Magnetically Regulated Disk Formation in the Inner 100 au Region of the Class 0 Young Stellar Object OMC-3/MMS 6 Resolved by JVLA and ALMA

Hauyu Baobab Liu
Institute of Astronomy and Astrophysics, Academia Sinica, 11F of Astronomy-Mathematics Building, AS/NTU No.1, Sec. 4, Roosevelt Rd, Taipei 10617, Taiwan, ROC; hyliu@asiaa.sinica.edu.tw

Received 2020 August 9; revised 2021 April 13; accepted 2021 April 14; published 2021 June 10

Abstract

We have carried out polarization calibration for archival Jansky Very Large Array (JVLA) (∼9 mm) full polarization observations toward the Class 0 young stellar object (YSO) OMC-3/MMS 6 (also known as HOPS-87), and then compared the results with the archival Atacama Large Millimeter Array (ALMA) 1.2 mm observations. The resolved spectral indices show that the innermost ∼100 au region of OMC-3/MMS 6 is marginally optically thin (e.g., τ ≲ 1) at ∼9 mm wavelength, such that the JVLA observations can directly probe the linearly polarized emission from nonspherical dust. Assuming that the projected long axis of dust grains is aligned perpendicular to magnetic field (B-field) lines, we propose that the overall B-field topology resembles an hourglass shape. The geometry of this system is consistent with a magnetically regulated dense (pseudo)disk, although this “hourglass” appears to be ∼40° inclined with respect to the previously reported outflow axis. In contrast, the inner ∼100 au region of this YSO is likely very optically thick (e.g., τ ≳ 1) at ∼1 mm wavelength. The electric field position angles resolved by JVLA and ALMA present ∼90° offsets on this region, which indicate that the dominant polarization mechanism at 1 mm wavelength is dichroic extinction. This is the second case where the (sub)millimeter dichroic extinction is demonstrated by the direct comparison between the JVLA and ALMA polarization observations.

Unified Astronomy Thesaurus concepts: Young stellar objects (1834); Interstellar magnetic fields (845); Polarimetry (1278); Circumstellar grains (239)

1. Introduction

Observing linear polarization of dust emission at (sub) millimeter bands has been an essential method for resolving magnetic field (B-field) topology in the interstellar medium from parsec scales down to ∼1000 au scales (for a review see Hildebrand et al. 2000). This approach has important applications in the studies of magnetic support against the self-gravitational collapse/fragmentation of molecular clouds and the redistribution of angular momentum around circumstellar disks due to magnetic torque. Typically, the observed (sub) millimeter linear polarization has been attributed to the optically thin emission of nonspherical dust grains. In addition, it is typically assumed that the projected long axes of dust grains are aligned perpendicular to B-field lines. In such cases, the 90° rotated electric field (E-field) polarization position angle (PA) corresponds to the projected B-field orientation. Based on this approach, the recent interferometric surveys at 0.85–1.3 mm wavelengths have suggested that the B field in low- or high-mass star-forming cores or envelopes may align either perpendicularly or parallel to outflow axes (e.g., Hull et al. 2014; Zhang et al. 2014; Cox et al. 2018; Galametz et al. 2018).

The originally weakly polarized or unpolarized dust emission can become linearly polarized when penetrating through a cool medium with aligned dust grains. This phenomenon, which is called dichroic extinction, is due to the more efficient dust absorption for the E field that is parallel to the long axis of the dust. In this case, the observed E-field PA corresponds to the projected B-field orientation in the absorbing medium. Dichroic extinction has been considered as an alternative polarization mechanism in the interpretation of the observations taken at infrared or shorter wavelengths (e.g., Reissl et al. 2017). It is less often considered in the interpretation of the observations taken at wavelengths longward of 1 mm (see Liu et al. 2018), since it is commonly assumed that the dust emission in circumstellar cores/envelopes is optically thin at such wavelengths. However, the spectral energy distribution analyses of Li et al. (2017) toward a sample of Class 0 young stellar objects (YSOs) have indicated that the dust optical depth in fact can be higher than 10 at 1 mm wavelength (see also Galván-Madrid et al. 2018).

For the specific Class 0 YSO, NGC 1333 IRS4A1, the hypothesized high optical depth has been unambiguously verified by the spectral line observations at 1–10 mm bands (Sahu et al. 2019; Su et al. 2019; De Simone et al. 2020). Shortward of the ∼1 mm wavelength, dust emission is essentially depolarized in this source owing to the high optical depths. The dust self-scattering (e.g., Kataoka et al. 2015) is unlikely to be an efficient polarization mechanism because it is hard to produce highly anisotropic radiation fields in environments with very high optical depths. Therefore, dichroic extinction, to our knowledge, is the only probable efficient linear polarization mechanism in this source at ∼1 mm wavelength. In this case, when comparing the polarization PA measured at ∼1 mm wavelengths with those measured at optically thinner, longer wavelength bands, one expects to see an exact 90° relative offset. This has been verified for the first time by the presently lone observational case study of Ko et al. (2020).

