Characterizing three-dimensional magnetic field, turbulence, and self-gravity in the star-forming region L1688

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ABSTRACT

Interaction of three-dimensional magnetic fields, turbulence, and self-gravity in the molecular cloud is crucial in understanding star formation but has not been addressed so far. In this work, we target the low-mass star-forming region L1688 and use the spectral emissions of $^{12}$CO, $^{13}$CO, C$^{18}$O, and H I, as well as polarized dust emissions. To obtain the 3D direction of the magnetic field, we employ the novel polarization fraction analysis. In combining with the plane-of-the-sky (POS) magnetic field strength derived from the Davis–Chandrasekhar-Fermi (DCF) method and the new Differential Measure Analysis (DMA) technique, we present the first measurement of L1688's three-dimensional magnetic field, including its orientation and strength. We find that L1688’s magnetic field has two statistically different inclination angles. The low-intensity tail has an inclination angle $\approx 55^\circ$ on average, while that of the central dense clump is $\approx 30^\circ$. We find the global mean value of total magnetic field strength is $B_{\text{tot}} \approx 135 \mu$G from DCF and $B_{\text{tot}} \approx 75 \mu$G from DMA. We use the velocity gradient technique (VGT) to separate the magnetic fields’ POS orientation associated with L1688 and its foreground/background. The magnetic fields’ orientations are statistically coherent. The probability density function of H$_2$ column density and VGT reveal that L1688 is potentially undergoing gravitational contraction at large scale $\approx 1.0$ pc and gravitational collapse at small scale $\approx 0.2$ pc. The gravitational contraction mainly along the magnetic field resulting in an approximate power-law relation $B_{\text{tot}} \propto n_H^{1/2}$ when volume density $n_H$ is less than approximately $6.0 \times 10^3$ cm$^{-3}$.

Key words: ISM:general—ISM:structure—ISM:magnetohydrodynamics—turbulence—magnetic field

1 INTRODUCTION

Magnetic field, turbulence, and self-gravity play vital roles in the evolution of molecular cloud (Larson 1981; Crutcher 2004; Ballesteros-Paredes et al. 2011; Crutcher 2012a; Hu et al. 2020b, 2021b; Alina et al. 2022). On cloud scales, turbulence and magnetic field can provide global support against gravitational collapse and gravitational contraction (Elmegreen 1993; Padoan 1995; Klessen et al. 2000; Crutcher 2004, 2012b; Lazarian et al. 2012; Federrath & Klessen 2012; Vázquez-Semadeni et al. 2019). However, turbulence additionally can produce compression and local density enhancements serving as seeds of star formation (Mac Low & Klessen 2004; McKee & Ostriker 2007; Federrath & Klessen 2012). In view of the importance, intense efforts to access these three factors have been made.

Typically the significance of turbulence can be measured by the emission line’s width due to the Doppler shift effect. Such measurement already revealed the supersonic nature of molecular cloud (Bieging et al. 2010; Shimajiri et al. 2011; Leroy et al. 2015; Federrath et al. 2016; Hu et al. 2021b). Measuring the magnetic field is even more challenging. The plane-of-the-sky (POS) magnetic field orientation can be traced by polarized dust emission based on the property that radiative torques (RATs) align dust grains with their semi-major axis perpendicular to the magnetic field (Lazarian & Hoang 2007; Andersson et al. 2015). The line-of-sight (LOS) magnetic field strength is traced by Zeeman splitting (Crutcher 2004, 2012a) or Faraday rotation (Tahani et al. 2018). However, because these measurements alone probe different regions of the multi-phase interstellar medium (ISM) or are sensitive to distinct density ranges, they cannot be easily combined to yield the full 3D magnetic field vector, including both 3D direction and total strength.

Due to this limitation, observational studies of turbulence, magnetic field, and self-gravity’s interaction still stay in two-dimension, i.e. either the POS or the LOS component. For instance, the Davis–Chandrasekhar–Fermi (DCF) method (Davis 1951; Chandrasekhar & Fermi 1953) is widely used to estimate the POS magnetic field strength (Hu et al. 2021b; Pattle et al. 2021; Hwang et al. 2021; Li et al. 2021; Hoang et al. 2022; Tram et al. 2022). The limitations of DCF were discussed extensively in literature (Skalidis et al. 2021; Lazarian et al. 2022; Chen et al. 2022; Liu et al. 2022), and an alternative Differential Alignment Measure (DMA; Lazarian et al. 2022) technique was introduced. In this paper, we use both techniques and compare their results.
To access the 3D magnetic field, we employ the recently proposed dust polarization fraction analysis (Hu & Lazarian 2023). This method uses the fact that the linear polarization fraction is sensitive to the efficiency with which grains are aligned with respect to the magnetic field, the POS magnetic field’s degree of disorder, and the 3D magnetic field’s inclination angle with respect to the LOS. Under the assumption of homogeneous dust grains’ properties, the observed polarization fraction in a strongly magnetized region, i.e., with an ordered POS magnetic field angle, is only determined by the inclination angle (Chen et al. 2019; Hu & Lazarian 2023). The inclination angle, therefore, can be calculated from the corresponding polarization fraction based on their correlation given in Hu & Lazarian (2023). This technique is termed Polarization Fraction Analysis (PFA). Combining with DCF or DMA, this technique opens a new way to characterize the 3D magnetic field, including both POS and LOS components’ orientation and strength. Especially, both the POS and the LOS components are inferred from the same polarization data set, the two components are not fully independent. PFA ensures the measured LOS and POS magnetic fields are from the same ISM phase and spatial region.

This work aims at providing the first observational analysis of 3D magnetic fields in nearby molecular clouds. We target the star-forming region L1688, which is one of the closest star-forming clouds located at a distance of approximately 139 pc (Wilking et al. 2008; Ortiz-León et al. 2018). It has a large and varied population of young stellar objects, serving as an excellent object for studying low-mass star formation (Dunham et al. 2015). Although L1688 has been investigated over a wide wavelength range providing intensive data sets, the interaction of 3D magnetic field, turbulence, and self-gravity has never been studied. In the paper below, we use the Planck (Planck Collaboration et al. 2020b), HAWC+ (Santos et al. 2019) polarized emission, and the Velocity Gradient Technique (VGT; González-Casanova & Lazarian 2017; Yuen & Lazarian 2017; Lazarian 2019 & Yuen 2018; Hu et al. 2018) to trace the POS magnetic field. PFA and DCF (or DMA) output the inclination angle and POS magnetic field strength, respectively. In addition, we assess the significance of turbulence from 12CO (1-0) and 13CO (1-0) emission lines obtained from the COMPLETE survey (Ridge et al. 2006). The C18O (3-2) observed with the APEX telescope provides information on a zoom-in region around Oph A (Liseau et al. 2010). As for the role of self-gravity, we use the probability density function (PDF; Ballesteros-Paredes et al. 2011; Collins et al. 2012; Burkhart 2018; Körtgen et al. 2019; Hu & Lazarian 2021) of Herschel’s column density (Ladjelate et al. 2020) as well as VGT to identify the gravity-dominated region.

This paper is organized as follows. In § 2, we briefly describe the observational data. In § 3, we introduce the statistic tools used in this work. In § 4, we present our results of the identified self-gravitating density (Ladjelate et al. 2020) as well as VGT to identify the gravity-dominated region. The uncertainties of polarization fraction and polarization angle are presented in Figs. A1 and A2. The uncertainties in our analysis in § 5 and give a summary in § 6.

2 OBSERVATIONAL DATA

2.1 12CO, 13CO, and C18O emission lines

In this work, we adopt the 12CO (1-0) and 13CO (1-0) emission lines over the L1688 cloud provided by the COMPLETE survey (Ridge et al. 2006). The observation was performed with the 14m Five College Radio Astronomy Observatory (FCRAO) telescope. Each line was measured with a total bandwidth of 25 MHz and 1024 channels, yielding an effective velocity resolution of 0.07 km/s. The Half Power Beam Width (HPBW) of the observation is ≈ 46″ for 12CO and ≈ 44″ for 13CO. The final data cube, however, is convolved onto a regular 23″ per pixel resolution. The RMS noise level per channel is ≈ 0.98 K for 12CO and ≈ 0.33 K for 13CO in unit of antenna temperature T_A. The radial velocity of the cloud’s bulk motion ranges from 0 to 7 km/s. We select the emissions within this velocity range for our analysis.

