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THE EFFICIENCY AND WAVELENGTH DEPENDENCE OF NEAR-INFRARED INTERSTELLAR POLARIZATION TOWARD THE GALACTIC CENTER

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ABSTRACT

Near-infrared polarimetric imaging observations toward the Galactic center (GC) have been carried out to examine the efficiency and wavelength dependence of interstellar polarization. A total area of about 5.7 deg² is covered in the J, H, and Ks bands. We examined the polarization efficiency, defined as the ratio of the degree of polarization to color excess. The interstellar medium between the GC and us shows a polarization efficiency lower than that in the Galactic disk by a factor of three. Moreover we investigated the spatial variation of the polarization efficiency by comparing it with that of the color excess, degree of polarization, and position angle. The spatial variations of color excess and degree of polarization depend on the Galactic latitude, while the polarization efficiency varies independently of the Galactic structure. Position angles are nearly parallel to the Galactic plane, indicating a longitudinal magnetic field configuration between the GC and us. The polarization efficiency anticorrelates with dispersions of position angles. The low polarization efficiency and its spatial variation can be explained by the differences in the magnetic field directions along the line of sight. From the lower polarization efficiency, we suggest a higher strength of a random component relative to a uniform component of the magnetic field between the GC and us. We also derived the ratios of degree of polarization $p_J/p_H = 0.581 \pm 0.004$ and $p_{KS}/p_J = 0.620 \pm 0.002$. The power-law indices of the wavelength dependence of polarization are $β_H = 2.08 \pm 0.02$ and $β_{KS} = 1.76 \pm 0.01$. Therefore, the wavelength dependence of interstellar polarization exhibits flattening toward longer wavelengths in the range of 1.25–2.14 μm. The flattening would be caused by aligned large-size dust grains.

Key words: dust, extinction – Galaxy: center – infrared: stars – ISM: magnetic fields – polarization

Online-only material: color figures

1. INTRODUCTION

Observations of interstellar linear polarization (hereafter just interstellar polarization) provide information about the magnetic field and properties of polarizing dust grains. Interstellar polarization is caused by non-spherical dust grains aligned by a magnetic field (dichroic extinction; see, e.g., reviews by Lazarian 2003, 2007).

The position angles of polarization yield the directions of magnetic fields on the plane of the sky. Mathewson & Ford (1970) compiled polarization data of nearly 7000 stars and showed the distribution of position angles in Galactic coordinates. The distribution of position angles for stars beyond 1 kpc of the Sun traces the structure of the large-scale Galactic magnetic field which runs almost parallel to the spiral arms, while that for stars within 600 pc traces the structure of the local magnetic field. The structure of the magnetic field is less simple at $l \sim 40°$, $80°$, and $260°$, and away from the Galactic plane such as in the active star-forming regions Taurus, Perseus, Ophiuchus, and Orion, where position angles deviate from the large-scale longitudinal pattern. The local magnetic field points toward $l \sim 80°$ and away from $l \sim 260°$ (Heiles 1976). From the direction of $l \sim 40°$, a loop structure extends toward the north Galactic pole. Toward the loop structure and the star-forming regions, the magnetic field is obviously perturbed from the uniform, large-scale structure. These facts indicate the existence of a random component of the magnetic field on a small scale in addition to a uniform component on a large scale.

The random component of the magnetic field can cause dispersion in the measured position angles and a decrease of the polarization efficiency. Polarization efficiency is defined as the ratio of the polarization degree to extinction such as $p_J/I_J$ and $p_{KS}/I_J$. If magnetic fields are tangled along the line of sight, the degree of polarization $p_J$ does not build up as much as it would in a uniform magnetic field. The extinction (as measured by $I_J$) or $E(λ_1 - λ_2)$ along a line of sight is determined only by the total column of dust, so that the polarization efficiency decreases (depolarization; Martin 1974). Thus, polarization efficiency is a useful measure for probing the random component of the magnetic field.

Serkowski et al. (1975) analyzed a sample of 180 nearby stars that were observed polarimetrically in the U, B, V, and R bands. They investigated the relation between color excess $E(B - V)$ and maximum polarization $p_{max}$ at the wavelength $λ_{max}$ and found an upper limit for the polarization efficiency,

$$p_{max}/E(B - V) \leq 9.0% \text{ mag}^{-1}. \quad (1)$$

The polarization efficiency changes from line of sight to line of sight below the upper limit.

Observations at optical wavelengths are limited to regions with small extinction (typically $A_V < 5$ mag). The behavior of the polarization efficiency at large extinction (up to
$A_V \sim 100$ mag) was studied by Jones (1989) and Jones et al. (1992) using near-infrared (NIR) wavelengths. They compiled $K$-band (2.2 $\mu$m) polarimetric measurements for about 100 sources at various locations and extinctions. The relation between polarization and extinction was modeled by assuming that interstellar polarization depends only on the geometry of the uniform and random components of the magnetic field. The model fits the observed relation between polarization and extinction well when equipartition of the energy density holds between the uniform and random components of the magnetic field.

Studies on the polarization efficiency of the diffuse interstellar medium (ISM) have been carried out using the comprehensive compilation of polarization data by Heiles (2000). Based on the polarization data for about 5500 stars distributed over the entire sky and mostly located at distances of $d \lesssim 4$ kpc, Foshál et al. (2002) found a nearly linear growth of average polarization degree with extinction up to $E(B-V) \sim 1$ mag, but noted that the polarization efficiency is much lower than what is expected from completely aligned grains in a uniform magnetic field. They found a polarization efficiency that was one-third that of the maximum found by Serkowski et al. (1975). They explained this result as depolarization due to the random component of the magnetic field and estimated the magnetic field strength ratio of the uniform to the random component, $B_u/B_r$, to be about 0.8, where $B_u$ and $B_r$ are the strengths of the uniform and random components.

In the innermost region of the Galaxy, only a few polarimetric observations have been conducted (e.g., Kobayashi et al. 1983, 1986; Creese et al. 1995). Kobayashi et al. (1983, 1986) measured polarization for a few dozen highly reddened ($H-K \lesssim 3$ mag) stars in the area at $l \sim 0^\circ$, $20^\circ$, and $30^\circ$ in the Galactic plane, and noted that the polarization efficiency is lower by a factor of about four compared with that in the solar neighborhood. Based on polarization measurements for 127 reddened stars, Creese et al. (1995) reported that greater extinction results in increased polarization, but the increase is smaller than expected. They concluded that the polarization efficiency is lower than that in the solar neighborhood. Their samples are not highly extincted ($H-K \lesssim 0.7$ mag) because they were selected from an $I$-band objective prism survey and were therefore relatively sparse and shallow.

