Tomography of the Ophiuchus Molecular Cloud with Velocity Features in C2H N = 1–0 Spectra: A Pilot Study of Coherent Sub-structures postprint

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Abstract

The C2H N = 1–0 transition was used to investigate the possible line of sight sub-structures from the dense and optically thick in 13CO J = 1–0 regions in the Ophiuchus star-forming molecular cloud. With a 0.2 K or lower noise, multi-peak spectra were obtained and then used for identifying sub-structures. There are clues, e.g., the core velocity dispersion remains unchanged with the increasing scale that this cloud has a mild thickness in the line of sight direction and a large amount of overlapping CO cores, as expected, at least two coherent layers have been found. The integrated intensity maps of these two layers are different in shape and morphology. Inferred from the point velocity dispersion, one sub-structure with a thickness of 1 pc was found, while other substructures were more likely to be fragments.

Full Text

Preamble

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Tomography of the Ophiuchus Molecular Cloud with Velocity Features in C2H N = 1–0 Spectra: A Pilot Study of Coherent Substructures

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Abstract

We used the C2H N = 1–0 transition to investigate possible line-of-sight substructures within dense, optically thick 13CO J = 1–0 regions of the Ophiuchus star-forming molecular cloud. With a noise level of 0.2 K or lower, we obtained multi-peak spectra that enabled the identification of substructures. The core velocity dispersion remains unchanged with increasing scale, suggesting that the cloud has moderate line-of-sight thickness and contains numerous overlapping CO cores. As expected, we identified at least two coherent layers with distinct shapes and morphologies in their integrated intensity maps. Analysis of the point velocity dispersion indicates that one substructure has a thickness of approximately 1 pc, while other substructures appear to be fragments.

Key words: ISM: structure — ISM: molecules — ISM: clouds

1. Introduction

The Ophiuchus molecular cloud (also known as the Ophiuchi molecular cloud) is a low-to-intermediate mass star-forming region located at a distance of 137.3 pc (Ortiz-León et al. 2017). This cloud comprises several Lynds sources, including L1688, L1689, and L1709. Based on extinction measurements, the dense regions in Ophiuchus exhibit column densities of 1×10^{20} cm^{-2} or higher (Abrahams et al. 2017). Star formation in the Ophiuchus molecular cloud has been triggered multiple times (Wilking et al. 2008, and references therein), with the filamentary structures extending from L1688 and L1689 likely caused by triggering events such as shocks from a nearby supernova or OB star association (Wilking et al. 2008).

Previous studies of Core Velocity Dispersion (CVD; Qian et al. 2012, 2018; Qian 2021) have estimated the line-of-sight thickness of the Ophiuchus molecular cloud to be approximately 3.5 pc (Qian et al. 2015). In addition to this moderate line-of-sight thickness, overlapping 13CO or dust continuum cores have been identified in dense regions such as L1688 and L1689 (Johnstone et al. 2000). Furthermore, 13CO J = 1–0 lines in most of the dense regions show double peaks, indicating multi-layered structures. Velocity coherency in spectral maps has been used to search for cores (Qian et al. 2012) and filaments (Panopoulou et al. 2014) in molecular clouds through simultaneous fitting in velocity space within position-position-velocity (p-p-v) datacubes. To search for larger-scale features such as sheets, we attempted to fit the spectrum at every point to decompose coherent features with different velocities and identify possible substructures.

Archival data for Ophiuchus include spectral line mapping (e.g., CO lines from the COMPLETE survey, Ridge et al. 2006) and dust continuum mapping (Johnstone et al. 2000). However, to separate these substructures, the data must have sufficient frequency resolution (smaller than the line width, e.g., 1 km s^{-1}), adequate spatial resolution to identify cores (e.g., 1 or better), and relatively high sensitivity (noise level of 0.2 K km s^{-1} or lower). Additionally, the transition should probe a wide range of volume densities (e.g., 10^3–10^5 cm^{-3} for optically thin emission) and evolutionary stages to cover the star-forming history of the molecular cloud (from zero to 10 Myr). Therefore, we selected archival C2H N = 1–0 data for Ophiuchus from the 13.7 m millimeter radio telescope at Delingha Observatory, Purple Mountain Observatory, with all observations conducted by the authors of this paper.

