**Magnetic fields in cometary globules – IV. LBN 437**

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**ABSTRACT**

We present results of our $R$-band polarimetry of a cometary globule, LBN 437 (Gal 96-15, $\ell = 96^\circ$, $b = -15^\circ$), to study the magnetic field geometry of the cloud. We estimated a distance of $360 \pm 65$ pc to LBN 437 (also one additional cloud, CB 238) using a near-IR photometric method. The foreground contribution to the observed polarization values was subtracted by making polarimetric observations of stars that are located in the direction of the cloud and with known distances from the *Hipparchos* parallax measurements. The magnetic field geometry of LBN 437 is found to follow the curved shape of the globule head. This could be due to the drag that the magnetic field lines could have experienced because of the ionization radiation from the same exciting source that caused the cometary shape of the cloud. The orientation of the outflow from the Herbig A4e star, LkHα 233 (or V375 Lac), located at the head of LBN 437, is found to be parallel to both the initial (prior to the ionizing source was turned on) ambient magnetic field (inferred from a star HD 214243 located just in front of the cloud) and the Galactic plane.

**Key words:** polarization – ISM: magnetic fields.

**1 INTRODUCTION**

Cometary globules (CGs) are molecular clouds that show a compact bright-rimmed head and a faint tail geometry that extends from the head and points away from a nearby photoionizing source. These objects were first noted by Hawarden & Brand (1976) on the Science and Engineering Research Council (SERC) IIIaJ Sky Survey plates. A group of $\sim 30$ CGs, the largest of such a system, has been identified in the Gum nebula (Sandqvist 1976; Reipurth 1983; Zealey et al. 1983). Cometary clouds are often found to be associated with H II regions and OB stars (Hawarden & Brand 1976; Sandqvist 1976; Schneps, Ho & Barrett 1980; Reipurth 1983; Zealey et al. 1983; Gylbudaghyan, Rodriguez & Canto 1986; Sugitani, Ukai & Ogura 1991; Block, Dyson & Madsen 1992; Ogura & Sugitani 1998; Maheswar et al. 2007). A number of CGs, however, are found to be relatively isolated, for example CG 12 (Williams et al. 1977; Maheswar, Manoj & Bhatt 2004). CGs are considered to be a subset of Bok globules with a size range of $0.1–1.0$ pc (Hawarden & Brand 1976; Zealey et al. 1983). They exhibit high densities, $10^3–10^5$ cm$^{-3}$ (Vilas-Boas, Myers & Fuller 1994; Bourke et al. 1995; Haikala & Olberg 2007) with the mass range of $10–100$ M$_\odot$ (Lefloch & Lazareff 1994; Haikala & Olberg 2007) and with a kinetic temperature of $\sim 15–35$ K (Harju et al. 1990; Cernicharo 1991; White 1993; Olano, Walmsley & Wilson 1994; González-Alfonso, Cernicharo & Radford 1995; Haikala & Olberg 2007). There is evidence for ongoing low-mass star formation in a number of CGs (e.g. Williams et al. 1977; Brand et al. 1983; Reipurth 1983; Petersson 1984; Santos et al. 1998; Ogura, Sugitani & Pickles 2002; Alcalá et al. 2004; Kim, Walter & Wolk 2005; Getman et al. 2007, 2008; Maheswar et al. 2007; Ikeda et al. 2008; Mookerjea & Sandell 2009; Nakano et al. 2012; Mükel & Haikala 2013; Rebull et al. 2013).

Processes involved in the formation and evolution of CGs have been discussed by a number of authors (e.g. Bertoldi 1989; Bertoldi & McKee 1990; Sandford et al. 1992; Lefloch & Lazareff 1994, 1995; Williams, Ward-Thompson & Whitworth 2001; Kim, Walter & Wolk 2003; Miao et al. 2006; Motoyama, Umemoto & Shang 2007). Pre-existing small, dense cores distributed in giant molecular clouds when exposed to the radiation from newly formed OB-type stars in a central OB association can develop cometary head–tail morphology. Thus, a compression of non-collapsing clumps by shock waves driven by the warm surface gas could possibly drive the inner cores to instability and gravitational collapse, triggering star formation. The enhanced rate of star formation seen in CGs based on the detection of *IRAS* point sources having their spectral energy distributions characteristic of young stellar or protostellar objects towards the compact heads of CGs (Bhatt 1993) could be a result of such triggered star formation.

Magnetic fields are thought to play a crucial role in the formation and subsequent evolution of molecular clouds (e.g. Mouschovias & Spitzer 1976; Basu 2000; Crutcher 2012). The effects of magnetic...
fields of various strengths and orientations on the formation and evolution of dense pillars and CGs at the boundaries of H II regions were investigated using 3D hydrodynamical simulations including photoionizing radiative transfer simulations by Henney et al. (2009) and Mackey & Lim (2011). They found that a strong initial magnetic field is required to significantly alter the non-magnetized dynamics because the energy input from the photoionization is so strong that it controls almost the entire dynamics. In the cases of weak and medium field strengths, an initially perpendicular field is dragged and made to align with the pillar during the dynamical evolution of the CGs. A strong perpendicular field, however, remains in its original configuration during the dynamical evolution of the globules.

