Morphology and Kinematics of Filaments in the Serpens and Perseus Molecular Clouds

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Abstract

We present H13CO+ (J = 1–0) and HNC (J = 1–0) maps of regions in Serpens South, Serpens Main, and NGC 1333 containing filaments. We also observe the Serpens regions using H13CN (J = 1–0). These dense gas tracer molecular line observations carried out with CARMA have an angular resolution of \( \sim 7'' \), a spectral resolution of \( \sim 0.16 \text{ km s}^{-1} \), and a sensitivity of 50–100 mJy beam \(^{-1} \). Although the large-scale structure compares well with the Herschel dust continuum maps, we resolve finer structure within the filaments identified by Herschel. The H13CO+ emission distribution agrees with the existing CARMA N2H+ (J = 1–0) maps, so they trace the same morphology and kinematics of the filaments. The H13CO+ maps additionally reveal that many regions have multiple structures partially overlapping in the line of sight. In two regions, the velocity differences are as high as 1.4 km s\(^{-1}\). We identify eight filamentary structures having typical widths of 0.03–0.08 pc in these tracers. At least 50% of the filamentary structures have distinct velocity gradients perpendicular to their major axis, with average values in the range of 4–10 km s\(^{-1}\) pc\(^{-1}\). These findings are in support of the theoretical models of filament formation by 2D inflow in the shock layer created by colliding turbulent cells. We also find evidence of velocity gradients along the length of two filamentary structures; the gradients suggest that these filaments are inflowing toward the cloud core.

Key words: ISM: clouds – ISM: kinematics and dynamics – ISM: molecules – ISM: structure – stars: formation

1. Introduction

The presence of filaments in molecular clouds has been well known for many decades (Schneider & Elmegreen 1979; Bally et al. 1987; Chini et al. 1997; Goldsmith et al. 2008). Far-infrared continuum images taken by Herschel demonstrated the prevalence of filamentary structure over a wide range of scales and trace filaments into areas of active star formation (André et al. 2010; Molinari et al. 2010). There is growing observational evidence that filaments play a fundamental role in the star formation process by setting the initial conditions for core formation and fragmentation and defining the morphology of the material available for accretion (Hacar & Tafalla 2011; Furuya et al. 2014; Beuther et al. 2015; Friesen et al. 2016; Henshaw et al. 2016; Teixeira et al. 2016). Some cores within filaments evolve to harbor YSOs, the properties of which depend on the filament physical characteristics (Myers 2009; Kritsuk et al. 2013).

Filaments are also commonly present in numerical simulations of turbulent molecular gas (Klessen et al. 2000; Boldyrev et al. 2002; Banerjee et al. 2006; Heitsch et al. 2009; Gong & Ostriker 2011; Peters et al. 2012; Gómez & Vázquez-Semadeni 2014). These filaments form at the interface of converging flows in regions of supersonic turbulence. However, the impacts of self-gravity (Moeckel & Burkert 2015), turbulence (Smith et al. 2014), and magnetic fields (Kirk et al. 2015) on filament formation and structure are still under study. Filament morphologies, their widths, their densities, and their orientations with each other and with respect to local magnetic fields can provide important insights into the filament formation process. For example, the systematics of filament width could be related to the sonic scale of turbulence (Federrath 2016), ion-neutral friction (Hennebelle & André 2013), or the presence of magnetic fields (Seifried & Walch 2015). Maps using molecular tracers with high angular resolution and/or high spectral resolution resolved some filamentary structures further to multiple filaments (Hacar et al. 2013; Lee et al. 2014), which are also found in simulations (Kirk et al. 2015; Moeckel & Burkert 2015; Smith et al. 2016; Clarke et al. 2017).

The kinematics of filaments (Schneider et al. 2010; Jiménez-Serra et al. 2014) can be useful indicators of the evolutionary processes involved in star formation. For example, velocity gradients along filaments have been postulated as mass infalls toward the clumps (Kirk et al. 2013), as projections of large-scale turbulence (Fernández-López et al. 2014), or as convergence of multiple flows (Csengeri et al. 2011; Henshaw et al. 2013). On the other hand, a velocity gradient perpendicular to the major axis has been postulated as effects of filament rotation (Olmi & Testi 2002), or infall due to self-gravity of gas compressed into a planar structure by supersonic turbulence (Gong & Ostriker 2011; Smith et al. 2016). Supersonic velocity dispersions are expected in the case of gravitationally accelerated infalling material that enters the filaments through shocks at the boundaries (Heitsch et al. 2009).

