, $u$, and its standard deviation of these 99 stars are 0.28%, (±)0.58%, −0.27%, (±)0.73%, respectively (see Figure 1). Field stars have intrinsic $H - K_S \sim 0.1$ mag on average according to Wainscoat et al. (1992) (see below), and the selected stars will have at most 0.9% if they follow the upper limit $P/E(H - K_S) = 9.0$%mag$^{-1}$ (Hatano et al. 2013). The polarization $q \sim 0.28\%$, $u \sim -0.27\%$ is also consistent with the results for disk star candidates ($PA \sim 0^\circ$ in the equatorial coordinates, which is $PA_{GP} \sim -30^\circ$) in Hatano et al. (2013) although the disk star candidates in Hatano et al. (2013) include reddened stars up to $H - K_S = 0.4$ mag and their mean $P$ is 0.8%. Kandori et al. (2006) states that the stability of SIRPOL is better than 0.3%, and they were unable to detect instrument polarization. Our results are consistent with it, and we regard our instrument polarization as being smaller than 0.3%. Also, the stability of SIRPOL in a long term has been demonstrated, but we have to be careful because in a recent paper Kandori et al. (2019) mention that the instrument polarization of SIRPOL can reach 0.26% due to inappropriate handling of skyflat frames. We will investigate this problem in a future paper.

3 Results

In table 1 we list the Galactic coordinates, $H$ and $K_S$ band mean magnitudes adopted from Dékány et al. (2015a, 2015b) and Matsunaga et al. (2016), extinctions $A_{K_S}$, distances $D$, polarization degrees $P$ and position angles $PA_{GP}$ in the $K_S$ band of the 52 Cepheids. We use
distance modulus for estimating distances to Cepheids as done by Matsunaga et al. (2016). Since Dékány et al. (2015b, 2015b) estimated the distances using their own extinction law, we have re-calculated the distance of the Cepheids reported by Dékány et al. (2015b, 2015b) in accordance with Matsunaga et al. (2016). We adopt the PLR of classical Cepheids from Matsunaga et al. (2013):

\[
M(H) = -3.256(\log Pd - 1.3) - 6.562, \tag{1}
\]

\[
M(K_S) = -3.295(\log Pd - 1.3) - 6.685, \tag{2}
\]

where \( Pd \) is their variation period in days. These PLRs and the extinction relation of \( A_{K_S}/E_{H-K_S} = 1.44 \) (Nishiyama et al. 2006) are combined with the observed magnitudes \( H \) and \( K_S \) to estimate the distance and the foreground extinction \( A_{K_S} \).

Figure 2 shows the distribution of the 52 Cepheids with filled circles. Only one Cepheid (MC10) is located close to the Galactic center, and all the others are located on the far side of the Galactic center. Although the polarization of these Cepheids is an integral quantity between the observer and the Cepheids along the line of sight, we can probe the magnetic field structure in the far side of the Galactic center if we perform some differential analysis. The information about the magnetic field structure in the far side was quite unclear even with Faraday rotation and other data (e.g. Han 2017, 2018).

The magnetic field component horizontal to the Galactic plane is dominant over the vertical magnetic field component. 38 Cepheids out of the 52 Cepheids have position angles of \( |PA_{GP}| < 20^\circ \) (in figure 3 and figure 4). Five Cepheids have large position angles of \( |PA_{GP}| \geq 45^\circ \), but their position angle errors \( \delta PA_{GP} \) are more than \( 10^\circ \), which means that the polarization signal to noise ratios are smaller than 3. We do not regard them representing the magnetic field correctly.

Kobayashi et al. (1983 & 1986) observed the Galactic longitudes of 0\(^\circ\), 20\(^\circ\), and 30\(^\circ\), and found difference in the polarization efficiency \( P_{K_S}/A_{K_S} \). The polarization efficiency at the Galactic longitudes of 20\(^\circ\) and 30\(^\circ\) is smaller than the one at the Galactic center of 0\(^\circ\). Since the Galactic longitudes \( l \) of the 52 Cepheids range from \(-9.8^\circ\) to \(+10.4^\circ\), we examine if the polarization efficiency \( P_{K_S}/A_{K_S} \) is different from field to field. Figure 5 shows the relationship between the Galactic longitude and the polarization efficiency of the 52 Cepheids. The polarization efficiency with \( |l| \leq 5^\circ \) is 1.39 \pm 0.55 \%/mag, and the polarization efficiency with \( |l| > 5^\circ \) is 1.15 \pm 0.63 \%/mag; the Cepheids in the outer part \( (|l| > 5^\circ) \) have polarization efficiency similar to the Cepheids close to the Galactic center \( (|l| \leq 5^\circ) \), and the polarization efficiency is not significantly different in our observed region.
It is believed that interstellar polarization depends on the magnetic field of constant and random components similar in strength (Jones et al. 1992). Then it might be natural to assume that the interstellar polarization degree gradually increases as a more distant and therefore more reddened star is observed. Also, the position angle of polarization is expected to be rather constant, and possibly along the Galactic plane ($|PA_{GP}| \sim 0^\circ$). We ask if such a picture of undisturbed magnetic structure holds in most of the observed Cepheid fields. We examine polarization efficiency and change in differential position angles $PA_{GP}$ as the reddening increases in the Cepheid fields, and we have classified them into three types of 1) fairly constant and regular magnetic field, 2) containing an abrupt change in the field direction, and 3) of rather complicated pattern. We tried to conduct a new polarimetric differential analysis with the observed 52 Cepheid fields, but it was difficult to derive accurate polarization of field stars in four Cepheid fields due to poor signal to noise ratios. Thus, we looked into the other 48 Cepheid fields.