The properties of polarizing dust grains can be examined by the wavelength dependence of interstellar polarization. Polarization $p_\lambda$ shows a convex curve with a peak $p_{\lambda_{\text{max}}}$ typically occurring at around $\lambda_{\text{max}} = 0.55$ $\mu$m, and a wing toward NIR wavelengths. Serkowski et al. (1975) made a determination of the wavelength dependence of polarization, empirically establishing “Serkowski’s law,”

$$p_\lambda / p_{\lambda_{\text{max}}} = \exp[-1.15\ln^2(\lambda_{\text{max}}/\lambda)].$$

The slope of the wing is represented by a power law as

$$p_\lambda \propto \lambda^{-\beta},$$

with $\beta$ of 1.6–2.0 from 1.25 to 2.2 $\mu$m (Nagata 1990; Martin & Whittet 1990; Martin et al. 1992). Creese et al. (1995) suggest no systematic trend in the observed $JHK$ polarization for about 10 reddened stars with respect to a power law. However, more samples should be needed to confirm this suggestion.

Now polarimetric imaging observations using several hundred thousand stars lying in the Galactic bulge as background sources enable us to measure polarization degrees, position angles, and color excess finely across the area and deeply to the line of sight. Therefore, we carried out NIR polarimetric imaging observations for a wide field ($\sim 3^\circ \times 2^\circ$) toward the Galactic center (GC). From the polarization efficiency and dispersions of position angles, we discuss the uniform and random components of the magnetic field along the line of sight on the Galactic scale. Furthermore, we verify whether the wavelength dependence of polarization at NIR is really represented by a power law or not, and examine what types of dust grains cause NIR polarization.

In Section 2, we describe observations and data reduction. In Section 3, we present results for the color excess, polarization, polarization efficiency, and wavelength dependence of polarization in our sample. In Section 4, we discuss the results as they relate to the magnetic field and polarizing grain properties toward the GC.

2. OBSERVATIONS AND DATA REDUCTION

Polarimetric imaging observations toward the GC have been carried out with an NIR polarimetric camera installed on the IRSF (InfraRed Survey Facility) 1.4 m telescope at the South African Astronomical Observatory (SAAO) in Sutherland. The NIR polarimetric camera consists of the single-beam polarimeter SIRPOL (a rotating achromatic (1.0–2.5 $\mu$m) half-wave plate and a wire grid polarizer; Kandori et al. 2006) and NIR camera SIRIUS (Nagashima et al. 1999; Nagayama et al. 2003). The camera is equipped with three 1024 pixel × 1024 pixel HAWAII arrays. This enables simultaneous observations in the $J$ (central wavelength $\lambda_J = 1.25$ $\mu$m), $H$ ($\lambda_H = 1.63$ $\mu$m), and $K_S$ ($\lambda_{K_S} = 2.14$ $\mu$m) bands by splitting the beam into the three wavelengths with two dichroic mirrors. The image scale of the arrays is 0′.45 pixel$^{-1}$, yielding a field of view of 460″ × 460″.

From 2006 to 2009, we have observed 459 fields toward the GC, and the total area covered is about 5.7 deg$^2$ (see Figure 1). The centers of fields were set at intervals of 400″. We obtained 10 dithered frames on the circle with a radius of 20″, yielding an effective field of view of about 420″ and overlaps between adjacent fields with a size of about 220″ × 220″. We performed 10 s exposures at four wave plate angles (0°, 45°, 22.5°, and 67.5°), resulting in a total exposure time of 100 s per wave plate angle for each field. Our observations were carried out under stable sky conditions on photometric nights. The seeing was typically 1′′–1′′.2, and 1′′–1′′ (FWHM) in the $J$, $H$, and $K_S$ bands, respectively. To make median sky frames we observed one of the two sparse stellar fields ($l = -2°933$, $b = 7°100$; $l = 4°525$, $b = 0°200$, respectively).
$b = -12:838$ for each one or two field(s), that is, as frequently as about every 10 or 20 minutes. Twilight flat frames were obtained before and after the observations. Dark frames were obtained at the ends of the nights. The polarimetric standard star R CrA No. 88 (Whittet et al. 1992) was observed 15 times through the observing runs, with 1.6 or 2 s exposures at each wave plate angle at 10 dithered positions.

We applied the standard procedures of NIR array image reduction, including dark-current subtraction, flat-fielding, sky subtraction, and frame combination using the IRAF software package. After subtraction of an averaged dark frame, each frame was divided by a normalized flat frame. Then the thermal emission pattern, the fringe pattern due to OH emission, and the retinal-anomaly slope pattern of the HAWAII arrays were subtracted from each frame with a median sky frame. This subtraction cannot be done adequately in the case where the intensity of OH emission or temperature abruptly changes, so we observed the field again. Finally, we obtained images by combining 10 frames at each wave plate angle, and Stokes $I$ images by combining $10 \times 4 = 40$ frames.

Photometry of point sources was performed using the DAOPHOT package in IRAF. We used the DAOFind task to detect point sources on Stokes $I$ images. Since the observed fields are highly crowded stellar fields, we obtained positions and magnitudes of detected sources on Stokes $I$ images from point-spread function (PSF) fitting photometry using the ALLSTAR task. A model PSF was constructed from bright and isolated sources whose numbers were typically 20–60, 50–90, and 60–90 on each image in the $J$, $H$, and $K_s$ bands, respectively. Positions on celestial coordinate systems were calculated referring to the Two Micron All Sky Survey (2MASS) Point Source Catalog (Skrutskie et al. 2006). The positional accuracy was estimated to be about 0.03. For photometric calibration, we compared magnitudes for the detected sources with those for the 2MASS Point Source Catalog sources in the observed field. In this comparison, magnitude transformations from the 2MASS system to the IRSF system were applied (Y. Nakajima 2007, private communication). The photometric accuracy is about 0.03 mag in all the $JHK_s$ bands.