The C18O (3-2) emission was observed with the 12m APEX telescope (Liseau et al. 2010). The observation at 329 GHz has HPBW ≈ 19″ and is sampled according to the Nyquist criterion onto 2.5″ per pixel. The data cube achieves a velocity resolution ≈ 0.11 km/s with a RMS noise ≈ 0.05 K in unit of T_A.

2.2 H I emission line and H2 column density

Cube of 21 cm H I emission were observed with the 100m NRAO Green Bank Telescope (Li & Goldsmith 2003). The data has beam resolution HPBW ≈ 9″ and is regridded to 4′ per pixel. The final data have a spectral resolution of 0.32 km/s and the corresponding RMS noise level is ≈ 0.15 K.

The H2 column density data with beam resolution ≈ 18.2″ is obtained from the Herschel Gould Belt Survey (André et al. 2010). The data of the Ophiuchus molecular cloud was presented in Ladjelate et al. (2020).

2.3 Polarized dust emission

The POS magnetic field orientation was inferred from the Planck 353 GHz and HAWC+ polarized dust thermal emission. In this work, we use the Planck 3rd Public Data Release (DR3) 2018 of High Frequency Instrument (Planck Collaboration et al. 2020a) at 353 GHz (HPBW ≈ 5′), HAWC+ band A (53 μm; HPBW ≈ 4.8″), and HAWC+ band C (89 μm; HPBW ≈ 7.8″). The polarization angle φ is defined through Stokes parameters I, Q, and U:

\[ \phi = \frac{1}{2} \arctan(-U, Q), \]  

where −U converts the angle from the HEALPix convention to the IAU convention and the two-argument function arctan is used to account for the π periodicity. The magnetic field angle is inferred from \( \phi_B = \phi + \pi/2 \).

To correct the observed polarization fraction \( p \) for the bias, we adopt the commonly used debiasing method (Wardle & Kronberg 1974; Pattle et al. 2019), under which the debiased \( p \) is given by:

\[ p = \frac{\sqrt{Q^2 + U^2} - \frac{1}{2}(\delta Q^2 + \delta U^2)}{I}, \]  

where \( \delta Q \) and \( \delta U \) are the uncertainties in Stokes \( Q \) and \( U \), respectively.

As for HAWC+, the debiased polarization fraction and corresponding uncertainty maps are directly available in SOFIA data archive (see Santos et al. 2019). We select only pixels with \( p/\delta p > 3 \) and \( I/\delta I > 100 \). A summary of the data sets is available in Tab. 1.

1 Based on observations obtained with Planck (http://www.esa.int/Planck), an ESA science mission with instruments and contributions directly funded by ESA Member States, NASA, and Canada.
Table 1. Information of observational data sets used in this work.

| Observation       | Frequency or wavelength | Beam resolution | Velocity resolution | Reference                      |
|-------------------|-------------------------|-----------------|--------------------|--------------------------------|
| H I               | 21 cm                   | 9''             | 0.32 km/s          | Li & Goldsmith (2003)           |
| \(^{12}\)CO (1-0) | 115.271 GHz             | 46''            | 0.07 km/s          | Ridge et al. (2006)             |
| \(^{13}\)CO (1-0) | 110.201 GHz             | 44''            | 0.07 km/s          | Ridge et al. (2006)             |
| C\(^{18}\)O (3-2) | 329 GHz                 | 19''            | 0.11 km/s          | Liseau et al. (2010)            |
| H\(_2\)          | -                       | 18.2''          | -                  | André et al. (2010)             |
| Planck polarization | 353 GHz               | 5''             | -                  | Planck Collaboration et al. (2020b) |
| HAWC+ polarization | 154 \(\mu\)m & 89 \(\mu\)m & 53 \(\mu\)m | 7.8'' & 4.8'' | -                  | Santos et al. (2019)            |

3 METHODOLOGY

3.1 Probability density function of H\(_2\) column density

The PDF of H\(_2\) column density is widely used to study turbulence and self-gravity in the ISM. The PDF follows a hybrid of log-normal distribution \(P_{\text{LN}}(s)\) in diffuse turbulence-dominated region and power-law distribution \(P_{\text{PL}}(s)\) in gravity-dominated region (Ballesteros-Paredes et al. 2011; Collins et al. 2012; Burkhart 2018; Körtgen et al. 2019; Hu & Lazarian 2021):

\[
P_{\text{LN}}(s) \propto \frac{1}{\sqrt{2\pi \sigma_s^2}} e^{-\frac{(\log(s) - \mu_s)^2}{2\sigma_s^2}}, s < S_t, \tag{3}
\]

\[
P_{\text{PL}}(s) \propto s^{\alpha s}, s > S_t,
\]

where \(s = \log(N_{\text{H}_2}/\overline{N_{\text{H}_2}})\) is the logarithm of the column density \(N_{\text{H}_2}\) normalized by its mean value \(\overline{N_{\text{H}_2}}\), \(S_t\) is transitional density between the \(P_{\text{PL}}\) and \(P_{\text{LN}}\), \(\mu_s\) is the mean logarithmic density, \(\sigma_s\) represents the standard deviation, and \(\alpha\) stands for the power-law distribution’s slope. The value of \(\alpha\) changes in roughly the cloud mean free-fall time from steep \(\approx -3\) to shallow \(\approx -1.5\). A shallow slope indicates a high star formation rate (Burkhart 2018).

3.2 Velocity gradient technique

VGT is a novel approach to tracing the POS magnetic field in molecular clouds. VGT relies on the theories of MHD turbulence and turbulent reconnection (Goldreich & Sridhar 1995; Lazarian & Vishniac 1999). It used the fact that the magnetized and turbulent eddies are anisotropic, i.e., elongating along the direction of magnetic field. The anisotropy means maximum velocity fluctuation appears in the direction perpendicular to the magnetic field. Consequently, the gradient of velocity fluctuation is also perpendicular to the magnetic field. However, in the case that gravitational collapse dominates over MHD turbulence, the velocity gradient’s orientation is determined by the infall acceleration being parallel to the magnetic field (Hu et al. 2020a, 2021b). The properties of velocity gradients were first theoretically predicted and then confirmed observationally.

Obtaining velocity information from observations is not trivial. One of the possible ways is using thin velocity channels, which are dominated by the effect of velocity caustics (Lazarian & Pogosyan 2000; Kandel et al. 2017). The effect means that real density structures with different velocities along the LOS are sampled into different velocity channels. The observed intensity structures in a velocity channel are distorted due to turbulence. When the velocity channel is narrow enough (i.e., the channel width is smaller than the velocity dispersion), the distortion is significant, and the observed intensity fluctuation is dominated by velocity fluctuation rather than density fluctuation (Lazarian & Pogosyan 2000). One can, therefore, use the thin velocity channels to get velocity fluctuations and calculate the velocity gradient. Further improvements are possible on the basis of the general theory of Position-Position-Velocity (PPV) statistics developed in Lazarian & Pogosyan (2000).

We adopt the VGT recipe used in Hu et al. (2022) and briefly describe it here. (i) each thin channel map was convolved with a 3×3 Sobel Kernel to create a raw gradient map (pixels are blanked out if their intensity is less than three times the RMS noise level); (ii) the mean gradient angle at each pixel is statistically calculated from the sub-block average method, in which the histogram of raw gradients’ orientation within a rectangle sub-block (size = 20×20 pixels, which is a numerically and empirically optimal value; Lazarian & Yuen 2018; Hu et al. 2021b) is fitted with a Gaussian distribution to find the most probable orientation; (iii) the cosine and sine values of each sub-block averaged gradient map is weighted with the corresponding channel’s intensity and integrated along the LOS to construct pseudo-Stokes parameter \(Q_g\) and \(U_g\). (iv) the POS magnetic field orientation inferred from VGT is then \(\phi_{\text{VGT}} = \frac{1}{2} \arctan(U_g/Q_g) + \pi/2;\)

The alignment between VGT measurement and polarization measurement is quantified by the Alignment Measure (AM; González-Casanova & Lazarian 2017), defined as:

\[
AM = 2\cos^2 \theta_r - \frac{1}{2}, \tag{4}
\]

where \(\theta_r\) is the relative angle between the two angles. AM is a relative scale ranging from -1 to 1, with AM = 1 indicating that two angles are parallel and AM = -1 denoting that the two are orthogonal.
3.3 Measuring magnetic field

3.3.1 Davis-Chandrasekhar-Fermi (DCF) method

Traditional DCF:
The POS magnetic field strength can be obtained via the DCF method (Davis 1951; Chandrasekhar & Fermi 1953). Assuming the variations of the magnetic field direction arise from isotropic incompressible turbulence and ordered variation in the magnetic field is insignificant, the magnetic field strength is expressed as:

\[ B = f \sqrt{4\pi \rho \sigma v / \sigma \phi}, \]  

where \( f = 0.5 \) is an empirically chosen correction factor (Ostriker et al. 2001), \( \rho \) is the volume mass density. \( \sigma v \) and \( \sigma \phi \) represent 1D turbulent velocity dispersion along the LOS and polarization angle’s dispersion on the POS. The uncertainty of polarization angle (given in Fig. A2 with a median value of \( \approx 14^\circ \)) may affect \( \sigma \phi \). In any case, we discuss more about the uncertainties related to the DCF method in § 5.3.