In this paper, we report on the case study toward an optically much thinner Class 0 YSO, OMC-3/MMS 6, which is located at a distance of ∼388 pc (Kounkel et al. 2017; also see Takahashi & Ho 2012 and Takahashi et al. 2019). By comparing the archival NRAO Karl G. Jansky Very Large Array (JVLA) ∼9 mm observations with the Atacama Large
Millimeter Array (ALMA) ~1 mm observations, we aim to test whether or not we can resolve the 90° relative PA offset expected from dichroic extinction. If true, then this source would be the second case that is verified with linear polarization due to dichroic extinction at ~1 mm wavelength. Such a result will infer that this polarization mechanism is not just limited to cases with exceptionally high optical depth, but could instead be rather common. Our data reduction is outlined in Section 2. The results are shown in Section 3. We will focus just limited to cases with exceptionally high optical depth, but would be the second case that is verifi-

whether or not we can resolve the 90° (ALMA images to a 0° resolution) observations with the JVLA observations, given that they have delivered from quality assurance 2.

fi

October. We directly utilize the of k measurements taken from the observations of project 2015.1.00341.S. They have been published in Takahashi et al. (2019). Our conclusion is given in Section 5.

2. Data Reduction

2.1. Archival ALMA Data

We retrieved the archival, full polarization ALMA observations taken from project 2015.1.00341.S. These have been published in Takahashi et al. (2019). There were $\theta_{\text{maj}} \times \theta_{\text{min}} = 0^\circ 14 \times 0^\circ 12$ ($54 \times 47$ au; PA = $-50^\circ$) observations (projected baseline ranges of 16–3200 $\lambda$; hereafter the low-resolution ALMA image) taken in 2016 October, and $\theta_{\text{maj}} \times \theta_{\text{min}} = 0^\circ 22 \times 0^\circ 20$ ($8.5 \times 7.8$ au; PA = $-82^\circ$) observations (projected baseline ranges of 76–14700 $\lambda$; hereafter the high-resolution ALMA image) taken in 2015 October. We directly utilize the official image products delivered from quality assurance 2.

In this paper, we only compare the low-resolution ALMA observations with the JVLA observations, given that they have similar angular resolutions. We smoothed the low-resolution ALMA images to a 0"15 ($\sim$58 au) circular synthesized beam before making the comparison with the JVLA observations (Section 2.2). We reinterpreted the polarization line segments qualitatively resolved from the high-resolution observations, although we caution that the interpretation based on the observations of only one single frequency band would need to be tested by observations at other frequencies (more in Section 4).

2.2. JVLA Ka Band Data

We have retrieved the archival, full polarization JVLA observations toward OMC-3/MMS 6, which were taken at the Ka band in the C and A array configurations (project code: 16A-197). The Stokes I images of these JVLA observations have been published in Tobin et al. (2020). All these observations utilized the 3 bit sampler and configured the backend to provide an 8 GHz bandwidth coverage by 64 spectral windows which covered the frequency ranges of 27.0–30.9 GHz (IF1) and 34.9–38.8 GHz (IF2). The pointing center for the observations on OMC-3/ MMS 6 (HOPS-87) was R.A. = $05^h 35^m 22.891^s$ (J2000), decl. = $-05^\circ 01^\prime 24^\prime 21^\prime$ (J2000), which was offset from OMC-3/MMS 6 to simultaneously cover another source, HOPS-88. The C configuration track we retrieved also pointed on R.A. = $05^h 35^m 18.915^s$ (J2000), decl. = $-05^\circ 00^\prime 50^\prime 87^\prime$ (J2000) and R.A. = $05^h 35^m 21.400^s$ (J2000), decl. = $-05^\circ 13^\prime 17^\prime 50^\prime$ (J2000) to observe the other two YSOs, HOPS-91 and HOPS-409. Further information for these observations has been summarized in Table 1.

We manually followed the standard data calibration strategy using the Common Astronomy Software Applications (CASA; McMullin et al. 2007) package release v5.6.2–3. We adopted the Perley–Butler 2017 flux standards (Perley & Butler 2017). After implementing antenna position corrections, weather information, a gain–elevation curve, and opacity model, we bootstrapped delay fitting and passband calibrations, and then performed the complex gain calibration. We performed gain-phase self-calibration for the C array configuration observations on OMC-3/MMS 6, HOPS-91, and HOPS-409 by combining all available spectral windows and using the solution intervals of 30, 180, and 90 s, respectively. We performed gain-phase self-calibration for the A array configuration observations by combining all available spectral windows and using a 600 s solution interval due to the limited signal-to-noise (S/N) ratios.