Background starlight while passing through molecular clouds gets polarized due to the aligned, aspheric dust grains present in them. The polarization is produced because of the selective extinction suffered by the light as it passes through the aspheric dust grains that are aligned to the magnetic field of the clouds. Though the exact alignment mechanism is still unclear (Lazarian 2003; Roberve 2004), the selective extinction due to aligned, aspherical dust grains would make the polarization vectors trace the direction of the plane-of-the-sky magnetic field of the molecular clouds. The contribution to the observed polarization depends on the amount of dust grains with sizes comparable to the wavelength of background starlight being observed (Goodman et al. 1995; Goodman 1996). Observationally, large grains are shown to exist inside dense clouds inferred through an increase in the value of the total-to-selective extinction ratio, $R_\lambda \sim 5$ (Wilking et al. 1980; Kandori et al. 2003; Whittet 2005; Olofsson & Olofsson 2010). Thus, polarization observations in optical wavelengths are sensitive to the grains located at the periphery of the clouds where the extinction suffered by background starlight is typically low (e.g. Goodman et al. 1995; Pereyra & Magalhães 2007; Ward-Thompson et al. 2009; Franco, Alves & Girart 2010). Therefore, the optical polarimetric method is useful to trace the magnetic field geometry of the outer layers of molecular clouds.

Optical polarimetric observations of stars projected in the regions of some of the globules have been made earlier to understand the role played by the magnetic field in (1) the formation of head–tail morphology, (2) the orientation of outflows and binary components, if present, and (3) the star formation process in them. Maps of magnetic field towards the IRAS VELA Shell and relatively large star-forming globules namely L810, B335 and ESO 210-6A have been made by Pereyra & Magalhães (2002) and Hodapp (1987), respectively. The magnetic field geometry of CG 22, CG 30-31 complex and CG 12 has been studied by Sridharan, Bhatt & Rajagopal (1996, Paper I), Bhatt (1999, Paper II) and Bhatt, Maheswar & Manoj (2004, Paper III), respectively. In continuation to the above series of works, we mapped the magnetic field geometry of a relatively isolated CG, LBN 437.

## 2 COMETARY GLOBULE, LBN 437

LBN 437 which is also known as Gal 96-15 (Odenwald & Lockman 1988) is the edge of a molecular cloud known as Kh149 and is also located on the border of an H II region, S126 (Sharpless 1959). The southern part of Kh149 is resolved into two condensation nuclei namely condensation A and B in $^{12}$CO and $^{13}$CO molecular line observations (Olano et al. 1994). LBN 437 does not have a prominent tail. The nuclear region of LBN 437 is coincident with a reflection nebula (DG187; Dorschner & Gürtler 1964) and contains a group of four H$\alpha$ emission line sources, namely LkH\textalpha\ 233 (or V375 Lac), a Herbig A4e star (Hernández et al. 2004) and other fainter members, namely LkH\textalpha\ 230, LkH\textalpha\ 231 and LkH\textalpha\ 232 (Maheswar & Bhatt 2008). LkH$\alpha$ 233 with its surrounding nebulosity is one of the classic examples of bipolar appearance in Herbig Ae/Be stars (Calvet & Cohen 1978). LkH$\alpha$ 233 is the exciting source of Herbig–Haro objects (Corcoran & Ray 1998) with collimated bipolar jets emanating at an angle of 68° with respect to the north. Manoj et al. (2006) derived a mass of $\sim 3 M_\odot$, a luminosity of $L = \sim 3 L_\odot$ and an age of $\sim 1$ Myr for LkH$\alpha$ 233. These are the youngest stars found associated with Lacerta OB1 (Lac OB1) association (Peltier, Allers & Liu 2011).

LBN 437 is considered to be at a distance of 460 pc on the basis of spatial and kinematic coincidence with the Lac OB1 association (Olano et al. 1994). But the distance to the Lac OB1 association itself is highly uncertain. The estimated distances are in the range of $\sim 360$ to $\sim 600$ pc (Kaltcheva 2009). Also, though LBN 437 is considered to be at 460 pc, LkH$\alpha$ 233 is estimated to be at a distance of 880 pc. But the presence of reflection nebulosity surrounding LkH$\alpha$ 233 confirms their association. The distance of 880 pc was adopted from Calvet & Cohen (1978), who estimated the distance based on the inference that the B1.5 V star HD 213976, which is found to be projected on the cloud, has a distance modulus of 9.6 ($\sim 830$ pc) and has negligible extinction ($A_v \sim 0.42$) so should be foreground to the cloud. In majority of the subsequent works, the authors have adopted this distance to LkH$\alpha$ 233 (e.g. Corcoran & Ray 1998; Manoj et al. 2006; Perrin & Graham 2007). However, from the revised parallax measurements of this star (3.08 ± 0.56 mas) by van Leeuwen (2007), the distance to this star is only $\sim 325^{+72}_{-56}$ pc (also see Allers et al. 2009). This implies that the distance of LBN 437 is at least $\sim 325$ pc if not more.

