ALMA High Angular Resolution Polarization Study: An Extremely Young Class 0 Source, OMC-3/MMS 6

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Abstract

Using the ≈16 km long baseline data obtained with the Atacama Large Millimeter/submillimeter Array (ALMA), we imaged the Stokes I emission and linearly polarized intensity (PI) in the 1.1 mm continuum band of a very young intermediate-mass protostellar source, MMS 6, in the Orion Molecular Cloud-3. The achieved angular resolution, 0″02 × 0″03 (≈10 au), shows for the first time a wealth of data on the dust emission polarization in the central 200 au of a protostar. The PI peak is offset to the southeast (SE) by ≈20 au with respect to the Stokes I peak. Its polarization degree is 11% with its E-vector orientation of the position angle ≈135°. A partial ringlike structure with a radius of ≈80 au is detected in PI but not in the Stokes I. Northwest (NW) and SE parts of the ring are bright, with a high polarization degree of ≳10%, and their E-vector orientations are roughly orthogonal to those observed near the center. We also detected an armlike polarized structure, extending to 1000 au scale to the north, with the E-vectors aligned along the minor axis of the structure. We explored possible origins of the polarized emission by comparing them with magnetohydrodynamical simulations of the toroidal wrapping of the magnetic field. The simulations are consistent with the PI emission in the ringlike and the extended armlike structures observed with ALMA. However, the current simulations do not completely reproduce observed polarization characteristics in the central 50 au. Although the self-scattering model can explain the polarization pattern and positional offset between the Stokes I and PI in the central 50 au, this model is not able to reproduce the observed high degree of polarization.

Key words: ISM: jets and outflows – ISM: magnetic fields – polarization – stars: formation – stars: individual (OMC-3/MMS 6)

1. Introduction

Magnetic fields are among the key elements that regulate star formation (Shu et al. 1987; Crutcher 2012), and organized magnetic fields are often observed in parsec-scale dense molecular clouds and cores. Even when the Lorentz force is insufficient to balance the gravity and to prevent contraction of the core (Crutcher 2012), the magnetic fields are still important in the star formation process. For instance, in large scales, the magnetic field seems to produce a disklike structure called a “pseudo disk” (Shu et al. 1987; Nakano 1988; Galli & Shu 1993). In the vicinity of the protostar, the Lorentz force plays a critical role in launching outflows and jets (Tomisaka 2002; Banerjee & Pudritz 2006; Machida et al. 2008; Commerçon et al. 2010; Tomida et al. 2010), which are commonly observed in the star-forming regions (e.g., Arce et al. 2007 and references therein). A strong magnetic field removes the angular momentum from the disk via magnetic braking (e.g., Mellon & Li 2008) and produces outflows (e.g., Machida et al. 2008; Tomisaka 2011), whereas the Ohmic dissipation promotes the disk formation and growth (e.g., Machida et al. 2011). These effects determine the properties of a rotationally supported disk in the early stage of the protostellar evolution.

A method to study the magnetic field structures in the protostellar core is to observe the linearly polarized thermal emission from magnetically aligned dust grains (e.g., Spitzer & Tukey 1949; Davis & Greenstein 1951; Hildebrand 1988; Rao et al. 1998, 2009, 2014; Lai et al. 2003; Girart et al. 2006, 2009, 2013, 2018; Lazarian 2007; Tang et al. 2013; Hull et al. 2014, 2017; Zhang et al. 2014; Cortes et al. 2016; Alves et al. 2018; Koch et al. 2018; Lee et al. 2018; Maury et al. 2018 and references therein). Because the degree of linear polarization observed in the star-forming cores is typically ≲5%, only a sensitive array such as ALMA can image dust polarization for faint sources and in their most internal parts (≲a few × 100 au). With the ALMA’s sensitivity and its angular resolution that enables to probe nearby protostars at 10 au scales, magnetic field structures can be traced in detail and measured magnetic field structures can be directly compared with magnetohydrodynamical (MHD) simulations (e.g., Machida et al. 2008; Tomisaka 2011; Li et al. 2014). Such observations are key to study the formation processes of rotationally supported disks and the launching mechanism of the jet and outflow.

At small scales (≲a few × 100 au), dust polarization is not always associated with the magnetic field and could also be related to other mechanisms, such as the self-scattering
In this work, the distance to the object, \( d = 414 \) pc, is adopted.

2. Observations and Data Reduction

2.1. The 1.1 mm Continuum Polarimetric Observations

The ALMA observations of MMS 6 were obtained through the science project 2015.1.00341.S (P.I. S. Takahashi) using two different array configurations. The high angular resolution observations were made in Cycle 3 on 2015 October 29 with the 16 km ALMA configuration in two consecutive observing blocks, and the lower angular resolution observations were made in Cycle 4 on 2016 October 9 and 11 with the 3.6 km ALMA configuration in five observing blocks. The phase center of all of the observations were R.A. (J2000) = 5h35m23s4200, decl. (J2000) = 05°01′30″350. Observing parameters associated with the three observations are listed in Table 1. High and low angular resolution observations had about 40 and 25 minutes on-source time, respectively, with about forty 12 m diameter antennas. The low and high angular resolution data sets cover projected baselines between 16 k\( \lambda \) and 3200 k\( \lambda \) and between 76 k\( \lambda \) and 14700 k\( \lambda \), respectively. The two data sets are insensitive to structures more extended than 1′0 and 0′′22, respectively, at the 10% level (Wilner & Welch 1994). Four spectral windows (SPWs) with 1.875 GHz bandwidth, centered at 256, 258, 272, and 274 GHz, are allocated with the time division mode for this polarization experiment, giving a total continuum bandwidth of 7.5 GHz.

The Common Astronomy Software Application (CASA; McMullin et al. 2007) version 4.5.0 was used for the standard ALMA data reduction. The calibration scripts were provided by the observatory. The calibration steps include (1) correcting the gains associated with the variable receiver and sky noise and phases associated with the water vapor along the line of sight, (2) providing the flux density scale with an observation of calibrator of known flux density, (3) removing the amplitude and phase frequency dependence (bandpass) for each SPW, (4) removing the amplitude and phase temporal dependence using a phase calibrator within a few degrees of MMS 6, (5) removing instrumental polarization using a bright polarized calibrator, J0522-3627, which was observed every 25 minutes during each execution, and (6) making appropriate data flagging as calibrations progress. The calibrated data from the two 16 km experiments were combined into the high-resolution data set. The data from the five 3.6 km experiments were combined into the low-resolution data set. The data points in the combinations were weighted by their theoretical S/N, which gives best theoretical S/N in the combined data sets.