These data have been known to be impacted by a delay bug of the JVLA.1 The CASA version we used has been patched to suppress the related delay errors. The residual delay errors at the mean observing frequency have further been removed during our gain-phase self-calibration. Since we combined spectral windows during the gain-phase self-calibration, there might be small, frequency-dependent residual delay errors that we cannot remove. Nevertheless, we do not expect these errors to be significant for our present science purpose.

For the C and A array configuration data, we calibrated the cross-hand delay and absolute polarization PA based on the observations of 3C147 and 3C48. When deriving these solutions, we limited the projected $uv$ distance ranges of 3C48 to 0–500 $\lambda$ since it was seriously spatially resolved at longer baselines. We calibrated the polarization leakage based on the observations on 3C84. The imaging processes and the achieved image quality are outlined in the following subsections.

2.2.1. Full Stokes Imaging

We produced images using the CASA tclean task. To confirm that using 3C48 and 3C147 as cross-hand delay and polarization PA calibrators do yield consistent results, we first performed full Stokes (I, Q, U, and V) mtmfs clean (Rau & Cornwell 2011) imaging (adopting nterm = 2 and with Briggs Robust = 2 weighting) for the C and A array configuration data separately, jointly with the two IFs. We only used point-like clean components because the convergence behavior of the multiscale clean is nonlinear and is sensitive to how the weighting terms are set. The achieved synthesized beams and the rms noise are summarized in Table 1. The observed peak Stokes I intensities at OMC-3/MMS 6, HOPS-91, and HOPS-409 in the C array configuration observations are 2.5, 0.59, and 1.3 mJy beam$^{-1}$, respectively.

For all of the covered target sources, we did not detect Stokes V at $>3\sigma$ from both the C and the A array configuration observations. We did not detect Stokes Q and U at $>3\sigma$ from HOPS-91 and HOPS-409 and will omit further discussion on them given that their Stokes I properties have been very well documented by Tobin et al. (2020). We provide the Stokes I, Q, U images and the polarization intensity (PI) images of OMC-3/ MMS 6 in Figure 1.

For OMC-3/MMS 6, we detected Stokes Q ($\sim 2\sigma$) and U ($\sim 7\sigma$) from the C array configuration observation. Given that

---

1. https://science.nrao.edu/facilities/vla/data-processing/vla-atmospheric-delay-problem
the achieved S/N in OMC-3/MMS 6 is high, the nondetection of Stokes Q and U from HOPS-409 is sufficient to rule out the hypothesis that the polarized intensities detected around OMC-3/MMS 6 were spurious. We detected Stokes U (∼4σ) from the A array configuration observations after tapering the data with a 0″2 two-dimensional (2D) Gaussian function (θmaj × θmin = 0″27 × 0″22, PA = 25°; rms noise ∼14 μJy beam−1). In spite of the very different S/N ratios and angular resolutions, the observed Stokes U from these two array configurations appear qualitatively consistent: the detected Stokes U intensities are positive and the Stokes U peak positions are southeast of the Stokes I peak positions. After confirming this, we proceeded to jointly image the C and A array configuration data to yield a better sensitivity.

The final C + A array configuration image achieved a θmaj × θmin = 0″14 × 0″087 (54 × 34 au, PA = 6°6) synthesized beam and an rms noise of 7.5 μJy beam−1 (Figure 1). We produced the PI, PA, and percentage (P) maps based on the Stokes I, Q, and U images. To avoid bias and spurious detections (see Vaillancourt 2006), we only utilized the pixels where the Stokes I intensities were above 5σ significance (approximately within a 2D sphere of ∼0″7 diameter, i.e., ∼70 synthesized Gaussian beam areas in terms of standard deviation), and where absolute values of the Stokes Q or U intensities were above 3σ significance. Assuming Gaussian random noise, the expected numbers of independent Stokes Q and U spurious detections are 0.2. To suppress the positive bias of the PI, we evaluated PI as √Q2 + U2 − σ2 where σ is the rms noise. We smoothed the final A + C array configuration images to a 0″15 circular synthesized beam before making a quantitative comparison with the ALMA observations (more in Section 2.1). We performed primary beam corrections to the Stokes I, Q, U, and PI images at the end of these processes.

### 2.2.2. Stokes I Imaging

The procedure introduced in Section 2.2.1 was to maximize sensitivity. In this section, we introduce the optimized imaging strategy for Stokes I intensity to robustly measure spectral indices (α) between the IF1 and IF2 of the JVLA data and between the IF2 of the JVLA data and the low-resolution ALMA data (Section 2.1). All images introduced in this section were produced using the CASA tclean task with the mtmfs parameter nterm = 2. We adopted a limited uv distance range of 16–3200 kλ, which is the same with the uv distance range of the low-resolution ALMA data.

