Polarimetric and Photometric Investigation of the Dark Globule LDN 1225: Distance, Extinction Law, and Magnetic Fields

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Abstract

We present results based on the optical R-band observations of the polarization of 280 stars distributed toward the dark globule LDN 1225. Parallaxes from Gaia data release 2 along with the polarization data of ~200 stars have been used to (a) constrain the distance of LDN 1225 as 830 ± 83 pc, (b) determine the contribution of interstellar polarization, and (c) characterize the dust properties and delineate the magnetic field (B-field) morphology of LDN 1225. We find that B-fields are more organized and exhibit a small dispersion of 12°. Using the 12CO molecular line data from the Purple Mountain Observatory, along with the column density and dispersion in B-fields, we estimate the B-field strength to be ~56 ± 10 μG, the ratio of magnetic to turbulent pressure to be ~3 ± 2, and the ratio of mass to magnetic flux (in units of the critical value) to be <1. These results indicate the dominant role of B-fields in comparison to turbulence and gravity in rendering the cloud support. B-fields are aligned parallel to the low-density parts (traced by a 12CO map) of the cloud; in contrast, they are neither parallel nor perpendicular to the high-density core structures (traced by 13CO and C18O maps). LDN 1225 hosts two 70 μm sources, which seem to be low-mass Class 0 sources. The ratio of total to selective extinction derived using optical and near-infrared photometric data is found to be anomalous (Rv = 3.4), suggesting the growth of dust grains in LDN 1225. The polarization efficiency of dust grains follows a power law with an index of −0.7, implying that optical polarimetry traces B-fields in the outer parts of the cloud.

Key words: dust, extinction – ISM: clouds – local interstellar matter – magnetic fields – polarization

Supporting material: machine-readable tables

1 Introduction

The small, compact, and isolated dark globules known as “Bok globules” (Bok & Reilly 1947) are the potential precursors to protostars. Initially, Barnard (1927) prepared a list of such dark regions in the sky, and later Lynds (1962) published a catalog with a larger number of such dark objects. Furthermore, Clemens & Barvainis (1988) have compiled a list of 248 small (mean size ~4”) and nearby (distance <1 kpc) molecular clouds. Subsequent studies have shown that these clouds exhibit signs of star formation such as collimated molecular outflows, compact infrared sources, and very low-luminosity objects (VELLOs) (Ferriking & Langer 1982; Reipurth 1983, 2008; Neckel et al. 1985; Vrba et al. 1986; Neckel & Staude 1990; Richer et al. 2000; Stecklum et al. 2007). The characteristics of newborn stars will depend on the physical conditions of the molecular cloud core prior to the onset of gravitational collapse.

Turbulence in the dark globules is sub- or trans-Alfvénic (Heyer et al. 2008; Franco et al. 2010), and the cores embedded in them are characterized with subsonic turbulence (Myers & Benson 1983; Goodman et al. 1998) such that their effect is inadequate to counteract the gravitational collapse. Therefore, magnetic fields (B-fields) are proposed to play a crucial role in regulating isolated low-mass star formation by controlling the stability and contraction of the cores in these clouds (Mouschovias 1976; Shu 1977; Shu et al. 1987). Moreover, it has been shown that B-fields are indeed important in regulating shape of the cloud fragments, guiding accretion flows, directing outflows, and collimating the jets of protostars (Vallée 2002; Girart et al. 2006; McKee & Ostriker 2007; Pudritz et al. 2007; Galli et al. 2009; Sugitani et al. 2010).

Here we study the morphological correlations between the cloud and B-fields, and investigate the relative importance of B-fields to turbulence and gravity in LDN 1225 (e.g., Myers & Goodman 1991; Ward-Thompson et al. 2000; Eswaraiah et al. 2013; Bertrang et al. 2014; Kandori et al. 2017; Jorquera & Bertrang 2018).

The dark globule LDN 1225 (or CB242 or H699 P16) with central coordinates of R.A.(J2000) = 23h11m58s and decl.
(2000) = +61°39'00" (or l = 111°41, b = +01°02) is located toward the Cepheus OB3 cloud complex (hereafter CepOB3). Based on the derived extinction and distance values of the stars projected toward the cloud, Maheswar & Bhatt (2006) have bracketed the distance of LDN 1225 as 400 ± 80 pc. Nonetheless, our study suggests that, being kinematically associated with CepOB3, LDN 1225 is located at 830 ± 83 pc. A catalog of dust clouds in the Galaxy by Dutra & Bica (2002) indicates that the spatial extent of LDN 1225 is 8' × 4', its opacity class is 4 (1 being the lightest and 6 the darkest; Lynd 1962), and the velocity relative to the local standard of rest (VLSR) based on CO data is −10.9 km s⁻¹ (Clemens & Barvainis 1988). Opacity class 4 (Lynd 1962) is similar to density class B (A being the most dense and C the least dense; Hartley et al. 1986). Therefore, according to the above opacity classes, LDN 1225 is a dark globule of intermediate density.

In this work, our goal is to investigate whether B-field support, relative to turbulence and gravity, is important to the formation and evolution of the dark globule LDN 1225. For this purpose, the B-field strength and its pressure, the turbulent pressure, the ratio of ordered to turbulent component of B-fields, the mass-to-magnetic flux ratio in units of the critical value, etc., have been estimated using R-band polarization and CO molecular line data. Polariometric data have been used in combination with parallaxes from Gaia data release 2 (Gaia Collaboration et al. 2018) to find the cloud distance, to estimate contribution of foreground polarization, and to determine the dust properties and B-fields in LDN 1225. Based on the distances, kinematic information, and the coherent B-fields on small and large scales, the membership of LDN 1225 to CepOB3 is discussed. The possible correlation between multiple components of polarizations and those of CO gas is discussed. We discuss the properties of two 70 μm sources and their association with LDN 1225. Optical photometric data have been used to characterize the extinction law in the foreground and cloud media. Furthermore, the polarization efficiency of the dust grains in the dark globule LDN 1225 is studied.

The outline of this paper is as follows. Section 2 describes the observation and reduction of various data along with the archival data sets. Analyses and results are presented in Section 3. Discussion based on our results is given in Section 4. A summary and conclusions of this work are provided in Section 5.

2. Observations, Data Reduction, and Archival Data Sets

2.1. Polarimetric Observations of LDN 1225

Polarimetric observations were carried out on five nights (2010 November 12 and 13, 2010 December 14, and 2013 November 1 and 2) using the ARIES Imaging Polarimeter (AIMPOL; Rautela et al. 2004) mounted at the Cassegrain focus of the 104 cm Sampurnanand telescope of the Aryabhata Research Institute of Observational Sciences (ARIES), Nainital, India. The observations were carried out in the R_c (λR_c = 0.670 μm) photometric band using a small area (370 × 370 pixel²) of the TK 1024 × 1024 pixel² CCD camera. The field of view (FOV) of AIMPOL is ~8 arcmin diameter on the sky. During the observations the FHWMs of the stellar images vary between 3" and 5". The read-out noise and gain of the CCD are 7.0 e⁻ and 11.98 e⁻/ADU respectively. As AIMPOL does not have the grid, we manually checked for any overlap of ordinary and extraordinary images of the sources. Fluxes of ordinary (I_o) and extraordinary (I_e) beams for all the observed sources with good signal-to-noise ratio (S/N) were extracted by standard aperture photometry after bias subtraction using the IRAF11 package. More details on the instrument and the detailed procedures used to estimate the polarization measurements are mentioned in Eswaraiah et al. (2011, and references therein).

All the measurements are corrected for both the instrumental polarization and offset polarization angle by observing unpolarized and polarized standard stars, respectively, from Schmidt et al. (1992). As given in Table 1, our results on the polarized standard stars are in good agreement, within the observational errors, with those from Schmidt et al. (1992). Measurements of one unpolarized standard star, HD 21447, as listed in Table 1, show that the instrumental polarization in the R_c-band is ≤0.1%. This is consistent with the fact that the instrumental polarization of AIMPOL has been monitored since 2004 on various observing nights as part of various projects and found to be less than 0.1% in different bands (Rautela et al. 2004; Medhi et al. 2008; Eswaraiah et al. 2011, 2012, 2013; Pandey et al. 2013; Kumar et al. 2014, 2016; Lee et al. 2018).

We have obtained the R-band polarizations of the stars. The instrumental polarization, P_R (%) of 280 stars list them in Table 2. This table also contains the stellar coordinates and Two Micron All Sky Survey (2MASS) photometric data.

Figure 1(a) displays the polarization vector map toward LDN 1225 using P_R and θ_R of 280 stars; it shows that the B-field geometry is not uniform. Of 280, 33 stars are distributed within the 8' diameter field containing the star-forming region NGC 7538, which is situated within the Perseus spiral arm of our Galaxy at a distance of 2.65 kpc (Moscadelli et al. 2009; Puga et al. 2010; Sharma et al. 2017). As these stars are not physically associated with LDN 1225 (located at ~830 pc), we exclude them from further analyses. We also omitted nine stars with near-infrared (NIR) excess ([J − H] ≥ 1.69 × [H − K]; see, e.g., Eswaraiah et al. 2013, 2017) because their polarizations might consist of intrinsic components due to an asymmetric

| Date     | P_R (%) | θ_R (deg) | P_R (%) | θ_R (deg) |
|----------|---------|-----------|---------|-----------|
| 2013 Nov 2 | 4.6 ± 0.1 | 114.6 ± 0.6 | 4.53 ± 0.03 | 114.5 ± 0.2 |
| 2010 Nov 12 | 4.6 ± 0.1 | 114.5 ± 0.4 | 4.53 ± 0.03 | 114.5 ± 0.2 |
| 2010 Dec 13 | 4.6 ± 0.1 | 114.2 ± 0.4 | 4.53 ± 0.03 | 114.5 ± 0.2 |

Note. ¹ V-band results from Schmidt et al. (1992).
### 2.2. Polarimetric Observations of Several Fields Covering Parts of CepOB3

To understand whether the large-scale B-fields of CepOB3 are preserved and have any effect on the small scales of LDN 1225, we also observed 19 additional fields covering different parts of CepOB3 using various polarimeters. Three fields with FOV of 8° diameter were observed in the R-band with AIMPOL on 2016 October 29, and the data are reduced by adopting similar procedures to those mentioned above in Section 2.1. Eight fields with FOV of 4° diameter were observed in the R-band on five nights (2014 November 19, 20, 25, 26, and 27) using the 2 m telescope of the Inter University Center for Astronomy and Astrophysics (IUCAA), Girawali Observatory, India. The instrument used was the IUCAA Faint Object Spectrograph and Camera (IFSOC) in the polarimetric mode (Sen & Tandon 1994; Ramaprabhak et al. 1998). Eight fields with FOV of 4° × 4° were observed on 2015 October 13 with the Triple Range Imager and Polarimeter (TRIPOL) mounted on the Lulin One-meter Telescope (LOT) at Lulin observatory, Taiwan (S. Sato et al. 2019, in preparation). TRIPOL acquired simultaneous observations in Sloan Digital Sky Survey (SDSS) g', r', and i'-bands, but we use only the r'-band data. The measurements from IMPOL and TRIPOL are corrected for both instrumental polarization and offset polarization angles.

