The Mid-Infrared Polarization of the Herbig Ae Star WL 16: An Interstellar Origin?

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ABSTRACT
We present high-resolution (0.4′′) mid-infrared (mid-IR) polarimetric images and spectra of WL 16, a Herbig Ae star at a distance of 125 pc. WL 16 is surrounded by a protoplanetary disk of ∼900 AU in diameter, making it one of the most extended Herbig Ae/Be disks as seen in the mid-IR. The star is behind, or embedded in, the ρ Ophiuchus molecular cloud, and obscured by 28 magnitudes of extinction at optical wavelengths by the foreground cloud. Mid-IR polarization of WL 16, mainly arises from aligned elongated dust grains present along the line of sight, suggesting a uniform morphology of polarization vectors with an orientation of 33° (East from North) and a polarization fraction of ∼2.0%. This orientation is consistent with previous polarimetric surveys in the optical and near-IR bands to probe large-scale magnetic fields in the Ophiuchus star formation region, indicating that the observed mid-IR polarization toward WL 16 is produced by the dichroic absorption of magnetically aligned foreground dust grains by a uniform magnetic field. Using polarizations of WL 16 and Elias 29, a nearby polarization standard star, we constrain the polarization efficiency, \( p_{10.3}/A_{10.3} \), for the dust grains in the ρ Ophiuchus molecular cloud to be \( \approx 1.0\% \) mag\(^{-1}\). WL 16 has polycyclic aromatic hydrocarbon (PAH) emission features detected at 8.6, 11.2, 12.0, and 12.7 μm by our spectroscopic data, and we find an anti-correlation between the PAH surface brightness and the PAH ionization fraction between the NW and SW sides of the disk.

Key words: techniques: polarimetric – ISM: dust, extinction – ISM: magnetic fields – stars: formation – stars: individual (WL 16, Elias 29)

1 INTRODUCTION
Magnetic fields (B-fields) play an important role in almost all stages of star formation as discussed in the comprehensive star formation review by McKee & Ostriker (2007). However, there are still many uncertainties about how B-fields regulate the protoplanetary disk formation and evolution. For example, magnetically driven core-collapse models [Shu et al. 1982, Galli & Shu 1993] predict an hourglass-shaped B-field geometry at early stages in the disk evolution, a scenario challenged by recent observations (e.g. Chapman et al. 2013, Davidson et al. 2011, Hull et al. 2013). The only way to address these issues is with high angular resolution observations of the B-field morphologies in a variety of young disks and their environments.

Polarimetry is a potentially incisive observational probe of B-field morphology [Barnes et al. 2012, Crutcher 2012, Matthews et al. 2009, Hull et al. 2014]. Dust grains can polarize light by scattering, dichroic absorption, or dichroic emission, the latter two processes attributed to non-spherical dust grains with their long axes aligned perpendicular to the B-field lines, perhaps as a result of radiative torque [Lazarian 2003, Hoang & Lazarian 2014]. Dichroic absorption by aligned non-spherical dust grains can partially polarization background starlight with the transmitted E-field direction parallel to the aligning B-field lines [Cashman & Clemens 2014]. Light scattering by spherical
and non-spherical dust grains can produce high fractional polarization prominently in the optical and near-IR. At far-IR and sub-mm wavelengths, aligned non-spherical dust grains emit polarized light with the emitted E-field direction being perpendicular to the B-field lines. In the mid-infrared (mid-IR, 8–30 μm), the situation becomes more complicated, since the observed polarization can be a combination of dichroic absorption, emission, and/or scattering \cite{Aitken2002}. Nevertheless, mid-IR polarimetry has some distinct advantages compared to other wavelength regions: the predicted emissive polarization is much larger than that at longer wavelengths \cite{Cho2007}, and we can potentially disentangle both the absorptive and emissive polarization components simultaneously along the line of sight and thereby infer the three-dimensional structure of the B-field \cite{Barnes2014,Smith2000}.