When we plot the field stars in a polarization degree $P$ vs. $H - K_S$ diagram, stars with larger polarization extend redward, and the slope $\Delta P/\Delta (H - K_S)$ reflects the polarization efficiency. Toward the Galactic center, Hatano et al. (2013) divided the field stars into two groups of disk sources with $H - K_S < 0.4$ mag consisting of A/F dwarfs and G/K giants, and bulge sources with $H - K_S \geq 0.4$ mag consisting of K/M giants. Similarly, we define the field stars with $H - K_S \geq 0.5$ mag as the bulge stars and calculate the gradient. If the magnetic field along the line of sight aligns well in the same direction, in the figure of polarization degree $P$ vs. $H - K_S$ color, the polarization slope should be great. We make linear fitting to the polarization of field stars with $H - K_S \geq 0.5$ mag and calculate the slope in each field. If the slope of polarization per color $\Delta P/\Delta (H - K_S)$ is more than $1.2 \%/$mag in both the color ranges of $0.5$ mag $\leq H - K_S \leq 1.5$ mag and $0.5$ mag $\leq H - K_S \leq 3.0$ mag (table 1), we define the field as $Dflag = 1$. Although this slope break is somewhat arbitrary, it corresponds to a fairly random magnetic field geometry in the compilation of infrared polarimetry by Jones et al. (1992) if we adopt the extinction law by (Nishiyama et al. 2006) and assume $H - K_S \sim 1-2$ mag. Only 10 Cepheid fields are classified to have $Dflag = 1$. In the remaining 38 Cepheid fields, two fields have turned out to be populated by field stars whose position angles change greatly as the $H - K_S$ color increases, and we have defined these two fields as $Dflag = 2$. As we show in the next section, the magnetic field orientation $PA_{GP}$ seems to change more than $45^\circ$ between the bulge and the background in these fields of view. In the other 36 Cepheid fields, the polarization degree does not increase very much ($\Delta P/\Delta (H - K_S) \leq 1.2$), and we do not notice any significant pattern. Their polarization is generally parallel to the Galactic
plane, but some of them show broad distribution of position angle in the polarization of field stars. We have defined these 36 fields as Dflag = 3.

We choose a field of view from each of the three types, and discuss the change of magnetic field structure in detail. We will present the analysis of the other 45 Cepheid fields elsewhere (Zenko et al. in preparation). We have selected Cepheid fields with large number of field stars in all of the foreground, bulge, and background categories. DC35 from Dflag = 1, DC5 from Dflag = 2, and MC15 from Dflag = 3 have been selected. These Cepheid locations are indicated with red points in figure 2. We discuss the result of polarimetric observation of each field.

3.1 DC35

DC35 was found by Dékány et al. (2015b), and its period was determined to be 13.5 d. Its polarization degree is more than 4%, and the 9th largest in the 52 Cepheids. Its position angle $PA_{GP}$ is $2^\circ$, and this $|PA_{GP}|$ is the 5th smallest, approximately parallel to the Galactic plane. The extinction $A_{K_S}$ to DC35 is relatively small among the 52 Cepheids (35th largest), so the polarization efficiency $P_{K_S}/A_{K_S}$ to DC35 is large. In the upper left panel of figure 6, the field stars with $\delta P_{GP} \leq 0.5\%$ are shown. The field stars around DC35 have similar polarization to DC35. Most of the field stars have polarization approximately parallel to the Galactic plane, and only a few field stars have polarization slightly tilted from the Galactic plane with small polarization degrees. Overall, these stars are evenly distributed in the field of view, and we find no significant local change in the magnetic field. Also, the field of view toward DC35 has constant polarization efficiency (1.8 %/mag) over the $0.5 \leq H - K_S \leq 3.0$ mag range, as shown in table 1.

We divide the $H - K_S$ data set in bins of equal size 0.5 mag, and draw the polarization maps (figure 9). Since most field stars have intrinsic $H - K_S$ of 0 - 0.2 mag (Wainscoat et al. 1992), the $H - K_S$ color can be regarded as similar to the color excess $E(H - K_S)$. From the smallest reddening map a) $0.0 \leq H - K_S < 0.5$ mag to the largest reddening map e) $2.0 \leq H - K_S < 2.5$ mag, coherent patterns of polarization parallel to the Galactic plane is always dominant, and the polarization degree $P$ grows greater as the color excess $E(H - K_S)$ becomes larger. In the map a), some stars have polarization slightly tilted to the Galactic plane from lower left to upper right, but in the maps b) - e), fewer and fewer stars have such polarization direction. This is apparent in the bottom panel of figure 6, where very slow gradient of overall distribution of smaller and smaller position angle $PA_{GP}$ toward larger $H - K_S$. Also, the standard deviation of position angle $PA_{GP}$ becomes smaller from a) $8^\circ.63$ to
b) 5°94 and c) 6°21. This might be understood very well if the magnetic field in the distance corresponding to $0.5 \, \text{mag} \leq H - K_S < 1.5 \, \text{mag}$ is well ordered in the Galactic plane direction. The position angles of these reddened stars are very close to that of the cepheid DC35.

3.2 DC5

DC5 was found by Dékány et al. (2015b), and its period was determined to be 12.3 d. Its Galactic latitude 0°4 is largest in our sample, but it is moderately extincted among the 52 Cepheids with $A_{K_S}$ of 2.4 mag, and also moderately polarized with $P$ of 3.1%. However, its position angle $PA_{GP}$ is 37°, and its $|PA_{GP}|$ is among the largest in the Cepheids with $P/\delta P > 3$ and therefore well determined $PA_{GP}$, along with DC9. This indicates a magnetic field oblique to the Galactic plane in this line of sight. In the upper left panel of figure 7, many field stars around DC5 have polarization similar to DC5, both in the degree and position angle. At the same time, some other field stars have polarization parallel to the Galactic plane. Furthermore, a few field stars have small polarization perpendicular to the Galactic plane. The magnetic field in this field of view is complicated. The gradient of the field stars with $0.5 \, \text{mag} \leq H - K_S \leq 1.5 \, \text{mag}$ is $1.8 \pm 0.3 \, \%/\text{mag}$, but that of the field stars with $0.5 \, \text{mag} \leq H - K_S \leq 3.0 \, \text{mag}$ is $1.0 \pm 0.1 \, \%/\text{mag}$, much smaller than the former.

In the bottom panel of figure 7, the position angles $PA_{GP}$ decrease to $\sim 10°$ in the range of field stars $0.5 \, \text{mag} \leq H - K_S < 1.5 \, \text{mag}$, but they increase again from $H - K_S \sim 1.5 \, \text{mag}$. If we look at the detail, the mean and standard deviation of position angle $PA_{GP}$ is $34° \pm 15°$ ($0.75 \, \text{mag} \leq H - K_S < 1.25 \, \text{mag}$), $15° \pm 9°$ ($1.25 \, \text{mag} \leq H - K_S < 1.75 \, \text{mag}$; except three field stars whose position angles $PA_{GP}$ are more than $3\sigma$ away from the mean position angle $PA_{GP}$), and $24° \pm 15°$ ($1.75 \, \text{mag} \leq H - K_S < 2.25 \, \text{mag}$). The magnetic field orientation changes greatly at $H - K_S \sim 1.5 \, \text{mag}$ to produce $10°$ or $20°$ polarization increase. We note that DC5 is more reddened ($H - K_S = 1.75 \, \text{mag}$) and has the position angle $PA_{GP} \sim 37°$.