Apart from our own observations, we use cataloged V-band polarization (Heiles 2000) of 16 stars located within the 5° x 5° field containing CepOB3. We make sure that this sample does not include stars with possible intrinsic polarization (e.g., Be stars, other emission type stars, young stellar objects, red/blue supergiants, Wolf–Rayet stars, etc.) with the help of the SIMBAD database. More details on the results and discussion based on the polarizations of CepOB3 are given in Sections 3.6 and 4.1.

### 2.3. Distances from Gaia DR2

The ESA Gaia mission (Gaia Collaboration et al. 2016a, 2016b) data release 2 (Gaia Collaboration et al. 2018, hereafter Gaia DR2) provides distance information for stars up to 21 mag. Of the 238 stars that have been used in the present study, 197 have Gaia DR2 parallaxes passing the 10σ criterion (i.e., ratios of parallaxes to their uncertainties, \(\omega/\sigma_\omega > 10\)). A search area of 1° radius around each star was used while matching the coordinates of our stars with those of Gaia DR2. Distances of all 197 stars are derived using the relation \(d = (1000/\omega)\) pc (where \(\omega\) is the parallax in milliarcseconds) and the distance error is estimated by propagating the distance–parallax relation. Based on the astrometric data of well-characterized red giant branch (RGB) stars in the Kepler field, Zinn et al. (2018, and references therein) have independently confirmed the offset in the parallaxes, \(\sim 52.8\) μas (microarcsecond), of Gaia DR2. However, we have not applied the offset in this study because our main concern is to find the distance of the cloud rather than to derive the distances of individual stars. The distances of the stars are given in column 9 of Table 2.

### 2.4. Photometric Observations toward LDN 1225

Optical photometric observations were performed on 2013 September 6 and 7 using the Himalaya Faint Object Spectrograph and Camera (HFOSC) of the 2 m Himalayan Chandra Telescope (HCT) of the Indian Astronomical Observatory (IAO), Hanle, operated by Indian Institute of Astrophysics (IIA), India. The central 2048 x 2048 pixel² area of the 2K x 4K CCD was used for data acquisition. The FOV of the instrument is 10° x 10° area with a pixel size of 15 μm and image plate scale of 0″293 pixel⁻¹. Photometric observations in BVRi bands were performed toward four fields around LDN 1225. We obtained multiple frames in
5. The total diameter, minor axis locations of the dark globule LDN 1225 and the star-forming region NGC 7538 velocity cuts are shown and labeled. Cut 1 is parallel the extent PR with NGC 7538, NIR excess sources containing LDN 1225, using dimensions of magnitudes and standard star magnitudes of the PG0231 instrument coefficients were measured using the instrumental magnitudes. Extinction and each B, R, and I filters were 300, 200, 90, and 90 s, respectively, in each field. Typical seeing during the observations was ~1.5′. The total area coverage of our optical photometric observations is ~17′ × 20′ around LDN 1225, which is shown with a white box in Figure 1(a). In order to apply a correction for atmospheric extinction as well as for instrument calibration, we observed the standard star field PG0231 (Landolt 1992) during the nights. PG0231 was observed at various air masses and the nights were photometric. Bias and flat frames were also acquired during the nights.

After bias and flat correction, we stacked all the images of individual fields in each filter. We performed point-spread function (PSF) photometry using the DAOPHOT package in IRAF to derive the instrumental magnitudes. Extinction and instrument coefficients were measured using the instrumental magnitudes and standard star magnitudes of the PG0231 field (Landolt 1992). These coefficients were applied to the instrumental magnitudes of LDN 1225 and thus we obtained the final, calibrated photometry. The individual catalogs of four fields were then merged to obtain the final catalog. Typical uncertainty in the photometric calibration is ~0.05, 0.03, 0.02, and 0.02 mag for the B, V, R, and I filters.

Table 3 lists 689 stars with optical (BVRI) plus NIR (JHKs) from 2MASS catalog) photometric data with uncertainties less than 0.1 mag. These data have been used in color–color diagrams to investigate the nature of the extinction law in the foreground and cloud media (see Appendix A).

2.5. 12CO (1–0), 13CO (1–0), and C18O (1–0) Data from the PMO MWISP Survey

In order to study the gas kinematics of the cloud LDN 1225, we used the 12CO(1–0), 13CO (1–0), and C18O (1–0) molecular line data from the Milky Way Imaging Scroll Painting (MWISP) project12 using the Purple Mountain Observatory (PMO) Delingha 13.7 m telescope located at Qinghai observing station (see Su et al. 2016). LDN 1225 was observed in 2015 November. The MWISP project is a new large-scale survey aiming to perform molecular line observations at the J = 1–0 transition of CO isotopes 12CO, 13CO, and C18O simultaneously. This survey has been specially intended to observe the northern Galactic plane (GP) within the Galactic coordinates of −10° < l < 15°; 15° < b < 5° and several other regions of interest. One of the main goals of the MWISP project is to investigate the physical properties of molecular clouds along the northern GP. The beam sizes are about 49′×51′3 at 115.3 GHz and 110 GHz, respectively. The nominal sensitivities (rms level) in the brightness temperature are 0.47 K in 12CO at the velocity resolution of 0.159 km s−1 and 0.26 K in 13CO and C18O at the velocity resolution of ~0.167 km s−1. The resultant data cubes have an FOV of 30′ × 30′ and a beam size of ~33″.

Figure 1. B-field orientation toward LDN 1225 before and after exclusion of unwanted stars (such as foreground (FG) and BG-NGC 7538 stars, stars around NGC 7538, NIR excess sources) and correction of interstellar polarization from the polarizations of background (BG) stars. (a) Polarization vector map of the region containing LDN 1225, using PN and β values of all 280 stars. The background is the color-composite of 2MASS Ks-band (red), Digitized Sky Survey (DSS) I-band (green), and DSS R-band (blue) images. Red contours represent the map of 12CO total integrated intensity, drawn at 3, 6, 9, 12, 15, 18, 21, and 24 K km s−1. The locations of the dark globule LDN 1225 and the star-forming region NGC 7538 (with a circle of 8′ diameter) are shown and labeled. The white dashed ellipse denotes the extent (major axis = 8.4′ diameter, minor axis = 4.2′ diameter, and position angle = 102°) of LDN 1225 based on the CO data (see Figure 8). A reference vector with PN = 6′ and β = 90° is shown. The Galactic plane making a position angle (PA) of 68° toward LDN 1225 is shown with a white line. The white box with dimensions of ~17′ × 20′ marks the region around LDN 1225 selected for optical photometry in BVRI bands. (b) Same as (a), but depicting the B-field map of the LDN 1225 cloud using the polarization measurements (PN and β) of 118 BG stars having accounted for interstellar polarization (see Section 3.5). Two position–velocity cuts are shown and labeled. Cut 1 is parallel (with position angle ~124°) and cut 2 is perpendicular (with position angle ~222°) to the elongation of LDN 1225.

12 http://www.radioast.nsdc.cn/mwisp.php
### Table 3

**Photometric Data of 689 Stars with Photometric Uncertainties Less than 0.1 mag**

| ID | R.A. (J2000) (h:m:s) | Decl. (J2000) (deg: [: ;: ;]') | V (mag) | (B − V) (mag) | (V − R) (mag) | (V − I) (mag) | J (mag) | H (mag) | Ks (mag) |
|----|----------------------|---------------------------------|--------|--------------|--------------|--------------|--------|--------|--------|
| 1  | 23:10:41.320         | 61:39:19.299                    | 18.349 ± 0.011 | 1.382 ± 0.028 | 0.871 ± 0.008 | 1.693 ± 0.044 | 15.47 ± 0.05 | 14.89 ± 0.07 | 14.66 ± 0.09 |
| 2  | 23:10:41.723         | 61:36:52.675                    | 16.572 ± 0.004 | 1.291 ± 0.008 | 0.747 ± 0.003 | 1.525 ± 0.010 | 14.22 ± 0.03 | 13.68 ± 0.04 | 13.56 ± 0.05 |
| 3  | 23:10:41.759         | 61:34:45.177                    | 16.364 ± 0.010 | 1.121 ± 0.016 | 0.686 ± 0.009 | 1.347 ± 0.009 | 14.15 ± 0.04 | 13.64 ± 0.04 | 13.56 ± 0.09 |
| 4  | 23:10:42.002         | 61:36:39.916                    | 17.455 ± 0.006 | 1.097 ± 0.012 | 0.710 ± 0.005 | 1.497 ± 0.022 | 15.14 ± 0.04 | 14.83 ± 0.06 | 14.57 ± 0.08 |
| 5  | 23:10:42.061         | 61:37:36.948                    | 18.338 ± 0.010 | 1.284 ± 0.026 | 0.875 ± 0.009 | 1.861 ± 0.037 | 15.48 ± 0.06 | 14.71 ± 0.05 | 14.73 ± 0.09 |
| 6  | 23:10:42.204         | 61:37:43.968                    | 17.588 ± 0.005 | 1.053 ± 0.012 | 0.722 ± 0.006 | 1.558 ± 0.022 | 15.15 ± 0.07 | 14.62 ± 0.07 | 14.44 ± 0.08 |
| 7  | 23:10:42.624         | 61:42:52.848                    | 16.808 ± 0.004 | 1.108 ± 0.011 | 0.782 ± 0.005 | 1.568 ± 0.003 | 14.30 ± 0.03 | 13.80 ± 0.04 | 13.64 ± 0.04 |
| 8  | 23:10:42.651         | 61:36:19.713                    | 16.675 ± 0.004 | 1.013 ± 0.007 | 0.669 ± 0.004 | 1.401 ± 0.011 | 14.53 ± 0.03 | 14.01 ± 0.04 | 13.93 ± 0.04 |
| 9  | 23:10:42.981         | 61:43:32.314                    | 16.859 ± 0.004 | 1.098 ± 0.011 | 0.764 ± 0.004 | 1.524 ± 0.003 | 14.48 ± 0.04 | 13.92 ± 0.05 | 13.77 ± 0.04 |
| 10 | 23:10:43.080         | 61:47:15.529                    | 18.162 ± 0.006 | 1.639 ± 0.040 | 1.141 ± 0.005 | 2.116 ± 0.006 | 14.76 ± 0.04 | 14.03 ± 0.05 | 13.78 ± 0.05 |
| 11 | 23:10:43.417         | 61:30:41.061                    | 18.966 ± 0.018 | 1.867 ± 0.073 | 1.137 ± 0.012 | 2.391 ± 0.046 | 15.52 ± 0.06 | 14.56 ± 0.05 | 14.52 ± 0.08 |
| 12(5) | 23:10:43.502    | 61:31:52.251                    | 15.229 ± 0.006 | 0.981 ± 0.003 | 0.534 ± 0.002 | 1.090 ± 0.006 | 13.47 ± 0.03 | 13.09 ± 0.03 | 12.97 ± 0.03 |

*Note.* In column 1, star IDs mentioned in parentheses are stars having polarization data (Table 2). (This table is available in its entirety in machine-readable form.)
monotonically increasing trend. However, the presence of a cloud (hence an increase in the number density of aligned dust grains of the cloud) along the line of sight through which background stellar light passes would cause an enhanced level of polarization at the cloud distance. As a result, a sudden jump in the level of polarization would prevail at the cloud distance. Any change in the orientation of B-fields can also be witnessed in the plot of distance versus polarization angle if the B-fields of the cloud are different from those of the FG medium.