Then CLEANed images were made using the CASA task “clean.” The Briggs weighting with robust parameter of 0.5 and natural weighting were used for the final low and high angular resolution images, respectively. To reduce residual phase errors and improve the dynamic range of the images, self-calibrations have been applied for the low angular resolution images. This process improved the maximum dynamic range by a factor of 1.8. The resulting synthesized beam sizes are 0″03 \( \times \) 0″02 (P.A. = 43°) and 0″15 \( \times \) 0″14 (P.A. = −80°) for the high angular resolution and low angular resolution images, respectively. The achieved rms noise level (1\( \sigma \)) for the high angular resolution and low angular resolution images (for Stokes \( I, Q, \) and \( U \)) are 63, 21, and 21 \( \mu \)Jy beam\(^{-1} \) and 130, 20, and 20 \( \mu \)Jy beam\(^{-1} \), respectively. The Stokes \( Q \) and \( U \) image rms is near the expected thermal noise level. However, the Stokes \( I \) image is limited by small residual phase errors that could not be calibrated using phase referencing. Still, a peak sensitivity at
Table 1
ALMA Observing Parameters for the Full Polarization Experiments

| Parameters                                      | X1aa2 and X269f | X368f, X435c, and X4b9d | X336 and X3d1d |
|------------------------------------------------|-----------------|--------------------------|-----------------|
| Observing date (YYYY MM DD)                    | 2015 Oct 29     | 2016 Oct 09              | 2016 Oct 11     |
| Number of antennas                              | 38              | 42                       | 44              |
| Primary beam size (arcsec)                      | 21              | 21                       | 21              |
| PWV (mm)                                        | 1.3–1.9         | 0.44–0.90                | 0.44–0.57       |
| Phase stability rms (degree)                    | 16–23           | 16–56                    | 10–15           |
| Polarization calibrator                         | J0522-3627      | J0522-3627               | J0522-3627      |
| Bandpass calibrators                             | J0423-0120      | J0510+1800               | J0510+1800      |
| Flux calibrator                                  | J0423-0120      | J0423-0120               | J0423-0120      |
| Phase calibrators (separation from the target)  | J0541-0541 (17")| J0532-0307 (27")        | J0541-0541 (17")|
| Central frequency USB/LSB (GHz)                 | 257/273         | 257/273                  | 257/273         |
| Total continuum bandwidth; USB+LSB (GHz)        | 7.5             | 7.5                      | 7.5             |
| Projected baseline ranges (kλ)                  | 76–14700        | 16–3200                  | 16–3200         |
| Maximum recoverable size (arcsec)               | 0.22            | 1.0                      | 1.0             |
| On-source time (minutes)                        | 41              | 12.5                     | 13              |
| Synthesized beam size (arcsec)                  | 0"03 x 0"02 (P.A. = 43°) | 0"15 x 0"14 (P.A. = 80°) |
| rms noise level of Stokes I, Q, and U (μJy beam⁻¹) | 63, 21, and 21  | 130, 20, and 20          |

Notes.
* antenna-based phase differences measured on the bandpass calibrator.
* The phase calibrator was observed every 1 minute and 8 minutes for the high angular and low angular resolution observations, respectively.
* Our observations were insensitive to emission more extended than this size scale structure at the 10% level (Wilner & Welch 1994).
* The natural weighting and the Briggs weighting (robust parameter of 0.5) are used for the high and low angular resolution imaging, respectively.
* Stokes I images are dynamic range limited.

The derived PI image is given by the quadrature sum of the $Q$ and $U$ images, $PI = \sqrt{Q^2 + U^2}$. The polarization angle in degrees is given by $E_{PA} = (1/2) \times \arctan(U/Q)$. PI and $E_{PA}$ were calculated using a CASA task “immath.” Debiasing level of $5\sigma$ in Stokes $Q$ and $U$ was used to derive PI. The estimated error of the PI is $\Delta PI = \sqrt{\Delta Q^2 + \Delta U^2 + (0.002 \times I)^2}$, which is the quadrature sum of the $Q$ and $U$ errors plus the nominal polarization calibration error. The estimated error of the polarization angle in degrees is $\Delta E_{PA} \approx (1/2) \times \Delta PI/PI$. There is a lower limit of $\Delta E_{PA}$ of $1^{\circ}$ related to the uncertainty of the position angle determination of the polarization calibrator and antenna feed orientation. The degree of polarization is $D_{frac} = PI/I$. Because of nonlineairties in the parameters, only those pixels that contain both more than $5\sigma$ signal level in the PI maps and $3\sigma$ signal level in the Stokes I maps were used for calculating $D_{frac}$. In this article, we use the term “E-vector” to refer to the observed polarization vector, and “B-vector” to refer to the observed polarization vector after rotating $90^\circ$.

2.2. The Molecular Line Observations

In addition to the 1.1 mm polarization observations, we also performed observations in the CO (2–1) and SiO (4–3) line emission from the same science project to trace the molecular outflow associated with MMS 6. These observations were done separately, but the data were obtained in a similar period as the lower resolution polarization observations. Two SPWs were allocated to measure CO (2–1) and SiO (4–3) using the frequency division mode, resulting in a velocity resolution of $\approx 0.06 \text{ km s}^{-1}$. The standard data reduction script provided from the observatory was used to calibrate the data sets using CASA. The Briggs weighting with robust parameter of 0.5 was used for CLEAN binning with the velocity width to $3 \text{ km s}^{-1}$. The resulting synthesized beam sizes of the CO (2–1) and SiO (4–3) images are $0"18 \times 0"15$ (P.A. = $-16^\circ 5$) and $0"22 \times 0"17$ (P.A. = $-27^\circ 7$), respectively. The achieved rms noise levels of the CO (2–1) and SiO (4–3) images are $3.6 \mu Jy \text{ beam}^{-1} \text{ km s}^{-1}$ and $2.7 \mu Jy \text{ beam}^{-1} \text{ km s}^{-1}$, respectively. The mean velocity maps (Figures 3 and 7) are produced from the data cube using a CASA task “immoment” with the clip levels of $3\sigma$ for CO (2–1) and $10\sigma$ for SiO (5–4). Details for the line data sets including both the analysis and interpretation will be presented in a forthcoming article (S. Takahashi et al. 2019, in preparation).

3. Results

3.1. Morphology and Polarization Vectors at Several 1000 au Scale

In Figure 2, we present the spatial distribution of the linearly polarized emission, Stokes $I$ emission, and $E$-vectors obtained from the 1.1 mm low angular resolution image. The image shows that the PI peak is closely associated with the Stokes $I$ peak, while showing clumpy substructures. These substructures (central 200 au) will be described in Section 3.2. In addition to the centrally concentrated substructures, we also detect extended emission both in Stokes $I$ and polarized emission. The emission is extended on 3000 au scale and shows substructures. The most prominent feature is an armlike structure detected in the northern part, as denoted by the orange line in Figure 2. The armlike structure is particularly clear in the PI map and also is detected in the Stokes $I$ at a 5–15$\sigma$ level. The $E$-vectors are aligned with the minor axis of the armlike structure, and their orientations change smoothly along them. To the north of the armlike structure, we find another faint component that is elongated north–south. This component was detected at a $5\sigma$ level in the polarized emission, and a part of the structure was marginally detected in Stokes $I$ at a $3\sigma$ level.
In addition, the Stokes $I$ shows an extended faint (3–6$\sigma$) emission in the southeast part of the core. Unlike the northern armlike structure, this component is not bright in the PI. Overall, $E$-vector orientations from the extended emission are aligned in the NW to SE direction, which is consistent with the large-scale orientation presented by Hull et al. (2014).