Modification of DCF:
The shortcoming of the traditional DCF is that the dispersion of angles is calculated about the mean, the latter being a poorly defined quantity in observations. To deal with this problem we propose a modified DCF, where we calculate the angle dispersion in a different way. In our study, \( \sigma \phi \) is characterized by angular statistics (Fisher 1995; Lazarian et al. 2018):

\[ \sigma \phi = \sqrt{- \log (\cos \phi)^2 + \langle \sin \phi \rangle^2}, \]  

where \( \langle \ldots \rangle \) stands for ensemble average. Note that in the formula, \( \phi \) is in the range of \( [-\pi, \pi] \), but the polarization angle in observational data is in the range of \( [-\pi/2, \pi/2] \). Therefore, we double the polarization angle when processing the observational data and divide \( \sigma \phi \) by two as the final result. Fig. 1 presents a simple numerical test of Eq. 6. We generate 10 sets of Gaussian random numbers (1000 numbers per set). Each set is assigned a dispersion and a random mean value. We see Eq. 6 accurately recovers the dispersion. For our purpose of using the DCF method, \( \sigma \phi \) is estimated for each sub-block with size 30 \( \times \) 30 pixels (pixel resolution: \( \approx 23\° \)) covering approximately 3 \( \times \) 3 independent beams of Planck observation. The uncertainties raised by the choice of sub-block size and other factors are discussed in § 5.3.

3.3.2 Differential Measure Approach (DMA)

One of the limitations of DCF is that it is difficult to obtain the dispersion of the angles and velocities over limited areas (see § 5). The subtraction of the thermal speed is also subject to errors. Moreover, DCF assumes that the observed fluctuations are purely raised Alfvén waves on the POS. The real MHD turbulence, however, is composed of compressible modes (Cho & Lazarian 2003).

These and other problems of DCF were addressed by the DMA technique in Lazarian et al. (2022). In what follows, we employ the simplest, version of the DMA. It was shown in Lazarian et al. (2022) that even this “naïve” version of the DMA provides better recovery of the magnetic field values compared to DCF. That simplified version can be presented as:

\[ B = f' \sqrt{4\pi \rho / D_v(l) / D_\phi(l)}, \]  

where \( D_v \) and \( D_\phi \) are the second order structure function of velocity centroid \( C(r) \) and polarization angle at scale \( l \), respectively. The adjustment factor \( f' \) depends on the composition of turbulence in terms of three basic MHD modes (Cho & Lazarian 2003) and the magnetic field’s inclination angle. Here we choose a constant scaling factor \( f' = 0.5 \) for the purpose of comparing DCF and DMA.

The quantities that enter the structure functions above are defined as:

\[ C(r) = \int T_{mb}(r, v)dv / \int T_{mb}(r, v)dv, \]

\[ D_v(l) = ((C(r) - C(r + l))^2), \]

\[ D_\phi(l) = ((\phi(r) - \phi(r + l))^2), \]

where \( T_{mb}(r, v) \) is \(^{12}\)CO brightness temperature, \( v \) is the LOS velocity, and \( r = (x, y) \) is the spatial position on the POS. Note, that \( D_v \) and \( D_\phi \) are scale-dependent, but their ratio is not and can give the mean magnetic field strength over a sub-block of interests via Eq. 7. The sub-block size is selected as 30 \( \times \) 30 pixels to keep consistent with the DCF method.

3.4 Polarization fraction analysis (PFA)

To access the angle \( \gamma \) that the total magnetic field inclined to the LOS, we use the PFA proposed by Hu & Lazarian (2023). It is well known that the polarization fraction is correlated with dust grains’ intrinsic properties, the POS magnetic field’s degree of disorder, and the 3D magnetic field’s inclination angle\(^2\) (Chen et al. 2019; Hu & Lazarian 2023). Assuming homogeneous conditions for dust grains, in a strongly magnetized region, \( M_{A, POS}^2 \ll 1 \), the fraction is mainly determined by the inclination angle. Here \( M_{A, POS} \) is the POS Alfvén Mach number. Obtaining the distribution of \( M_{A, POS} \) is non-trivial in observation\(^3\). However, \( M_{A, POS} \) is positively correlated with the dispersion of polarization angle, so we simplify the condition by using \( \sigma \phi \sim M_{A, POS} \) (Falcke-Gonzalves et al. 2008). Therefore, for such a region, we have (Hu & Lazarian 2023):

\[ \sin^2 \gamma = \frac{p_{off}(1 + p_{max})}{p_{max}(1 + p_{off})}, \]  

\[ \sigma_{\phi}^2 \ll 1, \]

where \( p_{max} \) is the maximum polarization fraction observed in a cloud and \( p_{off} \) is the polarization fraction corresponding to the region with \( \sigma_{\phi}^2 \ll 1 \). \( \sigma_{\phi}^2 \) is a second-order quantity so its uncertainty is even smaller and have only minimum effect.

The procedure to calculate the \( \gamma \) distribution is then: (i) calculating the map of \( \sigma \phi \) and finding the maximum value of \( p \) across the full cloud; (ii) dividing the map into a number of sub-blocks and getting the non-zero polarization fraction \( p_{off} \) corresponding to minimum \( \sigma \phi \) for each sub-block. To reduce uncertainty, here we take the polarization fraction’s average in the five positions satisfying \( \sigma_{\phi}^2 \ll 1 \) as \( p_{off} \); (iii) computing \( \gamma \) for each sub-block using Eq. 9. Same as the calculation of \( \sigma \phi \), we set the sub-block size to 30 \( \times \) 30 pixels to match the polarization dispersion map.

Note that PFA is different from another method proposed in Chen et al. (2019). There the observed polarization fraction in every pixel, together with \( p_{max} \), is used to derive a pixelized \( \gamma \) distribution. This method, however, assumes the polarization fraction is determined only by the inclination angle neglecting all magnetic field’s fluctuations, which could significantly decrease the polarization fraction in a turbulent molecular cloud.

\(^2\) Note PFA is measuring the (effective) mean inclination angle of an accumulation of various magnetic fields along the LOS.

\(^3\) The distribution of \( M_{A, POS} \) can be obtained from the velocity gradient’s dispersion (Lazarian et al. 2018; Hu et al. 2019) or the structure function analysis of velocity centroid (Xu & Hu 2021; Hu et al. 2021a).
4 RESULTS

4.1 Gravitational contraction and collapse

The PDF of H$_2$ column density is presented in Fig. 2. The PDF appears as log-normal at a low-density range, while it becomes power-law at a high-density range. In particular, the power-law part exhibits two distinct slopes. A shallow slope $s_1 \approx -0.99$ is observed in the range of $0.35 \leq s \leq 1.51$, while the slope becomes steep for $s \geq 1.51$. The power-law distribution indicates the presence of a self-gravitating medium while its slope characterizes the star formation activity. Slope $s_2 \approx -2.5$ suggests a rapid collapse process associated with a radial density distribution $\rho(r) \propto r^{-3}$, where $\rho$ is the volume mass density and $r$ is the radius to the center of collapse (Federrath & Klessen 2013). Slope $s_2 \approx -1$ suggests a rapid collapse process with an atomic density distribution $\rho(r) \propto r^{-2}$ in approximation. The two different slopes also result in two transition density $S_t \approx 0.35$ and $S_t \approx 1.51$ corresponding to column density $N_{H_2} \approx 5.5 \times 10^{21}$ cm$^{-2}$ and $N_{H_2} \approx 1.7 \times 10^{22}$ cm$^{-2}$, respectively. We outline the density structures within these two density ranges in Fig. 2. The high-density structures $N_{H_2} \geq 1.7 \times 10^{22}$ cm$^{-2}$ are more filamentary than the relatively low-density structures $5.5 \times 10^{21}$ cm$^{-2} \leq N_{H_2} \leq 1.7 \times 10^{22}$ cm$^{-2}$. While both of the structures are identified as gravity-dominated, it is more likely that the low-density structures are under global gravitational contraction at scale $\approx 1$ pc and high-density structures are gravitationally collapsing or fragmenting at scale $\approx 0.2$ pc. The corresponding infalling motion is evident in the increase of NH$_2$’s LOS velocity close to Oph B, C, E, and F (Choudhury et al. 2021).