Figures 3(a) and (b), respectively, show the distance versus $P_R$ and $\theta_R$ of 197 stars. Both $P_R$ and $\theta_R$ seem to increase as a function of distance up to 830 pc. In contrast, beyond 830 pc a sudden jump is followed by a scattered distribution in $P_R$ and a constant trend in $\theta_R$. Similarly, the Stokes parameters ($Q_R$ and $U_R$) also exhibit linearly decreasing or increasing trends up to 830 pc, beyond which they exhibit scattered distributions (Figures 3(c) and (d)). This abrupt change in $P_R$, $\theta_R$, $Q_R$, and $U_R$ at 830 pc is attributed to the presence of LDN 1225 at this distance.

As we have used stars with 10σ Gaia DR2 distances in our analyses, the expected measurement uncertainty at 830 pc would be 83 pc (10% of 830 pc). Therefore, we ascertain the distance of LDN 1225 as 830 ± 83 pc. This value supports the estimation of 730 ± 120 pc by other studies (Bruzual et al. 2003, see also Blaauw et al. 1959; Crawford & Barnes 1970; Sargent 1977; Ladd & Hodapp 1997; Hartigan et al. 2000; Kun et al. 2008).

In order to elucidate more on the above distance determination, we plot the differential polarization ($P_{R+1} - P_i$), polarization angle ($\theta_{R+1} - \theta_i$), and Stokes parameters ($Q_{R+1} - Q_i$ and $U_{R+1} - U_i$) versus distance (Distance$_{R+1}$) parameter as shown in Figure 4. The subscript $i$ varies from 1 to 196 in increasing order of distance. As the number of stars is 197, the total number of differential measurements would be 196. This plot offers crucial information on the changes in the patterns of polarization measurements of any star relative to those of its immediate foreground. However, in order to see the clear variations of the parameters at the cloud’s distance, we limit the data samples to distances of 2 kpc and plot distance on a linear scale.

Evidently all the differential parameters exhibit a clear transition from negative to positive (or vice versa) at 830 pc as denoted with a green arrow. Region I is dominated by the FG stars, and regions III and IV by BG stars. Stars with 747 (= 830 – 83) pc < Distance$_{R+1} < 83$ pc (blue circles) lie in region I only; in contrast, those with 830 pc < Distance$_{R+1} < 913$ (= 830 + 83) pc (red circles) are clearly distributed in both regions III and IV. This observed feature suggests evidence for clear changes in the polarization properties of the stars at 830 pc. These changes we attribute to the presence of cloud LDN 1225 at 830 pc.

3.3. Identification of Foreground and Background Stars, and Their Polarization Characteristics

As the distance of LDN 1225 is constrained as 830 ± 83 pc (above section), we consider 61 stars with distances <830 pc as foreground stars, noted as “FG” in column 10 of Table 2, whereas the 136 stars with distances ≥830 pc are background stars. However, there exists a star-forming region NGC 7538 (situated within the Perseus arm at 2.65 kpc; Moscagelli et al. 2009; Puga et al. 2010; Sharma et al. 2017) lying in the background of LDN 1225 but projected close (~15°) to it. In

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13 This relation is applicable only as a general average for lines of sight close to the plane of the Milky Way and for distances up to a few kiloparsecs from the Sun.
addition, we note below that there exists a background cloud component at the same location as LDN 1225, which is termed as the background cloud of LDN 1225. In order to examine the physical connection of this component with NGC 7538, we have constructed position–velocity (PV) plots along the two cuts (see Figure 1(b)) using $^{12}$CO data as shown in Figures 5(a) and (b). Evidently, the emissions from LDN 1225 and its background cloud are concentrated, respectively, at $V_{\text{LSR}} = -11.2$ km s$^{-1}$ and $V_{\text{LSR}} = -54.5$ km s$^{-1}$. These two components are located at the same position on the sky (distributed between two horizontal dashed lines) but at different distances (corresponding to two dashed vertical lines). Interestingly, the $^{12}$CO emission from NGC 7538 has been widely distributed between $\sim-40.6$ km s$^{-1}$ and $\sim-60$ km s$^{-1}$ with a prominent emission peak at $\sim-56$ km s$^{-1}$, which is close to the $-54.5$ km s$^{-1}$ component from the background cloud. Moreover, the existence of faint $^{12}$CO emission (green contours around $V_{\text{LSR}} = -54.5$ km s$^{-1}$ in Figures 5(a) and (b)) between the background cloud and NGC 7538 suggests a physical connection between them. Therefore, hereafter we consider that the background cloud of LDN 1225 is nothing but the region of NGC 7538 lying at 2.65 kpc.

Based on the above paragraph, we consider 18 stars with distances >2.65 kpc as the background stars of NGC 7538 and they are noted as “BG-NGC7538” in column 10 of Table 2. These stars are excluded from further analysis, because their polarizations might comprise the dust properties and $B$-field orientations of both clouds NGC 7538 and LDN 1225. The remaining 118 stars having distances between 830 pc and 2.65 kpc, as highlighted within the yellow background in Figure 3, were considered as the true background stars representing the dust properties and $B$-field orientation of the cloud LDN 1225. These stars are noted as “BG” in column 10 of Table 2.

Gaussian fits are performed to the polarization distributions of 61 FG and 118 BG stars as shown in Figure 6. The resultant mean and standard deviation of $P_{\text{BG}}$ and $\theta_{\text{BG}}$ are $1.4\% \pm 0.4\%$ and $61^\circ \pm 11^\circ$ for FG stars, and $2.8\% \pm 1.0\%$ and $87^\circ \pm 11^\circ$ for BG stars, respectively.

### 3.4. Foreground ISP

As shown in Figures 3(c) and (d), the Stokes parameters of 61 FG stars show a monotonically increasing trend by following a straight line. We took advantage of this clean set of data to evaluate the foreground interstellar polarization (ISP) component. We performed weighted linear fits (thick red lines) to the plots of distance versus $Q_R$ and $U_R$ parameters. The resultant parameters at 830 pc are $Q_{\text{ISP}} = -0.9\% \pm 0.1\%$ and $U_{\text{ISP}} = 1.4\% \pm 0.1\%$, and the corresponding $P_{\text{ISP}}$ and $\theta_{\text{ISP}}$ values are $1.7\% \pm 0.1\%$ and $61^\circ \pm 2^\circ$. These values are considered to be the ISP contribution. A similar methodology has been adopted to estimate the ISP contribution and retrieve the intrinsic polarizations of nearby clouds (e.g.,
Eswaraiah et al. 2013; Neha et al. 2018) and B[e] stars (e.g., Lee et al. 2018).

3.5. Foreground Polarization Correction to Infer B-field Structure in LDN 1225

In order to retrieve the true contributions of polarization from the cloud LDN 1225, we subtract ISP Stokes parameters \(Q_{\text{ISP}} = -0.9\% \pm 0.1\%, \ U_{\text{ISP}} = 1.4\% \pm 0.1\%\) vectorially from those \(Q_{\text{BG}}\) and \(U_{\text{BG}}\) of 118 BG stars and obtain intrinsic Stokes parameters \(Q_{C}\) and \(U_{C}\) of the cloud using the following relations.

\[
Q_{C} = Q_{\text{BG}} - Q_{\text{ISP}} \tag{1}
\]
\[
U_{C} = U_{\text{BG}} - U_{\text{ISP}}. \tag{2}
\]

We then estimate

\[
P_{C} = \sqrt{Q_{C}^{2} + U_{C}^{2}} \tag{3}
\]
\[
\theta_{C} = 0.5 \arctan(U_{C}/Q_{C}). \tag{4}
\]

Here, the subscript “C” stands for the component of the cloud, LDN 1225. The \(P_{C}\) values lie between 0.3\% and 6.8\%, with a Gaussian mean and dispersion of 2.4\% ± 1.0\%. The \(\theta_{C}\) values lie between 63° and 128°, with a Gaussian mean and dispersion of 106° ± 11°. This small dispersion in polarization angles implies a uniform B-field orientation within the parts of the cloud. The Gaussian fits to \(P_{C}\) and \(\theta_{C}\) are shown in Figures 7(a) and (b).

In order to test whether ISP has any significant impact on the cloud polarization parameters, we have constructed histograms of \(\Delta(P) = P_{C} - P_{\text{BG}}\) and \(\Delta(\theta) = \theta_{C} - \theta_{\text{BG}}\) as shown in Figures 7(c) and (d). The resultant mean and dispersion of the Gaussian fit of \(\Delta(P)\) are −0.5\% and 0.6\% and similarly those of \(\Delta(\theta)\) are 14° and 4°, respectively. This implies that the FG medium has a depolarization effect of −0.5\% on the cloud’s polarization and a systematic rotation effect of 14° on the cloud’s B-field component.

Figure 1(b) displays the B-field morphology of the LDN 1225 region based on the polarization measurements \((P_{C}\) and \(\theta_{C}\)) of 118 BG stars as depicted with yellow vectors. It should be noted here that these measurements are corrected for the ISP contribution. Based on the \(^{12}\)CO data, the position angle of the major axis of LDN 1225 is found to be \(\sim 102°\) (depicted with a

Figure 4. Differential polarization \(P_{i+1} - P_{i}\), polarization angle \(\theta_{i+1} - \theta_{i}\), and Stokes parameters \((Q_{i+1} - Q_{i}\) and \(U_{i+1} - U_{i}\) vs. distance \((\text{Distance}_{i+1})\) parameter for the stars used in Figure 3. We used the data up to 2 kpc and distance on a linear scale. Black vertical (at 830 pc) and horizontal dotted lines in each panel separate all the data into four regions. Region II is devoid of data (at most four stars in the panel of \(U_{i+1} - U_{i}\) vs. \(\text{Distance}_{i+1}\)) unlike the other three regions (I, III, and IV). In all the panels, region I is dominated by the FG stars, and regions III and IV by BG stars. Blue and red dotted vertical lines are drawn, respectively, at 747 and 913 pc, corresponding to the lower and upper limits of the ascertained distance of 830 pc with an uncertainty of 83 pc for LDN 1225. Blue circles represent stars in the range 747 pc < Distance\(_{i+1}\) < 830 pc; and red circles those with 830 pc < Distance\(_{i+1}\) < 913 pc. Green arrows mark a clear transition of the differential parameters from negative to positive (or vice versa) at the distance of 830 pc.
white dashed ellipse in Figure 1; see Section 4.5 and Table 5) and the mean $B$-field orientation inferred by optical polarimetry ($\theta_c$) of the globule is $106^\circ \pm 11^\circ$. This implies that the cloud structure (major axis of the globule) is nearly aligned parallel to the $B$-fields. This morphological correlation between the cloud structure and $B$-fields manifests an important role of $B$-fields in the formation of the globule, a detailed discussion of which will be given in Section 4.5.