In this work, we report the optical polarimetry of LBN 437 in order to study the magnetic field geometry at the periphery of the cloud. We measured optical polarization of stars that are projected on LBN 437 and mapped the plane-of-the-sky magnetic field. This paper is organized in the following manner: Section 3 describes the observations and the methods of data reduction. In Section 4, we present our results and discussion. In the same section, we discuss the procedure used to determine distance to the cloud and to determine the foreground polarization. Finally, we conclude our paper by summarizing the results in Section 5.

## 3 OBSERVATIONS AND DATA REDUCTION

Polarimetric observations were carried using the ARIES Imaging POLarimeter (AIMPOL; Rautela, Joshi & Pandey 2004) mounted at Cassegran focus of the 104 cm Sampurnanand telescope of Aryabhatta Research Institute of Observational Sciences (ARIES), Nainital, India, coupled with a TK 1024 × 1024 pixel$^2$ CCD camera. The AIMPOL consists of an achromatic half-wave plate (HWP) modulator and a Wollaston prism beam splitter. The observations were carried out in the $\lambda_{\text{eff}} = 0.630$ μm photometric band. The plate scale of CCD is 1.48 arcsec pixel$^{-1}$ and the field of view is ~8 arcmin in diameter. The full width at half-maximum varies from 2 to 3 pixels. The read-out noise and gain of CCD are 7.0 e$^{-}$ and 11.98 μe$^{-}$. The full width at half-maximum varies.

| Cloud ID | Date of observations (year, month, date) |
|----------|------------------------------------------|
| LBN 437  | 2011, November, 22, 23, 26; 2011, December, 20; 2012, October, 14, 19, 20 |
Fluxes of ordinary ($I_o$) and extraordinary ($I_e$) beams for all the observed sources with a good signal-to-noise ratio were extracted by standard aperture photometry using the IRAF package. The ratio $R(\alpha)$ is given by

$$R(\alpha) = \frac{I_o}{I_e} = P \cos(2\theta - 4\alpha),$$

where $P$ is the fraction of total linearly polarized light and $\theta$ is the polarization angle of the plane of polarization. Here $\alpha$ is the position of the fast axis of HWP at 0\textdegree, 22.5\textdegree, 45\textdegree, and 67.5\textdegree corresponding to four normalized Stokes parameters, respectively, $q[R(0\textdegree)], u[R(22.5\textdegree)], q[R(45\textdegree)]$ and $u[R(67.5\textdegree)]$. We estimate the errors in normalized Stokes parameters $(\sigma_R(\alpha)/\sigma_o, \sigma_e, \sigma_q, \sigma_u)$ in per cent using the relation (Ramaprakash et al. 1998)

$$\sigma_R(\alpha) = \sqrt{N_e + N_o + 2N_b}/N_o + N_e,$$

where $N_e$ and $N_o$ are the counts in ordinary and extraordinary beams, respectively, and $N_b = (N_{be} + N_{bo})/2$ is the average background counts around the extraordinary and ordinary rays.

Zero-polarization standard stars were observed during every run to check for any possible instrumental polarization. The typical instrumental polarization is found to be less than $\pm 0.1$ per cent. The instrumental polarization of the AIMPOL on the 104 cm Sampurnanand Telescope has been monitored since 2004 for various observing programmes and found to be stable (see Rautela et al. 2004; Medhi et al. 2008; Eswaraiah et al. 2011). The reference direction of the polarizer was determined by observing polarized standard stars from Schmidt, Elston & Lupie (1992). The results are presented in Table 2. We observed these unpolarized and polarized standards using the standard Johnson $R$ filter having $\lambda_{R_{ std}} = 0.630$ $\mu$m. Schmidt et al. (1992) used the Kron–Cousins $R$ filter for the observations of the standard stars. Because the instrumental polarization is found to be very low, we did not correct the observed degree of polarization. Nevertheless, we found a good correlation of the observed values with the standard values (see Table 2). The zero-point offset was corrected on every run using the offset seen between the standard position angle values given in Schmidt et al. (1992) and those obtained by us.

### 4 RESULTS AND DISCUSSION

Results of our $R$-band polarimetry of 70 stars projected in the direction of LBN 437 are presented in Table 3. We have tabulated the results of only those sources for which the ratio of degree of polarization ($P$ per cent) to error in the degree of polarization $(\sigma_p)$ is $P/\sigma_p > 2$. Column 1 of Table 3 shows the star identification in the increasing order of their right ascensions (RA). Columns 2 and 3 show the RA and the declination of the target objects. Columns 4 and 5 show the measured $P$ (per cent) values and the polarization position angles ($\theta$ in degree). The position angles are measured from the north increasing towards the east. In Fig. 1, we show the observed degree of polarization versus the position angles of 116 stars (open circles) with $P/\sigma_p > 1$. Of these, 70 stars with $P/\sigma_p > 2$ are identified using filled circles. Also shown in filled star symbols are the polarization results observed by us for the 10 stars that were obtained from a circular region of radius $1'$ around LBN 437 essentially to carry out foreground subtraction (see Section 4.1.2). The distances to these stars were estimated prior to making the observations using their parallaxes obtained from the catalogue produced by van Leeuwen (2007).