Herbig Ae/Be stars (1.5 < M_\star/M_\odot < 8) are the higher-mass counterparts to pre-main-sequence low-mass T Tauri stars, with which they share some photometric and spectroscopic characteristics \cite{Herbst1964, Hilenbrand1992}. WL 16 was discovered by Wilking & Lada \cite{Wilking1983} and identified as a late-stage Herbig Ae star embedded in the ρ Ophiuchus molecular cloud \cite{Ressler2003} (hereafter RB03). Key physical properties of WL 16 are given in Table 1. No outflow and only weak 1.3 mm emission are observed for this object (RB03). Because of its high extinction (A_V ≈ 25–30 mag), WL 16 is undetectable in the optical but displays extended, resolved emission in the mid-IR. The most plausible interpretation of the extended emission is that it is a disk with a diameter of nearly 900 AU. Kinematic modeling of near-IR CO vibrational overtone emission arising from the innermost region suggests that there is indeed a flat Keplerian gas disk \cite{Carr1993, Najita1996}. Nevertheless, whether the entire structure is an unusually large protoplanetary disk or a smaller disk associated with a remnant of the collapsing envelope is still unclear. The very extended emission is generally ascribed to a remnant of the collapsing envelope is still uncomputed normalized Stokes parameters Q and U, where q = Q/I and u = U/I. The degree of polarization \( p = \sqrt{q^2 + u^2 - \sigma_\theta^2} \), where the last term (the "debias" term) was introduced to remove the positive offset in the signal floor resulting from noise. The polarization PA is computed as \( \theta = 0.5 \arctan(u/q) \). The uncertainties \( \sigma_q \) and \( \sigma_u \) associated with the normalized Stokes parameters were derived using a 3-sigma clipping algorithm \cite{Robinson1987}, and they were then propagated through the analysis to obtain the polarization uncertainty \( \sigma_p \) and polarization PA uncertainty \( \sigma_\theta \). The total intensity (Stokes I) images of WL 16 in the three passbands provide clues to WL 16’s dynamical evolution. Finally, in Section 3 we summarize this work.

### 2 Observations

CanariCam is the mid-IR (8–25 μm) multi-mode facility camera of the 10.4-meter Gran Telescopio Canarias (GTC) on La Palma, Spain \cite{Telesco2003}. It has a field of view of 26′′ × 19′′ with a pixel scale of 0.079, which provides Nyquist sampling at 8.7 μm. In the polarimetry mode, the actual field of view is reduced to 26′′ × 26′′ after a focal mask (to avoid overlapping between o and e beams) is used. We obtained polarimetric images of WL 16 in three filters near 10 μm on 6 August 2013 and a low-resolution (R≈50) polarimetric spectrum of WL 16 from 7.5 to 13 μm on 4 and 5 July 2015 (Table 2), as part of the CanariCam Science Team guaranteed time program (PI: C. M. Telesco) at the GTC. The imaging and spectroscopic observations of WL 16 were interlaced with observations of standard star HD 145897 \cite{Cohen1999} for flux and point-spread-function (PSF) calibration, and the standard star Elias 29, selected from \cite{Smith2000} to calibrate the polarization position angle (PA). The achieved angular resolution (full-width at half maximum intensity) for the polarimetric images was 0′′.4–0′′.6 (Table 2). CanariCam was rotated so that the polarimetry field mask and the detector array’s long axis were aligned along the major axis of the disk at PA=60°. The standard chop-nod technique was applied with a 15″ chop throw in the North-South direction. For spectropolarimetry, we positioned the 1′′.04×2′′.08 slit with the slit’s longer axis oriented at 72° from the North to cover the brightest part of the disk. The chop throw was set at 8′′ in the North-South direction.

