Distance, magnetic field, and kinematics of the filamentary cloud LDN 1157

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ABSTRACT

Context. LDN 1157 is one of several clouds that are situated in the cloud complex LDN 1147/1158. The cloud presents a coma-shaped morphology with a well-collimated bipolar outflow emanating from a Class 0 protostar, LDN 1157-mm, that resides deep inside the cloud.

Aims. The main goals of this work are (a) mapping the intercloud magnetic field (ICMF) geometry of the region surrounding LDN 1157 to investigate its relationship with the cloud morphology, outflow direction, and core magnetic field (CMF) geometry inferred from the millimeter- and submillimeter polarization results from the literature, and (b) to investigate the kinematic structure of the cloud.

Methods. We carried out optical (R-band) polarization observations of the stars projected on the cloud to map the parsec-scale magnetic field geometry. We made spectroscopic observations of the entire cloud in the $^{12}$CO, $^{18}$CO, and $^{13}$CO (J = 1–0) lines to investigate its kinematic structure.

Results. We obtained a distance of $340 \pm 3$ pc to the LDN 1147/1158, complex based on the Gaia DR2 parallaxes and proper motion values of the three young stellar objects (YSOs) associated with the complex. A single filament of $\sim 1.2$ pc in length (traced by the Filfinder algorithm) and $\sim 0.09$ pc in width (estimated using the Radiff algorithm) is found to run throughout the coma-shaped cloud. Based on the relationships between the ICMF, CMF, filament orientations, outflow direction, and the hourglass morphology of the magnetic field, it is likely that the magnetic field played an important role in the star formation process in LDN 1157. LDN 1157-mm is embedded in one of the two high-density peaks detected using the Clumpfinder algorithm. The two detected clumps lie on the filament and show a blue-red asymmetry in the $^{12}$CO line. The $^{13}$CO emission is well correlated with the filament and presents a coherent structure in velocity space. Combining the proper motions of the YSOs and the radial velocity of LDN 1147/1158 and another complex, LDN 1172/1174, that is situated $\sim 2^\circ$ east of it, we found that the two complexes are moving collectively toward the Galactic plane. The filamentary morphology of the east-west segment of LDN 1157 may have formed as a result of mass lost by ablation through interaction of the moving cloud with the ambient interstellar medium.

Key words. ISM: clouds – polarization – ISM: magnetic fields – ISM: individual objects: L1157 – dust, extinction – ISM: kinematics and dynamics

1. Introduction

Observations from the Herschel Space Observatory, with its unprecedented sensitivity and resolution, revealed the omnipresence of a deep network of filaments (André et al. 2010; Men’shchikov et al. 2010) in quiescent and star-forming molecular clouds (e.g., Myers 2009; André et al. 2010; Arzoumanian et al. 2011; Kirk et al. 2013; Rivera-Ingraham et al. 2016). These filaments are often found to extend from dense star-forming hubs (Myers 2009; Liu et al. 2012; Galván-Madrid et al. 2013), and more star-forming sites are distributed along their length (e.g., Myers 2009; Schneider et al. 2012; André et al. 2014; Tafalla & Hacar 2015). These filamentary structures are described as either stagnant gas produced by large-scale compression flows (Peretto et al. 2012) or isothermal self-gravitating cylinders in pressure equilibrium with external medium (Fischera & Martin 2012; Heitsch 2013), or they are supported by helical magnetic fields (Fiege & Pudritz 2000a). To gain more insight into the processes involved in the formation of these filaments, it is important to study their internal structure, magnetic field geometry, and kinematics of gas.

Several models and simulations have been carried out to understand processes such as iso-thermal-driven turbulence (Padoan & Nordlund 2002; de Avillez & Breitschwerdt 2005;
Moedck & Burkert 2015), thermal (Vázquez-Semadeni et al. 2003; Audit & Hennebelle 2005; Heitsch et al. 2008) or gravitational (Nakajima & Hanawa 1996; Umekawa et al. 1999; Van Loo et al. 2014) instabilities that might influence the formation of filamentary structures in molecular clouds. Filaments in unbound and non-star-forming regions (Miville-Deschênes et al. 2010) suggest a paradigm in which they represent the early stages of core and star formation. In this paradigm, the dense material within molecular clouds is first accumulated into dense filaments that then fragment to form star-forming cores (Balsara et al. 2001; Gómez & Vázquez-Semadeni 2014). These fragments may continue to amass material through gravitational inflow, resulting in a flow pattern parallel to the filament axis (e.g., Balsara et al. 2001; Banerjee et al. 2006). Correlated magnetic fields on scales of 1–10 pc have been observed in interstellar clouds (e.g., Vrba et al. 1976; Heyer et al. 1987; McCutcheon et al. 1986; Goodman et al. 1992; Pereyra & Magalhães 2004; Chapman et al. 2011; Soam et al. 2015, 2017; Wang et al. 2017; Clemens et al. 2018). The magnetic fields may play an important role in regulating these flows. It is still unclear exactly how the magnetic fields, turbulence, and self-gravity compete or collaborate to form filaments first, then cores, and finally, stars.

According to Gómez & Vázquez-Semadeni (2014) and Smith et al. (2016), filaments arise as a result of anisotropic global collapse of the clouds. Initially, gas is accreted onto the cloud from the surrounding environment, and the magnetic field is expected to be perpendicular to the filament axis. While the low-density material is found to be aligned with the field lines, the dense filaments are seen perpendicular to the magnetic fields (Planck Collaboration Int. XXXII 2016; Planck Collaboration Int. XXXV 2016). This trend is also seen in the polarization observations of background stars in optical (e.g., Heiles 2000; Pereyra & Magalhães 2004; Alves et al. 2008) and near-infrared wavelengths (e.g., Goodman et al. 1992; Chapman et al. 2011).

However, as the gas density increases, the gas tends to flow along the filaments, dragging the field lines along with it and causing them to lie parallel to the filament axis (Gómez et al. 2018). The relative orientation of filaments with respect to the local magnetic fields (e.g., Li et al. 2009) and the kinematics of the gas both perpendicular and parallel to the filaments are therefore some observational signatures that are important for understanding the manner in which the material was accumulated during filament formation. To do this, it is crucial to identify and characterize isolated filaments that are at their earliest evolutionary stage of star formation.

In this paper, we present results of a study conducted on an isolated star forming molecular cloud LDN 1157 (L1157). The cloud is located in the Cepheus flare region and is spatially (Lynds 1962; Dutra & Bica 2002) and kinematically (Yonekura et al. 1997) associated with a complex containing a number of clouds: LDN 1147/1148/1152/1155/1157/1158 (hereafter L1147/1158 complex). There is an ambiguity in the adopted distance of the cloud. The most widely quoted distance of L1147/1158 is 325 ± 13 pc (Straizys et al. 1992). However, in several studies, distances of 250 pc (e.g., Looney et al. 2007; Podio et al. 2016) and 440 pc (e.g., Gueth et al. 1996; Avery & Chiao 1996) are also used. L1157 harbors a cold, extremely red object, IRAS 20386+66751 (hereafter L1157-mm), classified as a Class 0 source (Andre et al. 1993; Andre 1996) having a bolometric luminosity of 11 $L_\odot$ and bolometric temperature between 60–70 K (Gueth et al. 1997). The source shows a well-collimated bipolar outflow of ~5° spatial size (Bachiller et al. 2001) and a ~2° flattened envelope perpendicular to it (Looney et al. 2007). The position angle of the outflow measured counterclockwise from the north is 161° (Bachiller et al. 2001) with an inclination angle of ~10° (Gueth et al. 1996). The magnetic field orientation inferred from 1.3 mm polarization measurements shows an hourglass morphology, with the central vectors showing a position angle of ~148° measured counterclockwise from north (Stephens et al. 2013).

Using the column density map produced from the Herschel images, we traced a single filament that runs almost in the east-west direction and then changes its direction toward the south. The filament was traced using the Filfinder algorithm (described in Sect. 3.2). Both the east-west and the north-south segments of the filament are found to be ~5° in length. In Fig. 1 we show a color-composite image of the region containing the cloud L1157. The image was produced using the Herschel 250 μm, WISE 12 μm, and Spitzer 8 μm emission. Emission from the protostar, the bipolar outflow originating from it, and a well-defined filament structure extending to the west of the protostar is conspicuous in Fig. 1. The age estimates of L1157-mm, ~150 kyr (Bachiller et al. 2001; Froebrich 2005; Arce et al. 2008), suggest that the star formation was only recently initiated in L1157, and the conditions that led this cloud to form star(s) may therefore still be preserved. Additionally, the absence of any active high-mass star formation in the vicinity of L1157 (Kun et al. 2009) presents a simple case of isolated low-mass star formation occurring in a quiescent environment.

In this work, we first estimate the distance to L1147/1158 complex using the recently released Gaia DR2 parallax and proper motion values of the young stellar object (YSO) candidates associated with it. To investigate the role played by the parsec-scale magnetic field in the formation of L1157, we made optical R-band polarization measurements of stars that are
projected on a region of 20’ × 20’ field that includes the cloud. Because the Herschel continuum dust maps lack kinematic information, we made molecular line observations of the region containing the filament structure in L1157 in the 12CO, C18O, and N2H+ (J = 1–0) lines. Finally, using the Gaia DR2 proper motion values of the YSOs associated with the L1147/1158 and L1172/1174 complexes (an another complex situated 2° east of L1147/1158) and using the radial velocities of the cloud, we determine the motion of the complexes in space and discuss a possible origin of the filament in L1157.

The paper is organized in the following manner. We begin with a brief description of the observations, data, and the reduction procedure in Sect. 2. The results from the polarization and molecular line observations are presented in Sect. 3. We discuss the results we obtained in Sect. 4. We conclude the paper with a summary of the results in Sect. 5.

2. Observations and data reduction

2.1. Optical polarimetry

The polarimetric observations presented here were carried out over several nights in November 2015 at the Cassegrain focus of the 104 cm Sampurnanand Telescope, Nainital, India. We used the Aries Imaging POLarimeter (AIMPOL), which incorporates an achromatic rotatable half-wave plate (HWP) as modulator and a Wollaston prism beam splitter as the analyzer. The fast axis of the HWP and the axis of the Wollaston prism are kept perpendicular to the optical axis of the system. The fast axis of the HWP is rotated at four different angles 0°, 22.5°, 45°, and 67.5°. This provides two images of the object on the field of CCD camera that is of TK 1024 × 1024 pixel² size (see Rauteila et al. 2004). The plate scale and the gain of the CCD used are 1.48”/pixel and 11.93 3.1 e⁻ per ADU (analog-to-digital unit). The noise created while the CCD is read out is 7.0 e⁻.