#### 4.1 Distance to the cloud and foreground interstellar polarization

The observed polarization of any star background to a cloud has two components. One is due to the dust located in the cloud and the other is due to the dust in the interstellar medium (ISM) located between the observer and the cloud. Therefore, in order to obtain the true polarization (magnetic field) geometry of a cloud, it is essential to subtract the component due to the ISM vectorially from the observed polarization values. The contribution to the polarization values due to the foreground ISM can be estimated by measuring the polarization values of the foreground stars for which the distance estimations are already available. Subtraction of these values from the observed results can give the true estimate of polarization due to the cloud material alone. But subtraction of the foreground contribution is possible only when the distance to the cloud is known to avoid the use of background stars in the subtraction.

##### 4.1.1 Distance to LBN 437

We used the near-IR photometric method presented by Maheswar et al. (2010), which utilizes the vast homogeneous $IHK$, photometric data produced by the Two Micron All Sky Survey (Cutri et al. 2003) available for the entire sky, to determine the distance of LBN 437. Here we present a brief discussion of the method. The method uses a technique by which the spectral classification of stars lying towards the fields containing the clouds can be made into main sequence and giants. The observed $(J - H)$ and $(H - K_s)$ colours of the stars with $(J - K_s) \leq 0.75$ in the $(J - H)$ versus $(H - K_s)$ colour–colour (CC) diagram are de-reddened simultaneously using trial values of $A_V$ and a normal interstellar extinction law (Rieke & Lebofsky 1985). The best fit of the de-reddened colours to the

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*For a more rigorous discussion on the errors and limitations of the method, refer to Maheswar et al. (2010).*

### Table 2. Polarized standard stars observed in the $R$ band.

| Date of observation | $P \pm \varepsilon_P$ (per cent) | $\theta \pm \varepsilon_{\theta}$ (°) |
|---------------------|----------------------------------|-----------------------------------|
| HD 236633 (a)       | 5.38 ± 0.02/93:04 ± 0.15         |                                   |
| 22 Nov. 2011        | 5.1 ± 0.1                        | 93 ± 1                            |
| 26 Nov. 2011        | 5.4 ± 0.1                        | 92 ± 1                            |
| 20 Dec. 2011        | 5.4 ± 0.2                        | 93 ± 1                            |
| 14 Oct. 2012        | 5.6 ± 0.2                        | 99 ± 6                            |
| 19 Oct. 2012        | 5.6 ± 0.2                        | 99 ± 5                            |
| 20 Oct. 2012        | 5.4 ± 0.2                        | 99 ± 6                            |
| HD 236954 (a)       | 6.16 ± 0.17/110:0 ± 0.8          |                                   |
| 26 Nov. 2011        | 5.9 ± 0.1                        | 111 ± 1                           |
| 20 Dec. 2011        | 6.2 ± 0.4                        | 111 ± 2                           |
| BD+59°389 (a)       | 6.43 ± 0.02/98:14 ± 0.10         |                                   |
| 26 Nov. 2011        | 7.0 ± 0.1                        | 98 ± 1                            |
| 20 Dec. 2011        | 6.3 ± 0.1                        | 98 ± 1                            |
| 14 Oct. 2012        | 6.5 ± 0.1                        | 105 ± 7                           |
| HD 204827 (a)       | 4.89 ± 0.03/59:10 ± 0.17         |                                   |
| 20 Oct. 2012        | 5.0 ± 0.2                        | 66 ± 7                            |

(a) Values in the $R$ band from Schmidt et al. (1992).
Degree of polarization versus polarization position angles of 1.2 ± 12 stars chosen from Region I towards the direction of LBN 437.

The filled circles show the values with $P/\sigma_p \geq 2$ and the open circles show the values with $P/\sigma_p \geq 1$. Polarization values of stars obtained in 1° radius around LBN437 are also shown using star symbols.

intrinsic colours giving a minimum value of $\chi^2$ then yields the corresponding spectral type and $A_V$ for the star. The main-sequence stars, thus classified, are plotted in an $A_V$ versus distance diagram to bracket the cloud distance. The entire procedure is depicted in Fig. 2, where we plot the near-infrared CC diagram for the stars (with $A_V \geq 1$) chosen from Region I towards the direction of LBN 437. The arrows are drawn from the observed data points (open circles) to the corresponding de-reddened colours estimated using the method.

The values of maximum extinction that can be measured using the method are those for A0V-type stars ($A_V \approx 0.3$ mag). The extinction traced by the stars will decrease as we move towards more late-type ones.