In order to estimate the effect of confusion on the PSF-fitting photometry in crowded fields, we computed the completeness of the PSF-fitting photometry. We added 900 artificial sources with the brightness corresponding to the limiting magnitudes on each image at each wave plate angle in a reticulated pattern at intervals of $14''$ (30 × 30 sources), and performed source detection and aperture photometry as described above. We calculated the recovery rates of the added artificial sources and standard deviations of median flux of the recovered artificial sources among all wave plate angles in each field. The average recovery rates were 97.5%, 94.4%, and 94.3%, and the standard deviations of the median flux were 0.2%, 0.3%, and 0.2% on average in the $J$, $H$, and $K_s$ bands, respectively.

We merged sources on the Stokes $I$ image from PSF fitting photometry and sources on images at each wave plate angle from aperture photometry. Positions of sources obtained with PSF fitting photometry on Stokes $I$ images were used as the reference positions for merging. We matched sources on the Stokes $I$ image and images at each wave plate angle to the reference positions within a 1 pixel radius. In crowded fields, PSF-fitting photometry yields more precise positions of sources than DAOFind. We mitigated source confusion by using the precise reference positions for matching. Based on flux of sources at each wave plate angle, we calculated Stokes parameters $I$, $Q$, and $U$, and their statistical errors (calculated from noise of signal, sky background, dark current, and readout). The Stokes parameter $I$ was calculated from the flux on images at each wave plate angle, as well as the Stokes parameters $Q$ and $U$, not from the flux from the PSF fitting photometry on Stokes $I$ images, in order to minimize error due to variation of PSF among images at each wave plate angle and Stokes $I$ images. These Stokes parameters also have systematic errors originating from change of atmospheric conditions (seeing and transparency of atmosphere) at each wave plate angle for each field. To estimate these systematic errors we have made a comparison of normalized Stokes parameters $Q/I$ and $U/I$ of the same sources in overlapping regions between adjacent fields with sizes of about $420'' \times 20''$. We defined the same sources as the sources having closest positions within $1''$. Using the sources whose statistical errors of $Q/I$ and $U/I$ were less than 1%, average differences of $Q/I$ and $U/I$ were calculated in each overlapping region. The numbers of the same sources in each overlapping region were typically 10–50, 40–100, and 40–100 in the $I$, $H$, and $K_s$ bands, respectively. The means of the average differences of $Q/I$ and $U/I$ in overlapping regions were 0.33% and 0.35% in the $J$ band, 0.26% and 0.27% in the $H$ band, and 0.25% and 0.26% in the $K_s$ band. We adopted these values for the systematic errors of the normalized Stokes parameters $Q/I$ and $U/I$, and computed the total errors by combining the estimated systematic errors with the statistical errors in quadrature.

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7 IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

8 We related pixel coordinates to celestial coordinates using the OPM software, which is compiled by Dr. N. Matsunaga and based on the Optimistic Pattern Matching algorithm proposed by Tabur (2007).
Then the observed degree of polarization $p_{\text{obs}}$, position angle $\theta$, and their errors $\delta p$ and $\delta \theta$ were derived. $\theta$ is defined as the angle between the $E$-vector of polarization and the direction of the north celestial pole increasing to the east ($-90^\circ \leq \theta < 90^\circ$). To correct noise biasing we calculated degree of polarization $p$ using the following formula:

$$p = \sqrt{p_{\text{obs}}^2 - \delta p^2}$$

(Wardle & Kronberg 1974; Clarke & Stewart 1986). We regarded sources with $p_{\text{obs}} \leq \delta p$ as unpolarized ($p = 0$) sources. All the data were calibrated for the polarization efficiency of the wave plate and polarizer (95.5%, 96.3%, and 98.5% in the $J$, $H$, and $K_s$ bands; see Kandori et al. 2006).

We checked our analysis by comparing our polarimetry of the polarimetric standard star R CrA No. 88 with that by Whittet et al. (1992). The values $p$ and $\theta$ were derived by averaging normalized Stokes parameters $Q/I$ and $U/I$ obtained from 15 observations. Their errors $\delta p$ and $\delta \theta$ were determined from the standard deviations of the means of $Q/I$ and $U/I$. As shown in Table 1, we confirmed that our polarimetry is consistent with that of Whittet et al. (1992) within the errors in all the bands.

For an additional check of our analysis, we made a comparison of $p$ and $\theta$ of the same sources in overlapping regions in a similar way to the comparison of $Q/I$ and $U/I$. Using the same sources with $\delta p \leq 1\%$ and $\delta \theta \leq 10^\circ$, we calculated differences of $p$ and $\theta$. The numbers of the same sources in each overlapping region were typically 10–30, 20–80, and 10–70 in the $J$, $H$, and $K_s$ bands, respectively. Figure 2 shows differences of $p$ and $\theta$ as a function of means of $p$ for the sources. In the entire range of the measured polarization, the absolute differences of $p$ are mostly less than 1%, and those of $\theta$ are mostly less than 10°; the standard deviations of the differences of $p$ are 0.79%, 0.55%, and 0.49%, and those of $\theta$ are 6.9, 5.3, and 6.3 in the $J$, $H$, and $K_s$ bands, respectively.

Source detections at $J$, $H$, and $K_s$ were merged into a single source record using the positions in each band. First the $K_s$ sources were taken as seed detections; then $K_s$–$H$ pairwise matching was done, and this was followed by $K_s$–$J$ pairwise matching. The $H$ sources that were not matched in the previous process were taken as seeds, then $H$–$J$ pairwise matching was done. The match was acceptable if the source separation was less than 1°. We adopted the coordinates for the longest wavelength in the matching as the source coordinates. There are a total of 3,539,087 sources: 1,536,017, 2,979,994, and 3,190,511 sources detected in the $J$, $H$, and $K_s$ bands, respectively. The limiting magnitudes of our survey, defined as the level at which

**Figure 2.** Differences of $p$ (left side) and $\theta$ (right side) as a function of means of $p$ in the $J$ (top), $H$ (middle), and $K_s$ (bottom) bands based on the comparison of the same sources with $\delta p \leq 1\%$ and $\delta \theta \leq 10^\circ$ in overlapping regions.