Figure 3 shows the Stokes $I$ image from a large squared region in Figure 2, and it is compared with the mean velocity map from the CO molecular outflow. The Stokes $I$ emission associated with the compact central component shows an elongated structure in the north–south direction with an extension of 3$''$ (1200 au). The spatial distribution of the extended continuum emission shows enhancements on both edges of the CO molecular outflow. A depression in the Stokes $I$ emission is seen along the outflow, both in the north and the south. This implies that the interaction between the outflow and the surrounding material likely created the outflow cavity wall. The Stokes $I$ emission not only is detected from the area perpendicular to the molecular outflow, where we normally expect infalling material to a pseudo disk, but also is detected in the direction of the outflow where material may be swept up by the outflow.

The $E$-vectors associated with this outflow interacting area, especially in the southern component (highlighted in yellow lines in Figure 2 particularly at the south), show a different P.A. compared to the global $E$-vector orientations and seem to follow the interacting surface of the outflow.

3.2. Morphology and Polarization Vectors in the Central 200 au

Figures 4(a) and (b) show the images of the central 200 au region obtained in the low and high angular resolutions, respectively. The angular resolution of the image in Figure 4(b) of 0.02$''$ × 0.03 is close to the highest angular resolution currently available with ALMA at 1.1 mm and corresponds to a linear size scale of $\approx$8 $\times$ 12 au at the distance of MMS 6. Our high angular resolution images show that the MMS 6 continuum emission is very well resolved both in Stokes $I$...
and in the polarized flux displaying a series of intricate structures. The source size (FWHM) measured in Stokes I is $\approx 165$ synthesized beams. Furthermore, comparison of the high and low angular resolution Stokes I images indicates that we are recovering 96% of Stokes I flux in the central 200 au (i.e., central 0\textquoteleft5, the region denoted in the dashed circle in Figure 1(a)). This shows that nearly little or none of the emission in the central region is contained in a large, resolved-out, component.

Both the Stokes I and PI emissions show a peak around the center. However, the PI peak is offset to the southeast (SE) by 0\textquoteleft05 (\approx 20 au) with respect to the Stokes I peak. Hereafter we will refer to this concentrated PI structure as the “centrally concentrated component” (Figure 4(c)). The emissions of both Stokes I and PI are elongated along the NE to SW direction with P.A. $\approx 45^\circ$. The associated E-vectors are aligned to the minor axis of the elongated structure (P.A. $\approx 135^\circ$). Around this central structure, there are three more components called “NW,” “SE,” and “west” components (identified in Figure 4(c)), each displaying substructures, that, together, define an approximate ring surrounding the central component. Hereafter, we call this the “ringlike structure” (Figure 4(c)). The substructures seen within the ringlike structure are particularly clear within the SE component, with a size scale as small as the synthesized beam size (\approx 10 au).

The E-vectors associated with the NW and SE components are more or less azimuthally aligned (Figure 4(b)). The position angle of the E-vectors changes in the ringlike structure (i.e., the peaks of the P.A. distribution are 25\textdegree and 40\textdegree for the SE and NW components, respectively, whereas the peak of the P.A. distribution is 135\textdegree at the centrally concentrated component). Significant changes in the P.A. of 90\textdegree--105\textdegree occur in the central 0\textquoteleft5 region. The P.A. within the NW and SE components varies slightly with respect to the overall E-vector orientation. This implies that our data reveal not only the bulk structure but also the small-scale E-vector changes, which may be related to small-scale variations in the magnetic field due to local structural changes, dust property changes, or dynamics.

Finally, there is a clear polarization gap between the centrally concentrated component and the ringlike structure. The width of the gap is significantly larger than the beam size and is, therefore, not caused by the beam dilution. This gap implies that either the PI is intrinsically low or that the E-vector orientations originating from the centrally concentrated component and the ringlike structure are approximately orthogonal along the line of sight.
3.3. Polarization Degree

In Figures 5(a) and (b), we present the degree of the polarization, $D_{\text{frac}}$, as derived from the low angular resolution image. We find that $D_{\text{frac}}$ in the armlike structure shown in Figure 5(a) has a relatively high value of 15%–20%. For the central region in Figure 5(b), $D_{\text{frac}}$ is less than 3% for most of the area, but there are local peaks with $D_{\text{frac}}$ up to $\approx 8\%$. The locations of the peaks in $D_{\text{frac}}$ coincide with the local maxima of PI.

The distribution of $D_{\text{frac}}$ obtained with the high angular resolution image is presented in Figure 5(c), and the comparison of this central region between the low- and high-resolution images in $I$, $Q$, and $U$ is shown in Figure 1. The internal structures within the central 200 au are spatially resolved and show the following components: (i) the centrally concentrated component, showing the peak in PI with $D_{\text{frac}}$ of 11%, and (ii) the partial ringlike structure with $D_{\text{frac}}$ up to 19%. $D_{\text{frac}}$ is particularly high within the SE component. The locations of all the local maxima of $D_{\text{frac}}$ coincide well with the local peaks in PI.

Considering the central 0'5 region (denoted by the dashed circle in Figure 1(a)), there is no significant missing Stokes $I$ flux. Therefore, the derived $D_{\text{frac}}$ is not overestimated and shows most likely the intrinsic value. In contrast, for the central 2'0, comparison with low-resolution maps suggests that about 25% is missing in the Stokes $I$ emission. The relatively high $D_{\text{frac}}$ (7%–25%) derived for the extended structure, in the NE side with respect to the center in Figure 5(b), may be somewhat overestimated.

Finally, note that a comparison between the low- and high-resolution images presented in Figures 5(b) and (c) clearly shows that $D_{\text{frac}}$ becomes higher for the high angular resolution image toward local substructures. Those substructures contain highly organized $E$-vectors as small as a few $\times$ 10 au scale, whereas they are diluted by the beam and show considerably less $D_{\text{frac}}$ in the low-resolution map.