The $B$-field orientation of LDN 1225, inferred from the mean $\theta_c = 106^\circ \pm 11^\circ$, is offset by $38^\circ$ from the position angle, $68^\circ$,
of the GP at $b = 1^\circ22$ (white line in Figures 1(a) and (b) and dashed vertical line in Figure 6(b)). Nonetheless, within the error, the foreground component (mean $\theta_{FG} = 60^\circ \pm 11^\circ$) is parallel to the GP component, suggesting that the dust grains of the FG medium are aligned by the local $B$-fields that are parallel to the GP.

3.6. Polarizations of FG and Cloud Media of CepOB3 Based on Optical Polarimetry

By adopting the same distance criteria as for LDN 1225, we identify FG and BG stars in 19 fields of CepOB3 (Section 2.2). Furthermore, assuming that LDN 1225 and CepOB3 share a common ISP contribution (see Section 3.5), we correct for it from the polarizations of BG stars and then derive the cloud polarizations of 19 fields of CepOB3. The resultant weighted mean polarizations of foreground and cloud media of these 19 fields and their central coordinates, number of stars in each field, and the instrument (or source) used are given in Table 4.

Similarly, V-band polarizations of 15 stars, distributed within the $5^\circ \times 5^\circ$ area of CepOB3, are extracted from the catalog of Heiles (2000). Of these, nine are FG and six are BG stars according to their distances from Gaia DR2 as well as our analyses concerning the identification of FG and BG stars (see Section 3.3). Their coordinates, HD numbers, and polarizations are given in Table 4.

3.7. Gas Velocity Dispersion and Number Density in LDN 1225 Using PMO CO Data

In order to evaluate the relative importance of $B$-fields to turbulence and gravity, we need to estimate the $B$-field strength and its pressure. For this, we extract gas velocity dispersion ($\sigma_{V_{LSR}}$) and number density ($n(H_2)$) from the $^{12}$CO(1–0) molecular line data from the PMO MWISP project.

Figure 8 shows the $^{12}$CO(1–0) maps of total integrated intensity, velocity, and velocity dispersion. These maps were constructed using velocity channels ranging from $\sim -13 \text{ km s}^{-1}$ to $\sim -3 \text{ km s}^{-1}$, and having a brightness temperature ($T_b$) above three times the rms noise. This selection criterion on the range of velocity channels excludes CO emission from the background cloud NGC 7538 (at $\sim -54.5 \text{ km s}^{-1}$; see Figures 5(a) and (b)).

Using CASA software, a two-dimensional Gaussian is fitted to the CO map of velocity-integrated intensity of LDN 1225, and the resultant spatial extents of major and minor axes, and the position angle of the major axis are $8^\circ/6 \pm 0^\circ/2, 4^\circ/3 \pm 0^\circ/1$, and $102^\circ \pm 1^\circ$, respectively, and are represented with a black dashed ellipse in Figure 8. These values are consistent with those ($8^\circ/4, 4^\circ/2, and 102^\circ$) derived from Five College Radio Astronomy Observatory (FCRAO) CO data as given in the Vizier catalog.\(^{14}\)

The mean integrated intensity ($W(CO)$) distributed within the extent of LDN 1225 (black ellipse, Figure 8) is $17 \pm 4 \text{ K km s}^{-1}$. Using the CO-to-H$_2$ conversion factor, $X \equiv N(H_2)/W(CO) = (2.0 \pm 0.6) \times 10^{20} \text{ cm}^{-2}$ (K km s$^{-1}$)$^{-1}$ (Bolatto et al. 2013, see also Dame et al. 2001 and Sofue & Kataoka 2016), the mean column density $N(H_2)$ is estimated as $(3.4 \pm 1.3) \times 10^{21} \text{ cm}^{-2}$.

Assuming the diameter of the minor axis, $4^\circ/3 \pm 0^\circ/1$ (equivalent to $1.04 \pm 0.02 \text{ pc}$ at $830 \text{ pc}$), as the thickness of LDN 1225, the mean number density, $n(H_2)$, is $(1.1 \pm 0.4) \times 10^4 \text{ cm}^{-3}$.

A Gaussian fit to the $^{12}$CO spectrum of mean $T_b$ versus $V_{LSR}$ over the entire region of LDN 1225 resulted in a gas velocity dispersion $\sigma_{V_{LSR}} = 0.88 \pm 0.01 \text{ km s}^{-1}$. In addition, the fitted values of $V_{LSR}$ and $T_b$ are $-11.08 \pm 0.01 \text{ km s}^{-1}$ and $4.96 \pm 0.04 \text{ K}$, respectively.

3.8. B-field Strength in LDN 1225

Using the dispersion in the $B$-fields $\sigma_B = 11^\circ/4 \pm 0^\circ/3$ (see Section 3.5), gas velocity dispersion $\sigma_{V_{LSR}} = 0.88 \pm 0.01 \text{ km s}^{-1}$ (see Section 3.7), and the mean number density $n(H_2) = (1.1 \pm 0.4) \times 10^4 \text{ cm}^{-3}$ (see Section 3.7) for LDN 1225, we estimate $B$-field strength using the Davis–Chandrasekhar–Fermi method (more commonly referred to as the Chandrasekhar–Fermi (CF) method; Davis 1951; Chandrasekhar & Fermi 1953):

$$B = Q \left( \frac{\sigma_{V_{LSR}}}{\sigma_B} \right)$$

The mass density $\rho = n(H_2)m_H \mu_H$, where $n(H_2)$ is the hydrogen volume density, $m_H$ is the mass of the hydrogen atom, and $\mu_H \approx 2.8$ is the mean molecular weight per hydrogen molecule, which includes the contribution from helium. The correction factor $Q = 0.5$ is included based on studies using synthetic polarization maps generated from

\(^{14}\) Available at http://cdsarc.u-strasbg.fr/viz-bin/Cat?J/ApJS/144/47.
numerically simulated clouds (Ostriker et al. 2001), which suggest that B-field strength is uncertain by a factor of two for $\sigma_B \lesssim 25^\circ$. The estimated B-field strength is $56 \pm 10$ $\mu$G. Implications based on the relative importance of the B-field to turbulent pressure in the formation and evolution of the globule LDN 1225 are discussed in Section 4.2.

4. Discussion

4.1. Association of LDN 1225 with CepOB3

Based on a detailed comparison of $V_{\text{LSR}}$, distance, and B-fields of LDN 1225 with those of CepOB3, we discuss whether the two are associated. According to the $^{12}$CO and $^{13}$CO data (from PMO MWISP) of LDN 1225, the mean $V_{\text{LSR}}$ values are $-11.08 \pm 0.01$ and $-11.12 \pm 0.02$ km s$^{-1}$, respectively. These values are consistent with the mean $V_{\text{LSR}}$ of $-11.2$ km s$^{-1}$ of a number of dark globules, namely, LDN 1210, LDN 1216, LDN 1218, LDN 1220, LDN 1227, LDN 1232, etc. (Yonekura et al. 1997), which are part of CepOB3. Similarly, several dense clumps of CepOB3 such as LDN 1211, Cep A, Cep B, Cep C, Cep E, and Cep F are also found to have $V_{\text{LSR}}$ values within the range $-8$ to $-12$ km s$^{-1}$ (Sargent 1977; Yu et al. 1996). These inferences suggest that LDN 1225 is kinematically associated with CepOB3.

As per our present work, LDN 1225 is located at a distance of $830 \pm 83$ pc (see Section 3.2), which is consistent with the distance 700 pc assigned to LDN 1225 assuming its association with CepOB3 (Sargent 1977; Dame et al. 1987; Launhardt & Henning 1997). The distance of CepOB3 calibrated via principal component analysis (under the assumption of a universal relationship between velocity dispersion and spatial scale within the clouds) on the CO data of the FCRAO Outer Galaxy Survey is $730 \pm 120$ pc (Brun et al. 2003). Using the methanol maser parallaxes, the distance of Cep A is ascertained to be $700 \pm 40$ pc (Moscadelli et al. 2009). This distance is consistent with those quoted in other studies (Blaauw et al. 1959; Crawford & Barnes 1970; Sargent 1977; Ladd & Hodapp 1997; Hartigan et al. 2000; Kun et al. 2008). Therefore, LDN 1225, located at $830 \pm 83$ pc, is spatially and kinematically associated with CepOB3.

Furthermore, using the polarization observations of 19 fields (Figure 9(a)), we compare the B-fields in the FG and cloud media of CepOB3 with those of LDN 1225 to test whether the large-scale B-fields are preserved at smaller scales. B-field orientations of FG and cloud media of CepOB3, using our observations as well as data from Heiles (2000) (see Section 3.6), are shown in Figures 9(b) and (c). The weighted mean B-field orientation for the FG medium of CepOB3 is $67^\circ$ with a standard deviation of $26^\circ$ (Figure 9(b)), while that for LDN 1225 is derived as $61^\circ$ with a standard deviation of $11^\circ$ (see Section 3.3). This implies that the B-fields in the FG media of LDN 1225 and CepOB3 are fairly similar, and are dominated by the GP component of $68^\circ$. Similarly, the weighted mean B-field orientation in CepOB3 is $113^\circ$ with a standard deviation of $29^\circ$ (as shown in Figure 9(c)), while that for LDN 1225 is $106^\circ$ with a standard deviation of $11^\circ$ (see...
Section 3.5). This result again suggests that, within the uncertainty, the mean $B$-fields in CepOB3 and LDN 1225 are similar, implying that $B$-fields at the small scales of LDN 1225 are inherited from those at the large scales of CepOB3. Hence, these large-scale $B$-fields of CepOB3 could be important in governing the formation and evolution of LDN 1225.

Therefore, in conclusion, LDN 1225 has similar spatial, kinematic, and magnetic characteristics to CepOB3, thereby confirming their association.