4.2 POS magnetic field orientation

Figs. 3 and 4 show the POS magnetic field morphology traced by Planck and HAWC+ dust polarization, respectively. Planck focuses on a large field-of-view $\approx 1.6^\circ \times 1.6^\circ$ and large-scale magnetic field $\approx 0.2$ pc, while HAWC+ zooms in the dense core Oph A and provides information of small-scale magnetic field $\approx 0.003$ pc. We see that the large-scale magnetic field is along L1688’s north low-intensity tail. The magnetic field, however, is bent in the surroundings of the high-density clump appearing as a hourglass shape. This bending of the magnetic field happens exactly at the gravity-dominated region identified by the PDF (see Fig. 2). The hourglass magnetic field morphology is more apparent in the surroundings of the dense core Oph A (see HAWC+ 154$\mu$m in Fig. 4 and Santos et al. 2019 for a streamline visualization). The magnetic field is dragged into the densest region.

Apart from dust polarization, we also use VGT to trace the magnetic field morphology. VGT-H I, VGT-12CO, and VGT-13CO provide a view of large-scale magnetic field (H I: FWHM $\approx 20^\prime$, 12CO and 13CO: FWHM $\approx 7^\prime$) over the entire L1688 clump, while C$^{18}$O gives the information of small-scale magnetic field (FWHM $\approx 0.8^\prime$) in a zoom-in region. The magnetic fields inferred from VGT-12CO and VGT-13CO measurements are globally similar. VGT agrees well with the Planck polarization at L1688’s north low-intensity tail. Misalignment appears in the central dense clump coincident with the self-gravitating region identified by the PDF (see Fig. 2). The misalignment, therefore, comes from the effect of self-gravity and it is more significant in the dense-gas tracer 13CO. The misalignment, however, is usually less than 90$^\circ$ suggesting the gravitational collapse and gravitational contraction is not strong enough at scale $\approx 0.2$ pc and volume density $\approx 10^3$ cm$^{-3}$ so that the velocity gradient of turbulence is not overwhelmingly dominated by gravitational acceleration.

Importantly, although VGT-H I measurement is associated with the foreground and background rather than the molecular cloud, the VGT-H I magnetic field in the central dense clump agrees with Planck, VGT-12CO, and VGT-13CO measurements. This agreement means the variation of the magnetic field is insignificant in the foreground/background and the molecular cloud. The magnetic field in this case is expected to be strong so that the molecular gas’ motion is channeled by the magnetic field. The cloud is contracting and accreting gas along the magnetic field direction resulting in a disk-like or filamentary high-intensity clump Oph A, C, E, and F (see Fig. 2).

VGT-C$^{18}$O zooms in the small dense clump Oph A. The gradient’s orientation in the low-intensity region is almost along the west-east direction, while it changes by 90$^\circ$ in the high-intensity region being
Figure 3. Top: Morphology of magnetic fields revealed by the Planck polarization (streamlines) at 353 GHz and VGT (yellow segment) using $^{12}$CO ($J = 1-0$) emission. The magnetic field is overlaid with the intensity map of 353 GHz dust emission. The black circle represents the beamwidth of observation. Contours outline the intensity structures of $^{12}$CO starting from 5 K km/s. Middle: Morphology of magnetic fields revealed by VGT (colored segments) using $^{12}$CO emission. Colors on vectors present the AM of VGT and Planck polarization.

along the north-south direction. Comparing with HAWC+ polarization, the north-south orientation shows AM $= -1$, i.e., VGT is perpendicular to the polarization (see Fig. 6). This change of gradient’s orientation and perpendicular relative angle both suggest the high-intensity part of Oph A is undergoing rapid gravitational collapse at volumedensity $\sim 10^4$ cm$^{-3}$. Earlier Zeeman splitting measurements from OH or CN observations discovered that the molecular clouds at volume density $\sim 10^5 - 10^6$ cm$^{-3}$ are mainly self-gravitating (Crutcher 2012a). Our finding shows the volume density threshold for the collapse could be lower. However, more samples are required to achieve a statistically general conclusion.

4.3 Three-dimensional magnetic field orientation

The calculation of $\gamma$ relies on the dispersion of polarization angle and polarization fraction, which are displayed in Fig. 7. The northwest part of L1688 shows small-angle dispersion and a relatively high polarization fraction. However, the dispersion dramatically increases in the dense southwest part and the polarization fraction decreases to $\sim 2\%$. The low polarization fraction suggests that the large dispersion results from a small inclination angle so that the POS component is weak and more turbulent.

The distribution of $\gamma$ is presented in Fig. 7 and the histograms of polarization fraction and inclination angle are given in Fig. 8. The inclination angle of the northeast tail is around $45^\circ - 70^\circ$, but it changes to $10^\circ - 40^\circ$ in the southwest clump. The Planck polarization reported a maximum polarization fraction $\approx 22\%$ across the full sky (Planck Collaboration et al. 2020c), which should correspond to the case of inclination angle $\approx 90^\circ$.

For our data we have the maximum fraction $p_{\text{max}} \approx 10\%$ due to the depolarization effect caused by the changes in the magnetic

Figure 4. Top: magnetic fields inferred from HAWC+ polarization at 154 $\mu$m for a zoom-in region as indicated in the middle panel by a blue dashed box. Middle: magnetic fields inferred from HAWC+ polarization at 89 $\mu$m for a zoom-in region as indicated in Fig. 3 by a dashed box. Bottom: magnetic fields inferred from HAWC+ polarization at 53 $\mu$m for a zoom-in region as indicated in the middle panel by a black dashed box.
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Figure 5. Top: Morphology of magnetic fields revealed by VGT (colored segments) using H I emission. The magnetic field is overlaid with the N\textsubscript{H} column density map. Colors on vectors present the AM of VGT and Planck polarization. Contours outline the intensity structures of 13\textsubscript{CO} starting from 2.5 K km/s. Middle: same as top panel, but using 13\textsubscript{CO} emission. Bottom: magnetic fields inferred from VGT (colored segments) using C\textsubscript{18}O emission for a zoom-in region as indicated in the middle panel by a dashed box. Colors, except white, on polarization vectors, present the AM of VGT and HAWC+ polarization at 89 \textmu m polarization. White color means no corresponding polarization measurement.

Figure 6. Histogram of the AM calculated from VGT and polarization measurements.

field’s direction within the beam and along the LOS. To find out the uncertainty in obtained inclination angle due to the beam-average effect, we repeat the analysis for the HAWC+ zoom-in region presented in Fig. 3’s middle panel. Polarization in this region is measured at wavelength 89 \textmu m and 154 \textmu m (similar to Planck 353 GHz being submillimetre-wavelength), with beam resolution \approx 7.8'' and \approx 13.6'', respectively, so that the beam average effect is reduced. For 154 \textmu m, we get $p_{\text{max}} \approx 20\%$ and $p_{\text{off}} \approx 14\%$, which is averaged over the polarization fraction in the five positions associated with the smallest five $\sigma_\phi$. Consequently, we get $\gamma \approx 58\%$, which is a bit larger than that (\approx 40\%) derived from the Planck polarization. The difference, although not significant, does not necessarily mean the beam average effect vanishes, especially Planck’s $p_{\text{max}} \approx 10\%$ is only half of the one obtained from HAWC+. We expected the beam average effect appears in both Planck’s $p_{\text{off}}$ and $p_{\text{max}}$ so that its contribution in Eq. 9’s the numerator and denominator partially cancels off. Moreover, HAWC+ is measuring the magnetic field at smaller scale and denser regions, it is also possible the loss of grain alignment at high-density regions and local variation of the magnetic field contribute to the difference and uncertainty. We discuss it more in § 5.3.