3.4. Origin and Physical Properties of the 1.1 mm Continuum Emission

The total flux of the 1.1 mm continuum emission is measured to be 0.9 Jy using the area where the S/N is greater than 5 from the high angular resolution image. This flux includes the possible contribution of the free–free emission from the ionized jet from the protostar. The free–free emission can be extrapolated from the centimeter observations, with an assumption of the frequency dependence of $F(\nu) \propto \nu^{0.6}$.
Figure 4. Full polarization 1.1 mm continuum images at the central 400 au obtained from the low angular resolution (Figure 4(a)) and high angular resolution (Figure 4(b)) data sets. Gray scale and black contours present the linearly polarized flux, and blue contours and magenta lines present the Stokes I emission and the E-vectors. (a) Full polarization image obtained from the inner squared region of Figure 2. Contour levels of the Stokes I and polarized emission correspond to 6σ, 9σ, 12σ, 15σ, 20σ, 30σ, 40σ, 50σ, 100σ, 200σ, 400σ, and 800σ (1σ = 130 μJy beam⁻¹), and 10σ, 20σ, 30σ, 40σ, 50σ, 60σ, 80σ, 100σ, 120σ, 140σ, 160σ, and 180σ (1σ = 28 μJy beam⁻¹), respectively. (b) Full polarization image obtained from the high angular resolution image. Zoomed image within the white squared region in Figure 4(a). Contour levels of the Stokes I and polarized emission start at 5σ and 3σ with intervals of 10σ and 3σ, respectively (1σ = 63 μJy beam⁻¹ for the Stokes I emission and 1σ = 30 μJy beam⁻¹ for the PI). (c) High angular resolution PI image, same as Figure 4(b), overlaid with structure information referred in the main text. For all the images, the synthesized beam sizes are denoted in the bottom-left corners of Figures (a) and (b) with filled yellow ellipses.

Assuming that the measured peak flux mainly comes from the circumstellar materials associated with the central protostar, the estimated high brightness temperature of the dust can be compared to the expected gas temperature at the radius of 10 au. We conclude that the observed dust emission may become optically thick at radii ≲ 10 au.

On the other hand, the measured peak flux may be attributed to the multiple components integrated along the line of sight. The mean brightness temperatures estimated from the fitted total fluxes listed in Table 2 are 25 K (extended component), 27 K (elongated component), and 36 K (compact component). These are considered as the lower limits of the dust temperatures. From a theoretical approach, Tomida et al. (2017) presented the temperature distribution around the center region of the protostellar core using radiative transfer calculations. They found that the observed temperature integrated along the line of sight is ≈ 20 K in the midplane of the pseudo disk at r ≲ 200 au because of the optical depth effect. The fitted three components also have similar size structures (≈ 0′′.5 or ≈ 120 au) and, thus, likely trace emission from the pseudo disk. The observed brightness temperatures are lower than those predicted by Tomida et al. (2017). This finding implies that MMS 6 also has an optically thick pseudo disk with a relatively low temperature.

Assuming the respective mean dust temperatures of 25, 27, and 36 K for the extended, elongated, and compact components, an optical depth of τ ≈ 1, and a gas-to-dust ratio of 100, we have estimated the lower limits of the column density (N_H2), the gas mass (M_H2), and the number density (n_H2) as listed in Table 3. Here, the brightness temperatures estimated for the elongated and compact components are adopted as the dust temperature. A spherical geometry with the geometric mean of the major and minor axes of the source size is assumed in order to estimate the number densities.

The dust temperature for the extended component is assumed from previous multiwavelength observations of the large-scale structure (Sadanov et al. 2016). For those estimates, we adopted a dust emissivity index of β = 0.93 from Takahashi et al. (2009) and a dust absorption coefficient of κ_{ν,obs} = 0.037 cm² g⁻¹.

(Reynolds 1986; Anglada et al. 1998), Takahashi et al. (2009) measured a 3σ upper limit of 0.09 mJy in the 3.6 cm continuum band. Adopting this number as the upper flux limit attributed to the free–free jet, the free–free contribution at the 1.1 mm band is at most 0.7 mJy, which is ≲ 0.8% of the total Stokes I flux. This indicates that the thermal dust emission is dominating in the 1.1 mm continuum band and that the contribution from the free–free emission of the ionized jet is within the measurement errors.

To characterize the internal structures and their physical parameters from the Stokes I high angular resolution image, we used a two-dimensional Gaussian fit with multiple components. The fitting results are summarized in Table 2 and show three Gaussian components: (i) an extended component, (ii) an elongated component, and (iii) a compact component. The observed structures are well reproduced. The residual level of the fitting result is less than 1.5% with respect to the observed peak flux (i.e., the residual level is less than S/N = 1.7). Note that the fitting region includes the NW, SE, and west components. However, those components are bright in only the PI image. Hence, Stokes I fitting results are not affected by those substructures, but rather are based on the total material distribution.

The extended component shows structure sizes of ≈ 0″.3 (≈ 120 au) in FWHM. This size is comparable to the maximum recoverable size of the experiments. For a component that is more extended, flux will be missed by the lack of short antenna spacings. The elongated component has a fitted size of 0″.3 × 0″.05 (120 au × 20 au), with an aspect ratio of 5.8 with P.A. = 39°. Finally, a compact component of 0″.05 × 0″.01 (20 au × 4 au) is necessary to explain additional flux seen at the center. This compact component is barely resolved with respect to the synthesized beam.

The measured 1.1 mm peak intensity of 7 mJy beam⁻¹ corresponds to a brightness temperature of 192 K. Gas temperatures of ≳ 100 K are expected at the radius of ≈ 10 au from the protostellar source (e.g., Nakazato et al. 2003).
Polarization degree maps (gray scale) overlaid with the Stokes I emission (gray contours) and B-vectors (green vectors). (a) Large-scale image made from the low angular resolution data set. Contour levels of the Stokes I correspond to 5σ, 15σ, 25σ, 35σ, 45σ, 55σ, 65σ, 75σ, 85σ, 95σ, 105σ, 115σ, 200σ, 300σ, 400σ, 600σ, 800σ, and 1000σ (1σ = 130 μJy beam⁻¹). (b) Zoomed image of panel (a). (c) Zoomed image of panel (b) obtained from the high angular resolution data set. The contour levels of the Stokes I (gray) and the polarization degree (black) start from 5σ with 10σ interval (1σ = 63 μJy beam⁻¹) and start from 3% with the interval of 3%, respectively. The synthesized beam sizes are denoted in the bottom-left corners with filled yellow ellipses.

In addition, the origin of the linearly polarized dust continuum emission in the vicinity of protostars is not completely understood yet. It has been suggested recently that the linearly polarized (sub)millimeter dust emission may not be always associated with the magnetic field (e.g., Cox et al. 2018; Girart et al. 2018; Harris et al. 2018; Sadavoy et al. 2018). In Section 4.1, we summarize other possible mechanisms to align dust grains and/or to produce polarized emission, and, in Section 4.2, we compare the observed ALMA data with the various models. Finally, in Section 4.3, we further discuss the magnetic field morphology as inferred from the polarized emission and compare it with MHD simulations.