This paper presents high angular resolution maps of dense gas filaments in three active star formation regions, Serpens Main, Serpens South, and NGC 1333, to study the detailed morphology and kinematics of five filaments. This study derives from the CARMA Large Area Star Formation Survey (CLASSy), a CARMA key project that imaged 800 square arcminutes of Perseus and Serpens Molecular Clouds using the N2H+, HCN, and HCO+ J = 1–0 lines (Fernández-López et al. 2014; Lee et al. 2014; Storm et al. 2014). These clouds host a large number of young stars and protostars associated with hub-filament-type gas structures ( Gutermuth et al. 2008a, 2008b) and are hence well suited for studying the connection between filaments and star formation. N2H+ emission, which is a cold, dense gas tracer (Tafalla et al. 2002), was found to closely follow the far-infrared filamentary structure in high
column density regions (Fernández-López et al. 2014; Lee et al. 2014; Storm et al. 2014). Figure 1 shows the \(\text{N}_2\text{H}^+\) emission overlaid on the \textit{Herschel} dust continuum emission at 250 μm. The \(\text{N}_2\text{H}^+\) emission also revealed distinctive velocity gradients in a number of filaments. The HCN and HCO\(^+\) emissions, on the other hand, were found to be poor tracers of filaments. Storm et al. (2014) proposed that these lines were optically thick and, in the case of HCO\(^+\), affected by higher fractional abundances in lower-density gas that create an overlying absorption region.

To investigate whether the kinematics of filamentary structures are accurately traced by the CLASSy \(\text{N}_2\text{H}^+\) observations, we selected five filaments from the CLASSy regions to be observed using optically thin dense gas tracers \(\text{H}^{13}\text{CO}^+\) and \(\text{H}^{13}\text{CN}\). The mapped regions are marked in Figure 1 by the white circles. These molecules do not have the same chemistry as \(\text{N}_2\text{H}^+\); hence, they serve as a test of whether the observed kinematics is a bulk property of the material or if it arises from chemical or excitation effects. We refer to the observations presented in this paper as CLASSy-II observations.

The layout of the paper is as follows. In Section 2, we discuss how the observations were carried out, followed by the data calibration and reduction procedure. We present the maps for the various tracers for all the regions in Section 3. Section 4 deals with analyzing the individual regions and characterizing them. In Section 5, we report the trends in the morphology and kinematics of these observed regions. We further discuss some of these results in the context of the major questions in filament formation and their relation to star formation. We summarize our main results in Section 6.

2. Observations

The observations were made using the full CARMA array of 23 antennas in D and E configurations, providing an angular resolution of 7″. In CARMA 23-element mode, the correlator has four bands. In addition to the \(^{13}\text{C}\) isotopologues of HCO\(^+\) and HCN, HNC was also available in the correlator setting as a third tracer. In the case of NGC 1333, \(\text{N}_3\text{H}^+\) was observed instead of \(\text{H}^{13}\text{CN}\). The fourth band was used to observe the continuum at 90 GHz over a bandwidth of 500 MHz. The spectral line bands were 7.7 MHz wide with 159 channels, providing a resolution of \(\sim 0.16\) km s\(^{-1}\). The summary of the observations is given in Table 1, while the properties of the molecular tracer transitions are given in Table 2. The

![Figure 1. Herschel 250 μm maps (units: Jy beam\(^{-1}\) km s\(^{-1}\)) overlaid with \(\text{N}_2\text{H}^+\) integrated intensity contours (green) from CLASSy observations of the Serpens South, Serpens Main, and NGC 1333 molecular clouds. The contours are at (3, 6) × \(\sigma\), where \(\sigma = 0.25, 0.7,\) and 0.4 Jy beam\(^{-1}\) km s\(^{-1}\), respectively, for the three regions. The circles mark the CLASSy mosaic pointing centers and indicate the regions observed. The regions correspond to filaments that we name based on their locations with respect to the parent cloud cores. The Herschel beam is 18″ in diameter (shown in the lower right corner of each image).](image-url)
observations were carried out for a total of 308 hr over 61 tracks between 2013 August and 2015 February.