4.4 Velocity dispersion and mass density

The velocity dispersion $\sigma_v$ maps measured from $^{12}$CO and $^{13}$CO are presented in Fig. 9. $\sigma_v$ is calculated from the Full Width at Half Maximum (FWHM): $\sigma_v = \text{FWHM}/2.355$. We identify the central peak of the spectrum and the velocities corresponding to half of the central peak. The velocity difference is taken as the FWHM. We note that $^{12}$CO is typically optically thick and subject to self-absorption, which can result in a double-peaked line, which may raise a bit of overestimation in FWHM, or complicated velocity components. For the latter, we use only the most prominent component, as it represents the maximum turbulence. It is worth noting that $^{12}$CO is also sensitive to outflows, which can increase the velocity dispersion. Since we did not exclude the contribution of outflows, caution should be exercised.

4 Note that the condition of $\sigma_\phi^2 \ll 1$ used in PFA means the magnetic fluctuations are minimum in that position, so the depolarization is dominantly caused by the mean inclination angle.
in regions with significant outflows, such as VLA 1623 in Oph A and IRS 45/47 in Oph B (Ridge et al. 2006; White et al. 2015).

By assuming the excitation temperature can be approximated by dust temperature $T_{ex} = T_{dust}$, we convert the velocity dispersion to sonic Mach number $M_s = \sqrt{3\sigma_v / c_s}$ using the Herschel dust temperature map (Ladjelate et al. 2020). Here $c_s = \sqrt{T_{ex} / m_H \mu H_2}$ (k$g$ is Boltzmann constant, $m_H = 1.67 \times 10^{-24}$ g is the mass of a hydrogen atom, $\mu H_2$ is the mass of a hydrogen molecule).

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**Figure 7.** Top: the dispersion of (Planck) polarization angle. Middle: the polarization fraction. Bottom: the distribution of the inclination angle $\gamma$. Contours outline the intensity structures of $^{12}$CO starting from 5 K km/s.

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**Figure 8.** Histogram of Planck’s polarization fraction (top) and inferred inclination angle (bottom).

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**Figure 9.** The distribution of sonic Mach number $M_s = \sigma_v / c_s$. $\sigma_v$ is calculated from the linewidth of $^{12}$CO (top) and $^{13}$CO (bottom). Contours outline the intensity structures of $^{12}$CO (top) starting from 5 K km/s and $^{13}$CO (bottom) starting from 2.5 K km/s.
atom, and $\mu_{\text{H}_2} = 2.8$ is mean molecular weight, see Kauffmann et al. 2008) is the isothermal sound speed. We can see the central clump in the surrounding of Oph B, E, and F is highly supersonic with peak $M_s \approx 15$ for $^{12}$CO and $\approx 10$ for $^{13}$CO. The ambient gas is still supersonic but has smaller $M_s$ values. The global mean $M_s$ is around 5 for $^{12}$CO and around 4 for $^{13}$CO. The contribution from thermal speed to $\sigma_v$ is therefore insignificant for such a highly supersonic cloud.

The volume mass density $\rho$ is calculated from $\text{H}_2$ column density. As the central dense clump is gravitationally contracting and its POS projection is approximately circular, naturally, we can assume the L1688 is as deep as it is wide. The effective diameter is $L = 2\sqrt{A}/\pi$, where $A$ is the area within $^{13}$CO’s intensity contour of 5 K km/s (see Fig. 9) corresponding to the gravity-dominated region identified by the PDF and VGT (see Fig. 2). This contour well represents the clump’s POS projection as it covers the majority of the clump and part of the northeast tail. Here we get $L \approx 1.84$ pc and calculate the mass density map from $\rho = N_{\text{H}_2}\mu_{\text{H}_2}m_{\text{H}}/L$.

Figure 10. Top: the distribution of the POS magnetic field strength calculated from the DCF method. Bottom: the distribution of the total magnetic field strength $B_{\text{tot}}$. Contours outline the intensity structures of $^{12}$CO starting from 5 K km/s.

Figure 11. Top: the distribution of the POS magnetic field strength calculated from the DMA method selecting $l = 10$ pixels. Bottom: the distribution of the total magnetic field strength $B_{\text{tot}}$. Contours outline the intensity structures of $^{13}$CO starting from 5 K km/s.

Figure 12. The global mean value of the POS magnetic field strength calculated from the DMA method as a function of the separation $l$. Box gives ranges of the first (lower) and third quartiles (upper) and colored line represents the mean value.
4.5 Total magnetic field strength

4.5.1 3D Magnetic field strength via the DCF

For estimating the POS magnetic field strength over a region of interest, the DCF uses the velocity dispersion estimated from $^{12}\text{CO}$’s line broadening, the dispersion of magnetic field angle obtained from polarization’s angular statistics, and the mass density calculated from $\text{H}_2$ column density. These maps are presented in Figs. 2, 8, and 9. Particularly, the mass density map and $^{12}\text{CO}$’s velocity dispersion map are smoothed by the Gaussian filter to achieve the same resolution as Planck polarization’s dispersion map. The choice of $^{12}\text{CO}$ is based on the fact that VGT-$^{12}\text{CO}$ gives the best agreement with Planck polarization suggesting the self-gravity effect is minimum. The obtained POS magnetic field strength map is shown in Fig. 10. The POS magnetic field in the low-density northeast tail is stronger than the one in the central dense clump. However, this is caused by the projection effect.

We recover the total magnetic field strength by using the inclination angle. Without the projection effect, the central dense clump consequently exhibits the strongest total magnetic field due to compression and gravitational collapse. The maximum strength achieves $\approx 1100\mu\text{G}$, and the global mean value is $\approx 135\mu\text{G}$.

4.5.2 3D Magnetic field strength via DMA

Different from the DCF method, DMA uses the second-order structure function to calculate the velocity dispersion from the velocity centroid map and the magnetic field angle dispersion from the polarization map. The DMA-estimated POS magnetic field strength distribution is presented in Fig. 11. Here we select $l = 10$ pixels for calculating the structure-function (see Eq. 7). As we show in Fig. 12, the DMA estimation is insensitive to $l$. While variation exists, the global mean values of the POS component ($\approx 40\mu\text{G} - 50\mu\text{G}$), as well as the distributions, for different $l$ values are statistically similar. The slightly decreasing trend may be contributed by non-turbulent fields when considering large-scale fluctuations. In combination with the inclination angle distribution, we see the mean value of 3D magnetic field strength at $l = 10$ pixel is $\approx 75\mu\text{G}$, which is smaller than the DCF estimation.

Moreover, we also observe other apparent differences compared with the DCF estimation (see Fig. 10). In the north tail and central clump, the DMA-estimated magnetic field strength in high-density (relative to its surroundings, see Fig. 2) regions, is weaker. In general, we expect the effects of the self-gravity to distort the magnetic field direction and decrease the value of the magnetic field. In the high-density Oph A region, the magnetic field bending caused by self-gravity increases the polarization angle’s dispersion, but the DCF method used in this work does not account for such an effect. As a result, we expect that Oph A gives excessive angle dispersion, which results in underestimating the actual magnetic field strength (see § 5.3 for more discussion about uncertainty). However, DCF may intrinsically have overestimation (see § 5) so that the self-gravity effect is only apparent in DMA.