The data were reduced using custom IDL software, as described in \cite{Berry2014, Li2014}. We computed normalized Stokes parameters q and u, where \( q = Q/I \) and \( u = U/I \). The degree of polarization \( p = \sqrt{q^2 + u^2 - \sigma_\theta^2} \), where the last term (the "debias" term) was introduced to remove the positive offset in the signal floor resulting from noise. The polarization PA is computed as \( \theta = 0.5 \arctan(u/q) \). The uncertainties \( \sigma_q \) and \( \sigma_u \) associated with the normalized Stokes parameters were derived using a 3-sigma clipping algorithm \cite{Robinson1987}, and they were then propagated through the analysis to obtain the polarization uncertainty \( \sigma_p \) and polarization PA uncertainty \( \sigma_\theta \). The total intensity (Stokes I) images of WL 16 in the three passbands

**Table 1. Basic Properties of WL 16**

| Properties                  | Values | References |
|-----------------------------|--------|------------|
| Distance                    | 125 pc | RB03       |
| Stellar mass                | 4 M_\odot | RB03       |
| Luminosity                  | 250 L_\odot | RB03 |
| Disk inclination            | 62.2 ± 0.4° | RB03 |
| Disk PA                     | 60 ° ± 2° | RB03 |
| Accretion rate              | 10^{-6.8} M_\odot yr^{-1} | Natta et al. (2006) |
| Disk mass                   | <0.001 M_\odot | Andrews & Williams (2007) |
| Disk diameter               | 900 AU | RB03       |

\( ^a \) 0° for face-on  
\( ^b \) Position angle of the major axis of the disk
Figure 1. Total intensity maps of WL 16 at 8.7, 10.3, and 12.5 µm from top to bottom. Contours are surface brightness and logarithmically spaced. Parts of the disk structure are truncated by the CanariCam mask. Some peculiar features of the disk, including a spiral-arm-like structure (green dots) and a dark lane in the SW disk, which may indicate a disk warp, are highlighted.

are presented in Fig. 1. The polarization image at 8.7 µm, where the highest signal-to-noise ratio is achieved, is shown in Fig. 2. Polarizations in the Si2 (8.7 µm) and Si4 (10.3 µm) filters measured with an aperture of 1'' in radius centered on the star are given in Table 3. The Si6 (12.5 µm) data are too noisy to provide meaningful polarization information.

Note that in the polarimetric images, the upper and lower edges of the WL 16 disk are truncated by the focal mask, and the polarization vectors near the edges are unreliable and thus not displayed in Fig. 2. The data presented in Fig. 2 have been smoothed by 5×5 pixel (0.``4×0.``4 (50×50 AU), and only plotted where \( p/\sigma_p \geq 2.0 \) and \( p \leq 6\% \). The lengths of polarization vectors are scaled to the polarization percentage and orientations correspond to the polarization PA. The green vector at the center, which is oriented at 30° from North, is the polarization PA observed in the optical (Goodman et al. 1990) and near-IR (Sato et al. 1988) bands.

Figure 2. The 8.7-µm linear polarization map of WL 16 superimposed on (total intensity) contours. The polarization vectors are plotted at the center of each 5×5 binned pixels, corresponding to 0''4×0''4 (50×50 AU), and are only plotted where \( p/\sigma_p \geq 2.0 \) and \( p \leq 6\% \). The lengths of polarization vectors are scaled to the polarization percentage and orientations correspond to the polarization PA. The green vector at the center, which is oriented at 30° from North, is the polarization PA observed in the optical (Goodman et al. 1990) and near-IR (Sato et al. 1988) bands.

Figure 3. The low-resolution (R≈50) spectrum of the brightest central 1''6 (21 pixels) region of WL 16. The slit (white rectangle) is shown on the inset image of WL 16 at 8.7 µm. The raw data were smoothed with a boxcar of 3 pixels (0.06 µm) in width. PAH emission features are seen at 8.6, 11.2, 12.0, and 12.7 µm. The 8.6 µm feature originates from C-H in-plane bending. The 11.2, 12.0, and 12.7 µm features originate from C-H out-of-plane bending.