#### Comparing IF1 and IF2

We performed the mtmfs clean imaging for the IF1 and IF2 data separately. The JVLA observations resolved spatial variations of the spectral indices. To suppress the effect of synthesized beam smearing yet achieve sufficient S/N to constrain α, we adopted Briggs Robust = 0 weighting for both IFs.

We achieved a θmaj × θmin = 0″11 × 0″067 (44 × 26 au; PA = 12°) synthesized beam and a 13 μJy beam−1 rms noise at IF1 (mean frequency νIF1: 29.45 GHz), and achieved a θmaj × θmin = 0″088 × 0″056 (34 × 22 au; PA = 13°) synthesized beam and a 15 μJy beam−1 rms noise at IF2 (mean frequency νIF2: 36.65 GHz).

We smoothed the IF2 image to the synthesized beam of the IF1 image and then produced the spatially resolved spectral index2 αIF1-IF2 distribution map. Given that the IF1 and IF2 data were taken simultaneously, the derived αIF1-IF2 distribution was not systematically biased by the absolute flux calibration errors (i.e., the uncertainties were dominated by thermal noise). We will introduce the results of αIF1-IF2 in Section 3.2.

#### Comparing JVLA IF2 with ALMA

The JVLA observations are more limited by brightness temperature sensitivity than the ALMA observations. To compare them, we imaged the IF2 data using Briggs Robust = 2 weighting, which yielded a θmaj × θmin = 0″13 × 0″082 (50 × 32 au; PA = 6°8) synthesized beam and a 14 μJy beam−1 rms noise level. The peak intensity and the flux density (estimated by summing over the region above the 3σ contour) are 1.7 mJy beam−1 (145 K) and 3.9 ± 0.058 mJy, respectively. The recovered flux density is reasonably consistent with that of the Briggs Robust = 0 weighted image (Section 3.2). We smoothed this JVLA IF2 image to a 0″15 (58 au) circular synthesized beam and then produced the spatially resolved αIF1-ALMA2 distribution map by comparing with the low-resolution ALMA data introduced in Section 2.1. Assuming the nominal ∼10% absolute flux calibration errors for both the ALMA and the JVLA observations, the derived αIF1-ALMA2 can only be biased by up to ∼±0.1 thanks to the large-frequency leverage arm.

\[ \alpha_{IF1-IF2} = (\log F_{IF1} - \log F_{IF2}) / (\log F_{IF1} - \log F_{IF2}) \]
Figure 1. Stokes I, PI, Stokes Q, and U images (color maps) produced from the ALMA (top row; \( \theta_{\text{maj}} \times \theta_{\text{min}} = 0\arcsec 14 \times 0\arcsec 12, \) PA = -50\(^\circ\); rms noise = 32 \( \mu \text{Jy beam}^{-1} \)), JVLA A + C array (second row; \( \theta_{\text{maj}} \times \theta_{\text{min}} = 0\arcsec 14 \times 0\arcsec 087, \) PA = 6.6\(^\circ\); rms noise = 7.5 \( \mu \text{Jy beam}^{-1} \)), JVLA A array (third row, tapered; \( \theta_{\text{maj}} \times \theta_{\text{min}} = 0\arcsec 27 \times 0\arcsec 22, \) PA = 25\(^\circ\); rms noise = 14 \( \mu \text{Jy beam}^{-1} \)), and JVLA C array configuration observations (bottom row; \( \theta_{\text{maj}} \times \theta_{\text{min}} = 1\arcsec 3 \times 0\arcsec 59, \) PA = 42\(^\circ\); rms noise = 14 \( \mu \text{Jy beam}^{-1} \)). The plotting areas of the top three rows are the same as in Figure 2. The JVLA Stokes I images presented in the first column are also overplotted in the second column in green contours (\([1, 2, 4, 8, \ldots] \times 5\sigma \)). Gray dashed contours in the second column show the JVLA PI images, starting from the 3\( \sigma \) level and with 1\( \sigma \) intervals. Red and blue dashed contours in the third and fourth columns show the positive and negative Stokes Q and U intensities, starting from the \( \pm 3\sigma \) level and with 1\( \sigma \) intervals. In all panels we overplot the ALMA Stokes I image in black or white solid contours (375\( \sigma \), 750\( \sigma \), 1500\( \sigma \), 3000\( \sigma \)), for referencing positions. The synthesized beams are shown in the bottom left. The details of these observations are provided in Section 2.
3. Results

3.1. Stokes I and Polarization Properties

Figure 1 shows the Stokes I, Q, and U images, and the PI images, of OMC-3/MMS 6 that were produced from the data introduced in Section 2. There were similarities and differences between the ALMA image and the JVLA A + C configuration images. For example, they resolved positive Stokes Q intensities east of the Stokes I peak and positive Stokes U intensities southeast of the Stokes I peak. The major difference is that the ALMA observations resolved very significant negative Stokes U intensities around the Stokes I peak while this is not seen in the JVLA A + C configuration image.