\footnote{Note in other modified DCF methods, the effect of field line distortions whether due to self-gravity or otherwise are considered (Hildebrand et al. 2009; Houde et al. 2009). This effect can be handled by DMA that uses structure function to calculate the angle dispersion (Lazarian et al. 2022).}

Figure 13. The annulus-averaged total magnetic field estimated from DCF (the first panel), total magnetic field estimated from DMA (the second panel) column density (the third panel), and sonic Mach number calculated from $^{12}\text{CO}$ (the fourth panel) as a function of the distance to the cloud’s center. The width of each annulus is $\approx 0.15$ pc. The upper and lower black lines represent the maximum and minimum values, respectively. Box gives ranges of the first (lower) and third quartiles (upper) and the colored line represents the mean value.
4.6 Energy budget

To quantify how the magnetic field, turbulence, and self-gravity interact in L1688, we first assume the cross point (R.A. ≈ 246.65°, and Dec. ≈ −24.52°) of Oph A and B’s elongation as the collapsing center (see Fig. 2). Then we take the annulus average for the three quantities as a function of the distance to the center. The width of each annulus is ≈ 0.15 pc. As shown in Fig. 13, the magnetic field, $B_{tot}$, and column density have a significantly higher value in the vicinity (≈ 0.6 – 1.5 pc) of the collapse center, while they dramatically decrease in the envelope of the cloud (≈ 2.0 – 3.0 pc). The increment around the center can be easily understood because the gravitational contraction/collapse accretes gas and compresses the magnetic field. The infall velocity and gravity-driven turbulence also contribute to the velocity dispersion resulting in a high sonic Mach number.

We similarly take calculate the annulus-averaged energy density (i.e., pressure) of the magnetic field, turbulence, and gravitational potential as a function of the distance to the cloud’s center. The magnetic and isotropic turbulent pressure could be computed as:

$$P_{\text{mag.}} = \frac{B_{\text{tot}}^2}{8\pi},$$

$$P_{\text{tur.}} = \frac{3}{2} \rho v^2.$$  \hspace{1cm} (10)

As for the pressure of gravitational potential, we can consider that a mass element $\rho(r) dV$ (here $V$ represents volume) at radius $r$ is attracted by a central massive sphere. The pressure is then:

$$P_{\text{gra.}} = -\frac{GM(r)}{r} \rho(r),$$  \hspace{1cm} (11)

where $G$ is the gravitational constant and $M(r)$ is the sphere’s mass within radius $r$. $\rho(r)$ is taken from the annulus-averaged mass density.

As shown in Fig. 15, the magnetic field gives the strongest supportive pressure ≈ $10^7$ K cm$^{-3}$ for DCF and ≈ $5 \times 10^6$ K cm$^{-3}$ for DMA. Although the turbulence and gravitational potential pressure increases in the center’s vicinity (≈ 0.5 – 1.5 pc), their magnitudes are at a comparable level to the magnetic field’s pressure. In particular, instead of viral equilibrium, we observed $|P_{\text{gra.}}| > 2P_{\text{tur.}}$ due to the fact that the magnetic field acts against gravity so that the velocity dispersion is expected to be lower in the magnetized cloud. However, $|P_{\text{gra.}}|$ is slightly larger than $2P_{\text{tur.}}$ when the distance is larger than ≈ 1.5 pc and $2P_{\text{tur.}}$ exceeds $|P_{\text{gra.}}|$ in the center’s vicinity.
vicinity (≤ 1.5 pc). The higher 2\(P_{\text{surf}}\), pressure could be contributed by the infall velocity from gravitational collapse and gravity-driven turbulence suggesting the ambient material is falling into the center. The cloud’s averaged Jeans length is \(L_J = \sqrt{\frac{\pi c^2 \rho}{G^2}} \approx 0.70 \text{ pc}\) with a mean volume mass density \(\bar{\rho} \approx 3.52 \times 10^{-21} \text{ g cm}^{-3}\) (i.e., volume number density around 750 cm\(^{-3}\)). When the distance is less than the Jeans length, thermal support is stronger than self-gravity. Consequently, the global contraction slows down within \(\approx 0.70 \text{ pc}\), and local collapse and fragmentation appear.

### 4.7 Correlation of total magnetic field strength and volume density

The correlation between the total magnetic field strength and the volume mass density is an important aspect of the theory of star formation. Under the flux-freezing ideal MHD condition, the scaling \(B_{\text{tot}} \propto \rho^{2/3} \propto n_H^{2/3}\) corresponds to the isotropic gravitational contraction of a sphere (Mestel 1965; Hartmann et al. 2001; Vázquez-Semadeni et al. 2011), where \(n_H = 2n_{\text{H}_2} \approx 2N_{\text{H}_2}/L\) is the volume density of hydrogen atom. However, the scaling can be \(B_{\text{tot}} \propto n_H^{1/2}\) if the flux-freezing condition breaks due to reconnection diffusion (Lazarian 2005, 2014). In addition, the initial contraction can preferably take place along the strong magnetic field so that the gas settles into a flattened cylindrical structure perpendicular to the mean field (Mouschovias 1976; Scott & Black 1980; Crutcher 1999).

In Fig. 15, we show the logarithmic \(B_{\text{tot}} - n_H\) scatter 2D histogram. At a low-density regime, the scatter dots cover an extended area without apparent scaling relation. At high densities, the scatter is reduced, but characteristic scaling is still not clearly distinct. The scatter dots lie between scaling with slopes 1/2 and 2/3. We further bin the measured total magnetic field strength in uniformly spaced \(n_H\) bins with an interval of \(\approx 150 \text{ cm}^{-3}\), as shown in Fig. 16. For both cases of DCF and DMA measurements, when volume density is smaller than \(6.0 \times 10^3 \text{ cm}^{-3}\), the characteristic scaling is more close to 1/2. This indicates that the collapse is affected magnetic field. The measured turbulence can induce reconnection diffusion or the collapse can preferably take place along the strong magnetic field. However, one should note that it is possible the correlation of \(B_{\text{tot}} \propto n_H^{1/2}\) results from the intrinsic assumption of \(B_{\text{pos}} \propto \sqrt{4\pi\rho}\) in the DCF and DMA method.

### 5 DISCUSSION

#### 5.1 3D magnetic field in L1688

Probing the magnetic field in the molecular cloud is always challenging. In this work, we rely on dust polarization and VGT to access the POS magnetic field in the L1688 star-forming region. L1688’s low-intensity northeast tail follows the magnetic field direction. The magnetic field, however, is slightly bent in the vicinity of the central dense clump being an hourglass shape (see Fig. 3, HAWC+ 154 µm in Fig. 4, and Santos et al. 2019 for a better streamline visualization of HAWC+ 154 ). This hourglass feature is a very specific prediction of gravitational collapse in a region with a strong magnetic field (Galli & Shu 1993; Fiedler & Mouschovias 1993; Frau et al. 2011).

The magnetic fields measured by VGT-\textsuperscript{12}CO, VGT-\textsuperscript{13}CO, and VGT-HI generally agree with the one inferred from dust polarization. The agreement reveals the fact that the magnetic field is coherent up to volume density \(n_{\text{H}_2} \approx 10^3 \text{ cm}^{-3}\). In particular, VGT-H I traces the magnetic field associated with the foreground/background rather than the molecular cloud L1688. However, VGT-H I still agrees with VGT-\textsuperscript{12}CO, VGT-\textsuperscript{13}CO, and Planck polarization suggesting that L1688’s motion and evolution are regulated by a strong magnetic field.

An earlier study of Sullivan et al. (2021) reported an inclination angle \(\approx 57^\circ\) for the entire Ophiuchus molecular cloud assuming the magnetic field’s fluctuation is negligible. In this paper, we employ a new technique employing both polarization fraction and polarization angle dispersion to trace the magnetic field inclination angle with respect to the LOS. We find the magnetic field in L1688’s low-intensity northeast tail has an inclination angle \(\approx 55^\circ\), while the central clump’s magnetic field is inclined by \(\approx 30^\circ\) on average. Our estimation accounts for magnetic field fluctuations and explains the low polarization fraction in L1688.

#### 5.2 Dynamics of L1688

Based on the spectral emissions, \textsuperscript{12}CO column density, and polarization data, we evaluate L1688’s dynamical properties. The PDF of \textsuperscript{12}CO column density reveals two different power-law slopes. A shallow slope \(\approx -0.99\) is observed in the density range of \(5.5 \times 10^{21} \text{ cm}^{-2}\)
$\leq N_{H_2} \leq 1.7 \times 10^{22}$ cm$^{-2}$ and a steep slope $\approx -2.49$ appears for $1.7 \times 10^{22} \leq N_{H_2}$ cm$^{-2}$. These two different slopes suggest the L1688 is undergoing global gravitational contraction at large scale $\approx 1.0$ pc and gravitational collapse at small scale $\approx 0.2$ pc. The observed misalignment of VGT and polarization and the hourglass shape magnetic field morphology confirm this point. In particular, the relative angle of VGT-12CO/13CO and polarization are less than 90$^\circ$ suggesting that turbulence is still more dominated than self-gravity up to the volume density $n_{H_2} \approx 10^3$ cm$^{-3}$. However, the 90$^\circ$ relative orientation is observed in VGT-C$^{18}$O and HAWC+ polarization in a small dense core ($\approx 0.05$ pc) Oph A. Such 90$^\circ$ difference reveals a strong gravitational collapse in Oph A at density $n_{H_2} \approx 10^4$ cm$^{-3}$.