The polarization maps divided into five $H - K_S$ ranges are in figure 10. In the small $H - K_S$ ranges a) and b), many field stars show $\sim 50° \, PA_{GP}$, and in the maps c), d), and e) are mixture of such field stars and those polarized nearly parallel to the Galactic plane.

3.3 MC15

MC15 was found by Matsunaga et al. (2016), and its period was determined to be 16.5 d. Its polarization degree and extinction are both modest, and the position angle $PA_{GP}$ is $-23°$, having a large $|PA_{GP}|$ after DC5 and a few other Cepheids. Most field stars around MC15 have
similar polarization to MC15, both in the degree and position angle. Therefore, the magnetic field direction seem to be well aligned and slightly oblique to the Galactic plane in this line of sight.

However, we notice a group of field stars having polarization nearly parallel to the Galactic plane ($PA_{GP} \sim 0^\circ$) in the uppermost small area in figure 8. The line of sight to this small area seems to be different from the other part of this field. We also notice one small (< 2 arcmin) region of large extinction exists, with the center coordinates of $(l,b) = (1.9^\circ, -0.05^\circ)$, where we have very few stars whose polarization has been measured accurately. This small region does not seem to influence the MC15 field analysis as a whole.

In the other part, most field stars have small polarization degree $P$ of less than 3% and are evenly distributed. The gradient of the field stars with $0.5 \text{ mag} \leq H - K_S \leq 1.5 \text{ mag}$ is $1.0 \pm 0.2 \%$/mag, and that of the field stars with $0.5 \text{ mag} \leq H - K_S \leq 3.0 \text{ mag}$ is $1.0 \pm 0.1 \%$/mag. The field of view toward MC15 thus has constant polarization efficiency over the $0.5 \text{ mag} < H - K_S \leq 3.0 \text{ mag}$ range. We find no significant global change in the magnetic field. The polarization maps divided into five $H - K_S$ ranges are in figure 11. Some of the most reddened field stars $H - K_S > 2.0 \text{ mag}$ might be polarized nearly parallel to the Galactic plane (see the bottom panel of figure 8 also), but it is evident that many field stars reddened similarly to MC15 have polarization similar to MC15 ($PA_{GP} = -23^\circ$).

4 The differential analysis

Now we try to sort the stars in each field of view into three regions according to their distances. First, the majority of field stars belong to the bulge (e.g., Hatano et al. 2013), and are concentrated around the distance of the Galactic center $\sim 8 \text{ kpc}$. These are “bulge” stars. Second, the Cepheids are in the far side of the Galaxy, and their distances are well determined. The field stars which suffer interstellar extinction similar to the Cepheids go into the “background” category. Last, the field stars close to us can be detected in the optical wavelengths, and are listed in the Gaia DR2 catalog. They are “foreground” stars. Therefore, we will divide each field into the three regions a) foreground, b) bulge, and c) background, and calculate the differential polarization between them.

Our Cepheid fields are close to the Galactic plane, and most of the stars in the Gaia DR2 catalog is confined to the distance $D \leq 4 \text{ kpc}$. We define the stars as the “foreground” stars whose parallax ranges determined in the Gaia DR2 catalog cover the distance 4 kpc or closer. Following Hatano et al. (2013), who regarded stars with $H - K_S < 0.4 \text{ mag}$ as the disk stars, we set a color range of $0 \text{ mag} \leq H - K_S \leq 0.5 \text{ mag}$ and matched these stars with the
Gaia DR2 catalog, using a match radius of 1 arcsec. If we confine the match to the Gaia 10σ stars whose ratios of parallaxes to uncertainties $\omega/\sigma_\omega$ are greater than 10, very few matches are found. Therefore we use all the Gaia stars whose ratios of parallaxes to uncertainties are greater than 1. We remove the field stars whose distance are more than 4 kpc even if we assume $\omega + \sigma_\omega$ as their parallaxes.

We regard the field stars whose distances are similar to the Cepheids as the “background” stars. First, we compare the observed color magnitude diagrams of the field stars in figure 12 with the Galaxy stellar model by Wainscoat et al. (1992). The stellar types whose $H - K_\text{S}$ color and $K_\text{S}$ magnitude are compatible with the observed ranges, and also the distance to the Cepheids are M5III, M6III and A-G I-II. We calculate the mean $H - K_\text{S}$ color using these stellar types and stellar densities in Wainscoat et al. (1992). The mean background $H - K_\text{S}$ color of the DC35 field is 1.91 mag, DC5 is 2.03 mag, and MC15 is 1.88 mag; we regard all the stars in the $H - K_\text{S}$ color range of 0.5 mag around them as the “background” stars.

Near-infrared observations toward the Galactic center produced a double peak structure in the $H - K_\text{S}$ histogram; the small peak on the bluer side of the histogram corresponds to the foreground stars, and the main peak in the redder side of the histogram corresponds to the bulge stars (e.g., Nishiyama et al. 2009). In the $H - K_\text{S}$ histograms of the 48 Cepheid fields, many of them show a similar structure. In the color magnitude diagram (figure 12) and $H - K_\text{S}$ histogram (figure 13), stars (black dots) with photometric errors $\delta H < 0.06$ mag and $\delta K_\text{S} < 0.06$ mag and stars (red dots) with photometric errors $\delta H < 0.06$ mag, $\delta K_\text{S} < 0.06$ mag and polarimetric errors $\delta P_{K_\text{S}} < 0.5$ % are plotted. The peak of the red histogram $H - K_\text{S}$ color of the DC35 field is 0.95 mag, DC5 1.45 mag, and MC15 1.45 mag. We basically regard the field stars whose colors are within $\pm 0.25$ mag from the main peak of $H - K_\text{S}$ as the bulge star candidates. However, if the bulge color range overlaps with the foreground or the background color range, we limit the color range of the bulge so that they do not overlap. The color range of the DC35 and DC5 fields is within $\pm 0.25$ mag, and that of the MC15 field is within $\pm 0.18$ mag.