(A color version of this figure is available in the online journal.)

| Study                  | $p_J$ (%) | $\theta_J$ (°) | $p_H$ (%) | $\theta_H$ (°) | $p_{K_s}$ (%) | $\theta_{K_s}$ (°) |
|------------------------|-----------|----------------|-----------|----------------|---------------|---------------------|
| This study             | 3.83 ± 0.17 | 90 ± 1        | 2.66 ± 0.18 | 91 ± 1        | 1.60 ± 0.21  | 92 ± 3              |
| Whittet et al. (1992)  | 3.87 ± 0.06 | 90 ± 1        | 2.73 ± 0.07 | 92 ± 1        | 1.69 ± 0.08a  | 95 ± 1              |

**Notes.** a Note that the observations by Whittet et al. (1992) were made in a non-standard $K$ passband whose central wavelength is 2.04 μm. The value at 2.14 μm was calculated by the power-law extrapolation of the values measured at 1.64 and 2.04 μm in the same manner as Gerakis et al. (1995).
3. Results

3.1. MK Classifications and Locations

A color–color diagram for the sources is shown in Figure 3. The figure includes 165,858 sources that have $\delta p \leq 1\%$ in all the bands. There are three distinct populations; the majority of the sources fall within a feature extending parallel to the reddening vector from the locus of giants, while two weak concentrations of the sources are seen around $(H - K_S, J - H) \sim (0.1, 0.3)$ mag and $(0.2, 0.7)$ mag along the loci of dwarfs and giants. Based on the model by Wainscoat et al. (1992), we estimate what kind of sources can be detected in all the bands within the limiting magnitudes ($J \lesssim 14.0$ mag, $H \lesssim 13.4$ mag, and $K_S \lesssim 12.5$ mag). The model predicts the numbers of sources expected for each Morgan–Keenan (MK) classification (spectral type and luminosity class) at each distance from the Sun. Toward the GC, we would expect that most of the detectable sources are K/M giants located in the Galactic bulge. They are heavily reddened due to a large amount of intervening dust corresponding to the extended feature in Figure 3. Among the sources located in the Galactic disk ($\lesssim 4$ kpc from the Sun), A/F dwarfs and G/K giants are mainly detected. The two concentrations around the loci of dwarfs and giants predominantly consist of these dwarfs and giants with small extinction.

Out of 234,121 sources with $\delta p_H \leq 1\%$, there are 34,990 sources with $\delta p_H \leq 1\%$, and 558,647 sources with $\delta p_K_S \leq 1\%$. The number of sources $\times 10^2 / (0.05$ mag) is $\sim 1\%$, and 541,990 sources

$$\sigma_{E(H - K_S)} = \sqrt{\sum_C[\langle(H - K_S)_{C0} - \langle(H - K_S)_{C0}\rangle]^2 \times N_C} / \sum_C N_C. \tag{7}$$

where the sum is over the 29 spectral classes in the Wainscoat et al. (1992) model with luminosity classes of III and V (see their Table 2), $N_C$ is the total number of sources of class $C$ predicted by the model, and the intrinsic colors, $(H - K_S)_{C0}$, for each class are taken from Koornneef (1983) and Bessell & Brett (1988). For the uncertainty of $\langle(H - K_S)_{C0}\rangle$, we take the standard deviation of the intrinsic colors of sources from an equation:

The color excess $E(H - K_S)$ for a disk source is not so large compared with its error, and therefore cannot be accurately determined. We adopt only means of $E(H - K_S)$ for the disk sources for further discussions. From the means of $H - K_S$ (0.20 mag, 0.21 mag, and 0.22 mag) and average intrinsic color of the disk sources (0.07 mag, 0.08 mag, and 0.09 mag), the

The former are mostly A/F dwarfs and G/K giants located in the Galactic disk, while the latter are mostly K/M giants located in the Galactic bulge. The numbers of the disk and bulge sources amount to 58,007 and 138,644 with $\delta p_J \leq 1\%$, 54,102 and 457,928 with $\delta p_H \leq 1\%$, and 31,448 and 513,227 with $\delta p_K_S \leq 1\%$. Hereafter we call these sources the disk and bulge sources.

3.2. Color Excess

We calculate color excess for the disk and bulge sources using the equation:

$$E(H - K_S) = (H - K_S) - \langle(H - K_S)_{C0}\rangle. \tag{5}$$

The mean of the intrinsic colors of sources, $\langle(H - K_S)_{C0}\rangle$, is computed as follows. First we compute the numbers of sources expected in each band for each MK classification in the disk and bulge based on the model by Wainscoat et al. (1992) under the following criteria. The criteria for the disk and bulge sources are detection within the limiting magnitudes in each band, that is, detection with $J \lesssim 14.0$ mag, $H \lesssim 13.4$ mag, and $K_S \lesssim 12.5$ mag. An additional criterion for the disk sources is $H - K_S < 0.4$ mag, and that for the bulge sources is $H - K_S \geq 0.4$ mag. We compute $\langle(H - K_S)_{C0}\rangle$ by averaging the intrinsic colors of sources, $(H - K_S)_{C0}$, using the equation:

$$\langle(H - K_S)_{C0}\rangle = \frac{\sum_C \langle(H - K_S)_{C0} \times N_C\rangle}{\sum_C N_C}. \tag{6}$$

Figure 3. $J - H$ vs. $H - K_S$ color–color diagram for the sources that are detected in all the bands and have $\delta p \leq 1\%$ in all the bands. The thin and thick curves are the loci of dwarfs and giants, respectively. The data for O9–B9 dwarfs are from Koornneef (1983), and those for A0–M6 dwarfs and G0–M7 giants are from Bessell & Brett (1988). The arrow indicates a reddening vector whose slope is 1.72 (Nishiyama et al. 2006), and its length corresponds to extinction of $A_{K_S} = 1$ mag. The upper left cross denotes the average errors of colors for the sources. (A color version of this figure is available in the online journal.)
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3.3. Degree of Polarization and Position Angle

We plot a $K_S$-band polarization vector map for the disk and bulge sources in Figure 6. Zooming the online version of the map makes the $E$-vectors of the polarization for sources legible. Most of the sources show $E$-vectors of polarization nearly parallel to the Galactic plane, while some deviations exist. These deviations of $E$-vectors are seen in the regions where relatively few sources with large color excess are detected. Most of the detected sources with large color excess could be in/behind the nearby dense clouds. The deviated $E$-vectors would reflect the local magnetic field directions in nearby dense clouds.