A standard Johnson Rₖ filter with λₜ eff as 0.76 µm was used for polarimetric observations. The spatial resolution (full width at half-maximum, FWHM) corresponds to 2–3 pixels on the CCD. The data reductions are carried out using a software developed in Python to identify the ordinary and corresponding extraordinary images of each object in the field of view. The photometry is carried out using aperture photometry provided by the Image Reduction and Analysis Facility (IRAF) package. The intensities of ordinary and extraordinary images in the observed field are extracted to calculate the required ratio R(α). This ratio is defined as

\[
R(α) = \frac{I_{\lambda (α)}}{I_{\lambda (0)}} = \frac{1}{P \cos(2θ - 4α) + 1},
\]

where P is the strength of the total linearly polarized light, θ is the polarization angle in the plane of sky, and α is the angle of the half-wave plate fast axis with respect to the axis of the Wollaston prism. P and θ are calculated using normalized Stokes parameters q₁, u₁, and q₂, u₂ at angles 0°, 22.5°, 45°, and 67.5° respectively.

Standard polarized and unpolarized stars selected from Schmidt et al. (1992) are observed routinely to correct the polarization position angle offset and the instrumental polarization, respectively. The instrumental polarization derived from the unpolarized standards is found to be ~0.1% (e.g., Medhi et al. 2008; Soam et al. 2013). The polarization angles of the standard stars obtained from our observations were compared with those of the standard star values given by Schmidt et al. (1992), and the difference was applied as a correction to the polarization angles. In Table 1 we show the log of the polarization observations.

2.2. Radio observations

The molecular chemistry is different at various layers of the molecular cloud, which makes it difficult to discuss the kinematics with a single molecular tracer. We have chosen a set of molecules 12CO (J = 1–0), C18O (J = 1–0), and N2H+ (J = 1–0) to be observed with the same telescope to constitute a homogeneous set of same calibration. Because of the high difference in dipole moment of N2H+ and 12CO molecules, these data are sensitive to high- as well as low-density regions by using these tracers. The filamentary structure of L1157 cloud was mapped with these tracers using the 13.7 m diameter single-dish radio facility at Taeudek Radio Astronomy Observatory (TRAO), which is located at the Korea Astronomy and Space Science Institute (KASI) in Daejeon, South Korea. It operates in the wavelength range of 85–115 GHz. Observations were taken using the new receiver system Second QUabbin Observeratory Imaging Array-TRAO (SEQUOIA-TRAO). It consists of high-performing 16 pixel MMIC preamplifiers in a 4×4 array. The pointing accuracy was achieved to be ≤5’ using a standard X Cygnus source in the SiO line. The position-switch mode was employed to subtract the sky signals. At 115 GHz, the beam size (half-power beam width, HPBW) of the telescope is about 45” and the fraction of the beam pattern subtending main beam (beam efficiency) is 51 ± 2%. The system temperature was 550 K-600 K during the observations. The back-end system with fast Fourier transform spectrometer has 4096 × 2 channels at 15 kHz resolution (∼0.05 km s⁻¹ at 110 GHz). Because the optical system provides two side-bands, two different lines can be observed simultaneously. The C18O line, which reveals the dynamics of high-density regions of the cloud, was simultaneously observed with 12CO. The observations were performed using the on-the-fly (OTF) mapping technique, covering a region of 12’ × 12’ for 12CO and C18O and a 8’ × 8’ region for N2H+ in J = 1–0 transition. The center of the maps was 20h39m06.19s +68°02’15.09”.

\[\text{Table 1. Polarized standard stars observed in } R₁\text{ band.}\]

<table>
<thead>
<tr>
<th>Date of observation</th>
<th>P ± ϵP (%)</th>
<th>θ ± ϵθ (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HD 236633 (Standard values: 5.38 ± 0.02% 93.04 ± 0.15°)</td>
<td>4.9 ± 0.1</td>
<td>99 ± 1</td>
</tr>
<tr>
<td>3 November 2015</td>
<td>5.0 ± 0.1</td>
<td>101 ± 1</td>
</tr>
<tr>
<td>15 November 2015</td>
<td>5.1 ± 0.1</td>
<td>101 ± 1</td>
</tr>
<tr>
<td>16 November 2015</td>
<td>4.9 ± 0.1</td>
<td>101 ± 1</td>
</tr>
<tr>
<td>17 November 2015</td>
<td>6.3 ± 0.1</td>
<td>105 ± 1</td>
</tr>
<tr>
<td>3 November 2015</td>
<td>6.2 ± 0.1</td>
<td>105 ± 1</td>
</tr>
<tr>
<td>15 November 2015</td>
<td>6.0 ± 0.1</td>
<td>106 ± 1</td>
</tr>
<tr>
<td>16 November 2015</td>
<td>5.9 ± 0.1</td>
<td>105 ± 1</td>
</tr>
<tr>
<td>17 November 2015</td>
<td>6.2 ± 0.1</td>
<td>106 ± 1</td>
</tr>
</tbody>
</table>

References. (a) Values in the R band taken from Schmidt et al. (1992).
A first-order polynomial was applied to correct the baseline in the final spectra. The resulting $1\sigma$ rms noise levels in $T_A^*$ scale are $\sim0.3$ K for $^{13}$CO (1–0) and 0.1 K for the C$^{18}$O line, respectively. The final data cubes have a cell size of $22''$ and a $0.06$ km s$^{-1}$ velocity channel width.

3. Results

3.1. Polarization results

We made optical polarization measurements of 62 stars that are projected on an area of $0.3' \times 0.3'$ around the protostar L1157-mm. We show the measured degree of polarization ($P\%$) and polarization position angles ($\theta_p$) in Fig. 2. The polarization measurements for which the ratio of $P\%$ and its corresponding error is greater than 3 are plotted. For the majority of the sources, $P\%$ ranges between $-1$–$2\%$ and the $\theta_p$ ranges between $-110^\circ$–$140^\circ$. The mean values of $P\%$ and $\theta_p$ of the sources showing $P\% \geq 1$ are $2.1$ and $129^\circ$, respectively and the corresponding standard deviation values are $0.6$ and $11^\circ$, respectively. We also show the polarization values of 16 sources selected from a circular area of $5''$ radius about the protostar. Although 18 sources are present within our search radius, we rejected 2 sources: HD 200775 and HD 193533. The first, HD 200775, is an intermediate-mass Herbig Be star causing a reflection nebulosity, NGC 7023. Source HD 200775 is situated at a distance of $357 \pm 6$ pc (Bailer-Jones et al. 2018) and the $P\%$ and $\theta_p$ values given in the Heiles (2000) catalog are $-0.8 \pm 0.2$ and $-92^\circ \pm 7^\circ$. It is highly likely that the polarization measurements are affected by the intense emission from the nebulosity surrounding the star due to scattering. The second star, HD 193533, is an M3III and is classified as a variable star in the Simbad database. The distance, $P\%$, and $\theta_p$ values for this star are $301 \pm 5$ pc, $0.3 \pm 0.05$, and $142^\circ \pm 4^\circ$, respectively.

3.2. Identification of filaments and clumps

The whole L1147/1158 complex was observed by the Herschel telescope. The PACS (Poglitsch et al. 2010) and SPIRE (Griffin et al. 2010) instruments were used to observe the region simultaneously at 70, 160, 250, 350, and 500 $\mu$m wavelengths as a part of the Gould Belt Survey (André et al. 2010). The 160–500 $\mu$m Herschel images were used to construct an H$_2$ column density map and a dust temperature map of the entire complex at the spatial resolution of $36''$. The units of the SPIRE images, which are in MJysr$^{-1}$, were changed into Jy pixel$^{-1}$ using the task convertimageunit in the Herschel Interactive Processing Environment (HIPE). To fit the spectral energy distribution (SED) on a pixel-to-pixel basis, all the maps (PACS 160, and SPIRE 250 $\mu$m, 350, and 500 $\mu$m) were convolved to the 500 $\mu$m image using the kernels from Aniano et al. (2011) and regridded to a pixel scale of $14''$. The background flux density ($I_{bg}$) was determined using values from the pixels in a relatively darker patch in the sky. The emission of every pixel is assumed to be represented by a modified blackbody emission,

$$S_\nu(v) = \Omega(1 - \exp(-\tau_v))B_\nu(v, T_d),$$  
\( (2) \)

with

$$\tau_v = 0.1\mu m_H\kappa_v\tau_{H_2},$$  
\( (3) \)

where $S_\nu(v)$ is the observed flux density for a given frequency $v$ and the solid angle $\Omega$, $\tau(v)$ is the optical depth, $B_\nu(v, T_d)$ is the Planck function, $T_d$ is the dust temperature, $\mu m_H$ is the mass of hydrogen, $\mu m_H$ is the mean molecular weight taken as 2.8 (Kauffmann et al. 2008), and $N_{H_2}$ is the column density for hydrogen. All the fluxes were normalized to Jy pixel$^{-1}$. For the opacity, we assumed a functional form of $\kappa_v = 0.1 (\frac{\nu}{1000 \text{GHz}})^{\beta}$, where $\beta$ is the spectral emissivity index, and the value was taken as 2 (Schnee et al. 2010). The derived column density and dust temperature maps were regridded using the Astronomical Image Processing System (AIPS) to $3''$. Because we modeled the cold dust emission longward of 160 $\mu$m, the fit was relatively poorer near the protostar where contribution from warm dust would also be present. This prevented us from using a single blackbody model.