4.1 DC35

We show the relation between the distance and the polarization of the foreground stars in the upper left panel of figure 14. All the five stars close to us with $\omega \geq 0.9$ mas have the position angles $PA_{\text{GP}} \sim 0^\circ$ or slightly smaller, while the position angles of the other more distant foreground stars are distributed around $PA_{\text{GP}} \sim 15^\circ$. Therefore, a clear change in the
magnetic field direction seems to exist at a distance slightly more than 1 kpc. Such a small change is difficult to discern in the $H - K_S$ color discussion in the previous section. The median distance of these 46 foreground stars is 2.21 kpc, and their mean $H - K_S$ color is 0.31 mag. If we calculate the mean polarization degree, $P$ is $\sim 2\%$ and the mean position angle $PA_{GP}$ is $\sim 10^{\circ}$ (table 2). The polarization map (the left panel of figure 15) also demonstrates that the vectors of the foreground stars are the mixture of the two coherent patterns of $PA_{GP} \sim 0^{\circ}$ and around $\sim 15^{\circ}$.

We plot the foreground stars with the blue error bars in the Stokes $q_{GP} - u_{GP}$ plane in the Galactic coordinates (the upper left panel of figure 18), where the rightmost points are large polarization parallel to the Galactic plane, the uppermost points are polarization $45^{\circ}$ clockwise (east from the increasing $l$ direction) from the Galactic plane, the leftmost points are perpendicular to the Galactic plane, and so on. The foreground stars are located in a small region on the right side of the origin in this figure, so the magnetic field along the line of sight aligns in the same direction between the observer and the foreground stars. Comparing this Stokes $q_{GP} - u_{GP}$ figure with the upper left panel of figure 14 in detail, we can say that the magnetic field in this line of sight is in the direction of slightly negative $PA_{GP}$ (close to the $q_{GP}$ axis but in the the fourth quadrant of the $q_{GP} - u_{GP}$ plane) up to 1.1 kpc from us, and then in the positive $PA_{GP}$ direction (the first quadrant of the $q_{GP} - u_{GP}$ plane) to show the polarization of $PA_{GP} \sim 15^{\circ}$ around the distance of $D \sim 2 - 3$ kpc.

We have checked the dark cloud catalog by Dobashi (2011), and only one dark cloud No. 216 on the upper boundary of the DC35 field exists, with the center coordinates of $(l, b) = (4.3^\circ 33, -0^\circ 03)$ and the surface are of 18 arcmin$^2$; this cloud does not seem to affect the polarization of the field. We have also checked the $V$ band polarimetry catalog (Heiles 2000), but there are no stars located in the DC35 field of view. However, the web 3D dust map mentioned in Lallement et al. (2019) indicates a clear increase in reddening $E(B - V)$ at a distance around 1.2 kpc, which might correspond to the change in the position angle $PA_{GP}$ at $\omega \sim 0.9$ mas.

In the middle panel of figure 15, most of the vectors of the bulge stars seem to be aligned in the Galactic plane direction. In the bulge, the mean polarization degree $P$ increases and the position angle becomes closer to parallel to the Galactic plane than the foreground (table 2). Therefore, the differential polarization between the foreground and the bulge (table 3) shows polarization increase of more than 1% in the direction parallel to the Galactic plane. The polarization increase per color change $\Delta P / \Delta (H - K_S)$ is as high as 2.9 %/mag, indicating that a uniform magnetic component dominates between the foreground and the bulge. In the upper left panel of figure 18, the bulge stars (the green error bars) are located further right from the
foreground stars, indicating that the magnetic field between the foreground and the bulge along the line of sight aligns parallel to the Galactic plane very well.

The polarization vectors of the background stars are almost parallel to the Galactic plane in the entire field, and are quite consistent with the polarization of DC35 itself, which is at the distance $D$ of 12.0 kpc (the right panel of figure 15). The mean polarization degree $P$ of the background stars further increases and their position angle becomes even closer to parallel to the Galactic plane than the bulge (table 2). The differential polarization between the bulge and the background stars (table 3) shows further polarization increase of more than 1% in the position angle $PA_{GP}$ nearly parallel to the Galactic plane. The polarization increase per color change $\Delta P/\Delta(H - K_S)$ is large (1.7%/mag), indicating again that a uniform magnetic component dominates between the bulge and the background. In the $q_{GP} - u_{GP}$ diagram (the upper left panel of figure 18), DC35 itself is located near the extension of the distribution of foreground stars (in blue) and bulge stars (in green). Most of the background stars (in red) are distributed close to DC35. Although some of them are far from it, such field stars are located in the uppermost part in the field of view. A few bulge stars there also have polarization like them; thus this seems to be due to variation in the field of view.

### 4.2 DC5

All the 11 foreground stars have the position angles $PA_{GP} \sim 50^\circ$, and no foreground stars are polarized parallel to the Galactic plane $\sim 0^\circ$ in the upper right panel of figure 14. The median distance of these 11 stars is 0.83 kpc, and their mean $H - K_S$ color is 0.19 mag. The polarization map (in the left panel of figure 16) thus shows a coherent pattern of $PA_{GP} \sim 50^\circ$. The mean polarization degree $P$ is $\sim 1\%$ and the mean position angle $PA_{GP}$ is oblique to the Galactic plane (table 2). In the upper right panel of figure 18, the foreground stars are located in a region on the upper side of the origin (small $u_{GP} > 0$). This is the magnetic field up to the distance $D \sim 1.5$ kpc in this line of sight.

We have also checked the dark cloud catalog by Dobashi (2011), and two dark clouds, No. 7204 and 7208, exist near this field, with the center coordinates of $(l, b) = (-7^\circ.13, 0^\circ.283)$ and $(l, b) = (-7^\circ.05, 0^\circ.367)$ and the surface areas of 143 arcmin$^2$ and 141 arcmin$^2$; these clouds do not seem to affect the polarization of the field. The $V$ band polarimetry catalog by Heiles (2000) has no stars in the DC5 field of view, either.

In the middle panel of figure 16, the polarization vectors of the bulge stars seem to have broad distribution from $\sim 50^\circ$, which is similar to foreground stars, to nearly $\sim 0^\circ$, parallel
to the Galactic plane. The mean polarization degree $P$ of the bulge stars increases and the position angle $PA_{GP}$ becomes clearly closer to parallel to the Galactic plane than the foreground stars (table 2). The differential polarization between the foreground and the bulge (table 3) shows polarization increase of more than 2% in the direction parallel to the Galactic plane. The polarization increase per color change $\Delta P/\Delta(H-K_S)$ is large (2.0%/mag), indicating that a uniform magnetic component dominates between the foreground and the bulge. This is clear also in the upper right panel of figure 18, almost all of the bulge stars are located right of the foreground stars, which means that the magnetic field between the foreground and the bulge is in the direction parallel to the Galactic plane.