Figure 7 shows the relations between position angles and colors for the disk and bulge sources with $\delta p \leq 1\%$ in each band. There are two distinct populations in blue ($H - K_S < 0.4$ mag) and red ($H - K_S \geq 0.4$ mag) colors, corresponding to the disk and bulge sources, respectively (see Section 3.1 and Figure 3). The disk sources are prominent in the $J$ band, but less prominent in the $H$ and $K_S$ bands. The numbers of the disk and bulge sources amount to 38,425 and 118,045 with $\delta p \leq 1\%$ in each band. Most of the bulge sources have $\delta p \leq 1\%$ in each band, and have tails toward large color excess in all the bands. The numbers of the disk and bulge sources amount to 38,425 and 118,045 with $\delta p \leq 1\%$ in each band.

In a similar manner as $E(H - K_S)$, we present a map of $\theta_{K_S}$ for the bulge sources with $\delta \theta_{K_S} \leq 10\%$ in Figure 8. Most of the cells show values $0^\circ \leq \theta_{K_S} \leq 20^\circ$, which indicate that the magnetic fields between the GC and us are longitudinal on average. These values are close to the average position angle which traces the magnetic field configuration in the GC (16$^\circ$; Nishiyama et al. 2009a), suggesting that the Galactic magnetic field running nearly parallel to the spiral arms would connect to the toroidal magnetic field in the GC (see also Novak et al. 2003; Chuss et al. 2003).

In the relations between polarization degrees and colors for the disk and bulge sources (Figure 9), two distinct populations corresponding to the disk and bulge sources can also be seen. The disk sources have average polarization degrees of 2.1%, 1.2%, and 0.8% in the $J$, $H$, and $K_S$ bands, respectively. Meanwhile, the bulge sources extend redward and show correlations.
between $p$ and $H - K_S$ in all the bands; $p$ increases with increasing $H - K_S$. The slopes of the correlations correspond to the polarization efficiency (Section 3.4), and the difference of the slopes between the bands is due to the wavelength dependence of interstellar polarization (Section 3.5).

In Figure 10, we show a map of the mean $\langle p_{K_s} \rangle$. In a similar way to the spatial variation of $E(H - K_S)$ (Figure 5), that of $p_{K_s}$ is dependent on the Galactic latitude. Most of the cells in which $\langle p_{K_s} \rangle$ exceeds 5% are close to the Galactic plane, while in cells at higher Galactic latitude $\langle p_{K_s} \rangle$ is only 1%–2% or less. However, the spatial variations of $E(H - K_S)$ and $p$ do not completely coincide with each other. This is more obvious in the form of the spatial variation of the polarization efficiency (Section 3.4).

### 3.4. Polarization Efficiency

Starlight suffers both extinction and polarization in the passage through the intervening ISM. Starlight from the disk sources passes through the ISM between the GC and us (i.e., the ISM in the disk and bulge; see Section 3.1). From $p/E(H - K_S)$ for the disk and bulge sources, we examine the polarization efficiency of the ISM in the disk and that between the GC and us.

Combining means of $E(H - K_S)$ and $p$, we calculate the means $\langle p \rangle / \langle E(H - K_S) \rangle$ for the disk sources to be 16.2% mag$^{-1}$, 9.2% mag$^{-1}$, and 6.2% mag$^{-1}$ in the $J$, $H$, and $K_S$ bands, respectively (shown as arrows in the histograms). The average polarization efficiency of the ISM between the GC and us is considerably lower than that of the ISM in the disk, by a factor of about three.

We make a comparison between observed polarization efficiency and estimated upper limits $[p_f/E(H - K_S) = 25.0\% \text{ mag}^{-1}, \quad p_H/E(H - K_S) = 14.5\% \text{ mag}^{-1}, \quad \text{and} \quad p_{K_S}/E(H - K_S) = 9.0\% \text{ mag}^{-1}]$, which are estimated by extending the upper limit $[p_{\text{max}}/E(B - V) = 9.0\% \text{ mag}^{-1}]$ at optical wavelengths (Serkowski et al. 1975) to NIR wavelengths as follows. We convert color excess $E(B - V)$ to $E(H - K_S)$ by assuming that $E(H - K) = 5.14$. As for degree of polarization, first, $p_{\text{max}}$ is converted to $p_K$ (the value at 2.2 $\mu$m) using the average ratio $\langle p_{\text{max}}/p_K \rangle = 5.4$ (Jones 1989; Wilking et al. 1980). Then $p_{K_S}$ is extrapolated from $p_K$ following a power law $p_1 \propto \lambda^{-1.76}$, and $p_H$ and $p_J$ are calculated from $p_{K_S}$ using $p_H/p_J = 0.581$ and $p_{K_S}/p_H = 0.620$ (Section 3.5). The average polarization efficiency of the ISM in the disk is about two-thirds of the upper limits. Moreover, that of the ISM between the GC and us is no more than about a quarter of the estimated upper limits. Kobayashi et al. (1983) also suggested that the polarization efficiency toward the GC is considerably lower than that obtained in the solar neighborhood based on $K$-band polarimetry toward the GC (20$'$ x 20$'$).

The standard deviations of polarization efficiency $\sigma(p/E(H - K_S))$, which are larger than the average errors of $p/E(H - K_S)$, show that the polarization efficiency has spatial variation. As for $E(H - K_S), \theta_{K_S}$, and $p_{K_S}$, we present a map of $p_{K_S}/E(H - K_S)$ for the bulge sources in Figure 12. It shows large variation from

![Figure 6. $K_S$-band polarization vector map for the disk and bulge sources with $\delta p_{K_S} \leq 1\%$ and $\delta \theta_{K_S} \leq 10^\circ$. Each bar is parallel to the $E$-vector of polarization. The length of each bar is proportional to the degree of polarization. The color excess for the bulge sources is also shown as the color of the bars. The disk sources are shown by white bars. Each bar including the bar for 10% scale of the polarization degree at the upper right can be recognized by zooming the figure in the online journal. (A color version of this figure is available in the online journal.)](image)
the line of sight to line of sight in a range of about 1\%-5\% mag$^{-1}$, but does not depend on the Galactic longitude and latitude or on the Galactic structure.