Of the three molecular tracers, H13CO+ J = 1–0 has the simplest spectrum: a single line with no hyperfine components. H13CN J = 1–0 has three isolated hyperfine components. HNC J = 1–0 (Bechtel et al. 2006) has hyperfine components within a range of 200 kHz (0.66 km s⁻¹), which are barely resolved by our correlator channel width of 49 kHz; the primary effect is to modestly increase the observed line width. For comparison, N2H⁺ J = 1–0 has seven hyperfine components, of which three F₁ = 1–1 lines are within a range of 600 kHz, three and F₁ = 2–1 lines within 500 kHz, and one is an isolated F₁ = 0–1 line. Although all four molecules are dense gas tracers, H13CN has the highest critical density of ~10⁶ cm⁻³, while the other transitions have critical densities in the range of 200 kHz.

The phase calibrators were MWC 349, Mars, Mercury, and Uranus, as available during observations. The phase calibrators were 3C 84 and 3C 111 for NGC 1333 and 1743–048 for all Serpens regions. Although a bandpass calibrator was observed in all observation sessions, in many cases the phase calibrators were also used for bandpass calibration.

The MIRIAD package (Multichannel Image Reconstruction, Image Analysis and Display; Sault et al. 1995) was used to process the visibility data. The autocorrelation data from the 10 m antennas were used to make single-dish images. After iterative flagging and calibration of the visibilities, the single-dish maps were used with the interferometric visibility data to generate the data cubes using the MIRIAD Maximum Entropy Method program mosmonem. The combined deconvolution using the single-dish images helps in recovering the large-scale structure filtered out by the interferometer. The spectral channel rms noise is in the range of 50–125 mJy beam⁻¹, while the continuum rms noise is 0.4–1.0 mJy beam⁻¹ for the various fields.

3. Results

We generated integrated intensity (zeroth-moment) and velocity (first-moment) maps from the position–velocity data cubes using MIRIAD. We used only the channels near the line centers containing the signal and clipped the data at 2σ, based on the rms noise of each line map. For the first moment maps of N₂H⁺ and H¹³CN, line fitting including the contribution of all the hyperfine components was carried out to determine the velocity centroid.

We display the moment maps for H¹³CO⁺ and HNC and compare them with the CLASSy N₂H⁺ maps in Figures 2–6. The H¹³CN maps are weak, having a signal-to-noise ratio (S/N) of less than 4 along the filaments, which is not sufficient to do kinematic analysis. We present the H¹³CN integrated intensity map only for the Serpens South—NW region (Figure 7, left panel).

We find that the N₂H⁺ emission corroborates well with the H¹³CO⁺ emission, for both the integrated intensity and velocity maps. Although the N₂H⁺ emission intensity is more than five times brighter than the H¹³CO⁺ emission, the rms noise in the N₂H⁺ maps is also greater. So depending on the S/N of the N₂H⁺ maps in comparison to the H¹³CO⁺ maps, in some cases we have more extended emission in N₂H⁺ and vice versa. For example, in the Serpens South regions the filaments are traced much more extensively in N₂H⁺, while in the Serpens Main region we detect more structure and trace the known structures over larger areas in H¹³CO⁺.

The HNC emission traces most of the structures seen in N₂H⁺ and H¹³CO⁺, but the relative emission varies in different regions of the maps. HNC emission also has greater S/N than the H¹³CO⁺ maps by a factor of 2–4. In the Serpens South—NW region (Figure 2) it traces the NW part of the filament more than the central part, while in the Serpens Main—cloud center and E filament (Figure 4) the HNC emission is more extensive. In the NGC 1333—SE region (Figure 6), HNC traces the west side of the filament more than the east side by a factor of two, although in both H¹³CO⁺ and N₂H⁺ the relative emissions of the two sides are comparable.