If we proceed to the position of the Cepheid DC5 at the distance $D = 12.6$ kpc, the $PA_{GP}$ of polarization becomes oblique to the Galactic plane again. In the right panel of figure 16, the background stars show broad distribution from nearly $\sim 0^\circ$, parallel to the Galactic plane, to $\sim 50^\circ$, which is as indicated in the $H-K_S$ vs. polarization angle $PA_{GP}$ of the bottom panel of figure 7, in the more reddened and probably more distant stars. In the background, the mean polarization degree $P$ is almost unchanged from the bulge, and the position angle becomes tilted again from the Galactic plane (table 2). However, the differential polarization between the bulge and the background (table 3) is nearly 1% in the direction oblique to the Galactic plane. The polarization change per reddening $\Delta P/\Delta(H-K_S)$ is relatively high (1.5%/mag). Therefore, the magnetic field is tilted as large as $\sim 60^\circ$ (table 3, upper right panel of figure 18), and this change should exist between the bulge at the distance of $D \sim 8$ kpc and the position of DC5 at $D = 12.6$ kpc. The location of DC5 in the $q_{GP}-u_{GP}$ diagram is near the upper left end of the distribution of background stars (in red).

4.3 MC15

Almost all the foreground stars have polarization of $PA_{GP} \sim -30^\circ$ in the bottom left panel of figure 14. The median distance of these 28 foreground stars is 1.98 kpc, and their mean $H-K_S$ is 0.39 mag. The polarization vectors of the foreground stars (in the left panel of figure 17) thus show a coherent pattern of $PA_{GP} \sim -30^\circ$, oblique to the Galactic plane; the mean polarization degree is $\sim 0.9$% (table 2). The bottom left panel of figure 18 also shows that the foreground stars are located in the fourth quadrant ($q_{GP} > 0$, $u_{GP} < 0$) with small distances. Thus, the magnetic field up to $D \sim 3$ kpc is aligned reasonably well in this line of sight. The dark cloud catalog by Dobashi (2011) lists no dark cloud in the neighborhood of the MC15 field. The V band polarimetry catalog by Heiles (2000) has no stars in the MC15 field of view, either.
The bulge stars (in the middle panel of figure 17) show a coherent pattern of polarization, $PA_{GP} \sim -20^\circ$, except for the uppermost small area, as we notice in the section 3.3. The angle from the Galactic plane is smaller negative, and the mean polarization degree $P$ increases from 0.9 to 1.6% (table 2). This is evident in the bottom left panel of figure 18, where the bulge stars (the green error bars) are distributed broadly in the right side of the foreground; $q_{GP}$ increases and $u_{GP}$ does not change. Therefore, the magnetic field between the foreground and the bulge aligns parallel to the Galactic plane. However, its differential polarization (table 3) shows polarization increase of only $\sim 1.0\%$ in the direction parallel to the Galactic plane. The polarization increase per color change $\Delta P/\Delta(H - K_S)$ is rather small ($0.9\%$/mag), indicating that a random magnetic component dominates between the foreground and the bulge.

The Cepheid MC15 at $D = 10.9$ kpc has polarization whose $P = 2.3\%$ and $PA_{GP} = -23^\circ$, and the polarization vectors of the background stars (in the right panel of figure 17) show patterns slightly closer to parallel to the Galactic plane, with the marginally increased mean polarization degree $P$ of 2.0% (table 2). The differential polarization degree between the bulge and the background (table 3) is less than 0.6% in the direction nearly parallel to the Galactic plane. The polarization increase per color change $\Delta P/\Delta(H - K_S)$ is small ($1.4\%$/mag), and the background stars and MC15 itself (the red error bars and the black filled circle, respectively, in the bottom left panel of figure 18) overlap the bulge stars. Therefore, random magnetic components seem to dominate more here than between the foreground and the bulge.

5 Discussion

The three Cepheids DC35, DC5, and MC15 are at 12.0, 12.6, and 10.9 kpc from us, respectively, and located in the far side of the Galactic center, possibly in a spiral arm (e.g., the Far-3kpc arm; Dame & Thaddeus 2008; Han et al. 2018). Many of the field stars observed in the near-infrared are in the bulge, which is around 8 kpc from us; the polarization changes from the bulge stars to the Cepheids provide us with the information of the magnetic field in the distance range of 8–12 kpc. The polarization of background stars (table 2) is generally similar to the polarization of the Cepheids, so the classification of the field stars into the background on the basis of their $H - K_S$ color, and therefore the differential polarization in table 3 seems reasonable. The magnetic field in the DC35 and MC15 sightlines runs parallel to the Galactic plane in the far side of the Galactic center, but in the DC5 sightline, the magnetic field seems to be oblique to the Galactic plane.

Dflag of 1 is assigned to the lines of sight where the slope of polarization increase per
the \( H - K_S \) change is large all the way to the \( H - K_S \) color of 3.0 mag. According to the model by Jones et al. (1992), this slope corresponds to the ratio of constant to random magnetic components. The magnetic field in the line of sight to DC35 (Dflag = 1) seems to have greater constant components than MC15 (Dflag = 3), both in the far side and in our neighborhood \( (D \sim 1 \text{ kpc}) \). More lines of sight have been assigned to Dflag = 3, which means that random magnetic field components are often dominant in some regions in the range of \( \sim 12 \text{ kpc} \) to the far side of the Galactic center.

6 SUMMARY

We have measured near-infrared polarization of 52 Cepheid fields in the Galactic plane, toward the Galactic center. The magnetic field orientation between the Sun and the far side of the Galactic center seems to be close to parallel to the Galactic plane in most cases. We classify 48 Cepheid fields into three types on the basis of the polarization characteristics. We have chosen a field of view from each of the three types. The DC35 field shows the magnetic field nearly parallel to the Galactic plane, well aligned all the way of \( \sim 12 \text{ kpc} \) from the Sun to the Cepheid position in the other side of the Galactic center, with a very small change in the position angle we can detect at the distance of 1.1 kpc. However, sightlines which show such well aligned magnetic fields in the Galactic plane is rather small in number. The MC15 field, along with the other 36 Cepheid fields, indicates that random magnetic field components are significant. The DC5 field and the other field indicate that the magnetic field orientation changes more than 45° in the line of sight. The polarization increase per color change \( \Delta P/\Delta (H - K_S) \) varies from region to region, reflecting the change in the ratio of the magnetic field strength and the turbulence strength.