3 ORIGIN OF THE POLARIZATION

Our observations (Fig. 1) confirm that WL 16 is well-resolved and extended in the mid-IR, which was previously ascribed to the emission from PAHs and VSGs (RB03). Our spectrum (Stokes I) of WL 16 indeed shows PAH emission features at 8.6, 11.2, 12.0, and 12.7 µm (Fig. 3) that dominate the spectrum. Most pertinent to our primary focus on B-fields in disks is our finding that the 8.7 µm polarization vectors in WL 16 are roughly uniform in both magnitude and orientation across most of the field of view. This uniformity implies that the observed polarization results from grain alignment in a correspondingly uniform B-field.
Table 2. Observing Log

| Imaging | Filters | Δλ (μm) | Date (UT) | Integration Time (s) | Sensitivity (mJy/10σ/1 h) | FWHM (PSF) (") |
|---------|---------|---------|-----------|----------------------|--------------------------|-----------------|
| Si2     | 8.7     | 1.1     | 2013 Aug 6 | 946                  | 8.3                      | 0.50            |
| Si4     | 10.3    | 0.9     | 2013 Aug 6 | 873                  | 10.8                     | 0.60            |
| Si6     | 12.5    | 0.7     | 2013 Aug 6 | 952                  | 20.7                     | 0.40            |

Spectropolarimetry Source(s) Date Integration Time (s)

| Source(s) | Date (UT) | Integration Time (s) |
|-----------|-----------|----------------------|
| WL 16     | 2015 Jul 4&5 | 2648                |
| Elias 29  | 2015 Jul 4&5 | 530                 |

3.1 Extinction toward WL 16

The interstellar extinction toward WL 16 is relatively high, and our first task before characterizing the B-field giving rise to the polarization is to determine the relative roles of the polarization arising in the immediate disk environment and in the general intervening interstellar medium. The 2MASS stellar extinction map implies $A_V = 26.4 \pm 0.6$ mag at the location of WL 16 (Lombardi et al. 2008). It is not trivial to deduce the interstellar extinction for young stars, since they can also exhibit optical and near-IR excess emissions from their accreting disks. To help disentangle the interstellar extinction from the properties intrinsic to WL 16, we consider the two-color diagram as a tool to estimate the foreground interstellar extinction. Meyer et al. (1997) combined the observed near-IR properties of T Tauri stars and accretion disk models, and found that the dereddened colors of T Tauri stars occupy a narrow band, called the locus of classical T Tauri stars (CTTS locus), in the two-color ($JHK$) diagram. While recognizing that the CTTS locus is derived from T Tauri stars, and Herbig stars may have different properties, we nevertheless apply this method to WL 16 and Elias 29, taking their near-IR photometry (Table 4) from Cutri et al. (2003) and plot them on the $JHK$ two-color diagram in Fig.8. We decompose the total reddening into a component of interstellar extinction and a component of intrinsic reddening. We use the following relation to de-
Mid-IR polarimetry of WL 16

3.2 Decomposition of Absorptive and Emissive Polarization

We have shown that the extinction due to the foreground interstellar medium is significant, and therefore it may also account for much of the observed mid-IR polarization. However, the dust inside the disk can potentially emit polarized thermal emission that contributes to the net polarization as we see toward WL 16. To evaluate the contribution from emissive polarization, we adopted the method present in Aitken et al. (2004), which showed that, in the mid-IR, the emissive and absorptive polarization components can be identified, and separated from each other, using spectral polarimetry. Aitken’s method is based on their finding that the emissive and absorptive polarization profiles ($p_{em}(\lambda)$ and $p_{abs}(\lambda)$) are highly correlated across the 10-µm silicate feature, which is expected from the absorptive polarization of astronomical objects.

In practice, the absorptive profile, $p_{abs}(\lambda)$, is taken as that of the Becklin-Neugebauer (BN) object, which contains absorptive polarization alone, and the extinction curve, $\tau(\lambda)$, is derived from the observations of the Trapezium region of Orion. Aitken’s method has been successfully used by a number of studies to separate emissive and absorptive polarization components from the observed total polarization when spectral polarimetry, or imaging polarimetry at multiple wavelengths, is available (e.g., Smith et al. 2000; Barnes et al. 2012).