The HNC velocity maps are noticeably different from the corresponding H¹³CO⁺ and N₂H⁺ maps for most of the regions. This is because its spectrum shows absorption dips at many locations along the filaments. This results in two peaks on either side of the line center in H¹³CO⁺ and H¹³CN emission; the relative strengths of the two HNC peaks depend on the velocity of the absorbing material in the line of sight (see Figure 7, right panel). Since HNC is a main isotopic species with higher abundance, it is not surprising that it shows absorption in the J = 1–0 transition as was previously found for HCN and HCO⁺ (Lee et al. 2014; Storm et al. 2014). However, there are some regions, especially near the Serpens Main cloud core, where the HNC spectrum does not show absorption features. In these cases, there is a greater match in the moment maps between the different tracers. The variations in the HNC spectra are further discussed in Section 5.1.4.

4. Analysis

By themselves, the integrated intensity and velocity maps are insufficient to understand the finer structure in many of the studied regions. The H¹³CO⁺ (J = 1–0) channel maps are best suited for analysis especially in fields containing multiple substructures in close position or velocity proximity. This
species is optically thin and has an isolated spectral line (corresponding to the \( J = 1 \rightarrow 0 \) transition), while at the same time it has sufficient \( S/N \) to detect the filaments. The complex hyperfine structures (in \( N_2H^+ \) and HNC) or absorption features (in HNC) of multiple substructures can overlap, leading to degeneracy and challenges in disentangling the contributions of the separate components. However, these species have greater abundance than \( H^{13}CO^+ \), and hence they can easily map extensive areas.

To disentangle the structures, we compare individual channel maps in \( H^{13}CO^+ \) and use position–velocity diagrams to check for emission continuity. In this section, we present \( H^{13}CO^+ \) contour maps, averaged over three to four contiguous channels. These contours are overlaid on Herschel column density maps obtained from the Gould Belt Survey Archive (Pezzuto et al. 2012; Könyves et al. 2015) to compare the individual structures with the dust emission. We also use the isolated hyperfine component of \( N_2H^+ \) in regions having \( S/N > 2 \) to confirm our identification of the velocity-coherent structures. We use other indicators, such as variations in HNC absorption features and relative abundances, to further support the identifications of structures in complex regions.

Following the identification of velocity-coherent substructures, we determine their extent using contours at half the peak emission for each channel. These contours over multiple channels are stacked, and we establish the lengths of the major and minor axes for the combined area within these stacked contours. The minor axis gives a representative width value, while the major axis gives a minimum length estimate (within the observed area). It is to be noted that this method only gives a rough estimate of the extent of the individual structures. We use a more formal method for determining the widths by Gaussian curve fitting of cuts in the integrated intensity maps (discussed in details in Section 5.1.2), but it is applicable only to filaments not having overlapping substructures.

Only the structures having aspect ratios greater than 4 (as in Lee et al. 2014) and at least 0.25 pc long are considered in our velocity analyses. We identify eight such “filamentary structures” over the five regions by this method (see Table 3). All of them are aligned with the filaments identified in Herschel maps, although some are not resolved into multiple components in the low-resolution dust maps. Serpens South NW is the least complex region, having only one velocity-coherent structure along the Herschel filament. The Serpens

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**Figure 2.** Integrated intensity maps (top row) and velocity centroid maps (bottom row) for the Serpens South—NW filament in the \( N_2H^+, H^{13}CO^+, \) and HNC \( J = 1\rightarrow 0 \) lines. The integrated intensity map color bar values are given for \( H^{13}CO^+ \) in Jy beam\(^{-1}\) km s\(^{-1}\). The corresponding values for \( N_2H^+ \) and HNC maps are, respectively, 6.0 and 3.0 times the value for the \( H^{13}CO^+ \) maps. The velocity maps are all in units of km s\(^{-1}\). The \( N_2H^+ \) integrated intensity contours at \((2, 4, 6) \times \sigma \) (\( \sigma = 0.25 \) Jy beam\(^{-1}\) km s\(^{-1}\)) are overlaid on all the images. The synthesized beam is shown at the lower right of each image.
South—E region, the Serpens Main—S region, and the NGC 1333—SE region each have two partially overlapping velocity-coherent structures. Other authors have noted similar structures in observations and simulations and referred to them as subfilaments (Smith et al. 2014) or as fibers (Hacar et al. 2013). We refer to them as subfilaments or components and denote them by letters A and B. The Serpens Main—Cloud center and E filament region also has overlapping structures at the cloud center, but the Herschel filament east of the cloud does not have any identifiable substructure.