Figure 2 shows the JVLA (33 GHz) and the ALMA (265 GHz) low-resolution polarization images introduced in Sections 2.1 and 2.2.1, which have been smoothed to a 0″15 angular resolution. The Stokes I, Q, U, PI, PA, and polarization percentages measured by JVLA at the centroids of the presented line segments are summarized in Table 2. From Figure 2 we see that outward of the ∼50 au projected radius around the 33 GHz Stokes I peak, the E-field PAs observed at 33 GHz and 265 GHz are consistent with each other; inward of the ∼50 au projected radius they present an ∼90° relative offset. Such a discrepancy is also reproduced in the comparison between the JVLA image and the high-resolution ALMA image (Figure 3). The E-field PA resolved by the high-resolution ALMA image presents bimodality: the PA observed inward and outward of ∼50 au projected radius show a general, ∼90° relative offset with respect to each other.

The 33 GHz PI distribution presents a single peak southeast of the Stokes I peak (Figure 2). The 265 GHz PI distribution resolved by the low- and high-resolution ALMA images (Figures 2 and 3) presents three significant peaks. The central peak which locates close to the 33 GHz Stokes I peak is the strongest. The other two peaks are southeast and northwest of the central peak; their projected separations from the central peak are comparable.

Intriguingly, the 265 GHz Stokes I intensity distribution resolved by the high-resolution ALMA image appears lopsided with respect to the 33 GHz Stokes I peak (Figure 3). The overall morphology of the 265 GHz Stokes I intensity distribution resolved by the high-resolution ALMA image may resemble what was resolved by the previous high-angular-resolution ALMA ∼350 GHz observations toward the Class 0 YSO, HH212 (Lee et al. 2017): ∼50 au southeast of the 33 GHz Stokes I peak there is a 265 GHz dark lane that aligns in the northeast–southwest direction; this dark lane is sandwiched by brighter 265 GHz emission features.

3.2. Spectral Indices

The observed peak intensities in the JVLA IF1 and IF2 images are 0.70 and 1.2 mJy beam⁻¹, which correspond to the peak brightness temperatures (T_b) of 130 K and 220 K, respectively. The flux densities (F_ν; IF1: 1.6 ± 0.049 mJy, IF2: 3.8 ± 0.056 mJy) at both IFs were measured by summing over the region above the 3σ contour of the IF1 image. Based on these measured flux densities, we obtained a mean spectral index α_{IF1-IF2} of 3.95 ± 0.20. We have imaged the C and A array configuration data separately and obtained consistent measurements of α_{IF1-IF2}. Given that the C and A array configuration observations were based on different absolute flux calibrators (Table 1), this consistency means that the
chance that the $\alpha_{\text{IF1-IF2}}$ value is seriously biased by passband calibration errors is small.

Figure 4 shows the spectral index distributions measured between the ALMA and the JVLA observing frequencies ($\alpha_{\text{ALMA}}$), and the intraband spectral indices ($\alpha_{\text{IF1-IF2}}$) measured by the JVLA observations (see Section 2.2.2) for the inner ~100 au region. To give a qualitative sense about the resolved spectral indices, we note that assuming a constant temperature in a line of sight and Rayleigh–Jeans limit, when the dust opacity spectral index $\beta$ is close to the interstellar value 1.75, given an optical depth $\tau_{\nu} = 1.0$ (i.e., marginally optically thick/thin), the expected spectral index $\alpha$ at the frequency $\nu$ is 3.0. The value of $\alpha$ becomes smaller than 3.0 when $\tau_{\nu} > 1.0$. Under the same assumptions, the value of $\alpha$ is smaller when $\beta$ is smaller.

From outer to inner radii, the resolved $\alpha_{\text{IF2-ALMA}}$ gradually decreases from ~3.0 to ~2.0. The barely resolved $\alpha_{\text{IF1-IF2}}$ is consistent with $3.75 \pm 0.35$, where the uncertainty at the presented area is ~0.3 (estimated assuming Gaussian noise and standard error propagation). Given that the area presented with $\alpha_{\text{IF1-IF2}}$ is very small, the observed gradient of $\alpha_{\text{IF1-IF2}}$ may not be explained merely by noise. It is likely that we have resolved a small spatial variation of $\alpha_{\text{IF1-IF2}}$, although the absolute values of $\alpha_{\text{IF1-IF2}}$ can be biased by noise. In general, the barely resolved $\alpha_{\text{IF1-IF2}}$ is consistent with (marginally) optically thin dust emission at 33 GHz. The resolved $\alpha_{\text{IF2-ALMA}}$ indicates that the 265 GHz emission is very optically thick inward of the ~50 au projected radius.