4.1. Potential Origins of the Polarized Dust Emission

Figure 6 shows three possible mechanisms to produce polarized emission in the millimeter and submillimeter wavelengths. The first mechanism to produce the polarized dust emission is from magnetically aligned dust grains as proposed originally by Spitzer & Tukey (1949)—see also Davis & Greenstein (1951), Hildebrand (1988), and Lazarian (2007). Spinning dust grains interact with the magnetic fields and align their major axes perpendicular to the magnetic field. Therefore, thermal radiation from these grains produce polarized emission with the E-vector aligned perpendicular to the magnetic field, as presented in Figure 6(a) (e.g., Lazarian 2007). This is what has been mainly detected on the size scales of clouds, cores, and envelopes (e.g., Rao et al. 1998, 2009; Lai et al. 2003; Girart et al. 2006, 2009, 2013; Tang et al. 2013; Hull et al. 2014, 2017; Zhang et al. 2014; Koch et al. 2018; Kwon et al. 2018; Lee et al. 2018).

Another mechanism to produce millimeter wavelength polarized dust emission is self-scattering of the dust grains as proposed by Kataoka et al. (2015) and Yang et al. (2016). Even without any alignment of the grains in the disk, polarized emission is expected when the dust grains scatter an anisotropic radiation field. If the radiation energy flux is dominated in the azimuthal direction rather than in the radial direction, the self-scattering is expected to produce net polarization in the radial direction, as shown in Figure 6(b) by the polarization from a dust ring. Kataoka et al. (2015) predicted that the scattering at millimeter wavelengths is efficient if the dust grains are as large

\[(\lambda_{\text{obs}}/400 \mu m)^{-\beta}\] from Keene et al. (1982), where \(\lambda_{\text{obs}}\) is the observed wavelength of 1.1 mm with \(K_{\lambda_{\text{obs}}}=0.014 \text{ cm}^2 \text{ g}^{-1}\). Note that, for the large-scale emission (>0.05 pc), \(T_{\text{dust}}=25 \text{ K}\) and \(\beta=1.4\) were estimated toward MMS 6 from Herschel and GISMO/IRAM 30 m data sets (Sadavoy et al. 2016). By adopting their value of \(\beta\), the estimated dust masses increase by a factor of 1.7. Another factor that affects the estimates is the mass absorption coefficient. Sadavoy et al. (2016) adopted \(K_{\lambda_{\text{obs}}}=0.1 \text{ cm}^2 \text{ g}^{-1}(\nu_{\text{obs}}/1.0 \text{ THz})^\beta\) on the basis of Herschel results by Andrê et al. (2010). By adopting this number, \(K_{\lambda_{\text{obs}}}\) increases by a factor of 2.3, resulting in a corresponding decrease in the estimated dust masses.

The fitted source size of the extended component of \(\approx 0.18\) is consistent with the value reported from previous lower resolution Submillimeter Array (Ho et al. 2004) observations of the dust continuum emission at 850 μm (Takahashi et al. 2012). The estimated total mass in this article, \(M_{\text{dust}}\approx1 \text{ M}_\odot\), is about three times larger than that reported by Takahashi et al. (2012) because we have used in this article a dust temperature that is lower by a factor of 2. Assuming the same dust temperature as used in Takahashi et al. (2012), the derived physical parameters \(M_{\text{dust}}, N_{\text{H}_2}\), and \(n_{\text{H}_2}\) in this article would be more consistent with previous results (e.g., the estimated mass would be agreement within a factor of 1.3).

4. Discussion

As described in Section 3, the E-vectors derived from our ALMA 1.1 mm dust continuum emission data show totally different field patterns as compared with previous interferometric studies, such as those obtained with BIMA by Matthews et al. (2005) or with CARMA by Hull et al. (2014). One obvious factor is a significant difference in beam sizes, which is a factor of \(\approx 10,000\) in terms of the beam surface area, between the previous experiments and our ALMA high angular resolution data. It is natural to consider that the polarized emissions from the two different spatial scales trace totally different physical structures and phenomena inherent to each spatial scale. Comparison of these different angular-sized structures is important to understand how the magnetic field morphology is connected from a pseudo disk (\(\approx 10^3-10^4 \text{ au}\)) to a circumstellar disk (\(\lesssim \text{a few } \times 100 \text{ au}\)).
as 100 μm. In this model, a polarization degree of a few percent is expected for assuming spherical dust grains. This mechanism explains well some of the recent ALMA polarization results obtained toward protoplanetary disks or circumstellar disks, including HL Tau (Kataoka et al. 2017; Stephens et al. 2017), HD 14527 (Kataoka et al. 2016), IM Lup (Hull et al. 2018), DG Tau (Bacciotti et al. 2018), HD 163296 (Dent et al. 2019), VLA 1623 (Sadavoy et al. 2018; Harris et al. 2018), and GGD27 MMS 1 (Girart et al. 2018), as well as Class 0/I sources in the Perseus Molecular Cloud (Cox et al. 2018).

The third mechanism comes from dust grain alignment due to the anisotropic radiation, as proposed by Tazaki et al. (2017). Near the star, the dust alignment solely due to the anisotropic radiation is expected in the direction determined by the radiation flux. The dust grains are expected to be aligned with their minor axis parallel to the radiation direction, as illustrated in Figure 6(c). The polarization degree depends mainly on the maximum grain size, the shape of the grains, and the intrinsic alignment efficiency of the grains.

4.2. Comparison of Each Model

The ALMA polarization images presented in Figures 2 and 4 highlight the complex substructures within the protostellar core, MMS 6. Therefore, it is possible that the polarized emission may be different by regions. In this section, we discuss possible origins of the dust polarization by regions using the proposed three theoretical models.

4.2.1. Origin of the Polarized Dust Emission Scales of a Few × 1000 au

As described in Section 3.1, the organized E-vectors with P.A. ≈ 135° are detected at low angular resolution, as seen in the image presented in Figure 2. The E-vector orientations are consistent with those previously measured in the filament, the core (a few × 0.1 pc), and the envelope size scales (a few × 1000 au), as reported by Matthews & Wilson (2000), Matthews et al. (2001, 2005), Poiéde et al. (2010), and Hull et al. (2014). The mechanism to align the dust grains in those extended structures has been widely accepted to be the magnetic field. Hence, the origin of the extended polarized emission measured by the ALMA low angular resolution image appears to be consistent with a magnetic alignment of dust grains.

The E-vectors detected in the armlike structure (Figure 2) are aligned perpendicular to the elongated structure. Assuming that the mechanism producing the polarized emission is the magnetic alignment of dust grains (Figure 6(a)), the magnetic fields then run along the armlike structure, as denoted in Figure 5(a). However, without investigating the gas dynamics, it is difficult to conclude what the origin of the armlike structure is. This structure could be explained by a physical arm or just asymmetrical substructures within the pseudo disk. Similarly, extended substructures likely associated with the envelope are also detected toward Class 0/I sources, such as Per-emb-11, Per-emb-29, Per-emb-2, and Per-emb-5 in the Perseus Molecular Cloud by Cox et al. (2018). They are also bright in the polarized emission, and E-vectors are aligned to the minor axis of those extended substructures. Cox et al. (2018) interpreted this as a part of the hourglass morphology expected if the polarization traces magnetic field dragged by the accreting material. Their morphology, size scale, and E-vector orientations are similar to those observed in the armlike structure in MMS 6. In any case, the magnetic field does not deter gas infalling motions toward the central protostar through this structure. In Section 4.3, we will make further comparisons of the magnetic field models using a MHD simulation result.