Many of the filamentary structures show systematic variations in their velocity. In nonoverlapping filamentary structures, the local velocity gradients are calculated directly from the Moment 1 maps. For the overlapping structures, we trace the $^{13}$CO$^+$ spectral peak over the extent of the filament, identifying the peak corresponding to each structure. Their

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**Figure 3.** Same as Figure 2, but for Serpens South—E region. The integrated intensity maps are in units of 10.0, 1.0, and 4.0 Jy beam$^{-1}$ km s$^{-1}$ for N$_2$H$^+$, H$^{13}$CO$^+$, and HNC, respectively. The N$_2$H$^+$ contours are at $(5, 10) \times \sigma$ ($\sigma = 0.25$ Jy beam$^{-1}$ km s$^{-1}$).

**Figure 4.** Same as Figure 2, but for Serpens Main—cloud center and E filament. The integrated intensity maps are in units of 6.0, 1.0, and 3.0 Jy beam$^{-1}$ km s$^{-1}$ for N$_2$H$^+$, H$^{13}$CO$^+$, and HNC, respectively. The N$_2$H$^+$ contours are at $(3, 6, 9) \times \sigma$ ($\sigma = 0.7$ Jy beam$^{-1}$ km s$^{-1}$).
velocity gradients are calculated locally using the H$^{13}$CO$^+$ spectral peak velocity difference in different parts of the same velocity-coherent structure. They are reported as gradients only if they satisfy the following conditions: (i) the velocity monotonically changes in one spatial direction (generally along the filament or perpendicular to it), (ii) the velocity difference is greater than or equal to 0.2 km s$^{-1}$, and (iii) the above conditions are satisfied for a distance of at least 4 beam widths along the filament. From the multiple local velocity gradient values for each filamentary structure, we report the maximum, minimum, and mean gradients (see Table 3). The error in the gradient calculation can be estimated from the velocity difference errors reported in the table. They are generally less significant than the variation in the gradient values over a filamentary structure.

For our analyses, we use distances of 436 pc for the four Serpens regions (Ortiz-León et al. 2017) and 300 pc for the Perseus region (Schlafly et al. 2014). Both clouds have an average recessional velocity of 7.5–8 km s$^{-1}$. Dust temperatures in these filaments range from 12 to 15 K (Tanaka et al. 2013; Roccatagliata et al. 2015). We used the Spitzer catalog of YSOs (Dunham et al. 2015) and identified point sources in the Herschel 70 μm maps corresponding to the studied regions to compare their locations with respect to the structures identified by us.

We also calculate the mean H$^{13}$CO$^+$ and H$^{13}$CN velocity dispersions $\langle \sigma \rangle$ for the two isolated filaments, where we can
determine the value unambiguously by taking statistics over a large part of the structure. The nonthermal velocity dispersion is calculated using the expression 
\[ \sigma^2 = \langle \sigma^2 \rangle - kT / (\mu m_H) \]
where \( T \) is the kinetic temperature and \( \mu m_H \) is the mass of each molecule of the tracer (where \( \mu = 30 \) for \( \text{H}^{13}\text{CO}^+ \) and \( 28 \) for \( \text{H}^{13}\text{CN} \), and \( m_H \) is the atomic hydrogen mass). At typical filament temperatures of 12–15 K, the nonthermal dispersion is the main component of the overall dispersion. We compare this to sound speeds \( c_s \approx 0.22–0.25 \text{ km s}^{-1} \) at these temperatures.

4.1. Serpens South—NW Region

Figure 8 (top) shows the \( \text{H}^{13}\text{CO}^+ \) contours of the Serpens South—NW region, averaged over four channels. This region has no evident substructures, as can be confirmed from the position–velocity diagram for a representative cut across the filament. There is a velocity gradient of about 0.24 km s\(^{-1}\) over the 0.04 pc width of the filament in both the \( \text{H}^3\text{CO}^+ \) and \( \text{N}_2\text{H}^+ \) emission. This is seen all along the 0.4 pc length of the filament in the mapped area (Figure 2). The mean \( \text{H}^{13}\text{CO}^+ \) velocity dispersion for this filament (0.21 km s\(^{-1}\)) is transonic.