### 4. Discussion

Observations tend to show that the $B$ field is rather ordered instead of being random in star-forming regions. This implies that the role of $B$-field pressure is at least comparable with turbulent energy. In addition, it is also commonly considered that turbulent energy and gravitational potential energy are close to equipartition. These have led to the so-called standard
Figure 3. Images showing the inner ~100 au (radius) region of OMC-3/MMS 6. Left: Stokes I intensity image taken from the high-resolution ALMA observations (color). Right: PI taken from the high-resolution ALMA observations (color). Green contours and red line segments are the same as those presented in Figure 2. Blue line segments show the E-field line segments measured from the high-resolution ALMA observations. The synthesized beam of the JVLA image and the high-resolution ALMA image are presented in the bottom left. The gray ellipse in all panels shows the $0''15$ circular synthesized beam; the black ellipse shows the synthesized beam of the high-resolution ALMA image.

Figure 4. Spectral indices in the inner ~100 au (radius) region of OMC-3/MMS 6. Left: the spectral index map generated by comparing the low-resolution ALMA image and the JVLA IF2 image (i.e., $\alpha_{\text{IF2-ALMA}}$, see Section 2.2.2), where the spectral indices are presented for the region in which the spectral index uncertainties (assuming Gaussian noise and standard error propagation) are lower than 0.1. The detected lowest and highest spectral indices in this map are 2.1 and 3.0, respectively. Right: the spectral index map generated by comparing the JVLA IF1 and IF2 images (i.e., $\alpha_{\text{IF1-IF2}}$, see Section 2.2.2), where the spectral indices are presented for the region in which the spectral index uncertainties are lower than 0.3 (as a compromise due to the limited S/N). The detected lowest and highest spectral indices in this map are 3.4 and 4.1, respectively. Green contours and red line segments are the same as those presented in Figure 2. Blue line segments show the E-field line segments measured from the high-resolution ALMA observations. The synthesized beam of the JVLA image and the high-resolution ALMA image are presented in the bottom left. The gray ellipse in all panels shows the $0''15$ circular synthesized beam; the black ellipse shows the synthesized beam of the high-resolution ALMA image. The blue ellipse in the bottom right panel shows the synthesized beam of the spectral index map presented in that panel.
model for low-mass star formation, which describes the self-similar collapse of a circumstellar core/envelope, regulated by a well-ordered and modestly strong $B$-field (for a review see Shu et al. 1987). The expectations from this scenario are: (1) that self-gravitational collapse is more rapid along the $B$-field lines, leading to the formation of a flattened (pseudo)disk, and (2) a $B$-field on $\gtrsim 100$ au scales may resemble an hourglass shape because of the drag of collapsing motion in the horizontal direction.

Our interpretation for the OMC-3/MMS 6 observations is motivated by this scenario. Specifically, we hypothesize that there is a dense (pseudo)disk that is embedded in the parent gas envelope. Both the (pseudo)disk and the envelope are pinched by the rather uniform $B$ field; the innermost part of the (pseudo)disk may be similar to what was resolved from HH212 (Lee et al. 2017) although OMC-3/MMS 6 appears to be not as edge-on. At 265 GHz, which is optically thick, the far side of the (pseudo)disk appears as a bright semicircle while the nearside is self-obscured and thus appears fainter.

We suggest that throughout the observed area, the 90° rotated 33 GHz PA traces the projected $B$-field orientation. Around the projected area of the disk, in particular at the self-obscured dark lane (Figure 3), the 265 GHz polarization is mainly due to dichroic extinction. Therefore, the 265 GHz PA directly traces the projected $B$-field PA in this region. On the contrary, at the spatially more extended, low-brightness regions, the 265 GHz polarization is due to polarized dust emission and therefore the projected $B$-field PA is traced by the 90° rotated 265 GHz PA.

At the far side of the disk, the 265 GHz PA is low simply due to the very high optical depth. Around the projected area of the 265 GHz dark lane, there is a transition of the 265 GHz to the very high optical depth. Around the projected area of the disk, in particular at the self-obscured dark lane (Figure 3), the 265 GHz polarization is mainly due to dichroic extinction. Therefore, the 265 GHz PA directly traces the projected $B$-field PA in this region. On the contrary, at the spatially more extended, low-brightness regions, the 265 GHz polarization is due to polarized dust emission and therefore the projected $B$-field PA is traced by the 90° rotated 265 GHz PA.