C2H gas serves as a chemical evolution tracer for carbon chemistry (Pan et al. 2017). In early stages, ultraviolet (UV) photons dissociate carbon monoxide, allowing carbon to form other molecules and maintaining relatively high C2H abundance in the molecular cloud. As the cloud evolves, collapse increases extinction, preventing external UV photons from penetrating dense regions. Without continued carbon supply from CO dissociation, C2H abundances decrease in dense, high-extinction regions. The C2H N = 1–0 transition has six hyperfine structures that can be fitted to determine opacity, with separations of several kilometers per second in the spectra, making it easy to identify multi-peak features. Consequently, C2H in low-to-medium density regions serves as an ideal tracer for substructures.

This paper is organized as follows: Section 2 presents the basic information on the data and data reduction procedures, Section 3 contains the results and discussions, and Section 4 presents the conclusions.

2.1. Observation

The observations were performed with the 13.7 m millimeter radio telescope at Delingha, Qinghai Station of Purple Mountain Observatory (PMODLH), Chinese Academy of Sciences. The observations were carried out in the years 2012, 2013, and 2017. The observation regions were extended from only L1688 and L1689 to the whole Ophiuchus region that has 13CO emission. Details of the observations, including the source names used, the observing dates, the mapping areas, the center coordinates, the sampling time, and scan slew rate can be found in Table 1 .

The 3 × 3 multibeam array covering 85–115 GHz was used for mapping the Ophiuchus region. Both the upper and lower sidebands had 16384 channels across a 1000 MHz bandwidth, corresponding to approximately 0.2 km s^{-1} frequency resolution. The N2H^+ J = 1–0 (upper sideband) and C2H N = 1–0 (lower sideband) transitions were observed simultaneously. The observing frequency settings for all observations were identical. In this study, we used only the C2H N = 1–0 data.

Within the declination range of −24° to −25°, the elevation of the observatory was lower than 30°. Observations were performed when the mapping areas were close to maximum elevation. Depending on weather conditions, system temperatures from different beams of the array varied around 170 K but were always lower than 200 K. Detailed information on system temperatures and antenna temperature calibration can be found in our previous study (Pan et al. 2017). Results including mapping areas, N2H^+ J = 1–0, and C2H N = 1–0 integrated intensity maps will be presented in our next paper (D. Y. Jiang et al. 2025, in preparation).

2.2. Data Reduction

As only C2H data were used for this study, all data reduction procedures described below apply only to C2H N = 1–0 spectra. Further details on N2H^+ data processing, column density determination, and opacity fitting will be presented in our next paper (D. Y. Jiang et al. 2025, in preparation).

All original spectra from each observation were gridded on the servers at Delingha Station, using the noise level (σ) as the weighting factor. Cell sizes were set to 30 . After downloading all data from the observations mentioned in Section 2.1, we used the Gildas/CLASS software package for further processing. All spectra were combined to create a three-dimensional data cube (R.A., decl., and velocity). The 'nogrid' option was used for the Gildas/CLASS XY_{MAP} routine to prevent re-gridding of the spectra. To simplify the analysis, the channel width was slightly smoothed to 0.22 km s^{-1}. The center frequency was set to 87317.05 MHz, corresponding to the rest frequency of the C2H N = 1–0 transition. The velocity range for each spectrum was −20 to 20 km s^{-1}, including only one hyperfine structure of the C2H N = 1–0 transition. The resulting data cube contains 93,205 spectra, covering R.A. from 16h25m58s to 16h27m31s and declination from −25°56 31 to −21°25 31 .

Our study aims to confirm the existence of substructures. Therefore, we used the strongest hyperfine structure of C2H N = 1–0 (87317.05 MHz). If only one molecular structure exists along the line of sight, the spectra should show a single peak, as illustrated in Figure 1 [Figure 1: see original paper] (upper panel). If spectra exhibit multi-peak features (e.g., Figure 1, middle and lower panels), at least two molecular cloud components must be present along the line of sight.

Integrated intensity measurements are affected by noise. For spectra with very low integrated intensity, apparent multi-peak features may arise from noise rather than real structures. Therefore, we used 0.5 K km s^{-1} as the threshold, selecting 17,914 spectra from the total of 93,205. Gaussian fitting was then performed to obtain parameters for each component in these spectra.

We manually fitted peaks in all 17,914 spectra. First, we determined the number of peaks in each spectrum by visual inspection. Second, we applied the Gaussian fitting procedure from CLASS. Third, if obvious peaks remained in the residual (e.g., above 3σ from the peak-to-peak noise level), the Gaussian fitting iterated until a flat, noise-like spectrum was obtained. The fitted centroid velocity, line width, and integrated intensity of each Gaussian peak were saved with the spectrum coordinates for substructure identification.