There are no YSOs identified along the filament, although there are multiple Class 0/I sources near the filamentary hub at the southeastern end of the studied region.

4.2. Serpens South—E Region

Figure 9 shows two subfilaments in the Serpens South—E region running in the east-west direction—a weaker subfilament (A; red contours) that is wider and a parallel narrow subfilament (B; blue contours) having stronger emission. These are easily separable in the position–velocity diagram (middle panel of Figure 9). There is partial line-of-sight overlap between these two components. There is a large line-of-sight velocity difference over the region. It varies between 6.6 and 8.0 km s\(^{-1}\) according to the \( \text{H}^{13}\text{CO}^+ \) and \( \text{N}_2\text{H}^+ \) maps (see Figure 3). Subfilament “A” is more redshifted and has a velocity gradient across it, while “B” is blueshifted and has no consistent gradient across it. In the \( \text{H}^{13}\text{CO}^+ \) maps, because of low S/N, the gradient could be determined only in the east part.
Serpens Main

Notes.

NGC 1333

Serpens South

spectra taken at the location shown in the left panel. The peaks of H13CO+

Serpens South

Filament

location where the spectra are taken for comparison with other molecules. Right: H13CO+ (black, solid), HNC (brown, dashed), and H13CN (gray, dotted) J = 1–0 spectra taken at the location shown in the left panel. The peaks of H13CO+ and H13CN coincide, but the HNC spectrum shows an absorption dip.

Figure 7. Left: integrated intensity maps of Serpens South—NW filament using the H13CN J = 1–0 transition line. The map is in units of Jy beam−1 km s−1. The N2H+ integrated intensity contours are overlaid on the image as in Figure 2. The synthesized beam is shown at the lower right of the image. The blue circle marks the location where the spectra are taken for comparison with other molecules. Right: H13CO+ (black, solid), HNC (brown, dashed), and H13CN (gray, dotted) J = 1–0 spectra taken at the location shown in the left panel. The peaks of H13CO+ and H13CN coincide, but the HNC spectrum shows an absorption dip.

Table 3

Widths and Gradient Statistics of Filamentary Structures Using H13CO+ Maps

| Filament (Subfilament) | Representative Widtha (pc) | Gradient Directionb | (Δv) (km s−1) | Distance along Filamentc (pc) | Min  | Max  | Mean |
|------------------------|----------------------------|---------------------|---------------|-------------------------------|------|------|------|
| Serpens South—NW       | 0.06                       | across              | 0.24 ± 0.07   | 0.19                          | 3.9  | 6.8  | 5.5  |
| Serpens South—E (A)    | 0.08                       | across              | 0.22 ± 0.08   | 0.11                          | 3.6  | 5.3  | 4.2  |
| Serpens South—E (B)    | 0.04                       | across              | 0.54 ± 0.09   | 0.07                          | 5.7  | 12.0 | 8.9  |
| Serpens Main—E         | 0.04                       | across              | 1.06 ± 0.06   | 0.23                          | 2.7  | 10.3 | 4.6  |
| Serpens Main—S (A)     | 0.07                       | ...                 | 0.78 ± 0.15   | 0.29                          | 1.2  | 5.0  | 2.6  |
| Serpens Main—S (B)     | 0.05                       | along               | 0.30 ± 0.14   | 0.09                          | 8.1  | 12.2 | 9.9  |
| NGC 1333—SE (A)        | 0.05                       | ...                 |                |                               |      |      |      |
| NGC 1333—SE (B)        | 0.03                       | across              |                |                               |      |      |      |

Notes.

a The widths are calculated from the extent of contours in channel maps at half the peak emission. All the values vary in a range of about 0.03 pc over the length of the filament.

b Only monotonically changing velocities Δv ≥ 0.2 km s−1 over a part of the filament ≥4 beam widths long are considered as gradients.

c Distance along filament spine over which gradient statistics are taken, for both perpendicular and parallel gradients.

do velocity diagrams to distinguish the velocity-coherent structures. The gradient in the eastern part, although visible in the N2H+ maps as well, has a lesser magnitude and opposite sense compared to the inaccurately identified gradient in the central and western part and was thus not reported in Fernández-López et al. (2014).