To characterize the filament properties, we used the FilFinder algorithm to extract the filaments from the column density map. The FilFinder algorithm was developed to extract filamentary structures in clouds observed by Herschel (André et al. 2010). The extraction was performed by reducing the regions of interest to topological skeletons based on specified threshold intensities. Each element of the skeletons therefore represents the medial position within the extents of the required region (Koch & Rosolowsky 2015). The emission structures in L1157 were flattened to a percentile of 99 to smoothen the bright features in the image. While creating masks, the global threshold was taken as $\sim2.1 \times 10^{21}$ cm$^{-2}$ (3$\sigma$ above the background, $\sigma \sim 7.0 \times 10^{20}$ cm$^{-2}$) with a size threshold of 300 pix$^2$. The masks were reduced to skeletons using medial axis transform, which extracts one single filament. A single filament of $\sim1.2$ pc in length that runs throughout the coma-structure of the cloud is traced. For the purpose of analysis, we divided the filament into east-west and north-south segments. The orientation of the east-west segment is found to be 77$^\circ$ and a curvature of 76$^\circ$ with respect to the north increasing eastward. The extracted filament is shown in Figs. 1 and 3.
We used the well-known Clumpfind (Williams et al. 1994) routine to identify high-density regions in the filament from the column-density map. Based on the Clumpfind routine, we obtained two clumps: C1 and C2. They lie on the filament (Fig. 3). The centers of these clumps are 20h39m06.79s +68°02′12.27″ and 20h39m20.349s +67°59′03.74″, with a typical uncertainty in the positions of ∼10″ (Fehér et al. 2017). Clump C1 is located on the east-west segment where the protostar L1157-mm is currently forming, and clump C2 is found to be located on the north-south segment of the filament. Based on the absence of any 70 μm source associated with C2, we classify it as starless. We note that if we had used a 250 μm emission map instead of the column density map, the Clumpfind algorithm would resolve C2 into two separate clumps. The reason may be that spatial resolution of the 250 μm emission map is higher than that of the column density map. Because our molecular line observations also detect a single-density peak at the position of C2 due to relatively coarse spatial resolution, we consider C2 as a single clump in our study.

The radial profiles and widths of the filaments are two of the most important properties of prime interest for understanding the dominant physics (gravity, turbulence, and magnetic field orientation) that are involved in their formation. We constructed the column density profiles of the filament identified in L1157 using the publicly available package Radfil (Zucker & Chen 2018). The derived filament mask and the spine of the column density map derived from Filfinder were supplied as input. The spine was smoothed to obtain a continuous distribution in column density. The crest of the filament was sampled at an interval of 40 pixels (0.18 pc), which corresponds to three times the beam width (0.061 pc at 340 pc). Therefore the mean profile was constructed by averaging the profiles of the perpendicular cuts made at nine positions along the filament and setting the Fold = True in the Radfil to add all the profiles toward positive radial distance. We fixed the fit distance from 0.0 to 0.5 pc and evaluated the background at a distance of 0.5–0.6 pc from the filament crest (out of all possible trials conducted using the Radfil, the minimum value of the background column density was estimated from this distance range). A zeroth-order polynomial fit was applied to the background subtraction before we made the fits to the profile. The diameter of the flat inner plateau is found to be $2R_{\text{flat}} = 0.126 \pm 0.003$ pc. The observed mean column density profile was fit by a Gaussian model over the inner radius of 0.05 pc. The power-law index of the best-fit Plummer model is $p = 3.1 \pm 0.2$, while the mean deconvolved width of the best-fit Gaussian model is $FWHM = 0.09$ pc.

An elongated structure showing minimum values of both aspect ratio and column density contrast with respect to the background value is normally identified as a filament (Arzoumanian et al. 2019). The aspect ratio, defined as $R_{\text{fil}}/W_{\text{fil}}$, of the sole filament identified in L1157 is $1.20 \pm 0.14$. The intrinsic column density contrast, $N_{\text{H}_2}/N_{\text{H}_2}^\text{bg}$, of the filament is estimated to be $\sim 8$, where $N_{\text{H}_2}^\text{bg} = (N_{\text{H}_2}^\text{fil} - N_{\text{H}_2}^\text{bg})$ is the column density amplitude of the filament. The column densities of the pixels that form the extracted filament structure were averaged to obtain a representative value for the whole filament. One of the important consequences of obtaining a column density profile is that the mass per unit length can be calculated. We derived the mass per unit length ($M_{\text{line}}$) for each position along the filament using the best-fit Gaussian parameters: central column density ($N_{\text{H}_2}$) and standard deviation ($\sigma$). The lower right panel of Fig. 4 shows the distribution of the background-subtracted Gaussian mass-per-unit length along the crest of the filament at every cut, which was taken at an interval of 3 pixels (∼0.015 pc). The dashed horizontal line marks the critical mass-per-unit length that characterizes an isothermal cylindrical filament in equilibrium. The extreme end of the north-south segment of the filament (20h39m17s +67d57m56s) was taken as the starting point of the filament. The upper right panel in Fig. 4 shows the deconvolved FWHM derived from the Gaussian fitting of the mean column density radial profile as a function of distance along the filament crest. Although the cloud reflects as a single filament derived from the Filfinder algorithm, differences are found in the inner widths of the north-south and the east-west branches. The characteristic width of the east-west branch is better defined and constrained than that of the north-south branch. The positions for which we were unable to fit the radial profile with a well-defined Gaussian function are not included in the plot. The small dip near C2 corresponds to the region between the two peaks seen in the 250 μm Herschel map ($FWHM \sim 18″$), but which are barely noticeable in the column density map ($FWHM \sim 36″$).

3.3. Molecular line analysis

The CO isotopologs are commonly used to probe the gas at different densities. While the most abundant isotopolog, $^{12}$CO is considered to trace the most diffuse and external gas of molecular clouds, its rarer counterpart, $^{13}$CO is found to disappear from the gas phase in high chemically evolved regions because it condenses onto the surface of the dust grains (Caselli et al. 1999; Bergin et al. 2002; Cazaux et al. 2017). The $^{13}$CO molecular line, on the other hand, is considered to be the most efficient tracer of dense cores in clouds because the abundance of this molecule becomes enhanced when CO condenses onto the dust grains (Bergin & Tafalla 2007).

The kinematic information from the observed molecular lines was extracted by fitting Gaussian profiles to all our spectra using programs developed in Python. We examined an individual spectrum and fit it independently using one single component at each individual position in $^{13}$CO lines. We obtained a total of...
1089 spectra in $^{12}$CO and C$^{18}$O and 306 spectra in the N$_2$H$^+$ lines from the field containing the cloud L1157.

Various fundamental properties of the cloud like excitation temperature, optical depth, and the number density were derived using spectral data obtained at different positions of the cloud. Two assumptions were made to estimate the column density ($N_{18}$) based on the C$^{18}$O and $^{12}$CO lines: the molecules along the line of sight possess a uniform excitation temperature for the $J = 1-0$ transition, and the $J = 1-0$ excitation temperatures of the two isotopic species are equal (e.g., Dickman 1978; Sato et al. 1994). The emission from the $^{12}$CO molecule is optically thick, and the common excitation temperature ($T_{ex}$) was calculated from the peak $^{12}$CO brightness temperature using the expression

$$T_b^{12} = T_0^{12} [f_{12}(T_{ex}) - f_{12}(2.7)],$$

where $T_0^{12}$ is the temperature corresponding to the energy difference between the two levels given by $T_0^{12} = h
nu_{12}/k$, here $\nu_{12}$ is the frequency for $J = 1-0$ transition. In the same manner, the optical depth of the C$^{18}$O line ($\tau_{18}^{18}$) was also calculated from the peak brightness temperature and the excitation temperature ($T_{ex}$) using the expression,

$$T_b^{18} = T_0^{18} [f_{18}(T_{ex}) - f_{18}(2.7)][1 - \exp(-\tau_{18}^{18})].$$

The column density along the line of sight was calculated as,

$$N_{18} = \frac{3h\Delta v_{18}}{8\pi\mu^2} \tau^{18} Q \left[1 - \exp - \frac{\nu_o}{\nu_{18}}\right].$$

where $\Delta v_{18}$ is the line full width at half-maximum in velocity units, $\mu$ is the permanent dipole moment of the molecule, $h$ is the Planck constant, and $Q$ is the partition function. Again an assumption was made regarding the partition function, which depends upon the excitation temperatures of all significantly populated states of the molecule such as,

$$Q = 1 + \sum_{L=1}^{\infty} (2L + 1) \prod_{j=0}^{L} \exp[-\nu(J)/kT_{ex}(J)],$$

where $\nu(J)$ and $T_{ex}(J)$ are the frequency and excitation temperature of the transition $J = 1-0$, respectively. This means that we assumed that all the levels have the same $T_{ex}$. The partition function can be written as $Q = \frac{2\pi^2}{\nu T_{ex}}$. Not all the lines were fit to a perfect Gaussian, however. We therefore used the chi-square minimization to determine the goodness-of-fit. We obtained integrated intensity (moment 0) maps of $^{12}$CO and C$^{18}$O using spectral data cubes with position-position velocity information. The values below $3\sigma$ were not considered to obtain summation over the channels. The rms value of each line map was calculated as $\sqrt{\sum_{\text{channels}} T_{rms}}$, where $N$ is the number of channels used for integrating the emission, $\delta v$ is the velocity resolution, and $T_{rms}$ is the noise of the line profile.

The characteristic shape of the observed line profiles is a critical factor in determining the physical state of molecular gas in a region. Figure 5 in the left-hand panel shows the $^{12}$CO and C$^{18}$O (1–0) line profiles plotted together at different positions in the cloud, and the right-hand panel shows the average $^{12}$CO, C$^{18}$O, and N$_2$H$^+$ (isolated component) profiles over the half-maximum contour of the intensity map of N$_2$H$^+$ emission. The $^{12}$CO emission is detected throughout the observed region and conspicuously shows diverse line profiles with an asymmetric
structure detected in a large area. The $^{12}$CO lines show a wide line width and two velocity components especially in the cloud. This might either be due to self-absorption by the optically thick material at the systematic velocity of the cloud, if there is only a single cloud component, or to additional velocity components along the line-of-sight. The significant emission of the $^{13}$CO line ($\geq 3\sigma$) was obtained toward the high column density region seen in the Herschel dust map, as shown in Fig. 3. The $^{13}$CO line profiles show an optically thin feature, that is, a single Gaussian component. The absorption of the double-peaked profiles of $^{12}$CO lines coincides with the single peak of $^{13}$CO emission, confirming that there is only a single cloud component along the line of sight.