We apply this method to the polarimetry data of WL 16 and Elias 29, with the results shown in Figs. 4 and 5, respectively. Normalized Stokes parameters $q$ and $u$, polarization fraction $p$, and polarization position angle for WL 16 and Elias 29 are shown in each plot. The position angle $\theta$ for both WL 16 and Elias 29 are almost constant with wavelength from 8.0 to 13.0 µm, indicating that a single mechanism probably produces the polarization (Efstathiou et al. 1997). Should there be multiple components, we would usually expect $\theta$ to change with wavelengths (i.e., unless the absorbing and emitting fields are at 90°). In addition, the value of the polarization $p$ peaks around 10.3 µm, which is expected from the absorptive polarization of astronomical-silicate feature in this spectral region. The decomposition
Polarization Measurements of WL 16

| λ (µm) | Flux Density (Jy) | p (%) | θ (°) |
|--------|------------------|-------|-------|
| 8.7    | 5.32(0.50)       | 0.91(0.12) | 27.09(3.71) |
| 10.3   | 1.68(0.17)       | 2.05(0.48)  | 29.02(6.70) |
| 12.5   | 3.30(0.30)       | ..     | ..     |

Values in parentheses are 1σ uncertainties of measurements. All position angles are calibrated East from North.

Extinction and Polarization of WL 16 & Elias 29

|       | WL 16            | Elias 29          |
|-------|------------------|-------------------|
| Jσ    | 14.364 (0.029)   | 16.788 (0.178)    |
| Hσ    | 10.478 (0.023)   | 11.049 (0.044)    |
| Kσ    | 8.064 (0.016)    | 7.140 (0.021)     |
| A10.3 | 1.97 (0.30) mag  | 3.00 (0.37) mag   |
| p10.3 | 2.00 (0.24)%     | 3.21 (0.07)%      |
| p10.3/A10.3 | 1.02 (0.20) % mag⁻¹ | 1.07 (0.13) % mag⁻¹ |

*(Cutri et al. 2003)*, in units of magnitude

indicating that an absorptive-dominant polarization profile provides an excellent fit for both stars, with negligible emissive components (less than 0.25% for both cases). This result strengthens our conclusion that the mid-IR polarization of WL 16 is primarily due to absorption by interstellar silicate dust. Since absorption by elongated interstellar particles produces polarization parallel to the projected B-field, the direction of projected foreground magnetic field is about 33°±4° (measured from spectral polarimetry and averaged over the entire 10-µm band).

The observed polarizations at 10.3 µm for both WL 16 and Elias 29 are proportional to their respective values of interstellar extinctions as shown in Fig. 4. From this ratio, we derive a value for the polarization efficiency, which is defined as the ratio of polarization percentage to the extinction (Cashman & Clement 2014), (p10.3/A10.3) ≈ 1% mag⁻¹ in Table 4. The parameter can be useful for interpreting the polarization properties of other sources and understanding the dust alignment efficiency, B-field strength, and alignment mechanisms in dense molecular clouds. This value is within the 0–3% range derived in Smith et al. (2000). We note however that the observed polarization corresponds only to the B-field component projected on the sky (integrated along the line of sight), whereas the extinction depends on the total dust column density along the line of sight. Since there is no reason to assume that the projected B-field is the same everywhere, we recognize that the diagnostic power of this value of the ratio (p10.3/A10.3) beyond the immediate environment of WL 16 may be limited.

Intrinsic Polarization

While the observed polarization of WL 16 is mainly from the foreground, and the spectropolarimetry decomposition suggests a very low emissive polarization value (less than 0.25%), can we still place a limit on the intrinsic polarization from the disk? The emissive polarization percentage detected in the case of AB Aur, an archetypal Herbig Ae star (Li et al. 2016), is 0.5%. Assuming the foreground polarization is 2% with a fixed position angle, a 0.5% emissive polarization component could result in, at most, 7° deviation from the assumed foreground polarization orientation. The uncertainties of our measurements (Table 3 and Fig. 4) prevent us extracting from the total observed polarization any intrinsic emissive polarization component if it is less than 0.5%. Reiterating the limitation that we are only sensitive to the projected B-field, we place an upper limit of 0.5% on the intrinsic polarization in WL 16. The intrinsic emissive mid-IR polarization in WL 16 is therefore likely to be much lower than a few percent predicted by Cho & Lazarian (2007). Polarization from protoplanetary disks depends on the dust properties, e.g., dust sizes, oblateness, and composition, and also the entanglement of magnetic fields with dust grains, e.g., dust alignment and the strength of magnetic fields (Hughes et al. 2013). In the case of WL 16, it may result from a combination of these factors.