With the knowledge of the two-component structure using the H13CO+, we find that the isolated hyperfine line of N2H+ (J = 1–0, F = 0–1) shows similar trends to H13CO+, but by itself this line has much lower S/N than H13CO+ and is too weak to map the kinematics of the entire region.

4.3. Serpens Main—Cloud Center and E Filament

This is a complex region mapping the southeast part of the Serpens Main hub, with emission extending in various directions. When comparing to the larger-scale structures in the region using Herschel maps, we see that only two parts of the emission form long filaments, one in the east and the other in the south. The east filament is mapped completely in this
The slope indicates the velocity gradient for a cut across the channels between 7.24 and 7.88 km s\(^{-1}\) corresponding to the bottom right represents the resolution of the column density map, for which the position–velocity diagram is presented in the bottom panel. The black stars denote the locations of known Class 0/I YSOs. The yellow circle at the bottom right represents the resolution of the column density map, corresponding to the Herschel 500 \(\mu\)m beam. Bottom: position–velocity plot for a cut across the filament, showing a single velocity-coherent component. The slope indicates the velocity gradient.

region. The filament in the south is completely mapped in the Serpens Main—S region (discussed in the following section).

In the cloud center region, there is a large range of line-of-sight velocities from 6 to 9 km s\(^{-1}\). Using H\(^{13}\)CO\(^+\) channel maps, two sets of structures associated with different velocities are identified within the hub (Figure 10, right panel). Of these, the velocities above 8 km s\(^{-1}\) correspond to a separate velocity-coherent structure (marked in red in the left panel of Figure 10), while another set of structures have velocities in the range of 6–8 km s\(^{-1}\). This second set includes a convergent point at \((\alpha, \delta) = (18:29:59.8, +1:13:00)\) where three flows seem to intersect from east, southeast, and northwest, respectively (middle panel of Figure 10). We call them flows because they have a velocity gradient, such that their ends closer to the hub are highly blueshifted, possibly indicating acceleration in a potential well. The HNC spectrum has no absorption dips in the blueshifted set of structures but has very strong dips in the redshifted regions.

Of these flows, the one from the east is identified as a filament in our analysis. Most of the filament is isolated from the other structures and so can be analyzed from the moment maps. The filament has a velocity gradient of 1.1 km s\(^{-1}\) over its length of 0.23 pc. The gradient vector is oriented along the filament close to the hub (10.3 km s\(^{-1}\) pc\(^{-1}\)), but its magnitude reduces by a factor of four 0.2 pc away from the cloud center. Moving further from the hub, the gradient direction rotates by about 90° such that it is oriented almost across the filament near the easternmost extreme. The mean velocity dispersion over this filament is 0.33 km s\(^{-1}\), which is marginally supersonic.

In the central hub, three point sources SMM1, SMM3, and SMM4 are identified in the continuum map, but they are not closely associated with the multiflament intersection point. However, on comparing with the Spitzer YSO catalog (Dunham et al. 2015), two Class I/0 YSOs are identified within 5000 au projected distance from this point. Additionally, an outflow identified in previous CO maps (Davis et al. 1999) and the CLASSy HCO\(^+\) map can be traced to be originating close to the filament intersecting region.

4.4. Serpens Main—S Region

The northern part of this region maps into part of the cloud center of Serpens Main. In this upper part, two velocity components are identified at about 7.3 and 8.4 km s\(^{-1}\), respectively. The relatively blueshifted component has a greater spatial extent and does not show any absorption in the HNC spectrum compared to the relatively redshifted component.