### 4.2. Cloud Stability

To understand the importance of $B$-fields with respect to turbulence, we estimate the magnetic pressure and turbulent pressure using the relations $P_B = B^2/8\pi$ and $P_{\text{turb}} = \rho \sigma_{\text{turb}}^2$ (where $\sigma_{\text{turb}} = \sigma_{\text{turb}}^{\text{obs}}$) as $(12 \pm 5) \times 10^{-11}$ dyn cm$^{-2}$ and $(4 \pm 1) \times 10^{-11}$ dyn cm$^{-2}$, respectively. The mean $P_B/P_{\text{turb}}$ is estimated to be $3 \pm 2$, suggesting the dominant role of $B$-fields over turbulence.

To infer the importance of $B$-fields with respect to gravity, we estimate the ratio of mass to magnetic flux in units of the critical value using the following relation (Crutcher et al. 2004; Chapman et al. 2011),

$$\mu = \frac{(M/\phi)}{(M/\phi)_{\text{crit}}} = 7.6 N_0(H_2)/B_0,$$

where $N_0(H_2)$ is the column density, in units of $10^{21}$ cm$^2$, along the magnetic flux tube and $B_0$ is the total $B$-field strength in $\mu G$. The critical mass-to-flux ratio, $(M/\phi)_{\text{crit}} = 1/\sqrt{4\pi G}$ (Nakano & Nakamura 1978), corresponds to the stability criterion for an isothermal gaseous layer threaded by the perpendicular $B$-fields. A cloud region with $(M/\phi) > (M/\phi)_{\text{crit}}$, i.e., $\mu > 1$, will collapse under its own gravity and the cloud is considered to be supercritical. A cloud with $\mu < 1$ will be in a subcritical state because of the major support rendered by $B$-fields. On the basis of three reasons, (i) projection effects between $N_0(H_2)/B_{\text{tot}}$ and the actual measured $N(H_2)/B_0$ (where $B_0$ is the plane-of-the-sky $B$-field strength), (ii) $B$-fields parallel to the cloud structure, and (iii) randomly oriented $B$-fields with respect to the line of sight, the actual value of $\mu$ will become $(3/4)\mu_{\text{obs}}$ (Planck Collaboration et al. 2016, see their Appendix D.4). Therefore, Equation (6) can be rewritten as $\mu = 3.7N(H_2)/B_0$. Using $N(H_2) = (3.4 \pm 1.3) \times 10^3$ cm$^{-2}$ (see Section 3.7) and $B_0 = 56 \pm 10 \mu G$ (see Section 3.8) for LDN 1225, $\mu$ is estimated to be $0.35 \pm 0.15$. This value suggests that LDN 1225 is magnetically subcritical, implying strong support by the $B$-fields, at least for the outer low-density parts where optical polarimetry is reliable. However, the situation in regions of relatively high density may be different because of the dominance of gravity.

Based on the NH$_3$ observations of LDN 1225 by Scappini & Codella (1996), the peak emission occurs at $V_{\text{LSR}} = -11.5 \pm 0.1$ km s$^{-1}$, with a line width $\Delta V = 0.8 \pm 0.1$ km s$^{-1}$. They consider LDN 1225 to be an inactive globule. However, as per the IRAS Serendipitous Survey Catalog (Kleinmann et al. 1986), within the $8^\prime$ diameter, LDN 1225 hosts IRAS source IRAS 23094 + 6122 (see also Maheswar & Bhatt 2006). Additionally, in this study, based on mid-infrared (MIR) and far-infrared (FIR) images, we find that LDN 1225 hosts two bright MIR young stellar objects (YSOs) and two Herschel/PACS 70 $\mu$m sources (see Section 4.6). These sources are located in the dense parts of LDN 1225, suggesting that LDN 1225 is not a quiescent cloud but on the verge of collapse and forming stars.

### 4.3. Structure Function Analysis and the Ratio of Turbulent to Ordered $B$-field Strength

Structure function analysis (or angular dispersion function) has been used to derive the ratio of turbulent to ordered $B$-field strength $(\langle B^2/\phi \rangle)^{1/2}/B_0$. To separate the turbulent components from non-turbulent ones, we plotted $(\Delta \theta^2/I(I))^1/2$ (Falceta-Gonçalves et al. 2008; Franco et al. 2010; Poidevin et al. 2010; Santos et al. 2012, 2016; Eswaraiah et al. 2013; Franco & Alves 2015), the square root of the second-order structure

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**Table 4**

Weighted Mean Polarization Measurements of FG and BG Stars (ISP-corrected) of Various Fields of CepOB3

| Field/HD Number | R.A. (J2000) (h:m:s) | Decl. (J2000) (deg; ′; ″) | Weighted Mean $P$ (%) | Weighted Mean $\theta$ (deg) | Passband | No. of Stars | Instrument (or Source) |
|-----------------|----------------------|-----------------------------|-----------------------|-----------------------------|----------|-------------|-----------------------|
| (1)             | (2)                  | (3)                         | (4)                   | (5)                         | (6)      | (7)         | (8)                   |
| FG stars with $d < 830$ pc |
| 1               | 22:56:53.322         | 62:09:58.572                | 0.54 ± 0.14           | 63 ± 7                      | R        | 4           | AIMPOL                |
| 2               | 22:56:33.530         | 62:04:54.912                | 2.20 ± 0.10           | 73 ± 1                      | R        | 5           |"                     |
| 3               | 22:56:07.713         | 61:58:02.352                | 1.19 ± 0.08           | 109 ± 2                     | R        | 5           |"                     |
| 4               | 22:57:41.210         | 62:41:51.792                | 1.29 ± 0.13           | 69 ± 3                      | R        | 2           | IMPOL                 |
| 5               | 22:58:16.408         | 62:43:25.176                | ...                  | ...                         | R        | 0           |"                     |
| 6               | 22:57:02.560         | 62:39:01.188                | 0.61 ± 0.03           | 68 ± 1                      | R        | 4           |"                     |
| 7               | 22:56:50.930         | 62:34:53.292                | 1.31 ± 0.06           | 76 ± 1                      | R        | 3           |"                     |
| 8               | 22:56:51.355         | 62:31:18.084                | 1.41 ± 0.03           | 83 ± 1                      | R        | 4           |"                     |
| 9               | 22:58:19.392         | 62:38:45.744                | 0.11 ± 0.06           | 75 ± 14                     | R        | 1           |"                     |
| 10              | 22:57:34.209         | 62:35:53.484                | 1.00 ± 0.07           | 163 ± 2                     | R        | 3           |"                     |

Note. Also given are the central coordinates and number of stars in each field, the passband, and the instrument or source used for the data. R.A. and decl. (except those of the stars from Heiles 2000) are the central coordinates of the observed fields.

(This table is available in its entirety in machine-readable form.)
function or angular dispersion function (ADF),\textsuperscript{16} as a function of distance ($l$) as shown in Figure 10. We used the polarization angles ($\theta_C$) of 118 BG stars to compute $(\Delta \theta^2(l))_{\text{tot}}^{1/2}$, which depicts how the dispersion of the polarization angles changes as a function of the length scale in LDN 1225.

The square of the dispersion function can be approximated as follows (Hildebrand et al. 2009):

$$\langle (\Delta \theta^2(l))_{\text{tot}} - \sigma_M^2(l) \rangle = b^2 + m^2 l^2,$$

(7)

where $\langle (\Delta \theta^2(l))_{\text{tot}} \rangle$ is the dispersion function computed from the data. The quantity $\sigma_M^2(l)$ is the measurement uncertainty, which is simply the average of the variances on $\Delta \theta(l)$ in each bin. The quantity $b^2$ is the intercept of a straight line fit to the data (after subtracting $\sigma_M^2(l)$). Hildebrand et al. (2009) have derived the equation for $b^2$ to find the ratio of turbulent to large-scale ordered $B$-field strength:

$$\frac{\langle B^2 \rangle^{1/2}}{B_o} = \frac{b}{\sqrt{2 - b^2}}.$$

(8)

In Figure 10, we show the ADF versus displacement using $\theta_C$ of 118 BG stars for the LDN 1225 region. The errors in each bin are similar to the size of the symbols. Each bin denotes $\sqrt{(\Delta \theta^2(l))_{\text{tot}} - \sigma_M^2(l)}$, i.e., the ADF corrected for the measurement uncertainty. Bin widths are on a logarithmic scale. Only the first three data points were used in the linear fit.

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\textsuperscript{16} The ADF is defined as the square root of the average of the squared difference between the polarization angles measured for all pairs of points ($N(l)$) separated by a distance $l$. 

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**Figure 8.** $^{12}$CO(1–0) moment maps of the 30′ × 30′ area containing LDN 1225 using the data from PMO as a part of the MWISP project. (a) CO map of total integrated intensity (moment 0) of the region containing LDN 1225. (b) CO map of mean velocity (moment 1). (c) CO map of velocity dispersion (moment 2). These maps were made using velocity channels ranging from $\sim -13$ km s$^{-1}$ to $\sim 3$ km s$^{-1}$ and having a brightness temperature above three times the rms noise. The extent of LDN 1225 is shown with a dashed ellipse with major and minor axis lengths of 8′/6 and 4′/3, and with PA of 102°. The color bar in each panel corresponds to the respective map units. The center of cloud LDN 1225 is denoted with a plus symbol in each panel. The location of the source IRAS 23094 + 6122 is shown with a cross symbol. Circles and diamonds correspond to the Herschel/PACS 70 µm and MIR sources, respectively. Within the area of LDN 1225, the distributions of gas velocity (panel b) as well as gas dispersion (panel c) are found to be uniform.

**Figure 9.** (a) Polarization measurements of several fields to infer the $B$-field orientation toward CepOB3. Fields observed with optical polarimeters AIMPOL, TRIPOL, and IMPOL are shown. (b) $B$-field orientation in the foreground medium of CepOB3 using the weighted mean polarizations of stars with $d < 830$ pc. (c) Same as (b), but corresponding to the $B$-field map of CepOB3 using the polarizations of BG stars with 830 pc $< d < 2.65$ kpc and corrected for the ISP contribution. Locations of the clumps and globules are shown. Note here that in the case of a field containing more than two stars, their weighted means are plotted; otherwise their single measurements are shown. Similarly, we also plotted polarization of FG and ISP-corrected BG stars with data from Heiles (2000) using yellow vectors. In panels (b) and (c), the orientation of the Galactic plane with a position angle of 68° and a reference vector with 3% and 90° are shown. In all the panels the background is the 5′ × 5′ DSS R-band image and the cyan contours correspond to the extinction ($A_V$) map drawn from 2.5 to 6.5 mag with intervals of 0.5 mag (Dobashi et al. 2005).
to ensure that the length scale $l$ in the fit ($\sim 0.1 - 0.4$ pc) is greater than the turbulent length scale $\delta$ (which is of the order of 1 milliparsec (mpc) or 0.001 pc; e.g., Li & Houde 2008) and much shorter than the cloud length scale ($d \sim 1$ pc), i.e., $\delta < l < d$, to the data (Equation (7)) versus square of the distance. The fitted function is denoted with a thick dotted line.