3.1. Detections of the C2H N = 1–0 Transition

Previous studies reported no multi-peak features for C2H N = 1–0 lines at noise levels of 0.2–0.5 K (Pan et al. 2017). After observing the L1688 and L1689 regions for an extended period, we reduced the noise level to 0.2 K or lower. Some spectra now show more than one peak. For example, the spectrum in the lower panel of Figure 1 has a peak intensity of 0.7 K and clearly consists of two components with peak intensities of 0.6 and 0.8 K. At a noise level of 0.5 K, these would merge into a single peak. Thus, the Ophiuchus cloud contains different structures and is more complex than simple "fibers."

3.2. Sub-structure Identification

We identified possible substructures by searching for coherent velocity components. Currently, no automated code exists for this operation, so we performed the search manually. If a spectrum showed more than one peak, we examined up to eight surrounding spectra. Components with similar centroid velocities and line widths were considered to originate from the same substructure. Iterating this process through all fitting results, we successfully identified at least two layers of substructures.

We constructed integrated intensity maps from the two Gaussian components: one corresponding to higher velocities (3–6 km s^{-1}, upper panel of Figure 2 [Figure 2: see original paper]) and one to lower velocities (2–5 km s^{-1}, lower panel of Figure 2). The histograms of centroid velocities for the two components are displayed accordingly in Figure 2.

Substructures appear to be present only in L1688, as L1689 is visible in only one panel of Figure 2. Despite this limitation, both intensity maps show extended structures and compact core-like structures.

3.3. Point Velocity Dispersion and Comparison with Previous Core Velocity Dispersion Results

The structure of the Ophiuchus molecular cloud has previously been studied using core velocity dispersion (CVD) in 13CO (Qian et al. 2012). CVD calculates the relationship between the projected distance of two cores and their velocity difference. Theoretically, this relationship follows a formula similar to Larson's Law (Larson 1981), where the index γ indicates turbulence properties in the molecular cloud. The value γ 0.5 is currently accepted (Solomon et al. 1987). If a cloud has relatively large thickness, the projected distance L deviates from the true distance, and CVD becomes independent of L, making the power index approach zero (Qian et al. 2015). It is found that the Ophiuchus molecular cloud has moderate thickness, indicating possible complex structures (Qian et al. 2015). However, because 13CO spectra are optically thick, CVD cannot identify all cores or multi-layered structures.

To improve upon this, we calculated the Point (or Pixel) Velocity Dispersion (PVD) for the two C2H gas components using a technique similar to CVD. Rather than fitting Gaussian components to identify cores, we calculated the velocity difference δv and distance L for each pair of points. Point pairs in the same distance bins were grouped to calculate the velocity dispersion, where angle brackets ⟨...⟩ denote averaging. We used the distance of 137.3 pc (Ortiz-León et al. 2017) to convert angular separations to physical distances.

The PVD plots for the two C2H gas components are shown in Figure 3 [Figure 3: see original paper]. The PVD plot for the higher-velocity C2H gas components (upper panel) shows a break at 1 pc, while no clear break appears in the lower-velocity component plot (lower panel). These results indicate that the higher-velocity C2H gas components have a line-of-sight thickness of 1 pc. The thickness of the other component cannot be determined from the PVD plot. These different thicknesses suggest that the main part of Ophiuchus consists of at least two substructures: one similar to that shown in the lower panel of Figure 2, and others that are more like small fragments separated from the main Ophiuchus molecular cloud.

4. Conclusion

The conclusions of this work are as follows:

1. We performed C2H N = 1–0 observations of the entire Ophiuchus molecular cloud region with 13CO J = 1–0 emission. L1709 is the only new region with detectable C2H N = 1–0 emission.
2. Multi-peak features detected in C2H N = 1–0 spectra reveal at least two groups of substructures in the Ophiuchus molecular cloud.
3. L1688 is the only region with prominent substructures. Inferred from the point velocity dispersion, the main part of L1688 has a thickness of 1 pc.

The other substructures are more likely to be fragments.

As star-forming activities in the Ophiuchus molecular cloud were triggered several times, future work will focus on the relationships between these substructures and star formation triggers.

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Author Contributions

Lei Qian analyzed the results, discovered the substructures, and provided the study results and discussions. Zhichen Pan suggested this study and provided the data. Dongyue Jiang controlled the data quality and filtered the spectra for fitting. Zichen Huang worked on the spectral fittings and provided the fitting results.

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Note: Figure translations are in progress. See original paper for figures.