4.2.2. Origin of the Polarized Dust Emission within the Central 200 au

Our ALMA high angular resolution polarization image and the polarization E-vectors within the central 200 au show the two major components of centrally concentrated component and ringlike structure (Figure 4). We also identify the following characteristics: (i) there are very different spatial distributions between the Stokes I and the PI, (ii) there is a clear positional offset between the peak positions of the Stokes I and the PI, (iii) there is a clear ringlike gap that shows no detection of the polarized emission, (iv) a significant change in the P.A. of the polarization E-vector occurs across the gap, and finally (v) we measure a high polarization degree (≥10%) within the central 200 au. Each of these characteristics may be crucial in identifying the polarization mechanisms at play, and, hereafter we examine which of the five characteristics can be explained by the proposed polarization models. Table 4 summarizes how each of the characteristics could fit in each proposed polarization mechanism.

First, we consider the dust grain alignment due to the anisotropic radiation (Figure 6(c)). The azimuthally aligned polarized emission is expected for this case. The ringlike structure shown in MMS 6 shows a similar azimuthal pattern but does not trace back precisely to the center. In particular, the NW component is pointed to the NE of the Stokes I peak position. In addition, the E-vectors associated with the centrally concentrated component are aligned with the minor axis of the disklike structure, but not pointing toward the protostar, which is different from the predictions of the anisotropic radiation model. Our observational results, therefore, cannot unambiguously support this scenario.

Second, we consider the polarization E-vectors originated from the self-scattering of the dust (Figure 6(b)). The observed polarization E-vector is aligned with the minor axis of the centrally concentrated component. This is not inconsistent with the prediction of the E-vector orientation for a tilted disk (Kataoka et al. 2015; Yang et al. 2016, 2017). The observed positional offset between the Stokes I emission and the polarized emission can be explained by the optical depth.
Table 3
Physical Properties of Fitted Components

| Component       | Source Size (au) | $M_{\text{tot}}$ ($M_\odot$) | $\pi_{\text{HI}}$ (cm$^{-3}$) | $n_{\text{HI}}$ (cm$^{-3}$) |
|-----------------|-----------------|-----------------------------|-------------------------------|----------------------------|
| (i) Extended component | $133(\pm 1) \times 129(\pm 1)$ | $9.5e-01 (\pm 1.0e-02)$ | $6.4e+25 (\pm 6.9e+23)$ | $4.3e+10 (\pm 4.7e+08)$ |
| (ii) Elongated component | $130(\pm 15) \times 23(\pm 3)$ | $3.3e-03 (\pm 3.7e-04)$ | $4.4e+24 (\pm 4.9e+23)$ | $4.2e+09 (\pm 4.7e+08)$ |
| (iii) Compact component | $22(\pm 13) \times 5(\pm 6)$ | $1.3e-04 (\pm 6.6e-05)$ | $5.6e+24 (\pm 2.9e+24)$ | $3.1e+10 (\pm 1.6e+10)$ |

Furthermore, another recent ALMA study by Cox et al. (2018) of 10 young Class 0/I protostars shows that the polarization degree is relatively high ($\geq 5\%$) in the envelope but low in the inner disk ($\leq 1\%$). They suggested that self-scattering is dominant in the inner disk, whereas the magnetically aligned dust is likely dominant in the envelopes. In contrast, MMS 6 shows consistently high polarization degrees in the central 200 au, both for the centrally concentrated structure and the ringlike structure. Note that our MMS 6 image has a 10 au resolution, whereas the study by Cox et al. (2018) has a resolution of only $\approx 80$ au. Alternative possible explanations of the very different polarization degree observed within the central 200 au may be caused by the beam dilution effect, as pointed out in Section 3.3.

In summary, the self-scattering model can explain the polarization pattern and positional offset between the Stokes $I$ and the PI detected at the centrally concentrated component. This is consistent with other protostellar sources, such as GGD27 MMS 1 and VLA 1623. However, the self-scattering model cannot reproduce the high polarization degree observed in MMS 6. To further explore the possibility of the self-scattering effect for MMS 6, multiwavelength dust polarization experiments are crucial. If self-scattering is a dominant mechanism, we expect changes in the polarization degree as a function of the wavelength (Kataoka et al. 2015).

Finally, as a third model, we consider the magnetically aligned dust grain model (Figure 6(a)). In this model, the direction of the (uniform) interstellar magnetic field is given by the direction of the $B$-vector. Thus, the magnetic field projected onto the celestial plane is obtained as the perpendicular direction to the observed $E$-vectors as presented in Figure 5(c). In the centrally concentrated component, the interstellar magnetic field seems to run parallel to the major axis. The P.A. is measured to be $45^\circ$, which is consistent with the orientation of the large-scale magnetic field (Matthews & Wilson 2000; Matthews et al. 2001, 2005; Poidevin et al. 2010; Hull et al. 2014).

On the other hand, the magnetic field vectors located on the ringlike structure, especially at the SE and NW components, show the $E$-vectors (P.A. = 115–130$^\circ$) almost perpendicular to those associated with the centrally concentrated components. One possible way to explain the observed field configuration is a toroidal wrapping of the magnetic field lines. Tomisaka (2011) modeled magnetically driven molecular outflows through MHD and radiative transfer simulations. The results suggest that the toroidal magnetic field is dominant on $\leq 400$ au (i.e., size scale of pseudo disks) and that the projected magnetic field vectors change significantly depending on their viewing angle. According to Figure 5 of Tomisaka (2011), ALMA results share some characteristic structures expected from the simulation results.
when choosing the inclined models (i.e., the viewing angle of 45°–60° in this model). First, the magnetic field structures at the 200 au scale do not seem to follow the orientation of the large-scale outflow, but rather are associated with the toroidal component of the pseudo disk. Second, the brightness of the polarized emission within the toroidal component is not uniform, depending on the azimuthal angle. The ringlike structure observed in MMS 6 looks somewhat similar to those presented in Tomisaka (2011). Moreover, the relation between the magnetic field orientation and the core rotational axis (outflow axis) also adds another important factor in determining the magnetic field orientations (Kataoka et al. 2012). This will be discussed further in Section 4.3.

Among the three proposed scenarios, the magnetic field model seems to explain the overall distribution of both the Stokes I and polarized emission, not only the displacement of the peaks of Stokes I and polarized emission, but also the ringlike structures and depolarization gaps. The Stokes I emissions correspond to the spatial distribution of the column density combined with the dust temperature, whereas the polarized emissions correspond to the locations of the E-vectors; therefore, the magnetic fields are most organized and not necessary to correlate with the Stokes I emission. The observed high polarization degree, which cannot be reproduced by the self-scattering mechanism, can also be explained by the magnetically aligned dust model.