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Table 1. Cepheids found by Dékány et al. (2015a, 2015b) and Matsunaga et al. (2016), and their polarization measured in our survey. ID (DC and DCC stand for Dékány Cepheid and MC stands for Matsunaga Cepheid, and the number or name in their lists), Galactic longitude, Galactic latitude, $H$ and $K_S$ mean magnitude, $K_S$ extinction, distance, debiased polarization degree, its error, position angle $P.A_{GP}$ in Galactic coordinates, its error, gradients $G_1$ (0.5 mag $\leq H - K_S \leq$ 1.5 mag), gradients $G_2$ (0.5 mag $\leq H - K_S \leq$ 3.0 mag), and Dflag (Section 3). The mean magnitudes are from Dékány et al. (2015a, 2015b) and from Matsunaga et al. (2016) for the Cepheids discovered by them.

| ID      | $l$   | $b$   | $H$  | $K_S$ | $A_{K_S}$ | $D$  | $P$   | $P.A_{GP}$ | $G_1$ | $G_2$ | Dflag |
|---------|-------|-------|------|-------|-----------|------|-------|------------|-------|-------|-------|
|         | deg   | deg   | mag  | mag   | mag       | kpc  | %     | deg        | deg   | deg   |       |
| DC1     | -8.886| 0.068 | 13.32| 12.01 | 1.73      | 13.0 | 1.77  | $\pm$0.51  | 2.3   | $\pm$7.8| 0.18  |
| DC2     | -9.312| 0.047 | 14.19| 12.57 | 2.17      | 12.3 | 0.48  | $\pm$1.02  | -74.9 | $\pm$25.9| 0.33  |
| DC3/MC1 | -9.810| -0.050| 13.20| 12.04 | 1.53      | 11.2 | 1.88  | $\pm$0.61  | -14.2 | $\pm$8.8| 0.35  |
| DC4/MC4 | -7.509| -0.022| 13.53| 11.70 | 2.44      | 11.9 | 2.19  | $\pm$0.66  | 6.8   | $\pm$8.5| 1.56  |
| DC5     | -7.210| 0.447 | 13.61| 11.86 | 2.35      | 12.6 | 3.12  | $\pm$0.56  | 37.4  | $\pm$5.1| 1.76  |
| DC6     | -7.244| 0.120 | 16.66| 13.86 | 3.87      | 13.6 | 3.19  | $\pm$2.50  | 1.0   | $\pm$17.4| 1.51  |
| DC7/MC5 | -7.260| 0.064 | 15.94| 13.93 | 2.75      | 13.6 | 3.99  | $\pm$1.82  | 27.3  | $\pm$11.8| 1.46  |
| DC8     | -6.097| -0.119| 15.36| 13.41 | 2.67      | 11.9 | 1.87  | $\pm$2.91  | 47.1  | $\pm$23.9| 0.96  |
| DC9     | -6.708| 0.098 | 15.62| 13.27 | 3.23      | 11.1 | 3.98  | $\pm$1.23  | -40.5 | $\pm$8.5| 0.35  |
| DC10    | -3.175| -0.218| 13.78| 12.01 | 2.38      | 13.1 | 4.50  | $\pm$0.64  | 4.5   | $\pm$4.0| 1.05  |
| DC11    | -3.677| 0.040 | 15.83| 13.09 | 3.79      | 8.8  | 2.96  | $\pm$1.11  | -9.7  | $\pm$10.1| 1.07  |
| DC12    | -2.158| -0.078| 13.96| 12.13 | 2.47      | 12.3 | 4.33  | $\pm$1.19  | 3.5   | $\pm$7.6| 0.00  |
| DC13    | -2.416| -0.170| 13.48| 12.10 | 1.85      | 9.4  | 0.80  | $\pm$0.68  | -19.8 | $\pm$18.1| 1.23  |
| DC14    | -1.491| -0.079| 14.66| 12.05 | 3.58      | 12.1 | 4.09  | $\pm$0.97  | -15.2 | $\pm$6.6| 0.71  |
| DC15    | -1.508| 0.186 | 13.41| 11.62 | 2.41      | 11.6 | 4.68  | $\pm$0.78  | -28.9 | $\pm$4.6| 0.14  |
| DC16    | 2.593 | 0.149 | 14.69| 12.85 | 2.50      | 12.0 | 1.68  | $\pm$1.38  | -80.1 | $\pm$18.7| 1.03  |
| DC17/MC17| 2.456| 0.033 | 14.08| 12.13 | 2.64      | 12.9 | 4.01  | $\pm$1.39  | 2.9   | $\pm$9.2| 1.02  |
| DC18/MC14| 1.732| -0.001| 12.91| 11.48 | 1.90      | 11.7 | 2.54  | $\pm$0.85  | -16.6 | $\pm$9.0| 0.40  |
| DC19/MC16| 2.018| -0.041| 14.62| 12.30 | 3.17      | 10.8 | 1.57  | $\pm$0.77  | -1.1  | $\pm$12.8| 0.79  |
| DC20    | 2.982 | -0.185| 15.33| 13.08 | 3.09      | 9.8  | 4.66  | $\pm$1.50  | 5.1   | $\pm$9.0| 1.35  |
| DC21/MC18| 2.838| -0.035| 14.27| 12.25 | 1.90      | 12.8 | 2.33  | $\pm$1.13  | -38.7 | $\pm$12.4| -0.12 |
| DC22    | 2.767 | 0.088 | 15.47| 13.25 | 2.76      | 11.4 | 4.58  | $\pm$2.44  | -4.3  | $\pm$13.5| 0.13  |
| DC23    | 4.528 | 0.075 | 14.37| 12.64 | 2.34      | 12.3 | 2.62  | $\pm$1.06  | -18.2 | $\pm$10.6| 1.45  |
| DC24    | 5.822 | 0.115 | 15.31| 13.37 | 2.65      | 11.4 | 0.95  | $\pm$0.78  | -54.9 | $\pm$18.2| 1.61  |
| DC25    | 7.717 | -0.147| 14.67| 12.45 | 3.03      | 11.2 | 4.03  | $\pm$1.03  | -5.8  | $\pm$7.1| 0.88  |
| DC26    | 10.372| -0.189| 16.52| 13.00 | 4.89      | 10.5 | 2.27  | $\pm$1.03  | 64.8  | $\pm$11.7| 0.97  |
| DC27    | -9.222| -0.110| 13.19| 11.44 | 2.35      | 11.8 | 0.77  | $\pm$0.50  | -2.9  | $\pm$15.8| 0.17  |
Table 1. (Continued)