Subdividing the field containing a cloud is always better in order to avoid confusions that could arise due to any erroneous
classifications of giants as dwarfs. While the rise in the extinction due to the presence of a cloud should occur almost at the same distance in all the fields, if the whole cloud is located at the same distance, the wrongly classified stars in the subfields would show high extinction not at the same but at random distances. In the case of clouds with smaller angular sizes, other clouds that are located spatially closer and show similar radial velocities could be selected. Here the assumption is that the clouds that are spatially closer and share similar velocities are located almost at similar distances.

In the upper panel of Fig. 3, we show the two regions that are selected towards LBN 437 to determine the distance. Regions I and II include LBN 437 and Kh 149, respectively. The additional field, Region III (shown in the lower panel of Fig. 3) includes CB 238, a relatively small and isolated cloud located at ~4° west of LBN 437 ($l = 93.47$, $b = -12.63$; Clemens & Barvainis 1988). We included this cloud because the radial velocities of CB 238 (0.2 km s$^{-1}$; Clemens & Barvainis 1988) and LBN 437 (~0.2 km s$^{-1}$; Olano et al. 1994) are found to be similar. Furthermore, by comparing the images shown in the upper and lower panels of Fig. 3, it is quite apparent that the finger-like structure of CB 238 also points almost exactly to the same direction as is in the case of LBN 437. The same exciting source might be responsible for the current structure of both the clouds.

In Fig. 4, we present the $A_V$ versus $d$ plot for the stars from Regions I, II and III. The dash–dotted curve represents the increase in the extinction towards the Galactic latitude of $b = -15°$ as a function of distance produced from the expressions given by Bahcall & Soneira (1980). When compared to the values of extinction expected towards the latitude of $-15°$, a sudden increase in the extinction is noticeable in all the three panels at a distance close

\[ A(R) = A_\infty(b)(1 - \exp(-\sin b/H/R)). \]

Here, $A_\infty(b) = A_\infty(90°) \csc b$, where $A_\infty(90°) = 0.15$. They assumed an exponential variation of the density of the obscuring material with height above the Galactic plane, $\rho = \rho_0 \exp(-z/H)$, where the scaleheight $H$ is taken as 100 pc.
Magnetic field geometry of LBN 437

Figure 4. The $A_V$ versus $d$ plots for the stars from Regions I, II and III towards LBN 437 shown using filled circles. The dashed vertical line is drawn at 360 pc inferred from the procedure described in Maheswar et al. (2010). The dash–dotted curve represents the increase in the extinction towards the Galactic latitude of $b = -15^\circ$ as a function of distance, produced from the expressions given by Bahcall & Soneira (1980). A typical error bar is shown on a point at a distance of $\sim 360$ pc.

At this distance, LBN 437 would be at a height of 93 pc above the Galactic plane, close to the scaleheight of 100 pc assumed for the distribution of the obscuring material by Bahcall & Soneira (1980) in their Galaxy model. In general, for line of sight close to the plane of the Milky Way and for distances up to a few kiloparsec from the Sun, the visual extinction along the path length is taken as $\sim 1.8$ mag kpc$^{-1}$ (Whittet 2003). But because the scaleheight of the exponential distribution of obscuring material was taken as 100 pc by Bahcall & Soneira (1980), the dash–dotted line, showing the extinction, tends to become more flatter with the distance towards the direction of LBN 437.

In order to determine the distance at which the sudden jump in the extinction is occurring, we first grouped the stars into distance bins of bin width $0.18 \times$ distance. The centres of each bin are separated by half of the bin width. Because of very few stars at smaller distances, the mean value of the distances and the $A_V$ of the stars in each bin were calculated by taking 1000 pc as the initial point and proceeded towards smaller distances. The mean distance of the stars in the bin at which a significant drop in the mean of the extinction occurred was taken as the distance to the cloud, and the average of the uncertainty in the distances of the stars in that bin was taken as the final uncertainty in distance determined by us for the cloud (Fig. 5). The error bars on the mean $A_V$ values are calculated using standard deviation of $A_V$ values corresponding to each bin.

The vertical dashed line in $A_V$ versus $d$ plots, used to mark the cloud distance, is drawn at a distance deduced from the above procedure.

Our distance estimate of 360 pc to LBN 437 is consistent with the distance recently estimated by Allers et al. (2009) based on the photometric distances determined for HD 213976, LkH$\alpha$ 231 and LkH$\alpha$ 232. For HD 213976, they derived a distance of $383^{+153}_{-109}$ pc by comparing the absolute $J$-band brightness of this star with the mean absolute $J$-band brightness of Upper Scorpious objects. For LkH$\alpha$ 231 and LkH$\alpha$ 232, they showed that the observed $J$-band magnitudes of these objects are consistent with the similar spectral type (K2–K5) stars in the Taurus when placed at 325 pc. Our distance of 360 pc to LBN 437 is similar to the distance of Lac OB1 (368 $\pm$ 17 pc) estimated by de Zeeuw et al. (1999). At a distance of 360 pc, LBN 437 is located $\sim 90$ pc away from the Galactic plane.