4 DISCUSSIONS

4.1 PAHs in WL 16

WL 16 is rich in PAH emission features, making it useful for studying PAH properties in the environments of Herbig stars (Geers et al. 2002; DeVito & Hayward 1998). ISO/SWS and Spitzer/IRS spectra of WL 16 show emission features at 6.2, 7.7, 8.6, 11.2, 12.7, 16.4, and 17.0 µm identified with de-excitation via C–C or C–H vibrational transitions of the UV-excited PAHs (Leger & Puget 1984; Draine & Li 2001). The 3.3 µm PAH feature is not detected (Geers et al. 2007). Because a PAH molecule can be excited by a single UV photon, PAHs can trace the disk emission up to large distances from the star. The intensities of the C–C stretching and C–H in-plane bending modes, which fall in the 6–9 µm range, are generally stronger for ionized PAHs than PAH neutrals. We use the total intensity spectrum (Stokes I) from spectropolarimetry observations to derive the ratio of the 8.6 to 11.2 µm surface brightness profiles, I8.6 and I11.2 (bandwidth 0.33 µm), in order to trace the charge state of PAHs along the disk major axis (Joblin et al. 1999). The PAH features are often blended with neighboring PAH features (e.g.,...
the 8.6 µm feature is on the wing of 7.7 µm feature). To correct the blended PAH emission features and subtract the continuum, we adopt the package PAHFIT by [Smith et al. (2007)] to derive the power emitted in each PAH features. There is as much as a 10% brightness difference in the PAH features and continuum emission between the integrated NE and SW side disk flux. Figure 8b shows the derived spatial distribution of PAHs at 8.6 and 11.2 µm in the central 2'' region along the major axis of the disk. Although the spatial behaviors of 8.6 and 11.2 µm are slightly different, the SW disk intensity is much lower than that of the NE disk. Moreover, I_8.6/I_11.2 reaches the maximum (about 2.0) at the central region and decreases farther from the star (Fig. 8c), which means there are more ionized PAHs near the star, with neutral PAHs dominating the external region, as expected (Weingartner & Draine 2001).

Interestingly, we also notice (Fig. 8b) that, while the values of I_8.6/I_11.2 on the two sides of the disk are roughly comparable within 0.3 (38 AU) of the star, they are markedly different between the two sides of the disk beyond about 0.5 (63 AU), with I_8.6/I_11.2 being higher on the SW side than that of the NE side in these outer regions as shown in Fig. 8c. If the disk at this large radius is optical thin in the mid-IR, the asymmetry can be explained by the neutralization of PAHs through electron recombination: PAH cations recombine more effectively with electrons in the NE than they do in the SW (Li & Lunine 2003). However, WL 16, like most young Herbig-star disks (e.g., AB Aur, [Marinas et al. 2002]), probably has an optically thick disk, the mid-IR emission that we see most likely arises in a thin layer near the disk surface (the disk ‘atmosphere’) (Testi et al. 2014). Thus, the interpretation of the anti-correlation is not obvious. Complicated disk structures, such as an asymmetric puffed-up disk inner rim and disk warps, combined with the inclined viewing angle of disk, may provide explanations. To solve the puzzle, multi-wavelengths observations are necessary.

We do not see any polarization features at PAH emission bands (e.g., 8.6 and 11.2 µm) in the case of WL 16 (Fig. 4). Analytical modeling does predict detectable PAH polarization in astrophysical environments (Sironi & Draine 2004). Though the astrophysical conditions they considered may be different from the condition in protoplanetary disks, PAH polarization is too small (0.1–0.5%) to be distinguished from the contribution of linear dichroism by aligned foreground dust.