| ID        | l       | b       | H     | Ks    | As    | D     | P     | PAGP  | G1    | G2    | Dflag |
|-----------|---------|---------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
|           | deg     | deg     | mag   | mag   | mag   | kpc   | %     | deg   | %/mag | %/mag |       |
| DC28      | -7.559  | 0.086   | 12.91 | 11.09 | 2.45  | 11.0  | 1.50 ± 0.30 | 27.5 ± 5.5 | 0.60 ± 0.60 | 0.36 ± 0.11 | 3     |
| DC29/MC7  | -5.302  | 0.039   | 12.09 | 11.01 | 1.40  | 11.5  | 3.83 ± 0.80 | -20.7 ± 5.7 | 1.31 ± 0.19 | 1.41 ± 0.16 | 1     |
| DC30      | -1.801  | 0.103   | 13.05 | 11.72 | 1.76  | 11.6  | 2.55 ± 0.43 | 6.4 ± 4.7  | 1.05 ± 0.16 | 1.05 ± 0.16 | 3     |
| DC31      | -2.371  | -0.139  | 12.77 | 11.18 | 2.12  | 12.9  | 3.06 ± 0.44 | -2.2 ± 4.1  | 1.41 ± 0.27 | 0.92 ± 0.29 | 3     |
| DC32      | 2.073   | 0.047   | 13.90 | 12.35 | 2.08  | 12.4  | 2.88 ± 0.88 | 6.4 ± 8.8  | 1.35 ± 0.21 | 1.33 ± 0.11 | 1     |
| DC33      | 4.060   | -0.109  | 13.16 | 11.46 | 2.28  | 12.6  | 5.03 ± 0.56 | -10.0 ± 3.1 | 1.14 ± 0.21 | 1.15 ± 0.11 | 3     |
| DC34/MC21 | 3.915   | -0.003  | 13.47 | 11.47 | 2.71  | 11.1  | 1.00 ± 0.64 | 7.7 ± 15.2 | 0.55 ± 0.26 | 0.90 ± 0.16 | 3     |
| DC35      | 4.342   | -0.109  | 13.03 | 11.42 | 2.15  | 12.0  | 4.39 ± 0.71 | 1.7 ± 4.6  | 1.80 ± 0.19 | 1.80 ± 0.14 | 1     |
| MC2       | -9.634  | 0.058   | 12.83 | 11.54 | 1.70  | 12.8  | 1.46 ± 0.54 | 0.1 ± 9.9  | 0.47 ± 0.27 | 0.62 ± 0.22 | 3     |
| MC3       | -8.405  | -0.048  | 11.58 | 10.46 | 1.44  | 12.7  | 1.79 ± 0.20 | -1.4 ± 3.1  | 1.14 ± 0.19 | 1.18 ± 0.17 | 3     |
| MC6       | -6.198  | 0.010   | 10.30 | 9.20  | 1.40  | 10.7  | 3.40 ± 0.09 | -13.2 ± 0.8 | 2.39 ± 0.37 | 1.98 ± 0.27 | 1     |
| MC8       | -2.908  | -0.062  | 12.31 | 10.77 | 2.04  | 14.1  | 3.65 ± 0.34 | -19.5 ± 2.7 | 0.20 ± 0.25 | 0.46 ± 0.17 | 3     |
| MC9       | -2.058  | -0.013  | 12.08 | 10.47 | 2.14  | 11.4  | 2.61 ± 0.24 | -9.6 ± 2.6  | 0.74 ± 0.24 | 0.54 ± 0.16 | 3     |
| MC10      | -0.324  | -0.026  | 12.14 | 10.32 | 2.44  | 7.9   | 5.52 ± 0.27 | -18.6 ± 1.4 | 2.94 ± 1.30 | 0.98 ± 0.22 | 3     |
| MC15      | 1.897   | -0.031  | 12.58 | 10.95 | 2.17  | 10.9  | 2.29 ± 0.30 | -22.9 ± 3.7 | 1.02 ± 0.17 | 1.00 ± 0.12 | 3     |
| MC19      | 2.961   | 0.007   | 12.47 | 10.91 | 2.07  | 13.9  | 4.88 ± 0.42 | 8.2 ± 2.7  | -± -      | -± -    | -     |
| MC20      | 3.035   | 0.010   | 11.22 | 9.86  | 1.77  | 13.9  | 2.81 ± 0.16 | -2.3 ± 1.6  | -± -      | -± -    | -     |
| MC22      | 5.165   | -0.023  | 13.81 | 11.74 | 2.21  | 20.0  | 2.41 ± 0.67 | -17.1 ± 7.6 | 1.30 ± 0.27 | 0.94 ± 0.16 | 3     |
| MC23/DCC1 | 6.990   | 0.001   | 14.79 | 12.75 | 2.77  | 14.7  | 6.89 ± 1.2  | -13.6 ± 3.5 | -± -      | -± -    | -     |
| MC24/DCC1 | 6.996   | 0.001   | 14.85 | 12.73 | 2.89  | 13.8  | 3.67 ± 2.3  | -7.5 ± 11.5 | -± -      | -± -    | -     |
| MC25      | 7.486   | 0.059   | 13.90 | 11.99 | 2.58  | 15.0  | 2.55 ± 0.92 | 17.4 ± 9.9  | 0.26 ± 0.28 | 0.61 ± 0.16 | 3     |
| MC26      | 7.973   | 0.003   | 11.68 | 10.35 | 1.72  | 18.2  | 2.19 ± 0.29 | 5.0 ± 3.6  | 0.89 ± 0.23 | 1.26 ± 0.18 | 3     |
| MC27      | 8.094   | -0.035  | 11.91 | 10.23 | 2.25  | 14.9  | 2.48 ± 0.19 | -19.8 ± 2.1 | 1.43 ± 0.24 | 1.64 ± 0.16 | 1     |
| MC28      | 9.068   | -0.016  | 13.10 | 11.44 | 2.21  | 16.0  | 4.03 ± 0.44 | -9.6 ± 3.1  | 1.38 ± 0.21 | 1.79 ± 0.17 | 1     |
| MC29      | 9.674   | -0.012  | 12.74 | 10.94 | 2.42  | 10.7  | 1.52 ± 0.30 | 29.0 ± 5.5  | 1.24 ± 0.40 | 1.14 ± 0.25 | 3     |
Fig. 1. Stokes parameters $q_{GP}$ and $u_{GP}$ of all the field stars that are brighter than $K_S = 11$ mag and bluer than $H - K_S = 0.2$ mag in the 52 fields.