In addition to the listed individual mechanisms, the importance of a hybrid model combining them and the change of the dust alignment mechanisms across the wavelengths has been pointed out from the ALMA observations of HL Tau (Kataoka et al. 2017; Stephens et al. 2017). Their results suggest that the self-scattering mechanism dominates at 870 μm, a hybrid model of the self-scattering and the dust alignment due to the anisotropic radiation explains the results obtained at 1.3 mm, and the anisotropic radiation mechanism dominates at 3.1 mm. Multiwavelength polarization experiments will, therefore, be essential to distinguish the origins of the polarized emission and to disentangle the multiple mechanisms at play.

Moreover, we would like to note that a strong wind or jet might mechanically align the dust grains. Gold (1952) discussed dynamical interaction between gas and elongated dust particles. In this model, the major axis of dust grains prefers to align parallel to the supersonic gaseous flow; hence, the E-vectors should be observed along the outflow axis. Figure 7 presents a zoomed image of the SiO collimated outflow14 overlaid with the polarized emission. The observed E-vectors are aligned perpendicularly to the cavity of the outflow, particularly in the southern lobe.15 The observational result does not support the scenario expected by Gold (1952), whereas the result is more consistent with a scenario proposed by Lazarian & Hoang (2007), involving an alternative mechanical alignment of helical dust grains. In this scenario, the helical dust grains align with the minor axis being parallel to the gaseous flow (both supersonic and subsonic cases). This results in E-vector that are perpendicular to the gas outflow. However, the magnetic alignment also predicts E-vectors perpendicular to the gas outflow if the magnetic field is parallel to the gas velocity. Thus, the mechanical alignment proposed by Lazarian & Hoang (2007) and the magnetic alignment predict the same polarization pattern for the outflow region. Recent ALMA dust polarization observations reported similar E-vector configurations, likely tracing the outflow cavity in two other Class 0 sources, namely B335 (Maury et al. 2018) and L1157 (Kwon et al. 2018).

Finally, it is interesting to note that the polarized emission peaks seem to avoid to overlap with the SiO collimated outflow. The outflow may have impacted the ringlike structure, pushing aside the gas. Alternatively, the outflow and the ringlike structure are not in the same plane but are projected along the line of sight.

4.3. Comparisons with the MHD Simulations

High sensitivity and high angular resolution at millimeter and submillimeter wavelengths of the polarized dust emission became available with ALMA, enabling us to make direct comparisons between high angular resolution images and detailed theoretical models. In this section, we present comparison using our ALMA data MMS 6 with MHD simulations, and we discuss how the observational results could be further interpreted with a magnetic field model (i.e., the third model discussed in Section 4.2.2).

To take account of both the viewing angle of the system and the relation between the magnetic field orientation and the core rotational axis (outflow axis) and to compare the model results

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14 SiO data will be presented in a separated article (S. Takahashi et al. 2019, in preparation).
15 Most of the E-vectors on the northern lobe seem to trace the large-scale magnetic fields (P.A. ≈ 45° in Figure 7(b)), which likely originated from the foreground fields associated with the cloud or envelope.
with our ALMA data, we executed a three-dimensional nonideal MHD simulation according to the following steps. As the initial state of the prestellar core, we assumed a Bonnor–Ebert sphere with a central density of $2 \times 10^5$ cm$^{-3}$ and an isothermal temperature of 10 K. A uniform magnetic field ($B_0 = 26 \mu$G) and rigid rotation ($\Omega_0 = 1.0 \times 10^{-13}$ s$^{-1}$) are imposed, in which the magnetic field direction is inclined from the rotation axis by $45^\circ$. We use the Cartesian coordinate, in which we choose the direction of the $z$-axis to coincide with the direction of the initial magnetic field (i.e., $B_0 = (0, 0, B_0$). The rotation axis is in the $x-z$ plane as $\Omega_z = \Omega_0(\sqrt{2}, 0, 1/\sqrt{2})$. Here, the offset between the magnetic field axis and rotation axis is determined from the measured magnetic field direction (Hull et al. 2014) and the outflow axis (Takahashi & Ho 2012). The mass and radius of the prestellar core are $M_{\text{core}} = 8.7 M_\odot$ and $R_{\text{core}} = 2.5 \times 10^4$ au, respectively. Using the nested grid method (for details, see Machida et al. 2005), we calculated the core evolution from the protostellar runaway collapse phase to the protostellar phase, during which the outflow is launched, and the outflow reaches $\sim 5000$ au. The cell size of the finest grid is 0.2 au. The details of the MHD simulation are described in Machida & Hosokawa (2013). Note that, in this simulation, we used a sink cell technique, in which the central region was masked by the sink cell. Thus, we cannot resolve the central region or protostar itself.

The column density (reflects Stokes $I$), the polarized emission, and the magnetic field vectors are calculated and integrated along the line of sight to make a projected polarization map (Tomisaka 2011). An optically thin condition was assumed when making this projection. A viewing angle of $i = 60^\circ$ was used. This viewing angle was chosen so that the blue and redshifted outflow lobes do not overlap in agreement with previous outflow observations (Takahashi & Ho 2012). Also, the inclination angle of $60^\circ$ appears to be a better fit to explain our observed results as presented in Figure 5(c).

Figure 5 presents the MHD simulation result obtained for MMS 6 with $i = 60^\circ$. Figures 8 presents the MHD simulation result obtained for MMS 6 with $i = 60^\circ$. Figures 9(a) and (b) show the expected polarization maps plotted for two different size scales. We found that our ALMA images presented in Figures 8(a) and (c) share some characteristic structures predicted from the MHD simulation. First, the simulation results show that arms on the size scale of $\sim 500$ au are connected to the central component (Figure 9(a)). The magnetic field structures ($B$-vectors) within the arms are aligned along the major axis. The spiral arms are seen within the pseudo disk, which is produced owing to the magnetic field and the core rotation. The material in the arms accretes toward the central region through the spiral arms. Our ALMA data presented in Figure 5(a) show that the armlike structure extend to the 2000 au scale. The $B$-vector orientations are also aligned along the major axis of the structure, and the armlike structure is connected to the central component from the western side.

Second, within the central 100 au, the MHD simulation result shows a ringlike structure that produces a relatively high PI (Figure 9(b)). We see local peaks within the ringlike structure due to the effect of integrating polarized emission along the line of sight. The magnetic field vectors in the ringlike structure are aligned more or less along the minor axis of the structure with some fluctuation. In this simulation, although the PI shows a ringlike emission distribution, the column density (reflects Stokes $I$) increases toward the center. Moreover, within the ringlike structure, we can see PI variation (local peaks). $B$-vector orientations in the ringlike structure are also aligned along the minor axis of the structure, as seen in Figure 4(c).