The $^{13}$CO line width is found to be much narrower than that of $^{12}$CO. The well-studied outflow (Umemoto et al. 1992) is evident as broad high-velocity wings on either side of the $^{12}$CO line profiles when compared visually with the shape of the $^{13}$CO Gaussian component. Interestingly, at many positions along the filament and in surrounding regions around C1 and C2, the profiles show a blue-red asymmetry (Sect. 4.5). The N$_2$H$^+$ emission is detected toward both C1 and C2.

4. Discussion

4.1. Distance of the L1147/1158 complex

One of the most direct methods of determining distances to molecular clouds is estimating distances of the YSOs that are associated with the cloud (e.g., Loinard et al. 2007; Ortiz-León et al. 2018). The stellar parallax measurements obtained for these YSOs from the Gaia DR2 (Lindegren et al. 2018) offer an unprecedented opportunity to estimate distances to molecular clouds with improved accuracy and precision. A total of six YSO candidates have been identified so far toward the direction of L1147/1158 (Kun 1998; Kirk et al. 2009). We found a Gaia counterpart for three of the six YSO candidates well within a search radius of 1″. The Gaia results are presented in Table 2. We obtained their distances from the Bailer-Jones et al. (2018) catalog, and proper motion values in right ascension ($\mu_\alpha = \mu_\alpha \cos \delta$) and in declination ($\mu_\delta$) from the Gaia Collaboration (2018) catalog. Within the L1147/1158 complex (Yonekura et al. 1997), the dark cloud L1155 harbors two YSOs, 2MASSJ20361165+6757093 and IRAS 20359+6757093 and IRAS 20359+6745. Cloud L1158 hosts at its north-east edge an another YSO candidate, PV Cephei. The bright nebulosity associated with IRAS
Table 2. *Gaia* results of YSOs associated with the L1147/1158 and L1172/1174 complexes.

<table>
<thead>
<tr>
<th>Source name</th>
<th>RA (°)</th>
<th>Dec (°)</th>
<th>l (°)</th>
<th>b (°)</th>
<th>Distance (pc)</th>
<th>$\mu_\alpha$ (mas yr$^{-1}$)</th>
<th>$\Delta \mu_\alpha$ (mas yr$^{-1}$)</th>
<th>$\mu_\delta$ (mas yr$^{-1}$)</th>
<th>$\Delta \mu_\delta$ (mas yr$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2MASS J20361165+6757093</td>
<td>309.048672</td>
<td>67.952608</td>
<td>102.4221</td>
<td>15.9738</td>
<td>336$^{22}_{22}$</td>
<td>7.436</td>
<td>0.351</td>
<td>−1.514</td>
<td>0.284</td>
</tr>
<tr>
<td>IRAS 20359+6745</td>
<td>309.082855</td>
<td>67.942131</td>
<td>102.4205</td>
<td>15.9573</td>
<td>343$^{13}_{13}$</td>
<td>7.753</td>
<td>0.189</td>
<td>−1.469</td>
<td>0.143</td>
</tr>
<tr>
<td>PV Cep</td>
<td>311.474902</td>
<td>67.960735</td>
<td>102.9697</td>
<td>15.2315</td>
<td>341$^{6}_{6}$</td>
<td>8.228</td>
<td>0.126</td>
<td>−1.976</td>
<td>0.110</td>
</tr>
</tbody>
</table>

20359+6745 ([Magakian 2003]) and PV Cephei ([Scarrott et al. 1991]) are clear evidence of their association with their respective clouds. No detection was found in the *Gaia* DR2 database for the other three YSO candidates, L1148-IRS, which is associated with L1148 ([Kun 1998]), IRAS 20353+6742, which is associated with the L1147 IRS complex, and L1152 ([Benson et al. 1988]), and L1157-mm in L1157.

The mean value of the distance calculated from the three YSOs is 340 pc with a dispersion of 3 pc. The mean (standard deviation) values of the $\mu_\alpha$ and $\mu_\delta$ for them are 7.806 (0.326) mas yr$^{-1}$ and $−1.653$ (0.229) mas yr$^{-1}$, respectively. Similar distance and proper motion values shown by all the three YSOs indicate that they are spatially and kinematically associated with each other and that the complex is also located at a distance of 340 ± 3 pc from us. Similar values of $V_{lsr}$ (~2.6 km s$^{-1}$) shared by the individual clouds of the complex ([Harjupaa et al. 1991; Yonekura et al. 1997; Suzuki et al. 2014]) also support this argument. 

*Straiysys et al.* ([1992]), based on Vilnius photometry, which gives two dimensional classifications and the extinction suffered by the stars, estimated distances to the L1147/1158 cloud complex. Using ten reddened stars in the direction of L1147/1158, the authors estimated a distance of 325 ± 13 pc to the cloud.

The degree of P% measured in the optical wavelengths made using the pencil-beam of starlight passing through the interstellar medium is often found to correlate with the extinction ($A_V$) measured to that line of sight up to at least an $A_V$ of ~3 magnitudes ([Guetter & Vrba 1989; Harjupää et al. 1999]). As the distance to the observed stars increases, the column of the dust grains present along the pencil-beam therefore also increases, leading to a gradual increase in the P% if no significant depolarization occurs along the path. When the starlight passes through a molecular cloud, the measured P% will receive additional contribution from the dust grains present in it. This will lead to a sudden increase in the values of P% for the stellar background to the cloud, while the foreground stars will show very low values. The weighted mean values of P% and $\theta_\phi$ for the sources located at distances $<340$ pc are $0.1 ± 0.05$ and $65° ± 29°$, respectively. For the four sources located beyond

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at or beyond \( 340 \) pc, the weighted mean values of \( P\% \) and \( \theta_p \) represent the magnetic field geometry of the cloud. The two stars in our sample that are foreground stars show higher \( P\% \) values than those from the Heiles (2000) catalog. We subtracted the mean \( P\% \) and \( \theta_p \) values of these two foreground sources from the remaining sources vectorially and found the values to be \( 2.3 \pm 0.8 \) and \( 127^\circ \pm 12^\circ \). Therefore, \( 127^\circ \pm 12^\circ \) was taken as the orientation of the magnetic field in L1157 inferred through optical polarization. The magnetic field orientations thus obtained are overplotted on the DSS image as shown in Fig. 7a. The position of the protostar L1157-mm is shown as well. The length of the vectors corresponds to the \( P\% \) values and the orientations correspond to the \( \theta_p \) values measured from the north, increasing toward the east. The polarization measurements using background starlight in the optical wavelengths typically only hold for the regions of low \( A_V \) (\( \leq 5 \)). This is because although the dust grains deep inside the molecular clouds are efficient in diminishing background starlight, they are believed to be little efficient in polarizing the light in optical wavelengths (Goodman et al. 1995; Crutcher 2012). Therefore, the optical polarization vectors shown in the Fig. 7a basically trace the orientation of the magnetic fields at the envelope (low-density regions) of L1157. The magnetic field orientation is found to be well ordered at \( \sim 0.2–2 \) pc scales, which suggests that the intercloud magnetic field (ICMF) might have played an important role at least in the initial building up of the cloud.

The magnetic field orientation of a region can also be inferred through the observations of polarized thermal emission from the dust grains (Hildebrand et al. 1984; Goodman 1995; Greaves et al. 1999). Far-infrared and submillimeter polarimetric observations made by the Planck were used not only to infer the direction of the Galactic magnetic field, but also to place new constraints on the properties of dust (Planck Collaboration Int. XXI 2015; Planck Collaboration Int. XXXII 2016; Planck Collaboration Int. XXXV 2016). We used the 353 GHz (850 \( \mu \)m) data. The 353 GHz channel is the highest-frequency polarization-sensitive channel of the Planck. We produced the structure of the Galactic magnetic field in the vicinity of L1157 based on these data. We selected an image with a diameter of \( \sim 1^\circ \) centered on the cloud and smoothed it down to the 8\(^\circ\) resolution to obtain a good S/N. The results are shown in Fig. 2 using dots in gray. The \( P \) values range from \( \sim 2–8\% \) with a mean value of 4.4\% and a standard deviation of 1.6\%. The dust emission is linearly polarized with the electric vector normal to the sky-projected magnetic field, therefore the polarization position angles were rotated by 90\(^\circ\) to infer the projected magnetic field. The polarization position angles show a highly regular distribution with a mean value of 127\(^\circ\) and a standard deviation of 6\(^\circ\). The polarization vectors are presented in the 0.5\(^\circ\) \( \times \) 0.5\(^\circ\) DSS image, as shown in Fig. 7a. The vectors in blue are those from the 0.3\(^\circ\) \( \times \) 0.3\(^\circ\) circular region similar to where we carried out optical polarization observations. These results are shown in Fig. 2 using filled squares in black. We note that the positions showing relatively higher values of \( P \) show a relatively lower dispersion in \( \theta_p \). The mean and standard deviation of the source with \( P \geq 4\% \) are 129\(^\circ\) and 4\(^\circ\), respectively. The projected magnetic field geometry inferred from the optical and the Planck polarimetry agrees

\[ \begin{align*}
\text{(1)} & \quad \text{The entire sky was surveyed by the Planck in nine frequency bands, from 30 to 857 GHz, with unprecedented sensitivity, and angular resolutions varying from 30\!' at 30 to 4.8\!' at 857 GHz. Seven of the nine bands were sensitive to polarized thermal emission from Galactic dust.}
\end{align*} \]
4.3. Magnetic field strength

We used the Davis-Chandrasekhar & Fermi (DCF) (Davis 1951; Chandrasekhar & Fermi 1953) method to estimate the plane-of-the-sky magnetic field strength of L1157. The DCF method is formulated as

$$B_{\text{pos}} = 9.3 \times \sqrt{\frac{n_H}{\text{cm}^{-3}}} \times \frac{\Delta v}{\text{km s}^{-1}} \times \left(\frac{\Delta \phi}{1^\circ}\right)^{-1},$$

(8)

where $\Delta v$ is the FWHM of the CO(1–0) line, which is measured as $\sim 1.8 \text{ km s}^{-1}$. We used only those lines to measure FWHM that can be fit with a single Gaussian function. Here $n_H$ is the volume density of L1157, which is found to be 1000 cm$^{-3}$. To calculate the volume density, we used a column density of $8.0 \times 10^{20}$ cm$^{-2}$ and a depth of the cloud of 0.3 pc. We considered the extent of the column of the cloud material lying along the line of sight as three times the width of the filament, which is about 0.1 pc. In the equation, $\Delta \phi$ is dispersion in the distribution of polarization position angles, which is measured as $11^\circ$. The magnetic field strength in the envelope of L1157 is found to be $\sim 50 \mu$G.