4.1.2 Subtraction of interstellar polarization

In order to subtract the polarization component due to the foreground material from our observed values, we made a search for stars that are located within a circular region of radius 1° about LBN 437 and have their parallax values measured by the *Hipparcos* satellite. We obtained 10 stars for which the parallax measurements...
are available in the catalogue produced by van Leeuwen (2007). We rejected those that are classified as emission line stars, stars in a binary or multiple system or are peculiar according to the information provided by the SIMBAD. From the catalogue, we selected only those stars for which the values of the ratio of the error in parallax to the parallax measurements are \( \leq 0.5 \). The 10 stars thus selected are listed in Table 4 ordered according to increasing distance. We then carried out polarimetric observations of these stars in the \( R \) band using the AIMPOL. The polarization vectors corresponding to these stars are overplotted on the \( 2\times 2 \) Wide-Field Infrared Survey Explorer (WISE) 12 \( \mu \)m image of the field containing LBN 437, as shown in Fig. 6. The filled circles in black identify the target sources that we observed towards the head (enclosed in a square box) of LBN 437. The broken line in white is drawn parallel to the Galactic plane at \( b = -15^\circ \).

Table 4. Our \( R \)-band polarization results for nine foreground stars.

| ID | Star name | \( V \) (mag) | \( P \pm \epsilon_P \) (per cent) | \( \theta \pm \epsilon_{\theta} \) (°) | \( D^a \) (pc) |
|----|-----------|----------------|-----------------------------------|---------------------------------|----------------|
| 1  | HD 214283 | 9.0            | 0.12 ± 0.07 130 ± 9               | 192                            |
| 2  | HD 213659 | 8.0            | 0.07 ± 0.06 103 ± 11              | 196                            |
| 3  | HD 213421 | 8.2            | 0.27 ± 0.06 78 ± 5                | 224                            |
| 4  | HD 214022 | 8.5            | 0.19 ± 0.08 87 ± 8                | 234                            |
| 5  | HD 213835 | 6.5            | 0.11 ± 0.09 68 ± 12               | 256                            |
| 6  | BD+39 4868 | 9.5            | 0.17 ± 0.09 72 ± 10               | 262                            |
| 7  | BD+39 4890 | 9.5            | 0.22 ± 0.08 93 ± 8                | 297                            |
| 8  | HD 213976 | 7.0            | 0.22 ± 0.07 95 ± 6                | 325                            |
| 9  | HD 214243 | 8.3            | 0.23 ± 0.08 65 ± 7                | 357                            |
| 10 | HD 214524 | 7.5            | 0.23 ± 0.07 164 ± 7               | 385                            |

\( ^a \)Distances are estimated using the \textit{Hipparcos} parallax measurements taken from van Leeuwen (2007).

The polarimetric results of these foreground stars are shown in Fig. 7. The distances to these 10 stars range from 190 to 385 pc. There are nine stars that are at distances less than 360 pc. Of these nine, we excluded star 2 as the degree of polarization is both very low and below the instrumental polarization. For the purpose of subtracting the foreground polarization, we estimated the weighted mean of polarization values of remaining eight foreground stars and calculated the Stokes parameters. The weighted mean values of the degree of polarization and the position angles are found to be 0.2 per cent and 85°. Using these values, we calculated the mean Stokes parameters \( Q_{fg} = P \cos \theta \) and \( U_{fg} = P \sin \theta \) as −0.176 and 0.028, respectively. Then we calculated the Stokes parameters, \( Q \) and \( U \), of the target sources. The Stokes parameters \( Q \) and \( U \) representing the foreground-corrected polarization of the target stars are calculated using

\[
Q = Q_{fg} - Q_{bg}, \quad U = U_{fg} - U_{bg}.
\]  

The corresponding foreground-corrected degree of polarization \( P_c \) and position angle \( \theta_c \) of the target stars are calculated using the equations

\[
P_c = \sqrt{(Q_c)^2 + (U_c)^2}, \quad \theta_c = 0.5 \times \tan^{-1} \left( \frac{U_c}{Q_c} \right).
\]  

The histogram of the polarization position angles of the stars with \( P/\sigma_p \geq 1 \), after subtracting the foreground contribution, is shown in Fig. 9. Also shown using open circles is the degree of polarization
versus position angles of the target stars. The filled circles show the polarization values with $P/\sigma_p \geq 2$. No significant changes are noticed in the observed polarization results before and after the subtraction of the foreground contribution because the polarization due to the foreground dust component is very small, at the level of $\sim 0.2$ per cent. This implies that the polarization values obtained for the majority of the target stars projected on the head of LBN 437 are mainly caused due to the dust component that is associated with the cloud. This is also evident from the fact that the degree of polarization of HD 214243 which is located just in front of LBN 437 shows a very low polarization. The observed low polarization of this star could be either due to the star being at relatively high Galactic latitude or due to the local field direction being pointed along the line of sight.