As our optical polarimetric observations have a low resolution due to the limited number of point sources available, the minimum length we probed is $\lesssim 31$ mpc. The turbulent contribution to the total ADF is determined by the zero intercept of the fit to the data at $l = 0$. The net turbulent component, $b$, is estimated as $10^\circ \pm 2^\circ$ (or 0.17 $\pm$ 0.04 rad). This dispersion value ($10^\circ \pm 2^\circ$) estimated using structure function analysis is similar to the dispersion in $\theta_C$ obtained using a Gaussian fit ($\sigma_C = 11^\circ$; Section 3.5). The ratio of the turbulent to large-scale magnetic field strength ($\sigma(\theta) = \langle B_c^2 \rangle^{1/2} / B_0$) is computed using Equation (8) as 0.12 $\pm$ 0.03. This suggests that the turbulent component of the field is very small compared with the non-turbulent ordered B-field component, i.e., $B_t \ll B_0$, and that large-scale ordered B-fields are dominant over the turbulent component in LDN 1225.

4.4. Correlations among the Observed Multiple Components in CO Gas and B-fields

The CO mapping with the 1.2 m telescope of the Center of Astrophysics was carried out toward the Perseus arm, covering CepOB3, Cas A, and NGC 7538 (Ungerechts et al. 2000). Their survey revealed that $V_{LSR}$ of the Local Arm is between $+5$ and $-25$ km s$^{-1}$, which is clearly separated kinematically from the distant Perseus arm whose $V_{LSR}$ lies between $-45$ and $-80$ km s$^{-1}$ with a mean $V_{LSR} \sim -54.5$ km s$^{-1}$. It is worth stating here that there exists an emission-free irregular band between $-45$ km s$^{-1}$ and $-20$ km s$^{-1}$ in the PV diagram (Ungerechts et al. 2000, see their Figures 2(a) and (b)), suggesting a dearth of material within the inner arm. This is also true from PV cuts on $^{13}$CO data toward a small area containing LDN 1225 as shown in Figure 5. This result would also suggest the absence of an additional cloud component with a significantly different $B$-field orientation within the inner arm. Therefore, it is possible to claim that $\theta_R$ values lying between $\sim 70^\circ$ and $\sim 100^\circ$ (Figure 3(b)) and having distances between 830 pc and 2.65 kpc may correspond to the $B$-fields of LDN 1225, and hence the dispersion in the $\theta_R$ values is due to the turbulence within the cloud. However, a larger dispersion in the corresponding $P_R$ values spanning a range of $\sim 1.5\%$ to $\sim 5\%$ (Figure 3(a)) is owing to different optical depths, causing different amounts of polarization as traced by the background stars lying in different parts of the cloud.

Furthermore, the Local Arm possesses three gas components centered around $+5$, $-5$, and $-10$ km s$^{-1}$. The $-10$ km s$^{-1}$ component with relatively dense gas is attributed to CepOB3 located at $\sim 830$ pc, whereas the other two components with less dense gas may correspond to the diffuse foreground dust layers located between our Sun and CepOB3. It is interesting to state that the distribution of gas with components $-5$ and $-10$ km s$^{-1}$ exhibits a continuous spread, implying the presence of a uniformly distributed tenuous medium up to CepOB3. This is further corroborated by a continuous increase in the level of polarization as a function of distance (see Figure 3) as well as by a smooth variation of $P_R$ with $\theta_R$ (see Figure 2).

The presence of two components can be witnessed in the $P$ and $\theta$ distributions of FG and BG stars (Figure 6, Sections 3.3 and 3.5). The $B$-field component of the FG medium is oriented northeast–southwest (with a mean $\theta_{FG} = 61^\circ \pm 11^\circ$), while that of the cloud medium is east–west (with a mean $\theta_C = 106^\circ \pm 11^\circ$). These two components, with different mean polarization values, are separated at $P_R = 2\%$ and $\theta_R = 75^\circ$ (Section 3.1). In summary, our polarization observations revealing two distributions in both degrees of polarization and polarization angles are consistent with two CO cloud components centered around $\sim -5$ km s$^{-1}$ and $\sim -10$ km s$^{-1}$.
Figure 12. Locations of the 70 μm sources (circles) and the distributions of moment 0 maps of two 12CO gas components overlaid on multi-wavelength images: (a) DSS R-band image, (b) WISE 22 μm image, (c) Herschel/PACS 70 μm image, and (d) column density map. Red contours, drawn at 6, 10, 14, 18, 20, and 22 K km s$^{-1}$, correspond to the 12CO moment 0 map of LDN 1225 with mean $V_{\text{LSR}}$ = -11.2 km s$^{-1}$. Yellow contours, drawn at 6, 10, 14, 18, 25, 30, 35, 40, 45, 50, and 55 K km s$^{-1}$, correspond to the 12CO moment 0 map of a distant star-forming region in the Perseus arm with mean $V_{\text{LSR}}$ = -54.5 km s$^{-1}$. Two bright MIR sources, denoted with diamond symbols, are faint in the 70 μm image. The center of cloud LDN 1225 is denoted with a plus symbol. The location of source IRAS 23094+6122 is shown with a cross symbol. The beam size (53″; 0.2 pc) of the CO map is shown with a cyan circle in panel (c). The centers of the CO moment 0 emission peaks of two cloud components are shown with arrows in panel (d). The color bars in panels (c) and (d) correspond to the flux units of the respective image.

Table 5
Spatial Extents and Position Angles of LDN 1225 Based on the CASA 2D Gaussian Function Fitting to the Moment 0 Maps of 12CO, 13CO, and C18O

| Line | R.A (J2000) (h:m:s) | Decl. (J2000) (deg;") | FWHM$_{\text{major}}$ (arcmin) | FWHM$_{\text{minor}}$ (arcmin) | $\theta_{\text{cloud}}$ (deg) | $\Delta\theta = |\theta_{\text{cloud}} - \theta_C|$ (deg) |
|------|---------------------|------------------------|-------------------------------|-------------------------------|-------------------------|---------------------------------|
| 12CO | 23:12:16.62         | 61:38:24.27            | 8.6 ± 0.2                     | 4.4 ± 0.1                     | 102 ± 1               | 4 ± 11                          |
| 13CO | 23:12:01.11         | 61:39:13.50            | 4.4 ± 0.1                     | 3.1 ± 0.1                     | 52 ± 3                | 54 ± 11                         |
| C18O | 23:11:55.60         | 61:39:15.00            | 1.8 ± 0.1                     | 1.3 ± 0.1                     | 54 ± 8                | 52 ± 14                         |

Note. $\theta_C = 106^\circ \pm 11^\circ$, the mean B-field orientation in LDN 1225 after correcting for foreground (interstellar) polarization (see Section 3.5).
4.5. Geometry of LDN 1225 in 12CO, 13CO, and C18O Molecular Lines

Generally the 12CO emission comes from the tenuous gas distributed in low-density parts of the cloud, whereas the 13CO and C18O emissions come from the inner, denser gas. As LDN 1225 has been observed simultaneously at these three molecular lines, we compare the ambient mean orientation of the B-fields with the orientations of the major axes of LDN 1225 at different length scales and depths. These comparisons would reveal how the B-fields, turbulence, and gravity interact with the cloud material and govern its structure, stability, and contraction at different scales and depths (Eswaraiah et al. 2013). The advantage in using molecular lines to determine the cloud structure is that the foreground cloud component will be well separated from that of the background in velocity space.

We have employed a CASA 2D Gaussian fitting function on the moment 0 maps of 12CO, 13CO, and C18O, respectively shown with red, green, and magenta contours in Figure 11, and extracted the spatial extents and position angles of the cloud elongations. The corresponding fitted central coordinates, FWHMs of major and minor axes, and position angles are given in Table 5. The last column gives the offset ($\Delta(\theta)$) between the cloud position angles ($\theta_{\text{cloud}}$) traced by three CO lines and the mean B-field orientation ($\theta_C$, Section 3.5) of LDN 1225.

The $\Delta(\theta)$ from 12CO is $4^\circ \pm 11^\circ$, implying that low-density outer parts of the cloud are nearly aligned parallel with the ambient B-fields, suggesting the importance of B-fields in governing the cloud structure. However, $\Delta(\theta)$ values from 13CO and C18O are $54^\circ \pm 11^\circ$ and $52^\circ \pm 14^\circ$, indicating that, within the error, the PAs of the denser parts of the cloud are neither parallel nor perpendicular to B-fields. This suggests that B-fields of the low-density outer parts may not equally be important in governing the cloud structure in the high-density inner parts; in other words, turbulence and gravity might be crucial in these denser parts. In order to shed more light on these, we need to probe the B-fields in the denser parts, using NIR and submillimeter polarimetry.

4.6. Association of MIR and 70 $\mu$m Point Sources with LDN 1225

In order to determine whether LDN 1225 is a starless or star-forming cloud, we search for the YSOs by examining the multi-wavelength images of LDN 1225 as shown in Figure 12. We have identified two MIR (diamonds) and two 70 $\mu$m (circles) sources, respectively, in the images of WISE 22 $\mu$m (Figure 12(b)) and
To elucidate more on the association of YSOs, we have searched for the $^{12}$CO, $^{13}$CO, and C$^{18}$O emissions from LDN 1225 (top panels) and NGC 7538 (bottom panels), especially at the locations of the YSOs as shown in Figure 13. Evidently, all YSOs are distributed not only within the emissions from low-density tracers ($^{12}$CO/$^{13}$CO) but also within that from the dense gas tracer (C$^{18}$O) of LDN 1225. Moreover, despite a small amount of $^{12}$CO/$^{13}$CO emission, a complete lack of C$^{18}$O emission from NGC 7538 is witnessed at the sites of YSOs. This implies that LDN 1225 comprises denser gas than the background cloud. These results reinforce the fact that LDN 1225 is indeed a star-forming dark globule, hosting MIR and 70 µm sources in its denser parts.

4.7. Properties of 70 µm Sources

As 70 µm sources are brighter in FIR and fainter in NIR and MIR wavelengths (see Figure 12), their disks may constitute a negligible contribution to the shape of the spectral energy distribution (SED) at $\lambda \leq 100$ µm (e.g., Whitney et al. 2005). The main contributor to the SED of 70 µm sources could be their envelopes. In order to study the nature of these 70 µm sources (see Section 4.6 and Figure 13), we have performed aperture photometry on the Herschel images as documented in Balog et al. (2014), and modified blackbody fitting was performed on the fluxes at 70, 160, 250, and 350 µm as shown in Figures 14(a) and (b).