Moreover, L1688 is highly supersonic and strongly magnetized. The global mean $M_a$ is around 7 for $^{12}$CO and around 5 for $^{13}$CO. Its kinetic energy is approximately in viral equilibrium with gravitational potential energy, while the kinetic energy exceeds the gravitational potential energy at a scale less than $\approx 1.5$ pc due to the contribution from infall velocity and thermal energy. Based on the DCF method and estimated inclination angle, we find L1688’s maximum strength achieves $\approx 1100$ $\mu$G and the global mean value is $\approx 135$ $\mu$G. The magnetic field energy is larger than kinetic and gravitational potential energy by more than one order of magnitude. Such a strong magnetic field regulates the gravitational contraction so that we observe a power-law relation $B_{tot} \propto n_{H_2}^{1/2}$ in the volume density range of $n_{H_2} \leq 6.0 \times 10^3$ cm$^{-3}$. The reconnection diffusion, possibly assisted by the accumulation of matter along magnetic field lines is most likely the cause of the observed dependence.

5.3 Uncertainty

The major uncertainty in our estimation comes from the DCF method and the polarization fraction method. The DCF method assumes that (i) ISM turbulence is an isotropic superposition of linear Alfvén waves, (ii) the compressibility and density variations of the media are negligible, and (iii) the variations of the magnetic field direction and the velocity fluctuations arise from the same region in space. These assumptions could raise uncertainty. In particular, gravitational contraction and collapse can magnify both velocity and the magnetic field’s dispersion, resulting in overestimating the POS magnetic field strength. More discussion about the DCF method’s uncertainty could be found in Lazarian et al. (2022); Skalidis et al. (2021); Chen et al. (2022); Liu et al. (2022).

5.3.1 Uncertainty in the total magnetic field strength

Another uncertainty may come from our assumption of the cloud’s depth along the LOS for calculating the mass density. We assume a spherical cloud model for the calculation, $|P_{gra}|$ and $2P_{tur}$ may be underestimated with this assumption. If the cloud is highly sheet-like with a LOS length scale approximately one order of magnitude smaller than $L \approx 1.84$ pc (from the spherical model), $|P_{gra}|$ and $2P_{tur}$ could be comparable or greater than $P_{mag}$ from DCF (for DMA measurement, $P_{mag}$ is approximately four times lower). As the observed POS projection of the cloud is close to circular (see Fig. 2), the cloud can be sheet-like if it is compressed along the LOS direction. However, the magnetic field’s inclination angle is $\approx 30^\circ$ (see Fig. 8) and the insignificant variation of the magnetic field in the foreground/background and the cloud implies a strong magnetic field (see § 4.2). The cloud can be sheet-like if it is compressed along the LOS direction. We do not expect such a compression almost along the strong magnetic field. In any case, the cloud’s 3D real structure potential can be better determined by combining extinction maps and star distance provided by the Gaia mission (Zucker et al. 2021).

Earlier Zeeman measurements found that the LOS magnetic field strength in the H I self-absorption region in front of the cloud is around 10$\mu$G (Goodman & Heiles 1994; Troland et al. 1996). The Zeeman effect from dense tracer OH, however, is poorly sampled and we can expect the LOS magnetic field in the cloud to be stronger than 10$\mu$G. Nevertheless, Crutcher (2012a) statistically reported the upper limit of the LOS magnetic field strength is $\approx 100$ $\mu$G for volume density $n_{H_2} \approx 1.0 \times 10^9$ cm$^{-3}$ using Zeeman splitting measurement. Assuming a simple equivalent of the POS and LOS magnetic fields, the DCF-measured total magnetic field strength ($\approx 250$ $\mu$G for $n_{H_2} \approx 1.0 \times 10^9$ cm$^{-3}$, see Fig. 16) might be overestimated by a factor of 2, but the DMA measurement is more close to the Zeeman results. This overestimation may come from the limited sub-block size selected for calculating the angle dispersion. The velocity dispersion estimated from line broadening corresponds to the velocity fluctuation at injection scale $L_{inj}$, but the POS magnetic field angle’s dispersion for a small sub-block with size $s$ corresponds to the fluctuation at scale $s$. Compared to the angle dispersion for the entire cloud (i.e., at turbulence injection scale $L_{inj}$), the dispersion for a small sub-block is reduced by a factor of $\sim (s/L_{inj})^{1/3}$, assuming Kolmogorov-type turbulence. An additional decrease comes from the fact that the observed angle dispersion is a LOS-averaged quantity. This average for a small sub-block suppresses magnetic field angle dispersion by an additional factor $\sim (s/L_{inj})^{1/2}$ in a random walk manner. Thus the angle dispersion is totally underestimated by a factor of $(s/L_{inj})^{5/6}$ and the POS magnetic field is, therefore, overestimated. This overestimation results from a combination of the intrinsic typical DCF overestimation of field strength, and of the effects of the approaches to estimating velocity dispersion and magnetic field angle dispersion (Lazarian et al. 2022).

5.3.2 Uncertainty in the inclination angle

The polarization fraction analysis assumes that the intrinsic polarization fraction $p_0$ is constant throughout a cloud. This implicitly requires that dust grains’ properties, i.e., emissivity, temperature, etc., are homogeneous within the cloud. Such assumption would result in a systematic uncertainty of $0 \sim 20^\circ$ with a median value of $\sim 10^\circ$ (Hu & Lazarian 2023). On the other hand, this method requires $\sigma_\phi^2 \sim M_{A,POS} \ll 1$ in a strongly magnetized reference position. This condition may not be satisfied in the central dense clump as the observed $\sigma_\phi$ is large. However, as numerically shown in Hu & Lazarian (2023), the condition of $M_{A,POS}^2 \ll 1$ can be relaxed to $M_{A,POS}^2 \approx 1$ when the inclination angle is less than $30^\circ$. Such a small inclination angle ubiquitously dominates the depolarization effect so that it reduces the contribution from $M_{A,POS}^2$. Therefore, we expect the uncertainty from the condition of $M_{A,POS}^2 \ll 1$ is not significant in L1688.

On the other hand, polarization fraction is typically strongly anti-correlated with Stokes I, which is an effect usually due to the loss of grain alignment at high extinction $A_V$ (Whittet et al. 2008; Alves et al. 2014; Jones et al. 2015) or field variation along the LOS (Planck Collaboration et al. 2015b; Seifried et al. 2019), a phenomenon known as the “polarization hole”. In Fig. B1, we present the 2D histogram of the inclination angle $\gamma$ and $I$ and find $\gamma$ tends to be small with a high I. However, we note that a sharp drop of polarization fraction happens at hydrogen column density $N_{H} \sim 10^{22}$ cm$^{-2}$ (see Planck Collaboration et al. 2015a). Our analysis mostly covers low-density regions ($N_{H} < 10^{22}$ cm$^{-2}$, see Fig. 2). In Fig. 7, we see the large
dispersion of polarization angle and small inclination angle also appear in low-density regions (see also the 2D histograms in Fig. B2). It suggests that the magnetic field’s variation is indeed large. In addition, Pattle et al. (2019) studied high-density Oph A, Oph B, and Oph C and found that dust grains may remain aligned with the magnetic field. Considering the fact that the number of aligned large grains decreases in high-density regions (Hoang et al. 2021). The grain alignment, in low-density regions, should be better than those observed in Oph A, B, and C. For these two reasons, we, therefore, expect the depolarization due to field variation dominates L1688, especially in low-density regions.