### 4.2 Magnetic field geometry of LBN 437

The resultant foreground-corrected values of $P_c$ and $\theta_c$ are overplotted on the $0.65 \times 0.65$ WISE 12 $\mu$m image, as shown in Fig. 8. The length of the vectors corresponds to the degree of polarization and their orientation corresponds to the position angle measured from the north and increasing eastwards. The red vectors correspond to the values with $P/\sigma_p \geq 1$ and the yellow vectors show the values with $P/\sigma_p \geq 2$. The mean values of the degree of polarization and the position angles after foreground subtraction are found to be 1.6 per cent and 61°, respectively. From Fig. 9, if we select the sources with their degree of polarization $\geq 1$ per cent, evidently, there exist two groups. The first group has polarization position angles distributed from $\sim 0^\circ$ to $\sim 65^\circ$ and the second group has position angles distributed from $\sim 100^\circ$ to $\sim 160^\circ$. It can be noticed in Fig. 8 that the two components are not distributed uniformly over the cloud. While the first group is found to be concentrated towards the eastern parts of the cloud head, the second group is dominant towards the western parts of the globule. The mean and the standard deviation of the first and the second groups are 37° and 17°, and 125° and 17°, respectively. Evidently, the magnetic field lines traced by our polarization measurements follow the curved structure of the head.

In order to study the effects of the presence of magnetic field on the dynamics of the dense neutral gas, Mackey & Lim (2011) included the magnetic fields of various strengths and orientations to the 3D hydrodynamic simulations which included photoionizing radiative transfer also. Prior to this work, Henney et al. (2009) studied the photoionization of a dense clump of gas in 3D with an initially uniform magnetic field. They found that the presence of a strong magnetic field can significantly alter the evolution of a photoionized globule. Even without magnetic fields it was shown that the evolution of a photoionizing globule proceeds in two processes. The first, radiation-driven implosion (RDI; Bertoldi 1989) and the second, the acceleration due to the rocket effect (Oort & Spitzer 1955) producing elongated structures. The RDI provides initial compression to the neutral gas until it comes in equilibrium with the ionized gas while the rocket effect accelerates the globule away from the ionizing source producing elongated structures like elephant trunks that are seen towards the periphery of a number of H$\alpha$ regions.

![Figure 8: Polarization vectors plotted on the $0.65 \times 0.65$ WISE 12 $\mu$m image of LBN 437 after subtracting the foreground polarization contribution.](https://academic.oup.com/mnras/article-abstract/432/2/1502/2908449)
we infer that the ambient magnetic field orientation at the location close to the cloud is \( \sim 65^\circ \), which is also parallel to the Galactic plane at \( b = -15^\circ \). If the same field was inherited by LBN 437, the initial magnetic field orientation prior to the action of the ionizing source was \( \sim 65^\circ \), which is almost perpendicular to the direction of the ionizing radiation from 10 Lac.

The cometary head of LBN 437 might have been created when the ionizing radiation from the Lac OB1 members interacted with the cloud. Due to the subsequent dynamical evolution of the globule, the initially perpendicular magnetic field lines got dragged away from the ionizing source to follow the curvature of the globule head (as illustrated in Fig. 8 using the white broken curves). However, the effect of the ionizing radiation might not have been adequate enough to align the field lines completely along the direction of the ionizing radiation as is seen towards a number of regions e.g. M16 (Sugitani et al. 2007), CG22 (Paper I), etc., and as shown in the simulations (Henney et al. 2009; Mackey & Lim 2010, 2011). Therefore, either the strength of the initial magnetic field was sufficiently strong enough to resist a complete alignment of the field lines with the ionizing radiation or the ionizing source(s) was relatively far away that the extent of its effect on the globule was not very severe. Adapting a distance of 368 pc to both the Lac OB1 association (de Zeeuw et al. 1999) and 10 Lac (assuming it to be a member of Lac OB1), the spatial distance between 10 Lac and LBN 437 is estimated to be \( \sim 12 \) pc, which is much larger than those considered in the simulation studies in which the ionizing source is kept at distances of less than 1 pc from the globule initially (Henney et al. 2009; Mackey & Lim 2010, 2011). The Herbig Ae star, LkH\( \alpha \) 233, might have formed due to the gravitational collapse triggered by the compression due to the RDI process. The age of this star is estimated to be \( \sim 1 \) Myr (Manoj et al. 2006), which is sufficiently larger than the typical time-scale for the ionization front to pass through the cloud (Bertoldi 1989; Mackey & Lim 2011). According to the simulation results of Henney et al. (2009), the typical time-scale for the RDI process to occur in a globule of \( \sim 15 \) M\( \odot \) at a distance of less than 1 pc from the ionizing source is about 50 000 yr.