The computed envelope masses ($M_{env}$), bolometric luminosities ($L_{bol}$), and dust temperatures ($T_{dust}$) are 11 $M_\odot$ and 4 $M_\odot$, 5 $L_\odot$ and 8 $L_\odot$, and 13 K and 17 K, respectively, for sources 1 and 2. SED fits suggest that the envelopes of the two 70 µm sources are those of low-mass and low-luminosity Class 0 protostars.

Furthermore, we have used the above physical parameters of these sources to infer their final evolutionary status based on the $M_{env}$-$L_{bol}$ diagram (Figure 15). The location of the two 70 µm sources in comparison to the evolutionary tracks of protostars with different envelope masses and luminosities (André et al. 2008, and

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17 The column density map has been constructed by fitting the modified blackbody function to the Herschel PACS and SPIRE fluxes as described in Appendix D of Eswaraiah et al. (2017, and references therein). Data have been taken from the Herschel Infrared Galactic Plane Survey (Hi-GAL; Molinari et al. 2010).

18 Fluxes at 500 µm have been excluded, owing to the low resolution of the 500 µm beam. This is done in order to avoid bias in the fitting procedure due to overestimation of fluxes at 500 µm because of source confusion and the inclusion of excess background emission.
The reddening vector representing a normal reddening law (red lines correspond to the weighted linear fits made to the color–color slopes of the FG and BG stars, respectively. The curve in the top left panel ((V − I) vs. (B − V)) represents the locus of M-type dwarfs (Peterson & Clemens 1998). Twenty-seven FG and 16 BG M-type dwarfs, shown with squares, are not used in the fits. The reddening vector representing a normal reddening law (RV = 3.1) is drawn with AV = 2 mag in the top left panel.

**Figure 16.** The (V − I), (V − J), (V − H), and (V − Ks) vs. (B − V) two-color diagrams of group I stars having distances and photometric data (with uncertainties < 0.1 mag in BVLIJK, bands). The blue and red filled circles correspond to the photometric colors of 92 FG and 351 BG stars, respectively. The blue and red lines correspond to the weighted linear fits made to the color–color slopes of the FG and BG stars, respectively. The curve in the top left panel ((V − I) vs. (B − V)) represents the locus of M-type dwarfs (Peterson & Clemens 1998). Twenty-seven FG and 16 BG M-type dwarfs, shown with squares, are not used in the fits. The reddening vector representing a normal reddening law (RV = 3.1) is drawn with AV = 2 mag in the top left panel.

references therein) suggests that they may evolve into stars with final masses from 1 M☉ to 5 M☉ in the final phases of accretion (see the tips of the arrows in Figure 15).

### 4.8. Are the B-fields Important to the Star Formation in LDN 1225?

If B-fields are important in a cloud to form cores via the ambipolar diffusion process or a strong B-field model (Mouschovias 1976, 1991; Shu 1977; Shu et al. 1987; Mouschovias & Ciolek 1999), then (i) the B-field structure in the low-density subcritical envelope should be aligned with the cloud structure, (ii) the major axis of the high-density core should be perpendicular to the envelope B-fields, and (iii) B-fields within the core should follow an hourglass shape if the core is in a supercritical state and collapsing.

The first condition is true in LDN 1225 because the ratio of mass to magnetic flux in units of the critical value, μ, is <1, suggesting that the envelope is in a subcritical state (Section 4.2) and hence the low-density envelope is strongly supported by B-fields. In addition, being parallel to the low-density parts (Section 3.5), B-fields aid the cloud contraction, producing elongated core structures perpendicular to them. However, as the long axis of the core is neither parallel nor perpendicular to the ambient B-fields (Section 4.5), the second condition may not be true in LDN 1225.

High-density cores are in a supercritical state as they are collapsing to form stars (Section 4.6). As we have not probed the B-fields on the core scale and have not derived various parameters (B-field strength, B-field pressure, turbulent pressure, mass-to-flux ratio in terms of critical value, etc.), the examination of the strong B-field model (third condition) is beyond the scope of this work. Therefore, to shed more light on whether or not the B-fields are important on core scales, we need to probe the B-fields using NIR/submillimeter polarimetry.

### 4.9. Extinction Law

The mean size distribution of dust grains can be evaluated by using the parameter RV = A_V/E(B − V), the ratio of total to selective extinction, which is also termed the extinction law (Cardelli et al. 1989; Olofsson & Olofsson 2010). Though the mean RV for the Milky Way is 3.1, it varies from one line of sight to another. To characterize the extinction law toward LDN 1225, we have used two-color diagrams (TCDs) of the form (V − λ) versus (B − V), where λ is one of the magnitudes in broadband filters, R, I, J, H, Ks, or L. These diagrams are usually employed to characterize the extinction law in the...
foreground and cloud (or stellar cluster) media (e.g., Pandey et al. 2000, 2003, 2013; Samal et al. 2007; Eswaraiah et al. 2013; Kumar et al. 2014). As the distance of LDN 1225 and the numbers of FG/BG stars are known, as illustrated in Appendix A, we derive the RV values for the foreground and cloud media. For this purpose we have used the optical and NIR photometric data from Table 3.

Based on the TCDs (Figures 16 and 17) and estimated weighted mean RV values (see Appendix A for more details on the figures and table), the following points can be made: (a) FG and BG stars of groups I (stars with photometry) and II (stars with photometry plus polarimetry) exhibit two conspicuously different distributions represented by different slopes and RV values, (b) within the error, RV values of FG (BG) stars belonging to the two groups are nearly the same and consistent with each other, (c) the extinction law in the foreground medium is normal, i.e., RV ∼ 3.1, and characterized with mean dust grain sizes, and (d) the extinction law in the cloud medium is abnormal, i.e., RV ∼ 3.4, and characterized with relatively bigger dust grains in the regions of LDN 1225 that we probed with photometry and polarimetry.

Different dust sizes are found toward different Galactic lines of sight. For example, in the direction of the high-latitude translucent molecular cloud HD 210121 (Welty & Fowler 1992; Larson et al. 1996), RV is 2.1, whereas in the direction of the molecular cloud HD36982 in the Orion nebula, the RV values lie between 5.6 and 5.8 (Cardelli et al. 1989; Fitzpatrick 1999; Draine 2003). In our work, an abnormal extinction law (with RV ∼ 3.4) in LDN 1225 might have been produced by the bigger dust grains resulting from growth by means of dust coagulation or dust accretion processes. These processes could take place in the molecular clouds because of the prevailing different physical conditions such as low temperatures and high density.

4.10. Extinction versus Polarization and Polarization Efficiency

To understand the polarization efficiency of the dust grains of LDN 1225, as illustrated in Appendix B, we estimate the visual extinctions (AV) of the field stars (mainly normal main-sequence (MS) stars and giants) located toward LDN 1225 by dereddening their NIR colors (Table 3) shown in Figure 18. Figure 19(a) shows the plot of AV versus PR of all the stars (except two BG stars) are distributed below the observed upper limit of the polarization relation P/AV < 3% mag⁻¹ (Serkowski et al. 1975) and exhibit a linear trend as a function of extinction. The polarization efficiency (PR/AV) of the dust grains of LDN 1225 tends to follow a systematically declining trend as a
Figure 18. NIR color-color diagram of the 113 stars having both polarization and NIR colors. Of these, 57 stars shown with filled black circles have $(J − K_s) < 0.75$ mag and are used to estimate the extinction ($A_V$) values by dereddening their observed $(J − H)$ and $(H − K_s)$ colors. The remaining 56 stars, shown with filled gray circles, are distributed to the left of the locus of the unreddened MS stars and giants, the stars having $(J − K_s) > 0.75$ mag (M-type stars or giants). These stars were not used for estimating $A_V$ values. The blue vector depicts the extinction value of $A_V = 1.92$ mag derived for a star with an ID 89 (see Table 7), whose colors are dereddened using the NIR extinction method. The red curve and green dotted-dashed lines represent the unreddened MS and the giant branch (Bessell & Brett 1988), respectively. The locations of stars with different spectral types are identified on the MS locus. The dotted line indicates the locus of unreddened classical T Tauri stars (CTTSs). The parallel dashed lines are the reddening vectors drawn from the tip (spectral type M4) of the giant branch (left reddening line) and from the base (spectral type A0) of the MS branch. A reference reddening vector with $A_V = 2$ mag is shown in the upper left portion.

function of extinction ($A_V$), similar to other works (e.g., Gerakines et al. 1995; Goodman et al. 1995; Whittet et al. 2008; Eswaranah et al. 2013; Wang et al. 2017), by following a power law of the form $P/A_V ∝ A_V^{-\alpha}$ shown in Figure 19(b). A weighted power-law fit to the data points of 22 BG stars (three FG and two BG stars are excluded from the fit; see figure caption for more details) satisfies the relation $P_B/A_V ∝ A_V^{-0.7 ± 0.5}$. Within the error, the power-law index $−0.7$ ± 0.5 is consistent with the indices $−0.7 ± 0.1$ for the entire molecular cloud complex IC 5146 using $R_c$-band data (Wang et al. 2017), $−0.8 ± 0.1$ for Pipe-109 using $R$-band data (Alves et al. 2014), and $−0.7 ± 0.1$ for L2014 using $H$-band data (Cashman & Clemens 2014). These reported indices are generally found for the low-density parts of the cloud observed in optical wavelengths, having $A_V$ values of 1–4 mag. However, softer indices ($−0.3$ to $−0.5$) are found toward the dense parts of the clouds with regions of high extinction ($A_V > 5$ mag) observed in NIR wavelengths (Whittet et al. 2008; Jones et al. 2015; Wang et al. 2017).

The negative index $−0.7 ± 0.5$ implies that dust grains in the low-density outer parts produce higher polarization efficiency, while those in the relatively high-density inner parts produce lower polarization efficiency. This is due to the variation of several factors as a function of extinction (Jones 1989; Jones et al. 1992; Gerakines et al. 1995; Whittet 2005; Whittet et al. 2008): (a) the dust grains themselves (size, shape, composition, presence or absence of surface coatings), (b) $B$-field direction weighted according to the distribution of dust grains along the line of sight, (c) the efficiency of dust grain alignment, and (d) the physical conditions of the environment in which dust exists. As our optical polarimetry is confined to the low-density outer parts of LDN 1225, and due to a small dispersion in the mean $B$-field orientation of LDN 1225, we interpret that the observed polarization efficiency with an index of $−0.7 ± 0.5$ is due to changes in the properties and alignment efficiency of dust grains as a function of extinction.

The power-law index can also determine whether the observed polarization observations trace the $B$-fields in the cloud. Ideally, a power-law index of $−1$ may corresponds to the ceasing of dust grain alignment, producing null polarization and thereby providing no clues about the $B$-field orientation. However, in this work, the index of $−0.7$ suggests that the dust grains are still aligned and our optical polarimetry is able to trace the $B$-fields in relatively less dense, outer parts of the cloud.