To calculate the uncertainty in the magnetic field strength, we propagated the uncertainties in measured position angle and velocity dispersion values. The uncertainty in the magnetic field strength is $\sim 0.5 B_{\text{pos}}$. The field strength in the dense core region of L1157 has been reported to be 1.3–3.5 mG by Stephens et al. (2013) using their 1.3 mm dust continuum polarization observations. These values are about two magnitudes higher than our measurements, which suggests that the core has stronger magnetic fields than the envelope of L1157.

4.4. Correlations between magnetic field, filament, and outflow directions in L1157

The star formation process begins with the accumulation of matter from the ICM. In models where magnetic fields are dynamically more important than turbulence (e.g., Shu et al. 1987; Galli & Shu 1993a,b; Tomisaka 1998; Allen et al. 2003a,b), the accumulation of matter is controlled by the ICMF. The gas slides along the field lines (Ballesteros-Paredes et al. 1999; Van Loo et al. 2014), forming filamentary structures that are aligned perpendicular to the ICMF. In these filaments, cores are found to be forming (Polychroni et al. 2013; Könyves et al. 2015). Because the assembly of matter is guided by the magnetic fields, the ICMF direction is expected to be preserved deep inside the cores (Li et al. 2009; Hull et al. 2014; Li et al. 2015), predicting the ICMF to become parallel to the core magnetic field (CMF). The local CMF within individual cores (subcritical) provides support against gravity, preventing them from collapsing and thus accounts for the low efficiency of the star formation process (e.g., Mouschovias 2001). The neutral particles, coupled weakly to the ions and hence to the magnetic fields, can drift toward the center of the core, enabling it to amass more material. The increasing central mass gradually increases the mass-to-magnetic flux ratio, leading the core to become supercritical and driving it to collapse under gravity. Under the influence of gravity, the initial uniform magnetic field is expected to be dragged toward the center of the core, forming an hourglass-shaped morphology (Galli & Shu 1993a,b). As the collapse progresses, a pseudo-disk is expected to form in the central region with the symmetry axis of the pinching perpendicular to it. The protostellar object embedded deep inside the cores continues to build mass through accretion and simultaneously develops a bipolar outflow. Because the initial cloud angular momentum is expected to be hierarchically transferred to the cores and eventually to the protostar, the rotation axis (of the core or accretion disk) is
expected to become parallel to the ICMF and CMF (Machida et al. 2006; Matsumoto et al. 2006) and perpendicular to the core minor axis and the filament structure.

In this framework of magnetic field-mediated star formation, a number of observational signatures that show the role played by the magnetic fields are detected (e.g., Li et al. 2009, 2015; Hull et al. 2014). Some of these are (i) the relative orientations between (a) the ISMF and the CMF, (b) the ISMF and the long axis of the filament, (c) the ISMF, CMF, and bipolar outflows, (d) the filament and the outflows, and (ii) the hourglass morphology of the magnetic field at the core scale with the symmetry axis perpendicular to the major axis of the flattened pseudo-disc. We examined these relationships in L1157, which is not only successful in forming a star, but is also at its earliest stages of star formation, the initial conditions that led this cloud to form star may still be conserved.

The polarization measurements of the region surrounding L1157-mm were carried out at 1.3 mm (resolution 1.2′′) and 350 μm (10″) (Chapman et al. 2013; Stephens et al. 2013) with the aim to trace the magnetic field orientation in the inner regions of the core (Hildebrand et al. 1984; Goodman 1995; Greaves et al. 1999). The SHARP and CARMA vectors with their standard deviation have been quoted as \( P = 0.7% \pm 0.2% \) and \( \theta = 142^\circ \pm 9^\circ \), and \( P = 3.8\% \pm 0.1\% \) and \( \theta = 147.8^\circ \pm 0.8^\circ \), respectively. We adopted an orientation of \( 145^\circ \pm 9^\circ \) for the CMF, which is the mean value of the magnetic field directions inferred from the SHARP and CARMA results. The magnetic field inferred from the 1.3 mm polarization measurements is shown in the inset in Fig. 7b by overplotting the vectors on the WISE 12 μm image. The CARMA and SHARP polarization measurements were carried out at scales of ~400–1500 au and ~3500 au (using the distance of 340 pc), respectively, thus representing the CMF. The offset between the relative orientations of the IC MF inferred from the optical (and the Planck) polarimetry and the CMF obtained from the SHARP and CARMA is \( 18^\circ \pm 14^\circ \). The nearly parallel orientations of IC MF and CMF suggest that the CMF is anchored at the ICMF in L1157. The near parallel magnetic field geometry from large to core scales indicates that the fields have not been disturbed by turbulent motions resulting from the collapse of material during the star formation process in L1157.

The orientation of the magnetic field toward L1157-IRS was found to exhibit an hourglass morphology (Stephens et al. 2013). The symmetry axis of the hourglass morphology is found to be perpendicular to a flattened structure (~0.1–0.2 pc) seen in absorption against bright emission, possibly due to the polycyclic aromatic hydrocarbons from the diffuse interstellar medium in the background (Looney et al. 2007). The \( N_2H^+ \) emission, having a spatial extent of ~30,000 au and oriented 75° north to east (elongated perpendicular to the outflow; Chiang et al. 2010), is found to coincide with the absorption feature. These structures extend farther, at least at the western side of L1157-mm, and coincide with the east-west segment of the filament up to a length of ~0.5 pc. According to the \textit{Filfinder} algorithm, the east-west segment of the filament is oriented at an angle of 79° (consistent with the orientation of \( N_2H^+ \) emission) and makes an offset of 48° with respect to the ICMF and of 66° with respect to the CMF direction. The offset of 66° to the CMF with respect to the east-west segment of the filament suggests that the star formation in L1157 supports a scenario where the magnetic field is sufficiently strong enough to have influenced the formation of at least the east-west segment of the filament structure (Soler et al. 2013; Planck Collaboration Int. XXXV 2016). An alternative possibility for the formation of the east-west segment is discussed in Sect. 4.7. The north-south segment of the filament, however, is found to be almost parallel to the ICMF and CMF.

The relative orientation of the bipolar outflow and the filament (the absorption feature and the \( N_2H^+ \) emission) in L1157 is found to be \( 8^\circ \pm 10^\circ \) (assuming an uncertainty of 10° in the determination of the outflow position angles, e.g., Soam et al. 2015), which means they lie almost perpendicular to each other. When we consider the outflow direction as a proxy for the rotation axis, then the orientation of outflow with respect to the filament provides evidence for the manner in which matter was accumulated prior to the initiation of the star formation. In L1157, the material might have first become accumulated onto the filament channeled by the magnetic field lines aligned perpendicular to it, and then, as the density increased, the flow pattern changed direction and might have flown along the filament toward the core. In this scenario, we would expect the rotation of the protostar to be perpendicular to the filament because the local spin motion depends on the flow direction (Clarke et al. 2017; Stephens et al. 2017).

The offsets between ICMF and the outflow direction and between CMF and the outflow direction is \( 34^\circ \pm 16^\circ \) and \( 16^\circ \pm 14^\circ \) (see also Stephens et al. 2013), respectively, which suggests that the CMF is relatively more aligned with the outflow than the ICMF. Examples of alignment and misalignment or random alignment of outflows and magnetic field exist in the literature. Although studies have shown that the outflows are preferentially misaligned or are randomly aligned with the magnetic fields, L1157-mm shows a good alignment, especially between the directions of the outflow and CMF (see also Hull et al. 2013). Misalignments between magnetic fields and outflows are suggested as an essential condition to allow the formation of a circumstellar disk (Krumholz et al. 2013).

4.5. Properties of the matter along the filament

To study the dust properties and large-scale velocity field of the gas lying along the spine of the filament identified toward L1157, we derived the peak line temperature, velocity centroids, and velocity dispersion by making Gaussian fits to all \( CH_3O \) spectra with an \( S/N \geq 3 \). The results are presented in Fig. 8 as a function of the positions along the main axis of the filament. The southern end of the north-south segment of the filament is taken as the starting point. The positions of the two condensations C1 and C2 identified using the \textit{Clumpyfind} routine are marked. To compare the properties of dust and gas emission in the cloud, we convolved and regridded the dust column density map at ~36′′ grid using the beam size of TRA O (~49′′ at 110.20 GHz) (Jeong et al. 2019). The advantage of this approach is that the comparison is made over the same area on the source, but the disadvantage is that all the spatial structures smaller than this beam size are smoothed out.

In panels (a) and (b) of Fig. 8 we show the derived dust column density and the dust temperature calculated using the \textit{Herschel} data along the filament. The column density ranges from \( 1.7 \times 10^{21} \) to \( 1.3 \times 10^{22} \) cm\(^{-2}\). The average dust column density of the filament is \( \sim 5 \times 10^{21} \) cm\(^{-2}\). The dust temperature ranges from 12 to 15 K with an average temperature of 13 K. The column density and the dust temperature both peak at the position of L1157-mm. However, the values remain nearly constant in the north-south and east-west segments of the filament. The peak value of the dust column density in the filament, \( 1.3 \times 10^{22} \) cm\(^{-2}\), is found at the position of C1 where L1157-mm is embedded. The mass-per-unit length values along the length of the filament were derived using the radial profile analysis as shown in Fig. 4.
latter ones to the western end of the east-west segment of the filament. There is a strong tendency that a blue asymmetry in the $^{12}\text{CO}$ line profile is seen in a high column density region, while no clear asymmetry in these lines is seen in the low column density region. The $^{12}\text{CO}$ line profiles at positions 1–3 in the north-south segment of the filament show a blue asymmetry. As we approach the C2 (positions 4–7), the $^{13}\text{CO}$ profile shows a blue-red asymmetry, with the blue peak brighter than the red peak. Then the line profile becomes more symmetric until position 12. The profile again shows a blue-red asymmetry as we approach C1 and continues until position 17. $^{18}\text{O}$, which is an optically thin tracer, peaks at the velocity of the self-absorption, suggesting that the double-peaked profiles of $^{12}\text{CO}$ (Fig. 9 in panels 4–7 and 13–17) are most likely due to inward motions, assuming that the gas in the inner parts of C1 and C2 has a warmer excitation temperature than that toward the envelope. The inward motions seen here might be interpreted as due to collapse or infall motion (Lee et al. 1999, 2001; Tafalla et al. 1998). The linear extent of the infall motion is $\sim0.15$ pc. The $^{18}\text{O}$ lines are well fit with a Gaussian profile throughout the filament. The $^{18}\text{O}$ line width around clump C2 is found to be narrower than that found around core C1. The $^{12}\text{CO}$ lines at positions 23–30 peaks at the systematic velocity of the cloud with an additional red component that is most likely due to inward motions, assuming that the gas in the inner parts of C1 and C2 has a warmer excitation temperature than that toward the envelope. The inward motions seen here might be interpreted as due to collapse or infall motion (Lee et al. 1999, 2001; Tafalla et al. 1998). The linear extent of the infall motion is $\sim0.15$ pc. The $^{18}\text{O}$ lines are well fit with a Gaussian profile throughout the filament. The $^{18}\text{O}$ line width around clump C2 is found to be narrower than that found around core C1. The $^{12}\text{CO}$ lines at positions 23–30 peaks at the systematic velocity of the cloud with an additional red component that is most likely caused by the effect of the red lobe of the outflow.