Dispersions of position angles $\sigma(\theta_{KS})$ anticorrelate with $\langle p_{KS}/E(H - K_S) \rangle$. We calculate $\sigma(\theta_{KS})$ for the bulge sources with $\delta p_{KS} \leq 10^\circ$ in each cell and show its map in Figure 13. Some cells show $\sigma(\theta_{KS})$ significantly larger than the average error of $\theta_{KS}$ for the bulge sources (5\%). In a comparison between the spatial variations of $p_{KS}/E(H - K_S)$ and $\sigma(\theta_{KS})$ (Figures 12 and 13), we can see a trend of the larger the $\sigma(\theta_{KS})$, the lower the $\langle p_{KS}/E(H - K_S) \rangle$ and vice versa. This tendency is shown in the relation between $\langle p_{KS}/E(H - K_S) \rangle$ and $\sigma(\theta_{KS})$ (Figure 14).

Figure 7. Position angles $\theta$ vs. $H - K_S$ colors for the disk and bulge sources with $\delta p_J \leq 1\%$ and $\delta \theta_J \leq 10^\circ$ (top), those with $\delta p_H \leq 1\%$ and $\delta \theta_H \leq 10^\circ$ (middle), and those with $\delta p_{KS} \leq 1\%$ and $\delta \theta_{KS} \leq 10^\circ$ (bottom). The means, standard deviations, and average errors of $\theta$ (top) and $H - K_S$ for the sources.

(A color version of this figure is available in the online journal.)

Figure 8. Map of $\theta_{KS}$. Each pixel represents a mean of $\theta_{KS}$ for the bulge sources with $\delta p_{KS} \leq 1\%$ and $\delta \theta_{KS} \leq 10^\circ$ in each cell with a size of $2^\circ \times 2^\circ$. The white pixels include no sources and means cannot be measured.

(A color version of this figure is available in the online journal.)

Figure 9. Degrees of polarization $p$ vs. $H - K_S$ colors for the disk and bulge sources with $\delta p_J \leq 1\%$ (top), those with $\delta p_H \leq 1\%$ (middle), and those with $\delta p_{KS} \leq 1\%$ (bottom). The means, standard deviations, and average errors of $p$ for the disk (left values) and bulge (right values) sources are shown at the upper right of the panels. The upper left crosses in each panel denote the average errors of $\theta$ and $H - K_S$ for the sources.

(A color version of this figure is available in the online journal.)
Figure 10. Map of $p_{KS}$. Each pixel represents a mean of $p_{KS}$ for the bulge sources with $\delta p_{KS} \leq 1\%$ in each cell with size of $2' \times 2'$. (A color version of this figure is available in the online journal.)

Figure 11. Histograms of the polarization efficiency $p/E(H-K_S)$ for the bulge sources with $\delta p_{J} \leq 1\%$ (top), those with $\delta p_{H} \leq 1\%$ (middle), and those with $\delta p_{KS} \leq 1\%$ (bottom). The dashed lines in each panel are $p_{max}/E(B-V) = 9.0\%$ mag$^{-1}$, which correspond to $p_{max}/E(H-K_S) = 9.0\%$ mag$^{-1}$ (Serkowski et al. 1975). The means, standard deviations, and average errors of $p/E(H-K_S)$ for the bulge sources are shown at the upper right of the panels (the means are also represented by arrows). The average errors of $p/E(H-K_S)$ are derived from statistical and systematic errors of $p$ and $E(H-K_S)$. The dash-dotted lines in each panel show the means of $p/E(H-K_S)$ for the disk sources with $\delta p \leq 1\%$ in each band.

Figure 12. Map of $p_{KS}/E(H-K_S)$. Each pixel represents a mean of $p_{KS}/E(H-K_S)$ for the bulge sources with $\delta p_{KS} \leq 1\%$ in each cell with size of $2' \times 2'$. (A color version of this figure is available in the online journal.)

Figure 13. Map of $\sigma(\theta_{KS})$. Each pixel represents a dispersion of $\theta_{KS}$ for the bulge sources with $\delta p_{KS} \leq 1\%$ and $\delta \theta_{KS} \leq 10^\circ$ in each cell with size of $2' \times 2'$. The cells including one or no source(s) are drawn by white pixels. (A color version of this figure is available in the online journal.)

Figure 14. $\langle p_{KS}/E(H-K_S) \rangle$ vs. $\sigma(\theta_{KS})$ for the cells including more than two sources. The crosses and error bars represent medians and standard deviations of $\langle p_{KS}/E(H-K_S) \rangle$ in $2^\circ$ width bins of $\sigma(\theta_{KS})$. (A color version of this figure is available in the online journal.)
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Figure 15. Spatial distribution of the sources that are detected in all the bands and have $\delta p \leq 1\%$ and $p \geq 10\delta p$ in all the bands. The solid lines show the observed area.

Figure 16. $p_J$ vs. $p_H$ (top) and $p_J$ vs. $p_{HK}$ (bottom) for the sources that are detected in all the bands and have $\delta p \leq 1\%$ and $p \geq 10\delta p$ in all the bands. The upper left crosses in each panel denote the average errors of $p$.

(A color version of this figure is available in the online journal.)

The medians of $\langle p_{HK}/E(H - K_S) \rangle$ in each bin of $\sigma(\theta_{KS})$ ($2^\circ$ in width) show the highest value at the bin of $\sigma(\theta_{KS}) = 2^\circ - 4^\circ$, decrease with increasing $\sigma(\theta_{KS})$, and then become almost flat toward bins of larger $\sigma(\theta_{KS})$.