5. Summary and Conclusions

We have performed single $R_c$-band polarimetric and multi-band $(BV(RI)_{c})$ photometric observations of the stars distributed toward the dark globule LDN 1225. A total of 280 stars were found to have $R_c$ polarization data satisfying the $2\sigma$ criterion and also 689 stars are found to have optical plus 2MASS photometric data with uncertainties less than 0.1 mag. We use multi-wavelength images from DSS, WISE, Spitzer, and Herschel, parallaxes from Gaia DR2, and CO molecular line data from PMO. In this work, we investigate the distance of LDN 1225, the distribution of dust and $B$-field orientation as a function of distance, the importance of $B$-fields in the formation and evolution of the cloud, and the extinction law in the foreground and cloud media.

The main results of our study are summarized below.

1. Based on the plots of distance versus polarization, polarization angles, and Stokes parameters, we ascertain the distance of LDN 1225 as 830 ± 83 pc.

2. The total sample with polarization data is classified into foreground and background stars, based on the individual stellar distances in comparison to the cloud distance. FG and BG stars exhibit bimodal distributions in both the level of polarization and polarization angles.

3. FG stars exhibit increasing trends in their polarizations and Stokes parameters. We make use of these samples to characterize the ISP contribution, and this is subtracted to infer the $B$-field geometry of the cloud.

4. Using the dispersion in the cloud’s $B$-field orientations, gas velocity, and number density from PMO CO data, we estimate the $B$-field strength as $56 ± 10 \mu G$, by using the Davis–Chandrasekhar–Fermi relation. We find that the magnetic pressure is three times higher than the turbulent pressure, and also that the ratio of mass to magnetic flux in units of the critical value is less than one. These results imply the dominance of $B$-fields over turbulence and gravity in the envelope of LDN 1225.

5. The morphological correlations between $B$-fields and cloud geometry at different optical depths, as probed by $^{12}$CO, $^{13}$CO, and C$^{18}$O molecular lines, depict that $B$-fields might not be so important on the core scale of LDN 1225.
6. Based on the WISE and Herschel images along with the CO molecular line data, we find that LDN 1225 hosts two MIR and two 70 μm sources, thereby reinforcing that LDN 1225 is not a starless but a star-forming dark globule.

7. Structure function analysis suggests that the contribution from the turbulent component of magnetic fields is very small compared with that from the non-turbulent ordered component in LDN 1225.

8. B-fields in LDN 1225 remain coherent with the large-scale B-fields of CepOB3.

9. Using the distance versus polarizations, CO molecular line data, and B-fields, we infer that LDN 1225 is associated with and located at the same distance as CepOB3.

10. Using the photometric colors, the extinction law is tested in the foreground and cloud media. We find that the foreground medium is characterized with the normal extinction law, but the cloud medium with an abnormal extinction law.

11. The polarization efficiency of the dust grains of LDN 1225 declines as a function of extinction and yields a power-law exponent of \(-0.7 ± 0.5\), implying that our optical polarimetry is capable of tracing B-fields in the low-density parts of LDN 1225.

In conclusion, we make use of the polarization and distance information to study the dust distribution and its properties, and the B-field orientation of the cloud. This can serve as an important tool to probe the 3D topography of the interstellar medium and B-fields toward molecular clouds and star-forming regions. Photometry has been utilized to investigate the nature of the extinction law to characterize the dust properties. Polarimetry, along with the molecular line data, serves as an efficient tool to study the correlations between the multiple polarization and cloud components. Multi-wavelength (dust extinction and emission) polarization data, covering different length and density scales, are essential to test models of star formation.

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**Facilities:** ARIES:1m (AIMPOL polarimeter), LO:1m (TRIPOL polarimeter), IGO:2m (IFOSC in polarimetric mode——IMPOL), HCT:2m (HFOSC).

**Appendix A**

**Color–Color Diagrams and Estimation of Total to Selective Extinction (RV)**

Figure 16 shows the color–color diagrams of the 111 FG stars (with distances < 830 pc) and 375 BG stars (distances between 830 pc and 2.65 kpc) depicted using blue and red filled

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**Figure 19.** (a) Plot of extinction (AV) vs. polarization (PR) for the 27 stars located toward LDN 1225 and satisfying the criteria (J − Ks) < 0.75 mag and AV/σAV > 2 (see Appendix B). The dashed line denotes the observed upper limit on polarization, PR/AV = 3 (mag)−1 (Serkowski et al. 1975), and corresponds to optimum dust grain alignment in the general interstellar medium. (b) Same as (a), but for polarization efficiency, AV vs. PR/AV. The 22 BG stars with distances >830 pc, represented with filled circles, are used in the weighted power-law fit as shown with a thick curve. The resultant fit values are quoted in the plot. It is to be noted here that, of the 27, three FG stars having distances < 830 pc and PR < 2.5%, and two BG stars distributed above the line PR = 3 × AV, as depicted with open squares (in both panels (a) and (b)), are not used in the weighted power-law fit performed in panel (b).
Group I have photometric data, while group II have both photometric and polarimetric data. These M-type stars are identified based on a comparison of their $(B - V)$ versus $(V - I)$ colors with the intrinsic locus of M-type dwarfs (Peterson & Clemens 1998) shown with a curve in the top left panel of Figure 16. We have excluded M-type stars from the further analysis because they would affect the true reddening law of the cloud by occupying the location of reddened background stars. The remaining 92 FG stars and 351 BG stars with photometry (hereafter group I) were used to perform the weighted linear fits, and the resultant slopes are given in Table 6. Similarly, shown in Figure 17, we also estimate the slopes based on the weighted linear fits to the color–color combinations of 30 FG and 57 BG stars with photometry plus polarimetry (hereafter group II). The fitted slopes along with their uncertainties are given in Table 6. In group I, M-type stars seem to have more contamination on the reddened BG stars (Figure 16); in contrast, this is not pronounced in group II (Figure 17).

To estimate the value of $R_V$ for LDN 1225, we use the following relation (see Neckel & Chini 1981):

$$R_V = \frac{m}{m_{\text{normal}}} R_{\text{normal}},$$  

(9)

where $m$ and $m_{\text{normal}}$ are the slopes of the two-color combinations, respectively, for the FG or BG stars and unreddened main-sequence stars following the normal extinction law (taken from the stellar models by Bertelli et al. (1994), and also see Table 3 of Pandey et al. 2003). $R_{\text{normal}}$ corresponds to the normal extinction law and is considered to be 3.1. Using Equation (9) and the fitted slopes (see columns 3 and 5 of Table 6), we estimate $R_V$ values along with their uncertainties for the FG and BG stars of the two groups and these are given in columns 4 and 6 of Table 6. The weighted mean $R_V$ values are $3.10 \pm 0.01$ (standard deviation = 0.14) and $3.36 \pm 0.01$ (standard deviation = 0.14), respectively, for FG and BG stars of group I. Similarly, the weighted mean $R_V$ values are $2.87 \pm 0.01$ (standard deviation = 0.12) and $3.41 \pm 0.01$ (standard deviation = 0.15), respectively, for the FG and BG stars of group II. Discussion based on the derived $R_V$ values is given in Section 4.9.

### Appendix B

#### Estimation of Visual Extinction ($A_V$)

Figure 18 shows the NIR color–color ($(J - H)$ versus $(H - K_s)$) diagram of 113 stars having polarization data. NIR photometric data of these stars were extracted from the 2MASS point source catalog (Cutri et al. 2003). All the sources have uncertainties less than 0.1 mag, corresponding to S/N > 10, and with a photometric quality flag of “AAA”. We used the following relations (see Maheswar et al. 2010):

$$(J - H)_0 = (J - H) - 0.107 \times A_V,$$  

(10)

$$(H - K_s)_0 = (H - K_s) - 0.063 \times A_V.$$  

(11)

These relations utilize the extinction law of Rieke & Lebofsky (1985). In this method, various $A_V$ values having an interval of 0.01 mag were used for dereddening the observed colors, and these sets of dereddened colors were matched to the intrinsic colors as illustrated in Figure 18 using a blue arrow. The $A_V$ value at which the dereddened colors matched the intrinsic colors, giving a minimum chi-square value, yields the best $A_V$ of a star. The NIR extinction method estimates the $A_V$ value of a star by dereddening its observed colors ($(J - H)$ and $(H - K_s)$) to match with its intrinsic colors ($(J - H)_0$ and $(H - K_s)_0$) by using the following relations (see Maheswar et al. 2010):

Estimated $A_V$ values along with uncertainties for 57 stars are listed in Table 7. This table also lists the IDs, coordinates, NIR colors, and polarization values. Further analysis uses only 32 stars that satisfy the criterion $A_V / \sigma_{A_V} > 2$. The derived $2 \sigma A_V$ values range from 0.9 mag to 3.3 mag with a mean of...
Table 7
Total Extinction $A_V$ Values of 57 Stars Derived Using the NIR Extinction Method

| ID   | R.A. (J2000)    | Decl. (J2000)   | [J − H] (mag) | [H − K_s] (mag) | $P_A$ (%) | $A_V$ (mag) |
|------|----------------|----------------|---------------|-----------------|-----------|-------------|
| 05   | 23:10:43.502   | 61:31:52.251   | 0.40 ± 0.04   | 0.08 ± 0.04     | 1.8 ± 0.5 | 0.4 ± 0.5   |
| 12   | 23:10:54.662   | 61:32:45.974   | 0.52 ± 0.04   | 0.22 ± 0.05     | 2.7 ± 0.7 | 2.8 ± 0.6   |
| 15   | 23:10:56.201   | 61:31:54.080   | 0.25 ± 0.05   | 0.16 ± 0.07     | 1.5 ± 0.5 | 2.5 ± 0.8   |
| 19   | 23:11:00.097   | 61:33:54.450   | 0.43 ± 0.05   | 0.12 ± 0.05     | 2.5 ± 0.7 | 1.0 ± 0.6   |
| 20   | 23:11:03.445   | 61:41:30.120   | 0.39 ± 0.04   | 0.08 ± 0.04     | 2.3 ± 0.2 | 0.4 ± 0.5   |

Note. ID numbers, coordinates, NIR colors, and polarization values are also given. ID numbers are same as those of Table 2.

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The corresponding mean column density is $N_H = (2.2 ± 0.2) \times 10^{21}$ cm$^{-2}$ (using the relations $N_H = 2N_{HI}$ and $N_{HI} = (2.21 ± 0.09) \times 10^{18}$ cm$^{-2}$; see Güver & Özel 2009; Valencic & Smith 2015). This value, within the error, is consistent with the column density, $(3.4 ± 1.5) \times 10^{21}$ cm$^{-2}$, derived using the $^{13}$CO integrated emission of LDN 1225 (see Section 3.7).