Table 4

| Magnetic Field | Self-scattering | Anisotropic Radiation |
|----------------|-----------------|-----------------------|
| (i) Spatial distribution difference between Stokes $I$ and PI | $\bigcirc$ | $\bigtriangleup$ | $\times$ |
| (ii) Peak positional offset between the Stoke $I$ and PI | $\bigtriangleup$ | $\bigcirc$ | $\bigtriangleup$ |
| (iii) Ringlike depolarized region (ringlike gap) | $\bigcirc$ | $\bigtriangleup$ | $\times$ |
| (iv) Change of the $E$-vector orientations across the ringlike gap | $\bigcirc$ | $\bigcirc$ | $\bigtriangleup$ |
| (v) High polarization percentage of $\geq 10\%$ | $\bigtriangleup$ | $\times$ | $\bigtriangleup$ |

Note.

$^\text{a}$ $\bigcirc$: Result can be reproduced by the existing models, $\bigtriangleup$: Result could be explained by the proposed model qualitatively, but no clear cases are reported as publication before. $\times$: Result cannot be explained by the existing models.

In summary, by adjusting the viewing angle around the outflow driving region, the present MHD simulation can qualitatively explain the characteristic features of the ALMA observations, such as the $B$-vector orientations, in both the large (1000 au scale) and small (within a few 100 au) scales. The magnetic field model also explains differences in the spatial distribution between the Stokes $I$ and the PI.

5. Summary and Future Prospects

Using ALMA, we performed full polarization high angular resolution observations of the dust continuum emission at 1.1 mm toward a very young intermediate-mass protostellar source, MMS 6/OMC-3. We have achieved the spatial angular resolution of $0.03 \times 0.02$ corresponding to a linear size scale of $\approx 10$ au at the distance to the source. The main findings of the study are as follows.

1. Our high angular resolution image shows the complexity of the Stokes $I$ emission and PI within 200 au of the center. Although Stokes $I$ emission shows a single peak toward the

16 The inclination angle $i$ is the angle between the direction of the initial magnetic field and the line of sight. $i = 0^\circ$ is defined as the $z$-direction.
center, the dust polarization map shows two different components, which are characterized as the centrally concentrated component and the ringlike structure with a clear depolarization gap between the two components. Stokes I emission and PI also show a clear positional offset.

2. The detected E-vectors are spatially resolved in the central 200 au and clearly show organized structures. Significant changes in the E-vector position angles of $90^\circ$–$105^\circ$ are observed from the partial ringlike structure, particularly at the SE and NW components to the centrally concentrated component. A high polarization percentage of $\gtrsim 10\%$ is derived in the central 200 au both in the ringlike structure and the centrally concentrated component.

3. We have analyzed origin of the polarized emission and three main mechanisms to align dust grains and/or to produce polarization: (i) magnetic field, (ii) self-scattering, and (iii) anisotropic radiation. On the basis of a comparison with the available data, the magnetic field scenario appears to explain best the observed characteristics. The E-vector orientations in the centrally concentrated component are also consistent with the self-scattering model with an optically thick disklike structure. However, the polarization degree appears to be significantly higher than the expected value for the self-scattering mechanism.

4. The armlike structure is also observed on large scales ($\approx 2000$ au). The detected polarization E-vectors are aligned along the minor axis of the armlike structure, which is consistent with magnetically aligned dust in the field parallel to the major axis of the arm.

5. We also performed an MHD simulation to further explore the magnetic field structures at the vicinity of the protostar. After taking into account the viewing angle effect and the misalignment between the initial magnetic field orientation and core rotational axis (i.e., outflow axis adjusted for the case of MMS 6), the calculated projected polarization image reproduces most of the characteristic structures observed in the ALMA images, including the ringlike structure and the armlike structure. This
agreement further supports that the origin of the dust alignment for this source can be explained by a toroidal wrapping of the magnetic fields. However, the observed centrally concentrated component is not reproduced because of the limitations of the current MHD simulations.

This is the first time that study of the polarization could be done in such detail in a protostellar core and that new questions and issues have come up that need to be further scrutinized. From the observational side, multiwavelength polarization experiments with similarly high angular resolution will be crucial to assess the hybrid models by investigating contributions from the self-scattering and dust alignment by anisotropic radiation. From the theoretical side, taking into account the optical depth effect and the contribution from the central protostar will help to further study the polarization properties in the central 200 au. These improvements will be done in our next articles.

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References
Alves, F. O., Girart, J. M., Padovani, M., et al. 2018, A&A, 616, A56
Andrâ, P., Men’shchikov, A., Bontemps, S., et al. 2010, A&A, 518, L102
Anglada, G., Villuendas, E., Estalella, R., et al. 1998, AJ, 116, 2953
Atee, H. G., Shepherd, D., Gaeth, F., et al. 2007, in Protostars and Planets V, ed. B. Reipurth, D. Jewitt, & K. Keil (Tucson, AZ: Univ. of Arizona Press), 245
Bacciotti, F., Girart, J. M., Padovani, M., et al. 2018, ApJL, 865, L12
Banerjee, R., & Padrid, R. E. 2006, ApJ, 641, 949
Chini, R., Reipurth, B., Ward-Thompson, D., et al. 1997, ApJL, 474, L135
Commerçon, B., Hennebelle, P., Audit, E., Chabrier, G., & Teyssier, R. 2010, A&A, 510, L3
Cortes, P. C., Girart, J. M., Hull, C. L. H., et al. 2016, ApJL, 825, L15
Cox, E. G., Harris, R. J., Looney, L. W., et al. 2018, ApJ, 855, 92
Crutcher, R. M. 2012, ARR&A, 50, 29
Davis, L., Jr., & Greenstein, J. L. 1951, ApJ, 114, 206
Dent, W. R. F., Pinte, C., Cortes, P. C., et al. 2019, MNRAS, 482, L29
Galli, D., & Shu, F. H. 1993, ApJ, 417, 243
Girart, J. M., Beltrán, M. T., Zhang, Q., Rao, R., & Estalella, R. 2009, Sci, 324, 1408
Girart, J. M., Fernández-López, M., Li, Z.-Y., et al. 2018, ApJL, 856, L27
Girart, J. M., Frau, P., Zhang, Q., et al. 2013, ApJ, 772, 69
Girart, J. M., Rao, R., & Marrone, D. P. 2006, Sci, 313, 812

Figure 9. Projected polarization images produced by the MHD simulation presented in Figure 8. Viewing angle of $\theta = 60^\circ$ and $\phi = 0^\circ$ are used to integrate over the system. Panel (a) shows the large-scale image (central 900 au region), and (b) shows a zoomed image (central 120 au). Definitions of the coordinate and image size follows those from Tomisaka (2011). Column density, magnetic field orientations, and PI are denoted in gray contours, black lines, and color images overlaid with black contours, respectively. Polarization (color) is calculated from the relative Stokes parameters (Lee & Draine 1985; Tomisaka 2011), assuming that the dust properties, dust alignment degree, and dust temperature are all uniform. Thus, the unit of the PI is arbitrary and the color indicates only the relative difference of the PI.