At the far side of the disk, the 265 GHz PA is low simply due to the very high optical depth. Around the projected area of the 265 GHz dark lane, there is a transition of the 265 GHz polarization mechanism from the dichroic extinction regime to the polarized dust emission regime. Due to synthesized beam smearing, the observed 265 GHz PA is low where such a transition occurs. The presence of these low-polarization “holes” or “gaps” explain why the 265 GHz PA image presents three strong peaks. We do not require a complicated $B$-field topology (e.g., due to strong turbulence) to explain the low PA “holes” resolved in the inner $\sim 100$ au region of OMC-3/MMS 6. Our hypothesis is that the $B$ field is relatively well ordered on this spatial scale. The “disk” part of our model may be analogous to the radiative transfer simulation presented in Figures 7(g), (h) of Lin et al. (2020).

The 33 GHz Stokes I intensity contours (e.g., Figure 2) may provide a good indication of the projected area of the embedded disk. We tentatively use the $35\sigma$ contour to indicate the projected area at the (pseudo)disk. We avoid interpreting the 265 GHz PA at the area which is bounded by the $35\sigma$ and $100\sigma$ contours of the 33 GHz Stokes I intensity image, since we are less certain about the radiative transfer and beam smearing in that area.

Figure 5 shows the overall $B$-field topology we suggest based on the above discussion. From this figure, we see that the $B$-field topology can be described with an hourglass shape. The $B$ field appears predominantly poloidal and does not present large pinch angles, which may be expected from the nonideal magneto-hydrodynamics simulations (see Li et al. 2011, Zhao et al. 2016, and references therein). It is intriguing that this “hourglass” appears inclined with respect to the axis of the molecular outflow (Takahashi & Ho 2012), although the ALMA high-resolution observations show that the $B$-field PA has a better consistency with the outflow axis at the innermost region. The $B$ field may be misaligned with the disk (see Machida et al. 2020, Hirano et al. 2020, and references therein). Otherwise, the disk may be warped on small spatial scales (e.g., Sakai et al. 2019; Bi et al. 2020).

So, does dust scattering matter? With our assumption of disk PA and inclination, the $E$-field PA of the scattered light is indeed consistent with what was resolved by the high-resolution ALMA image around the central PI peak (Figure 3). Nevertheless, to reproduce the observed features in OMC-3/MMS 6 does not seem to require dust self-scattering to dominate the linearly polarized intensity at 265 GHz. In addition, merely reproducing the observed PA is not yet sufficient to justify polarized scattered light being prominent. Given the high optical depth at 265 GHz, to reproduce the observed polarization percentages by dust self-scattering may require fine-tuning the density structures to make the local 265 GHz radiation field sufficiently anisotropic over an extended range of disk radii (Takahashi et al. 2019; see also Kataoka et al. 2015). In any case, the 33 GHz PI still needs to be reproduced with aligned dust. Therefore, our proposed overall $B$-field topology will not be affected by the consideration of dust scattering.

5. Conclusion

We have reanalyzed the archival JVLA ($\sim 9$ mm) and ALMA ($\sim 1.2$ mm) full polarization observations toward the Class 0 YSO OMC-3/MMS 6 (also known as HOPS-87). We
found that inward of the ∼50 au projected radius, the polarization (E-field) PAs observed by JVLA and ALMA present a nearly 90° relative offset, while they are very consistent with each other on larger spatial scales. This region is likely very optically thick (e.g., $\tau \gg 1$) at ∼1 mm wavelength such that the dominant polarization mechanism is dichroic extinction. The system becomes a lot optically thinner (e.g., $\tau \lesssim 1$) at ∼9 mm wavelength, thus the observations can directly probe the polarized emission of nonspherical dust which is predominantly aligned with the $B$ field.

We make a general warning that many previous (sub) millimeter interferometric linear polarization observations toward Class 0 YSOs and high-mass star-forming cores may require reinterpretation if dichroic extinction has not been considered as one of the plausible polarization mechanisms. Our development has revealed how to correctly infer the $B$-field direction in the inner ∼100 au region around Class 0 YSOs based on ALMA observations. It is unlikely one can make it based on the observations at only one single frequency band. The inference is thus expected to be more challenging in high-mass star-forming regions given their higher optical depths and the likelihood of more complicated thermal structures.

We interpret the inner ∼100 au region of OMC-3/MMS 6 as an inclined (pseudo)disk which is pinched by the predominantly poloidal magnetic field ($B$ field), which has an hourglass shape. Our proposed $B$-field configuration may be consistent with what is theoretically expected for a Class 0 YSO which is regulated by modestly strong $B$-field and ambipolar diffusion. It is intriguing that the resolved $B$-field PA in the inner ∼50–100 au region is ∼40° offset from the previously reported outflow axis. The disk may be warped on an unresolved spatial scale. It could also be possible that the $B$-field lines are not perfectly aligned with the rotational axis of the disk.