Fig. 2. Distribution of the 52 Cepheids in the face-on view of the Galactic disc. Red dots are the three Cepheids analyzed in detail (Section 3. and 4.). The Sun - Galactic Center (asterisks) distance is assumed to be 8 kpc.

Fig. 3. Polarization of the 52 Cepheids. The red vectors are measurements with small errors $P/\delta P > 3$, but the black vectors are those with $P/\delta P < 3$. 
Fig. 4. Histogram of $PA_{GP}$ for the 52 Cepheids. The red filled boxes are measurements with small errors $P/\delta P > 3$, and the black filled boxes are those with $P/\delta P < 3$.

Fig. 5. Polarization efficiency $P/A_{K_s}$ vs. Galactic longitude $l$ for the 52 Cepheids. The red filled circles are measurements with small errors $P/\delta P > 3$, but the black filled squares are those with $P/\delta P < 3$.

Table 2. The mean polarization of foreground, bulge, and background stars in each field of view.

| ID   | $P_{\text{fore}}$ | $PA_{\text{GP,fore}}$ | $P_{\text{bulge}}$ | $PA_{\text{GP,bulge}}$ | $P_{\text{back}}$ | $PA_{\text{GP,back}}$ |
|------|-------------------|------------------------|---------------------|-------------------------|-------------------|-----------------------|
|      | %                 | deg                    | %                   | deg                     | %                 | deg                   |
| DC35 | 1.99 ± 0.61       | 11.84 ± 9.12           | 3.72 ± 0.70         | 5.42 ± 5.05             | 5.12 ± 1.67       | 0.45 ± 5.92           |
| DC5  | 1.12 ± 0.49       | 45.58 ± 12.74          | 2.78 ± 1.29         | 13.64 ± 10.67           | 2.79 ± 1.33       | 22.72 ± 13.75         |
| MC15 | 0.87 ± 0.46       | -30.97 ± 13.71         | 1.61 ± 0.91         | -15.31 ± 15.99          | 2.06 ± 1.31       | -9.39 ± 13.49         |

* These $P$ values have not been corrected for positive statistical bias.
Fig. 6. Polarization of the DC35 field. The Cepheid DC35 (red dot) and 439 field stars whose polarization is detected with $\delta P_{K_S} < 0.5 \%$. Upper left: Polarization map in the Galactic coordinates. A 1% reference bar is shown in lower left. Upper right: Degree of debiased polarization $P$ vs. $H - K_S$ colors. Bottom: Position angle $P_{AGP}$ vs. $H - K_S$ colors. The black horizontal line represents the orientation of the Galactic plane.
Fig. 7. DC5 (red dot) and 211 field stars. Same as figure 6.
Fig. 8. MC15 (red dot) and 467 field stars. Same as figure 6.
Fig. 9. Polarization maps of DC35 field divided into bins of 0.5 mag of $H - K_S$. (a) $H - K_S$ range from 0.0 to 0.5 mag. Blue dots are foreground stars, described in Section 4. (b) 0.5 mag $\leq$ $H - K_S$ < 1.0 mag. (c) 1.0 mag $\leq$ $H - K_S$ < 1.5 mag. (d) 1.5 mag $\leq$ $H - K_S$ < 2.0 mag. (e) 2.0 mag $\leq$ $H - K_S$ < 2.5 mag.

Table 3. Differential polarization.

From observer (0) to foreground (1),
from foreground (1) to bulge (2), and
from bulge (2) to background (3) in each field of view.

| ID    | Diff | unit | 0 → 1 | 1 → 2 | 2 → 3 |
|-------|------|------|-------|-------|-------|
| DC35  | $\Delta P$ | %    | 1.99  | 1.86  | 1.58  |
|       | $\Delta P_{\text{AGP}}$ | deg  | 11.84 | -1.50 | -11.55 |
| DC5   | $\Delta P$ | %    | 1.12  | 2.50  | 0.88  |
|       | $\Delta P_{\text{AGP}}$ | deg  | 45.58 | 1.84  | 63.13 |
| MC15  | $\Delta P$ | %    | 0.87  | 0.98  | 0.59  |
|       | $\Delta P_{\text{AGP}}$ | deg  | -30.97| -1.47 | 7.75  |
Fig. 10. Same as figure 9, but for DC5.
Fig. 11. Same as figure 9, but for MC15.

Fig. 12. $K_S$ vs. $H - K_S$ color magnitude diagram for stars with $\delta K_S < 0.06$ mag. Red dots are stars whose polarization is measured with $\delta P_{K_S} < 0.5\%$, and black dots are those with $\delta P_{K_S} > 0.5\%$. Field names are shown in upper right.
Fig. 13. Histograms of $H - K_s$ color for stars with $\delta K_s < 0.06$ mag. Field names are shown in upper right. The red histograms are stars whose polarization is measured with $\delta P_{K_s} < 0.5 \%$, and the black ones are those with $\delta P_{K_s} > 0.5 \%$. Vertical lines are the mean background $H - K_s$ color of each field: 1.86 mag for DC35, 2.03 mag for DC5, and 1.88 mag for MC15.
Fig. 14. Parallax vs. polarization degree $P$ and position angle $PA_{GP}$ of foreground stars cross-matched with the Gaia DR2 catalog. Field names are shown in upper left.

Fig. 15. Polarization maps of DC35 field divided into foreground (left) in blue, bulge (middle) in green, and background (right) in red. The red filled circle surrounded by a black frame is the Cepheid position.
**Fig. 16.** Same as figure 15, but for DC5.

**Fig. 17.** Same as figure 15, but for MC15.
Fig. 18. Stokes parameters $q_{GP}$ and $u_{GP}$ of field stars, foreground (blue), bulge (green), and background (red). Field names are shown in lower right. Black filled circles are Stokes parameters of each Cepheid.