However, the extent to which loss of grain alignment contributes to the polarization hole at parsec scales remains contentious. For instance, Seifried et al. (2019) performed a numerical study showing that dust grains remain well aligned even at high volume densities \( n > 10^5 \) \( \text{cm}^{-3} \) and \( A_V > 1 \). A more recent study of Hoang et al. (2021) estimated the maximum \( A_V \) that grains still align with magnetic fields. They found for gas density of \( n \approx 10^4 \), \( 10^5 \), \( 10^6 \) \( \text{cm}^{-3} \), the maximum \( A_V \) for grain alignment is \( \sim 20.3, 8.2, 3.3 \) for the standard maximum size of interstellar dust \( \sim 0.25 \) \( \mu \text{m} \). These values of \( A_V \) further increase in the presence of radiation from stars. For our targets, the maximum volume density is around \( 10^4 \) \( \text{cm}^{-3} \) (see Fig. 16) and the maximum \( A_V \) is around 20 by adopting a linear relation between the hydrogen column density and \( A_V \) (\( N_H = 2.21 \times 10^{21} A_V \); Güver & Özel 2009). Nevertheless, for high-density regions, like Oph A, Oph B, and Oph C, the loss of grain alignment can be a potential bias in the PFA analysis.

5.4 Comparison with other studies

The magnetic fields within the Ophiuchus cloud have been extensively studied across different wavelengths. Early optical and near-infrared polarimetry techniques revealed magnetic fields in regions of low extinction (Vrba 1977; Wilking et al. 1979; Sato et al. 1988). Measurements at high-extinction regions are obtained through far-infrared polarization. For example, the JCMT BISTRO POL-2 Survey, as summarized in Pattle et al. (2019), measured the POS magnetic field orientation for Oph A (Kwon et al. 2018), Oph B (Soam et al. 2018), and Oph C (Liu et al. 2019) at 850\( \mu \text{m} \), as well as HAWC+ observations at 53, 89, and 154\( \mu \text{m} \) (Santos et al. 2019). In addition, Kwon et al. (2018) used the DCF method to derive the POS magnetic field strengths for Oph A cores (0.2\( \mu \text{pc} \)), which were found to range from 0.2 to 5 mg. Similarly, Liu et al. (2019) found the POS magnetic field strength in Oph C to be approximately 0.1-0.2 mg. In our analysis, we utilized Planck polarization to derive the magnetic field strength at a larger scale (= 6\( \mu \text{pc} \)). Our results generally agree with those of the low-density Oph C, but are smaller than those of the dense Oph A. This outcome is expected as magnetic field strength typically increases in smaller, denser cores, especially when self-gravity dominates, as suggested by Pattle et al. (2015) and our VGT analysis. In any case, JCMT polarization has a higher resolution of 0.01 \( \mu \text{pc} \) compared to Planck. The PFA and DMA analysis methods used in this study can be applied to JCMT observations to obtain 3D magnetic field information at small scales.

6 SUMMARY

In this work, we study L1688’s 3D magnetic field and dynamics. We employ the data sets of spectral emissions of \( _{12}\text{CO}, _{13}\text{CO}, _{18}\text{O} \), and \( H\text{I} \), Planck 353 GHz and HAWC+ 89\( \mu \text{m} \) & 53\( \mu \text{m} \) polarized dust emission. We apply a number of statistical tools to the data sets, including the probability density function of column density, the Velocity Gradient Technique (VGT), the polarization fraction analysis (PFA), and both the Davis–Chandrasekhar-Fermi (DFC) method and Differential Measure Analysis (DMA) technique. Our main discoveries are:

(i) The PDF of L1688’s column density exhibits two distinguished power-law distributions suggesting different star formation activities (or rates) in the two corresponding density ranges. From the power-law PDF, we find L1688 is likely undergoing gravitational contraction at scale \( \approx 1.0 \) \( \text{pc} \) and gravitational collapse at scale \( \approx 0.2 \) \( \text{pc} \).

(ii) Using the VGT method, we found that the magnetic fields associated with H I foreground/background and molecular cloud L1688 are statistically coherent.

(iii) For the small Oph A clump, we found that VGT-C\( ^{18}\text{O} \) measurement is perpendicular to the magnetic field derived from HAWC+ polarization. It suggests the presence of the gravitational collapse in Oph A, particularly at a volume density larger than \( n_{H_2} \geq 10^4 \) \( \text{cm}^{-3} \).

(iv) We used the PFA method to estimate the magnetic field’s inclination angle distribution in L1688. We find the low-intensity tail has a mean inclination angle \( \approx 55^\circ \), while the central dense clump’s mean inclination angle is \( \approx 30^\circ \).

(v) Based on the DCF method and the distribution of estimated inclination angles, we showed that L1688 has a relatively strong total magnetic field with a mean strength \( \approx 135 \) \( \mu \text{G} \).

(vi) We tested the new method, i.e., the Differential Measure Approach, for estimating magnetic field strength in L1688. The mean value of the total magnetic field is \( \approx 75 \) \( \mu \text{G} \), smaller than that from the DCF’s estimation.

(vii) We found the strong magnetic field in L1688 regulates the large-scale gravitational contraction so that it mainly takes place along the magnetic field. Consequently, we observed the a power-law relation \( B_{tot} \propto n_{H_2}^{1/2} \) when volume density is approximately less than \( 6.0 \times 10^3 \) \( \text{cm}^{-3} \).

(viii) Based on the estimated total magnetic field strength, we found that gravitational contraction is present in a strongly magnetized and supersonic cloud.

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DATA AVAILABILITY

The data underlying this article will be shared on reasonable request to the corresponding author.

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Figure A1. The uncertainty map of the polarization fraction $p$. Contours outline the intensity structures of $^{12}$CO starting from 5 K km/s.

Figure B1. The 2D histogram of inclination angle derived from PFA and Planck emission intensity at 353 GHz.

APPENDIX A: UNCERTAINTY OF $P$

In Fig. A1, we present the uncertainty map of the polarization fraction $p$. The uncertainty is calculated from:

$$
\delta p = \left( \frac{Q^2 \delta Q^2 + U^2 \delta U^2}{I^2 (Q^2 + U^2)} + \frac{\delta I^2 (Q^2 + U^2)}{I^4} \right)^{1/2}, \tag{A1}
$$

where $\delta I$, $\delta Q$, and $\delta U$ are the uncertainties in Stokes $I$, $Q$, $U$, respectively. Within the contours, the uncertainty is generally less than 1%. Particularly, for the dense Oph A, B, C, E, F regions, the uncertainty is around 0.2%.

The uncertainty of polarization angle $\phi$ is:

$$
\delta \phi = \frac{1}{2} \sqrt{\frac{Q^2 \delta U^2 + U^2 \delta Q^2}{(Q^2 + U^2)^2}}. \tag{A2}
$$

We present the map of $\delta \phi$ in Fig. A2. The median value of $\delta \phi$ is around 14°.

Figure A2. The uncertainty map of the polarization angle $\phi$. Contours outline the intensity structures of $^{12}$CO starting from 5 K km/s.

APPENDIX B: CORRELATION OF INCLINATION ANGLE AND PLANCK EMISSION INTENSITY

Fig. B1 presents the 2D histogram of inclination angle derived from PFA and Planck emission intensity. We see the inclination angle tends to be small values at large intensity. As we discussed in § 5, there are two possible reasons: (1) the magnetic fields have significant variations; or (2) the loss of grain alignment at high extinction.

In Fig. B2, we plot the 2D histogram of polarization angle dispersion and column density. We find in low-density regions ($N_H < 5.8 \times 10^{21}$ cm$^{-2}$), the dispersion of polarization angle is significant, corresponding to the small inclination angles observed in L1688’s southwest (see Fig. 7). Similarly, we also plot the 2D histogram of VGT-$^{12}$CO angle dispersion, which is insensitive to grain alignment, and column density. Similar large angle dispersion associated with low-density is also observed. We, therefore, expect the depolarization due to field variation dominates L1688’s southwest so the (effective) inclination angle is indeed small.

In addition, we find the angle dispersion of VGT-$^{12}$CO is also significant at $N_H \approx 1.54 \times 10^{22}$ cm$^{-2}$. This corresponds to the regions of dense Oph A, B, and C cores and we expect self-gravity is responsible for the variation of VGT-$^{12}$CO.
Figure B2. The 2D histogram of polarization angle dispersion (top), as well as VGT-\(^{12}\)CO angle dispersion (bottom), and column density.