3.5. The Wavelength Dependence of Polarization

Here we examine the wavelength dependence of polarization. Out of the detected sources, we select 3651 sources that have $\delta p \leq 1\%$ and $p \geq 10\delta p$ in all the bands. Hereafter we use these sources in this section. Of these sources, 3647 have $H - K_S \geq 0.4$ mag, and therefore they are bulge sources (Section 3.1). Figure 15 shows the spatial distribution of the sources. The distribution of these bulge sources is a little clumpy in regions where extinction is moderate (not especially small and large) but the sources are seen in a diverse area in $l$, $b$ (see also Figure 5). In Figure 16, the correlations $p_J$ versus $p_H$ and $p_J$ versus $p_{HK}$ are good with linear regressions of $\langle p_{HK}/p_J \rangle = 0.581 \pm 0.004$ and $\langle p_{HK}/p_H \rangle = 0.620 \pm 0.002$ (Table 2). The scatter around the best-fitting lines is 0.076 and 0.047 for $p_{HK}/p_J$ and $p_{HK}/p_H$, respectively. The scatter can be explained by the observational error in $p_J$: the average errors are $\langle \delta(p_{HK}/p_J) \rangle = 0.055$ and $\langle \delta(p_{HK}/p_H) \rangle = 0.063$. Thus, the wavelength dependence of polarization does not change significantly from line of sight to line of sight in our sample.

Assuming a power law ($p_\lambda \propto \lambda^{-\beta}$), and using the equations

$$\beta_{JH} = -\frac{\ln(p_{HK}/p_J)}{\ln(\lambda_{HK}/\lambda_J)},$$

$$\beta_{HK} = -\frac{\ln(p_{HK}/p_H)}{\ln(\lambda_{HK}/\lambda_H)}.$$  

we calculate indices $\beta_{JH}$ and $\beta_{HK}$ for the sources. Histograms of $\beta_{JH}$ and $\beta_{HK}$ are shown in Figure 17. The means $\langle \beta_{JH} \rangle$ and $\langle \beta_{HK} \rangle$ for the sources are $2.08 \pm 0.02$ and $1.76 \pm 0.01$, respectively (Table 2). The errors of the means and the average

| $p_{HK}/p_J$ | $p_{HK}/p_H$ | $\beta_{JH}$ | $\beta_{HK}$ |
|----------|----------|-------------|-------------|
| Mean      | 0.581 ± 0.004 | 0.620 ± 0.002 | 2.08 ± 0.02 | 1.76 ± 0.01 |
| Standard deviation | 0.076 | 0.047 | 0.46 | 0.25 |
| Average error | 0.055 | 0.063 | 0.36 | 0.37 |
errors of $\beta_{\text{HI}}$ and $\beta_{\text{HK}}$ for the sources are derived in a similar manner to $p_{\text{HI}}/p_f$ and $p_{\text{K}_{\alpha}}/p_{\text{HI}}$. Although these values are not inconsistent with the empirical values of 1.6–2.0 (Nagata 1990; Martin & Whittet 1990; Martin et al. 1992). $\langle \beta_{\text{HI}} \rangle$ is larger than $\langle \beta_{\text{HK}} \rangle$. The degree of polarization decreases more slowly than a power law as the wavelength becomes longer from 1.25 to 2.14 $\mu$m; the wavelength dependence of polarization appears to flatten toward longer wavelengths.

### 4. DISCUSSION

#### 4.1. Low Polarization Efficiency and Its Spatial Variation

As for the polarization efficiency of the ISM between the GC and us, we revealed (a) low efficiency compared to that of the ISM in the disk (Figure 11), (b) spatial variation throughout the observed area (Figure 12), and (c) an anticorrelation with the dispersions of position angles (Figure 14). To explain our results, we discuss the polarization efficiency in relation to two factors: (1) the polarizing grain properties and (2) the magnetic field direction.

Polarizing grain properties such as shape, size distribution, and composition could affect the polarization efficiency. However, the wavelength dependence of polarization shows little or no spatial variation in our sample (Section 3.5). This suggests that the polarizing grain properties are almost uniform and that the result of (b) cannot be explained by factor (1), the polarizing grain properties.

Superposition of the ISM with different magnetic field directions along the line of sight could affect the polarization efficiency. The lines of sight toward the disk and bulge sources cross multiple ISM with a range of physical conditions. The interstellar magnetic field consists of uniform and random components (Heiles 1987, 1996). The uniform component corresponds to the large-scale Galactic magnetic field, which runs almost parallel to the spiral arms (Heiles 1996; Han 2009). The magnetic field direction in a given ISM segment (defined as a part of the ISM; in each segment, both the magnetic field direction and the degree of grain alignment are constant) can deviate from the direction of the Galactic magnetic field due to the presence of a random local component. Due to the differences in the magnetic field directions, superposition of the ISM along the line of sight lowers the polarization efficiency (depolarization). Since the ISM between the GC and us generally consists of more ISM with different magnetic field directions, depolarization would be larger and the polarization efficiency should be lower than the ISM in the disk (result of (a)). To explain the observed dispersions of position angles (Figure 13), nonuniform structures of the magnetic field and/or density with a size of less than 2$''$ (cell size) are needed. Gosling et al. (2006, 2009) detected such a nonuniform density distribution with a size of 5''–15''. Larger (smaller) differences of the magnetic field directions would cause lower (higher) polarization efficiency and a larger (smaller) dispersion of position angles (results of (b) and (c)). Of these two factors, only factor (2), the differences in the magnetic field directions along the line of sight, can explain our results.

#### 4.2. The Magnetic Field Strength Ratio of the Random Component to the Uniform Component

We discuss the magnetic field strength ratio of the random component to the uniform component based on the observed relation between extinction and degree of polarization. For the relation, Jones et al. (1992) constructed two models depending on the geometry of magnetic fields along the line of sight. One is the two-component model, and the other is the wave model.

In the two-component model, the magnetic field direction is determined by a combination of the uniform and random components in each optical depth length (segment); in each length $\Delta \tau_{\text{KS}} = 0.1$, the random component of the magnetic field decorrelates. A segment corresponds to a part of the diffuse ISM (with a typical length of a few tens of parsecs) or a dense cloud (a fraction of a parsec). Fitting the model to the data, Jones et al. (1992) concluded that the uniform and random components have equal energy density; this is their case of $\sigma_\text{KS}/B = 0.6$, where $\sigma_\text{KS}$ is the dispersion of the random component and $B$ is the strength of the uniform component. We compare our data with their results in the model (Figure 18(a)). Optical depths $\tau_{\text{KS}}$ are calculated from color excess $E(H - K_S)$ using the relations $A_{K_S}/E(H - K_S) = 1.44$ (Nishiyama et al. 2006) and $\tau_{K_S} = A_{K_S}/2.5 \log 10 e$. Some of the bulge sources are distributed below the boundary with $\sigma_\text{KS}/B = \infty$. Taking errors of $\delta \tau_{K_S}$ into consideration, these measurements can move to the region above the boundary. The bulge sources show relatively lower polarization efficiency than their best-fit result and almost lie between $\sigma_\text{KS}/B = 0.6$ and $\sigma_\text{KS}/B = 1.2$. The polarization efficiency toward the GC measured by Kobayashi et al. (1983)
as shown by the open circles is also lower than their best-fit result. These indicate that the energy density of the random component is higher than that of the uniform component of the magnetic field toward the GC.