Using near-IR imaging polarimetry aided by the adaptive optics, Perrin et al. (2004) showed the presence of a narrow, unpolarized dark lane consistent with an optically thick circumstellar disc blocking the direct light from LkH\( \alpha \) 233. This dark lane is found to be almost perpendicular to the axis of the outflow which is oriented at an angle of \( 68^\circ \) with respect to the north (Melnikov et al. 2008). The results obtained by Perrin et al. (2004) was explained using models with an inclination angle of 80° implying that the outflow from LkH\( \alpha \) 233 is almost on the plane of the sky. Matsumoto, Nakazato & Tomisaka (2006), using the polarized thermal dust emission from magnetohydrodynamic simulations of protostellar collapse and outflow, showed that the alignment of an outflow with the magnetic field depends on the strength of the magnetic field inside the cloud core (at the 1000 au scale). They found that a magnetic field strength of \( 80 \) \( \mu G \) could make the outflow align preferentially with the mean polarization vector of the cloud core. We find that the initial ambient magnetic field (\( 65^\circ \)) and the outflow directions are almost parallel to each other. This suggests that at the time of the triggered formation of LkH\( \alpha \) 233, and the subsequent outflow phase of the protostar, the magnetic field might not have got modified inside the cloud allowing for an alignment between the outflow and ambient magnetic field directions. Also, the magnetic field strength inside the cloud might be greater than \( 80 \) \( \mu G \) which comes in the range of medium and strong regimes considered by Mackey & Lim (2011) in their simulations. A very little modification of the original field orientation towards LBN 437 also

![Figure 9. Histogram of the polarization position angles of the stars with $P/\sigma_p \geq 1$ after subtracting the foreground polarization contribution. Also shown is the distribution of degree of polarization versus position angles of target stars. The filled circles show the values with $P/\sigma_p \geq 2$ and the open circles show the values with $P/\sigma_p \geq 1$. The broken lines show the position angles of Galactic plane and the direction of outflow from the star LkH$\alpha$ 233.](https://academic.oup.com/mnras/article-abstract/432/2/1502/2908449)
supports for a relatively strong magnetic field that could be prevailing there.

LBN 437 was observed in molecular lines of CO, NH\(_3\), and H\(_2\)CO (Olano et al. 1994). In H\(_2\)CO(1\(\rightarrow\)0) and \(^1\)3CO(1\(\rightarrow\)0) and (2\(\rightarrow\)1) line observations, they found that the head part has an elongated configuration of size \(\sim 1.6 \times 0.4\) pc\(^2\) (corrected for the 360 pc distance). The NH\(_3\)(1,1) and (2,2) inversion line observations of the globule head showed the existence of a cold and dense core of elliptical shape. The major axis of the elliptical core is found to be oriented perpendicular to both the ambient magnetic field and the outflow from LkH\(_{α}\) 233. LBN 437 does not possess a well-defined tail. The motion of the clouds is parallel to the ambient magnetic field direction. It would be interesting to carry out polarimetric observations of the background stars in near-IR and optical wavelengths to infer the magnetic field geometry at the inner high-density regions and the tail part of the globule.

A large-scale magnetic field mapping of the region containing CGs is required to understand the processes involved in the evolution of such globules. Such results could be used to compare with those from the simulations. Also required are the near-IR and submillimetre polarimetry of these globules to get the inner field orientations which could allow us to understand the relationship between the outflow and the magnetic field orientations better.

5 CONCLUSIONS

In this work, we present the results of optical linear polarization measurements of 70 stars projected towards a CG, LBN 437. The main results obtained in this study are given below.

(i) We determined a distance of 360 \(\pm 65\) pc to two clouds, namely LBN 437 and CB 238, using near-IR photometric method.

(ii) To interpret the magnetic field geometry of the globule in relation with the globule structure and outflow from the Herbig Ae star, LkH\(_{α}\) 233, we subtracted the contribution of the foreground dust component from our results using polarimetric observations of 10 stars (obtained from a circular region of radius \(1°\) about LBN 437) with distances already known from the parallax measurements of the \textit{Hipparcos}. The star, HD 214243, located at a distance of 357 \(\pm 102\) pc shows a polarization position of 65\(^°\). We considered the position angle of this star to be the orientation of the ambient and the cloud magnetic field prior to the cloud being subjected to the ionizing radiation. Interestingly, this field is found to be oriented parallel to the Galactic plane at the latitude of the cloud.

(iii) LBN 437, thus, presents a scenario where the direction of the initial field lines prior to its being affected by the ionizing radiation was perpendicular to the direction of the ionizing radiation. We found that the magnetic field lines in the globule are curved in a manner that they follow the curvature of the globule head. The possible explanation is that the magnetic field lines might have got dragged due to the radiation from the same ionizing source that was responsible for the cometary shape of the cloud.

(iv) The outflow direction from LkH\(_{α}\) 233 is found to be parallel to both the ambient magnetic field and the Galactic plane at the location of the cloud.

The magnetic field geometry of the inner high-density region towards the head, the tail part and the region covering Kh 149 would be very useful to understand the formation history of LBN 437 and its surrounding environment.

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