The values of the observed line width (FWHM) of the $^{18}\text{O}$ profiles range from $\sim0.3$ to 0.6 km s$^{-1}$. We fit a single Gaussian profile to all the $^{18}\text{O}$ profiles and obtained the peak velocities. The mean value of $V_{\text{lsr}}$ of full L1157 filament was found to be $2.65 \pm 0.05$ km s$^{-1}$. The systematic velocity of the cloud was estimated by taking an average of the velocities at positions where significant emission in the $\text{N}_2\text{H}^+$ line

![Fig. 8. Results of $^{18}\text{O}$ (1–0) and dust emission analysis along the cloud filament length.](image)

(right lower panel). Ostriker (1964) considered the mass-per-unit length or line mass of an isothermal filament in equilibrium as $2\pi^{2/3}G \rho \sim 15 M_\odot$ pc$^{-1}$ at 10 K. The mass-per-unit length along the filament in L1157 ranges from 4–38 $M_\odot$ pc$^{-1}$. The line masses around C1 and C2 are higher than the equilibrium value, which implies that these parts of the filament are supercritical. The values obtained around C1 and C2 are consistent with those found toward the Taurus molecular cloud (Palmeirim et al. 2013).

The mean column density profile of the L1157 cloud is described with a Plummer-like function (right lower panel). Ostriker (1964) considered the mass-per-unit length or line mass of an isothermal filament in equilibrium as $2\pi^{2/3}G \rho \sim 15 M_\odot$ pc$^{-1}$ at 10 K. The mass-per-unit length along the filament in L1157 ranges from 4–38 $M_\odot$ pc$^{-1}$. The line masses around C1 and C2 are higher than the equilibrium value, which implies that these parts of the filament are supercritical. The values obtained around C1 and C2 are consistent with those found toward the Taurus molecular cloud (Palmeirim et al. 2013).

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The seven components in the $^{13}$CO line were simultaneously fit with seven Gaussian forms, with the line parameters given by Caselli et al. (1995). We obtained $V_{lsr}$ of the cloud, line width, and total optical depth of all the components using the fitting results. The peak velocity in the $^{13}$CO line at 3.64-2.78 km s$^{-1}$, which is adopted from the $^{13}$CO peak velocity. The spatial positions of the profiles are shown with filled white boxes in the $250 \mu$m $Herschel$ image (upper right corner) from 1–30, starting from extreme south toward the west along the filament. The protostar L1157-mm and clump C2 are marked by black and white arrows, respectively. The integrated intensity contours of $^{12}$CO image (upper right corner) from 1–30, starting from extreme south toward the west along the filament. The protostar L1157-mm and clump C2 are marked by black and white arrows, respectively. The integrated intensity contours of $^{13}$CO (1–0) line along the positions of the filament, except at the position where the north-west segment of the filament shows discernible variation. No notable variation of the filament shows an almost constant value of $V_{lsr}$ (∼2.7 km s$^{-1}$). Compared to this, the velocity structure of the south-north branch shows discernible variation. No notable variation in the values of $V_{lsr}$ obtained from $^{13}$CO lines is seen along the filament, except at the position where the north-west segment of the filament changes direction toward the east-west segment. The $^{13}$C$^{18}$O (1–0) line emission was detected. The variation in the centroid velocity ($V_{lsr}$) all along the spine of the filament is subsonic as $V_{lsr}$ observed line width obtained from the Gaussian fitting analysis generally arise from turbulence in a cloud or core-scale mechanisms. We separated out the thermal component from the observed line width obtained from the Gaussian fitting analysis with the assumption that the two components are independent of each other. The nonthermal component is calculated as,

$$\sigma_{nt} = \sqrt{(\sigma_{th})^2 - (\sigma_{th})^2}$$

(9)

where $\sigma_{th}$ is $\sqrt{kT/\mu m_{H}}$, thermal velocity dispersion, $\mu$ is the molecular weight of the observed $^{13}$CO molecule, $T$ is the gas temperature, and $k$ is the Boltzmann constant. The Mach number ($M$) is defined as the ratio of the nonthermal component ($\sigma_{nt}$) and isothermal sound speed ($c_s$) shown in panel (d) of Fig. 8. The variation shows the extent of nonthermal motions distributed along the positions of the filament. We find that much of the gas in the filament is subsonic as $M \leq 1$. Only the region

Fig. 9. Distribution of the $^{13}$CO (black) and $^{12}$CO (red) (1–0) line along the positions of the Filfinder skeleton. The dotted line shows the $V_{lsr}$ of the cloud, which is adopted from the $^{13}$C$^{18}$O peak velocity. The spatial positions of the profiles are shown with filled white boxes in the $250 \mu$m $Herschel$ image (upper right corner) from 1–30, starting from extreme south toward the west along the filament. The protostar L1157-mm and clump C2 are marked by black and white arrows, respectively. The integrated intensity contours of $^{13}$CO (1–0) shown in red are obtained by summing the flux over velocity intervals from 2.2–3.0 km s$^{-1}$. The contours start from 6$\sigma$ with intervals of 4$\sigma$, where $\sigma \sim 0.019$ K km s$^{-1}$. The cyan contours show the blueshifted (toward the north) and redshifted lobe (towards the south) of the bipolar outflow. The levels for the blueshifted lobe range from 0.12–0.5 in steps of 0.08 K km s$^{-1}$, and for the redshifted lobe, they are in range of 3.9–6.9 K km s$^{-1}$ in intervals of 1 K km s$^{-1}$. The $^{12}$CO line was integrated from −2.2 to +2.3 km s$^{-1}$ for the high-velocity wings in the southern lobe and from 3.0 to 3.9 km s$^{-1}$ in the northern lobe.
around the protostar shows the signature of turbulent motions as $\sigma_{\text{fit}} \geq c_s$. The $^{18}\text{O}$ peak line temperature is plotted as a function of position in panel (e) of Fig. 8. The intensity peak observed in $^{18}\text{O}$ toward C1 is found to be shifted from the peak intensity in dust emission. The reason for this might be the depletion of the $^{18}\text{O}$ molecules from the gas phase in the high-density regions. On the other hand, the $^{18}\text{O}$ line intensity peaks in the vicinity of C2 ($T_{\text{mb}} \sim 3.0$ K) and remains roughly constant at $T_{\text{mb}}$ of 1.0–3.0 K throughout the parts of the filament. The $^{18}\text{O}$ emission is lower at the position of C1, where dust emission is brightest and $^{18}\text{O}$ is comparable to other positions along the east-west branch. In contrast to this, $^{18}\text{O}$ emission is strongest at the position of C2, where dust emission is second brightest. $^{18}\text{O}$ might be highly depleted or photodissociated in the region around C1. However, clump C2 appears to be less strongly depleted than core C1. This suggests that C2 is a chemically younger core than C1. Overall, L1157 is velocity-coherent and mostly subsonic throughout its length, but there is internal dynamics around cores C1 and C2.

We derived the total mass of the cloud by summing all the N(H$_2$) values falling within the half-maximum contour level in the intensity map of C$^{18}$O as shown in Fig. 9, where it covers the high-density region of the cloud. The corresponding pixels in the dust column density map were used to calculate the mass of the cloud by dust emission. The mass of the L1157 cloud based on the gas emission was estimated as $\sim 8 M_\odot$, whereas the mass of the cloud by dust emission was calculated as $16 M_\odot$. There is a difference by a factor of more than 2 between the mass ($M_{\text{gas}}$) calculated from $^{18}\text{O}$ observations and the Herschel dust emission map. We expect the coupling of gas and dust in the ISM at volume densities of $\sim 10^3$ cm$^{-3}$, which do not correspond to the critical density of C$^{18}$O molecules (Goldsmith 2001). The typical uncertainty in estimating the M(H$_2$) value using dust emission is a factor of 2. The dominant factor contributing to the error in the mass estimation is the uncertainty in the opacity law. This value is an upper limit because we lack information on the inclination of the filament. The difference between the M(H$_2$) values derived from gas and dust can be attributed to various factors. The C$^{18}$O molecules can deplete and freeze out onto dust grains in high-density regions ($n_{\text{H}_2} \geq 10^3$ cm$^{-3}$) and low temperatures ($T \leq 20$ K). In addition, Herschel is capable of tracing the dust column, where the temperatures are higher, but the C$^{18}$O line might be affected by the interstellar radiation field (ISRF) and become photodissociated at less dense regions of the cloud (e.g., Caselli et al. 1999; Tafalla et al. 2004; Spezzano et al. 2016).

The gas column density can change as a result of variation in CO-to-H$_2$ conversion factor or abundance ratio of optically thick $^{12}\text{CO}$ and optically thin C$^{18}$O tracers according to metallicity and column density gradients (Pineda et al. 2010; Bolatto et al. 2013).