4.2 Disk Morphology

The total intensity maps (Fig. 1) of WL 16 reveal intriguing asymmetric features in the disk, including: (1) an S-shaped, spiral-arm-like structure extending to both sides of the disk (green dots in Fig. 1); (2) a dark lane immediately outside the spiral-arm-like structure in the SW disk, at 1''3 (163 AU) from the star; (3) twisted surface brightness contours, i.e., position angles of the contours’ major axes are changing from 95° (at smaller radii) to 50° (at larger radii); and (4) an asymmetric brightness distribution, the NE side being significantly brighter than the SW side of the disk. Though especially obvious in the PAH bands, some of these features are also seen in the continuum. In general, they appear to be qualitatively consistent with the scenario of an warped inner disk with respect to the outer disk as the result of precession induced by an unseen planet or stellar companions (Dong et al. 2013). In this scenario, the dark lane in the SW could be a shadow cast by the disk warp. The illumination of a warped inner disk can mimic spiral features (Quillen 2003). Although the twisted contours could be a result of a stellar companion of WL 16, a search for such a companion turned out to be unsuccessful (Barsony et al. 2003). At 40'' away, Elias 29 is the nearest (in projection) star of WL 16, but there is no obvious evidence that these two objects are dynamically related. We expect high-resolution and high-sensitivity radio telescopes, such as ALMA and IRAM, could lead to our new understanding of the dynamic and structure of the object.

5 CONCLUSIONS

We present mid-IR polarimetric imaging and spectral observations of WL 16 obtained with GTC/CanariCam. WL 16 has a well resolved, extended disk (diameter ∼900 AU) in the mid-IR with ∼2% polarization. Our main conclusions are as follows:

(i) Spectropolarimetry of WL 16 firmly supports the hypothesis that the observed mid-IR polarization is dominated by absorptive polarization arising from aligned non-spherical dust grains in the foreground. Polarized emission from dust inside the disk is non-measurable with an upper limit 0.5%. Because, in the most widely accepted dust alignment mechanisms, the absorptive polarization is parallel to the direction of B-field, we interpret the observed polarization map as indicating that the B-field in the molecular cloud is fairly uniform with projected orientation of about 33° from North. The direction is consistent with the near-IR polarization at WL 16 and the large-scale optical b Ophiuchus star forma-
tion region polarimetry. Though our original goal was to probe the B-field inside the protoplanetary disk, our study shows the importance of characterizing the foreground polarization as well.

(ii) The maximum values of the polarization of WL 16 and the nearby-polarized standard Elias 29 are proportional to their interstellar extinction. Using this ratio, we are able to characterize the polarization efficiency of dust grains in the dense molecular cloud, \( p_{10.3}/A_{10.3} \approx 1\% \, \text{mag}^{-1} \). Keeping in mind that the observed polarization is associated with the projected B-field component, the parameter may be useful for constraining the dust alignment efficiency and properties in this region and for interpreting the observed polarization to other sources.

(iii) WL 16 is rich in PAH emission features and we have detected the 8.6, 11.2, 12.0, and 12.7 \( \mu \text{m} \) features in its disk. We see an asymmetry in the ratio \( I_{8.6}/I_{11.2} \) between the two sides of the disk, with the NE (SW) side being brighter (fainter) at both 8.6 and 11.2 \( \mu \text{m} \) but with a lower (higher) value of \( I_{8.6}/I_{11.2} \). This anti-correlation may be explained by complicated disk structures, e.g., warps and asymmetric disk inner rim.

(iv) The total intensity maps of WL 16 reveal asymmetric features, such as the S-shaped spiral-arm-like structure, twisted contours, asymmetric brightness distributions, and a dark lane on the SW side of the disk. These may indicate a disk warp, with future observations, especially with ALMA and IRAM, likely to fully clarify this picture.

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