In the wave model, a magnetic field is described as a wave. The amplitude of the wave determines the extent to which the magnetic field direction in each segment fluctuates along the line of sight. Jones et al. (1992) fitted the model to the data, also concluding that the energy density of the magnetic field is in equipartition with the kinematic energy density of moving clouds; this is their case of \( V_{\text{rms}}/V_{\Lambda} = 1.0 \), where \( V_{\text{rms}} \) is the rms motion of individual clouds of gas and dust attached to the magnetic field lines and \( V_{\Lambda} \) is the Alfvén speed. The comparison between our data and their results in the model is shown in Figure 18(b). The measurements below the boundary with \( V_{\text{rms}}/V_{\Lambda} = \infty \) can also move to the region above the boundary if we take errors of \( \delta p_{K} \leq 1\% \). Compared to their best-fit result with \( V_{\text{rms}}/V_{\Lambda} = 1.0 \), the bulge sources show relatively lower polarization efficiency, most of which are distributed between \( V_{\text{rms}}/V_{\Lambda} = 1.0 \) and \( V_{\text{rms}}/V_{\Lambda} = 1.5 \). This means that the turbulent energy density is higher than the magnetic energy density in the ISM toward the GC.

The comparison in either case suggests a higher magnetic field strength of the random component compared to that of the uniform component between the GC and us. Such a trend is also observed in the solar neighborhood (Heiles 1996; Fosalba et al. 2002). Gas motions such as turbulence, gravitational contraction of dense clouds, expansion of HII regions, and supernova explosions distort the magnetic field and produce its random component. These processes would be strongly active in the direction of the GC (see, e.g., a review by Morris & Serabyn 1996) and would contribute to the higher magnetic field strength ratio of the random to the uniform component toward the GC. The processes cause relatively large deviations of the magnetic field directions from the direction of the uniform component (the Galactic magnetic field). Low polarization efficiency and its spatial variation would be explained by superposition of the diffuse ISM and dense clouds with such deviations of the magnetic field directions along the line of sight.

### 4.3. Flattening in the Wavelength Dependence of Polarization

In our results, \( \langle \beta_{H} \rangle \) is larger than \( \langle \beta_{HK} \rangle \); the wavelength dependence of polarization shows flattening from 1.25 to 2.14 \( \mu m \). In previous studies (Wilking et al. 1980, 1982; Nagata 1990; Crease et al. 1995), similar flattening is also seen.

The value \( \langle \beta_{H} \rangle (2.08 \pm 0.02) \) is close to the power-law index \( \alpha (1.99 \pm 0.02) \) of the wavelength dependence of extinction toward the GC (Nishiyama et al. 2006). However, \( \langle \beta_{HK} \rangle (1.76 \pm 0.01) \) is clearly below \( \alpha \), and flattening cannot be seen in the wavelength dependence of extinction from the H to K\(_{S}\) band. At longer wavelengths beyond 3 \( \mu m \), both the wavelength dependence of polarization (Nagata 1990; Martin et al. 1992; Nagata et al. 1994) and extinction (Nishiyama et al. 2009b and references therein) show flattening.

The wavelength dependence of polarization is determined by polarizing grain properties such as shape, size distribution, and composition. From a comparison between observational data and theoretical models, the polarizing grain properties can be examined. Kim & Martin (1994, 1995a, 1995b) fitted models of infinite cylindrical and spheroidal dust grains to a modified Serkowski’s law (Whittet et al. 1992) and a single power law \( (\beta = 1.65) \) for \( \lambda = 1.64–5 \mu m \) to examine the size (mass) distribution of dust grains. They obtained the most satisfactory result by adopting perfectly aligned oblate dust grains (axial ratio of 6:1). The resultant mass distribution has a peak at a dust size of about 0.2 \( \mu m \) and a shoulder from the peak through a dust size of 0.6–1.0 \( \mu m \) (see Figure 3(b) of Kim & Martin 1995b). The shoulder is required to fit the infrared polarization with a power-law behavior, which is the excess above the Serkowski’s law. To explain the flattening (i.e., the excess above a power-law behavior), greater numbers of such large-size dust grains would be necessary.

## 5. CONCLUSION

We have made polarimetric imaging observations toward the GC in order to examine the efficiency and wavelength dependence of interstellar polarization at NIR. The results are as follows.

1. The polarization efficiency of the ISM between the GC and us is lower than that of the ISM in the disk, by a factor of about three on average.
2. The spatial variation of the polarization efficiency does not depend on the Galactic structure in contrast with those of color excess and degree of polarization.
3. Position angles are almost parallel to the Galactic plane, suggesting that the magnetic field between the GC and us has a longitudinal configuration and connects to the toroidal magnetic field in the GC.
4. The dispersions of position angles increase with decreasing polarization efficiency. It is likely that the polarization efficiency is reduced by the different directions of magnetic fields along the line of sight (depolarization).
5. The comparison of our data with the models by Jones et al. (1992) suggests that the random component has a higher strength than the uniform component of the magnetic field.
6. The ratios of the degree of polarization are \( p_{H}/p_{J} = 0.581 \pm 0.004 \) and \( p_{K}\)/\( p_{H} = 0.620 \pm 0.002 \), which correspond to \( \beta_{H} = 2.08 \pm 0.02 \) and \( \beta_{HK} = 1.76 \pm 0.01 \) for the power-law indices of the wavelength dependence of polarization. The degree of polarization is higher than that expected from a single power law toward longer wavelengths (flattening from 1.25 to 2.14 \( \mu m \)). The flattening invokes greater numbers of aligned large-size dust grains in the mass distribution derived by Kim & Martin (1995b).

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