### 4.6. Physical parameters of clump C2

Clump C1, which is currently forming the protostar L1157-mm, shows supersonic turbulent motions in the C$^{18}$O lines. The dust temperature was found to be $\sim 15$ K. Previous studies have characterized C1 using dust continuum and line-mapping observations at different spatial and spectral resolutions (Gueth et al. 1997). In this section we determine the properties of C2 to characterize its evolutionary state. Clump C2 has a peak dust temperature ($T_d$) $\sim 12$ K and peak column density $\sim 9 \times 10^{21}$ cm$^{-2}$. As discussed earlier, there exists a blue-red asymmetry in $^{12}\text{CO}$ lines towards the center of C2, and C$^{18}$O peaks at the velocity of the self-absorption, indicating an inward motion (Figs. 9 and 10). The lack of high-velocity wings in the line profile suggests that the region is not affected by the outflow, although the southern edge of the blueshifted lobe of the outflow spatially coincides with the outer periphery of C2. The outflow is almost in the plane of sky with an inclination angle of 10$^\circ$ (Gueth et al. 1996). We quantified the outflow energetics with its mass and kinetic energy as $0.05 M_\odot$ and $1.2 \times 10^{43}$ ergs, respectively. The sources of uncertainty in estimating the outflow parameters depend on the velocity boundary between the high-velocity wings and the ambient velocity and the inclination angle with respect to the line of sight. The gravitationally binding energy of C2 is calculated as $0.53 \times 10^{43}$ ergs. Thus, the outflow has the potential to disturb the ambient gas and may affect C2 in the future. The motion of the gas molecules around C2 is very quiescent, with subsonic turbulence and high C$^{18}$O intensity. Figure 8c shows that the subsonic nonthermal motions are mostly associated with the region around C2. The properties of prestellar or starless cores in low-mass star-forming regions such as Taurus and Ophichus have been studied in detail (di Francesco et al. 2007; Gregersen & II 2000; Onishi et al. 2002; Motte et al. 1998), and the values found here for C2 are consistent with the typical properties of a starless core.

The measure of nonthermal line widths using molecular line diagnostics can be used to investigate whether the core is virially bound. We derived the virial mass of C2 using the averaged total velocity dispersion of the C$^{18}$O line. If the mass of the clump is less than the virial mass, the cloud is not gravitationally bound and may expand. We derived the virial mass using the formula (MacLaren et al. 1988).

$$M_{\text{vir}} = \frac{k \sigma^2 R}{G},$$

where $k$ depends on the density distribution, $G$ is the gravitational constant, and $R$ is the cloud radius. The total velocity...
displacement is given by the equation

$$
\sigma = \sqrt{\frac{kT_{\text{kin}}}{\mu m}} + \sigma_{\text{nt}}^2
$$

(11)

Assuming a Gaussian velocity distribution and density profile distribution as \( \rho \propto r^{-2} \), we can also express this equation in terms of solar mass as \( M_{\text{viral}} = 126 \Delta v^2 R \), where \( \Delta v \) is the FWHM velocity of the \( ^{18}C_2 \) lines in km s\(^{-1} \) along the line of sight, and \( R \) is the radius in parsec units. By approximating \( C_2 \) as an ellipse on the sky projection, the radius of the core was estimated as \( R = \sqrt{FWHM_x \times FWHM_y} \), where FWHM\(_x\) and FWHM\(_y\) are the FWHM diameters along the major and minor axis, respectively. The value of the average FWHM velocity of the gas was calculated to be 0.5 km s\(^{-1} \). We calculated the effective radius of \( C_2 \) as \(-0.1\) pc using the FWHM of the major axis \(-1.3\) and of the minor axis \(-0.7\). The virial mass of \( C_2 \) was estimated to be \(-3.1\) \( M_\odot \). The main contribution to the uncertainty in the calculation of the virial mass comes from the uncertainty in the distance estimate, which is \(-1\%\). The variation of 5\% in the value of virial mass is due to the distance uncertainty. We summed all the pixels whose column density values fell within the derived radius of clump \( C_2 \) in a moment-zero map of the \( ^{18}C_2 \) line. The total gas mass of \( C_2 \) is calculated to be \(-2.5 \pm 0.3\) \( M_\odot \). We found that clump \( C_2 \) is on the verge of being gravitationally bound because \( M_{\text{viral}} \sim M_{\text{gas}} \). The dust mass around clump \( C_2 \) is calculated to be \(-5\) \( M_\odot \) using the same region as in the calculation of the gas mass.

The \( ^{18}N_2H^+ \) line traces the dynamics of the dense central part of the core, and the \( ^{12}C_2 \) line traces the dynamics of the surrounding less dense material in the envelope. We studied the core-to-envelope motion around \( C_1 \) and \( C_2 \) by comparing the centroid velocity of the \( ^{18}N_2H^+ \) and \(^{12}C_2 \) lines and the velocity dispersion. The velocities of the different tracers match, as we also show in Fig. 8. The average difference in centroid velocities of \(^{12}C_2 \) and \( ^{18}N_2H^+ \) around clump \( C_2 \) is 0.03 \( \pm 0.02 \) km s\(^{-1} \) and around core \( C_1 \), it is 0.06 \( \pm 0.02 \) km s\(^{-1} \), which means that the velocities of the different tracers differ on average by less than one-fifth or one-third of the sound speed. This good match rules out any significant relative motions between different density regimes of the gas, and in particular, it rules out the possibility of any systematic drift between the dense cores (traced by \( ^{18}N_2H^+ \)) and the surrounding gas (traced by \(^{12}C_2 \)). This result agrees well with previous studies that probed the relative motion between the dense inner region and the envelope of the cores (Kirk et al. 2007; Walsh et al. 2004; Ayliffe et al. 2007). The line width obtained for the \( ^{12}C_2 \) line is found to be relatively broader (by one to two channels around core \( C_1 \)) than that of \( ^{18}N_2H^+ \) (1–0), as shown in Fig. 11. The difference in line width around core \( C_1 \) is within a channel spacing for the two tracers. The motions in \( C_2 \) are subsonic in the \(^{12}C_2 \) and \( ^{18}N_2H^+ \) lines compared to the motion of \( C_1 \). This line broadening is consistent with previous studies, where starless cores were expected to have less turbulent motions and protostellar cores show a broader line width (Kirk et al. 2007).

The \( ^{18}N_2H^+ \) and \(^{12}C_2 \) lines can be used to determine the extent of the chemical evolution of the dense cores. \( ^{18}N_2H^+ \) can only form in a significant amount after \(^{12}C_2 \) freezes out onto dust grains because both the molecules form by competing reactions (Caselli et al. 1999). \( ^{18}N_2H^+ \) is observed to be good tracer of gas at densities \(-10^5–10^6 \text{cm}^{-3} \), whereas \(^{12}C_2 \) is depleted at these densities (Tafalla et al. 2002). At later stages of the evolution, when the central protostar formation has taken place, the \( ^{18}N_2H^+ \) is destroyed by the rise in temperature, and CO molecules start to form. We used the integrated intensity of the \(^{18}N_2H^+ \) and \(^{12}C_2 \) lines to calculate the intensity ratio. If this ratio is higher than one, it implies that the core has not evolved to the extent that the carbon molecules could freeze out onto the surface of dust grains, and therefore the core is chemically young. We averaged the intensity values around the starless core \( C_2 \) where significant (\( \geq 3\)\(\sigma \)) emission of \( ^{18}N_2H^+ \) is obtained. The ratio is found to be greater than one, which implies that the core has not yet evolved chemically. Core \( C_1 \) shows a highly enhanced distribution of the \( ^{18}N_2H^+ \) line. This may be due to the significant depletion or photodissociation of \(^{12}C_2 \) molecules in the core. These molecules usually play a role for the destruction of \( ^{18}N_2H^+ \) (Caselli et al. 1999). \( ^{18}N_2H^+ \) in \( C_2 \) core is also enhanced, but not as much as \( C_1 \) core. This can also be explained by an overabundance of \(^{12}C_2 \) molecules compared to \( C_1 \) core.

4.7. Motion of the L1147/1158 and L1172/1174 complexes

A PanSTARRS z-band (\( \lambda_{\text{eff}} = 6868.5 \text{ Å} \)) image (Chambers et al. 2016) of the field containing L1157 (the contrast of the original image is adjusted to highlight the features) in the Galactic coordinate system is shown in Fig. 12. The shape of the southern boundary of the east-west segment is found to be sinuous. Odenwald & Rickard (1987) and Odenwald (1988) have catalogued a number of high-latitude cometary or filamentary objects gleaned from IRAS images and suggested that their morphologies might be a result of cloud-ISM interaction. A flow of velocity of \( V \) around an object of length \( L \) can be characterized using the Reynolds number \( Re = \rho LV/\mu \), where \( \rho \) is the ambient fluid density, and \( \mu \) is the fluid viscosity. While flows of extremely low (\(-10\)) and intermediate (\(-50\)) values of \( Re \) are expected to show a smooth laminar flow pattern and irregular structures and vortices, respectively, higher values of \( Re (\geq 100) \) are expected to produce a fully turbulent flow. Odenwald (1988) suggested that for a relatively low value of \( Re \) (\( \leq 10 \)), the mass lost by ablation through the motion of a cloud through ambient medium can form long sinuous filaments.

To calculate the space velocity of the L1147/1158 complex, which is required to estimate the value of \( Re \), we made use of the proper motion values of the YSOs associated with the region and the radial velocities of the clouds. Because the L1147/1158

![Fig. 11. Variation of the velocity dispersion measured in the \(^{18}C_2 \)O and \(^{12}N_2H^+ \) profiles. The filled circles are the points near \( C_1 \), and unfilled circles are the points around \( C_2 \).](image-url)
(l \sim 102.2^\circ, b \sim +15.3^\circ) and L1172/1174 (l \sim 104.03^\circ, b \sim +14.3^\circ) complexes are located close to each other (~2^\circ) in projection and share similar radial velocities (Myers et al. 1983; Yonekura et al. 1997), we also included the YSOs associated with L1172/1174 in our analysis. A total of 58 YSO candidates are identified so far in the vicinity of L1172/1174 (Kun et al. 2017). We found counterparts for 20 of them well within a search radius of 1\,\mu\text{as}\,\text{yr}^{-1}. As in the case of L1147/1158, we obtained their distances from the Gaia DR2 catalog and \(\mu_\alpha^*\) and \(\mu_\delta\) values from the Gaia Collaboration (2018) catalog. Again, we considered only sources whose parallax and proper motion values are greater than or equal to three times the median absolute deviation values of the distance and the proper motions.