The National Radio Astronomy Observatory (NRAO) is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc. This article makes use of the following ALMA data: ADS/JAO. ALMA No. 2015.1.00341.S. ALMA is a partnership of ESO (representing its member states), NSF (USA), and NINS (Japan), together with NRC (Canada), MoST and ASIAA (Taiwan), and KASI (Republic of Korea), in cooperation with the Republic of Chile. The Joint ALMA Observatory is operated by ESO, AUI NRAO, and NAOJ. H.B.L. is supported by the Ministry of Science and Technology (MoST) of Taiwan (grant Nos. 108-2112-M-001-002-MY3).

Facilities: JVLA, ALMA.

Software: astropy (Astropy Collaboration et al. 2013), Numpy (van der Walt et al. 2011), CASA (v5.6.0, McMullin et al. 2007).

ORCID iDs

Hauyu Baobab Liu © https://orcid.org/0000-0003-2300-2626

References

Astropy Collaboration, Robitaille, T. P., Tollerud, E. J., et al. 2013, A&A, 558, A33
Bi, J., van der Marel, N., Dong, R., et al. 2020, ApJL, 895, L18
Cox, E. G., Harris, R. J., Looney, L. W., et al. 2018, ApJ, 855, 92
De Simone, M., Ceccharelli, C., Codella, C., et al. 2020, ApJL, 896, L3
Galametz, M., Maury, A., Girart, J. M., et al. 2018, A&A, 616, A139
Galván-Madrid, R., Liu, H. B., Izquierdo, A. F., et al. 2018, ApJ, 868, 39
Hildebrand, R. H., Davidson, J. A., Dotson, J. L., et al. 2000, PASP, 112, 1215
Hirano, S., Tsukamoto, Y., Basu, S., & Machida, M. N. 2020, ApJ, 898, 118
Hull, C. L. H., Plambeck, R. L., Kwon, W., et al. 2014, ApJS, 213, 13
Kataoka, A., Muto, T., Momose, M., et al. 2015, ApJ, 809, 78
Ko, C.-L., Liu, H. B., Lai, S.-P., et al. 2020, ApJ, 889, 172
Kounkel, M., Hartmann, L., Loinard, L., et al. 2017, ApJ, 834, 142
Lee, C.-F., Li, Z.-Y., Ho, P. T. P., et al. 2017, SciA, 3, e1602935
Li, J. I.-H., Liu, H. B., Hasegawa, Y., & Hirano, N. 2017, ApJ, 840, 72
Li, Z.-Y., Krasnopolsky, R., & Shang, H. 2011, ApJ, 738, 180
Lin, Z.-Y. D., Li, Z.-Y., Yang, H., et al. 2020, MNRAS, 493, 4868
Liu, H. B., Hasegawa, Y., Ching, T.-C., et al. 2018, A&A, 617, A3
Machida, M. N., Hirano, S., & Kitata, H. 2020, MNRAS, 491, 2180
McMullin, J. P., Waters, B., Schiebel, D., Young, W., & Golap, K. 2007, in ASP Conf Ser. 376, CASA Architecture and Applications, ed. R. A. Shaw, F. Hill, & D. J. Bell (San Francisco, CA: ASP), 127
Perley, R. A., & Butler, B. J. 2017, ApJS, 230, 7
Rau, U., & Cornwell, T. J. 2011, A&A, 532, A71
Reissl, S., Seifried, D., Wolf, S., Banerjee, R., & Klessen, R. S. 2017, A&A, 603, A71
Sahu, D., Liu, S.-Y., Su, Y.-N., et al. 2019, ApJ, 872, 196
Sakai, N., Hanawa, T., Zhang, Y., et al. 2019, Natur, 565, 206
Shu, F. H., Adams, F. C., & Lizano, S. 1987, ARA&A, 25, 23
Su, Y.-N., Liu, S.-Y., Li, Z.-Y., et al. 2019, ApJ, 885, 98
Takahashi, S., & Ho, P. T. P. 2012, ApJL, 745, L10
Takahashi, S., Machida, M. N., Tomisaka, K., et al. 2019, ApJ, 872, 70
Tobin, J. J., Sheehan, P. D., Megeath, S. T., et al. 2020, ApJ, 890, 130
Vaillancourt, J. E. 2006, PASP, 118, 1340
van der Walt, S., Colbert, S. C., & Varoquaux, G. 2011, MCSE, 13, 22
Zhang, Q., Qiu, K., Girart, J. M., et al. 2014, ApJ, 792, 116
Zhao, B., Caselli, P., Li, Z.-Y., et al. 2016, MNRAS, 460, 2050

\[9\]