Fig. 13. Proper motion values and distances of the 23 YSO candidates associated with the L1147/1158 and L1172/1174 complexes. The darker and lighter shaded ellipses are drawn using three and five times the median absolute deviation values of the distance and the proper motions, respectively.

The proper motions of the sources measured by the Gaia are in the equatorial system of coordinates. To understand the motion of objects in the Galaxy, we need to transform the proper motion values from the equatorial to the Galactic coordinate system.

\[
\begin{pmatrix}
\mu_\alpha^* \\
\mu_\delta
\end{pmatrix}
= \frac{1}{\cos b}
\begin{bmatrix}
C_1 & C_2 \\
-C_2 & C_1
\end{bmatrix}
\begin{pmatrix}
\mu_\alpha \\
\mu_\delta
\end{pmatrix},
\]

where the term \(b = \sqrt{C_1^2 + C_2^2}\) and the coefficients \(C_1\) and \(C_2\) are given as

\[
C_1 = \sin \delta_G \cos \delta - \cos \delta_G \sin \delta \cos (\alpha - \alpha_G)
\]

\[
C_2 = \cos \delta_G \sin (\alpha - \alpha_G).
\]

The equatorial coordinates (\(\alpha_G, \delta_G\)) of the north Galactic pole are taken to be 192\,\degree.85948 and 27\,\degree.12825, respectively (Poleski 2013). The proper motion of the YSO candidates in the Galactic coordinates are drawn in Fig. 14. The mean values of \(\mu_\alpha\) and \(\mu_\delta\) are found to be 3.499 and \(-6.815\) mas yr\(^{-1}\), respectively, and the corresponding proper motion position angle is found to be 153\,\degree. The arrows show the sense of the motion of the sources on the sky plane. If we assume that the cloud and the YSO candidates are expected to share similar kinematics as a result of being born inside the cloud, then the arrows should also represent the motion of the clouds on the sky plane. The reflection nebulosity around a number of these YSO candidates provides evidence that they are clearly associated with the cloud.

Based on our N\(_2\)H\(^+\) observations, the \(V_{\text{lsr}}\) velocity of L1157 is found to be \(+2.65\) km s\(^{-1}\). Yonekura et al. (1997) carried out
ties of these nine clouds is found to be directed to the north Galactic pole. The mean values of the L1147/1158 complex, and the dashed lines show the L1172/1174 complexes. The box in bold lines shows the L1147/1158 complex, and the number density of the ambient medium is estimated to be \( 0.17 \text{ cm}^{-3} \) along the Galactic plane and an exponential scale height of 125 pc (Odenwald 1988). Assuming that the cloud is in pressure equilibrium with the ambient medium, we estimated the temperature of the ambient medium to be \( 10^5 \text{ K} \) using the average values of the number density and temperature of the cloud calculated from the dust emission. We used \( v = 7 \text{ km s}^{-1} \) and \( L = 1 \text{ pc} \) in the calculation. The low value of \( R_\odot \) for L1157 and found it to be \( R_\odot \). The main contribution to the uncertainty in the calculation of \( R_\odot \) comes from the large uncertainty in the estimation of the density and the viscosity of the ambient medium. We ignored the effects of the magnetic field in our calculation because the offset between the projected magnetic field and the direction of the cloud motion is \( \sim 30^\circ \). Studies with various values of offsets between the orientation of the magnetic field lines and the direction of the cloud motion have shown that only for large enough offsets do magnetic fields play a significant role in the dynamical evolution of the cloud (Mac Low et al. 1994; Jones et al. 1996; Miniati et al. 1999).

The number density of the ambient medium is estimated to be 0.09 cm\(^{-3}\) by adopting a density of 0.17 cm\(^{-3}\) along the Galactic plane and an exponential scale height of 125 pc (Odenwald 1988). Assuming that the cloud is in pressure equilibrium with the ambient medium, we estimated the temperature of the ambient medium to be \( 10^5 \text{ K} \) using the average values of the number density and temperature of the cloud calculated from the dust emission. We used \( v = 7 \text{ km s}^{-1} \) and \( L = 1 \text{ pc} \) in the calculation. The low value of \( R_\odot \) is consistent with the smooth morphology of the cloud structure, as depicted in Fig. 12.

Several shell structures, such as the Cepheus flare shell (CFS), which is an old supernova remnant, and Loop III, which is a giant radio continuum feature (Kirk et al. 2009), are taken as signature of multiple supernova explosions that might have occurred toward the region. The complexes L1147/1158 and L1172/1174 are regions where the projected magnetic fields show a rotation in the position angles toward the Galactic center, opposite to the Galactic rotation, and toward the Galactic north pole, respectively. We computed the position of the complexes (X, Y, Z) as \( (\sim 80, 319, 85) \text{ pc} \). The resulting velocity of the complexes as a whole is found to be \( \sim 7 \text{ km s}^{-1} \).

The Planck magnetic field vectors from a region containing the two complexes are also shown in Fig. 14. Although there are regions where the projected magnetic fields show a rotation in the position angles toward the Galactic center, as a whole, the projected field orientation toward the region is found to be almost parallel to the Galactic plane. The projected field direction obtained from the median value of the Galactic polarization position angles is \( \sim 5^\circ \) from the north. This implies that the projected motion of the complexes creates an angle of \( 32^\circ \) with respect to the projected magnetic field orientation. Following the procedure from Odenwald & Rickard (1987) and Odenwald (1988), we made a rough estimate of the value of \( R_\odot \) for L1157 and found it to be \( R_\odot \). The main contribution to the uncertainty in the calculation of \( R_\odot \) comes from the large uncertainty in the estimation of the density and the viscosity of the ambient medium. We ignored the effects of the magnetic field in our calculation because the offset between the projected magnetic field and the direction of the cloud motion is \( \sim 30^\circ \). Studies with various values of offsets between the orientation of the magnetic field lines and the direction of the cloud motion have shown that only for large enough offsets do magnetic fields play a significant role in the dynamical evolution of the cloud (Mac Low et al. 1994; Jones et al. 1996; Miniati et al. 1999).

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L1172/1174 are located outside the CFS but at the periphery of Loop III (Kirk et al. 2009). It is possible that these supernova events may have transferred the material toward the high-latitude regions and that the material now moves downward toward the Galactic plane. Harjunpaa et al. (1991) studied the entire L1147/1158 complex and noted that the southeastern boundary of the complex shows a remarkably sharp edge parallel to the Galactic plane. Alternatively, the sharp boundary and the velocity gradient might be due to the bulk motion of the cloud material. The star formation in the clouds associated with the complexes might be a result of their interaction with the ambient medium as they travel.

5. Conclusions

We presented results of a study conducted on the molecular cloud L1157, which is part of the cloud complex L1147/1158. Currently, a Class 0 protostar, L1157-mm, with a spectacular bipolar outflow is being formed. The extreme youth of the protostar implies that the initial conditions that guided the cloud to form a star may still be preserved. We made R-band polarimetry of the cloud to trace the magnetic field geometry of the cloud. We also made observations in the $^{12}$CO, C$^{18}$O, and N$_2$H$^+$ ($J = 1-0$) lines to investigate the kinematics of the material associated with the cloud. The main results are summarized below.

1. We estimated the distance to the L1147/1158 complex using the YSOs associated with the cloud complex. The distances of the YSOs were estimated based on the parallax measurements and the proper motion values obtained from the Gaia DR2 database. The estimated distance is $340 \pm 3$ pc.

2. We obtained polarization measurements of 62 stars projected toward the direction of L1157 (within a region of $0.3^\circ \times 0.3^\circ$ field). Based on the plot of the degree of polarization versus distance for the stars observed by us and those from the Heiles (2000) catalog, we present additional evidence of the cloud at a distance of $\sim 340$ pc.

3. Using the Filfinder algorithm on the dust column density map of L1157 obtained from the Herschel data, we traced a filament that is found to be $\sim 1.2$ pc in length and oriented at a PA of $79^\circ$ (east-west segment). Near to the protostar, the filament changes its orientation and becomes almost perpendicular (north-south segment). Using the Radfil algorithm, we estimated the average filament width to be $\sim 0.09$ pc, and the radial distribution of the material was fit with a Plummer-like density profile with a power-law index of $p = 3$. Using the Clumpfind algorithm, we identified two cores (C1 and C2) that are found to be located in the filament. In one of these cores, L1157-mm is currently embedded.

4. The ICMF traced by our R-band polarization measurements of the stellar background to the cloud is found to be well ordered at a $\sim 0.2-2$ pc scale. The geometry of the ICMF inferred from the Planck 353 GHz data was found to agree well with our R-band polarization results. The strength of the magnetic field calculated based on our data is found to be $\sim 50 \mu G$. The ICMF is oriented at a PA of $127^\circ \pm 12^\circ$.

5. Based on the relative orientations between the ISMF, CMF, filament, outflow, and the hourglass morphology of the magnetic field at the core scale with its symmetry axis orthogonal to the major axis of the flattened pseudo-disk, we suggest that the magnetic field has played an important role in the evolution of L1157 to becoming a star-forming core.

6. We made $^{12}$CO, C$^{18}$O, and N$_2$H$^+$ line observations of the entire region covering the L1157 cloud. C$^{18}$O is detected at points throughout the $\sim 1.2$ pc long filament and is found to correlate well with the dust emission. A blue-red asymmetry is observed in $^{12}$CO toward both C1 and C2, with C$^{18}$O peaking at the systematic velocity of the cloud. This signifies...
infall motion of the material. We found no significant change in the $V_{lsr}$ velocity along the filament, except at the location where the north-south segment changes its direction toward the east-west segment of the filament. The $N_2H^+$ ($J = 1-0$) line also shows a systematic change in the velocity across C1 that is suggestive of a bulk motion in the gas.

7. The east-west segment of the filament presents a sinuous structure. It is believed that the sinuous features seen in clouds occur due to cloud-ISM interaction. The dynamical state of such interactions depends on the Reynolds number, which is found to be $\sim 3$ in L1157. For such a low value ($\lesssim 10$) of Reynolds number, the cloud motion through the ambient medium can cause mass loss by ablation and can form long sinuous filaments.

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