This region also has two substructures along the filament, which originate from the hub in the north (see Figure 11) and are more than 0.3 pc in length. These velocity-coherent subfilaments “A” and “B” are parallel to each other and cross over in the projected sky plane at \((\alpha, \delta) = (18:29:59.5, +1:09:45)\), corresponding to an emission peak in the integrated intensity maps (see Figure 5). The position–velocity diagrams for cuts along the two subfilaments reveal their velocity distribution. Subfilament “A” has velocities in the range 8.2–8.7 km s\(^{-1}\) with no evident gradients. Subfilament “B” has a velocity gradient along the filament such that the line-of-sight velocities are 7.5 km s\(^{-1}\) at the south end of the filament and 8.5 km s\(^{-1}\) close to the cloud center. As in the Serpens Main—E filament (discussed in the previous section), this subfilament also indicates accelerated flow closer to the cloud center. The gradient changes from 1.2 to 5.0 km s\(^{-1}\) pc\(^{-1}\), going toward the cloud center.

The N\(_2\)H\(^+\) emission identifies both these subfilaments but does not trace the lower half of “B” because of insufficient S/N. In their kinematic analysis, Lee et al. (2014) used a single-velocity-component fit for most regions. They used a two-velocity-component fit only in regions where there is a large velocity difference between the components (\(>1\) km s\(^{-1}\)) that could be resolved unambiguously. They detected two subfilaments using the integrated intensity maps since the subfilaments had well-defined ridges, spatially resolved by the CARMA beam. However, they used a single-component fit to obtain the velocity maps because the velocity difference between the components in the northern part is \(<0.5\) km s\(^{-1}\), and were thus unable to capture the extent of the two components in the overlapping regions.

The velocity gradient observed across the filament in the lower half of the H\(^{13}\)CO\(^+\) first-moment map (see Figure 5) is not a true gradient; it is an effect of the overlapping subfilaments. This case is similar to that observed by Beuther...
et al. (2015) in the dense filament IRDC 18223 and by Moeckel & Burkert (2015) in simulations.

South of the intersection points of “A” and “B,” the spectrum corresponding to emission from “A” is wide and at places divides into two peaks separated by two to three channels. In the HNC integrated intensity map, the width of “A” is lesser than in H$^{13}$CO$^+$, strengthening the case for an additional substructure in this region possibly having different physical parameters. However, there is insufficient evidence in our data to identify this substructure with certainty. Three Class 0/I/flat-spectrum YSOs are identified along the length of the filament. Of them, one flat-spectrum YSO is located close to the crossover point of the subfilaments.

4.5. NGC 1333—SE Region

This region has a filament with two substructures running parallel to each other from northwest to southeast. As shown in Figure 12, the eastern subfilament (A) has a velocity in the range of 8.1–8.4 km s$^{-1}$ with a fork toward the south. The western subfilament (B) has a velocity gradient across its 0.03 pc width changing gradually from about 7.8 to 7.5 km s$^{-1}$. As explained at the beginning of this section, we measure the gradient using the spectral peak locations corresponding to the same velocity-coherent structure. This is shown in the bottom right panel of Figure 12. In some sections of subfilament “A,” there is a small gradient in the opposite sense compared to that for “B.”

The relative intensities of the two subfilaments are comparable, with both N$_2$H$^+$ and H$^{13}$CO$^+$. However, the HNC emission from the right subfilament is about two times brighter than that from the left. The difference in the HNC emission compared to the other two tracers strengthens the interpretation that there are two distinct subfilaments having different physical parameters.

The four YSOs corresponding to the components of IRAS 4 are located in the upper right part of the mapped region. They appear bright in the CLASSy-II continuum (360 and 130 Jy beam$^{-1}$ peak intensities, respectively) maps. Neither of the outflow axes from these protostars (Koumpia et al. 2016) is oriented along the filament in this region. Stephens et al. (2017)
postulated that the lack of correlation between outflow axis directions and the filament orientations indicates that the angular momentum axis of a protostar may be independent of the large-scale structure.

5. Discussion

On comparing the CLASSy-II observations with the Herschel dust continuum maps and the CLASSy N$_2$H$^+$ maps, we find that the structures traced by all the maps are similar on a large scale. However, on smaller scales (<0.1 pc), the finer structure of these filaments becomes evident in the CARMA maps. In many of the regions we identify multiple substructures, instead of a single uniform filament identified in the Herschel maps.

Using just the CLASSy N$_2$H$^+$ maps, it was argued that the finer structure could be real or could alternatively be due to N$_2$H$^+$ abundance variations caused as a result of N$_2$H$^+$ depletion by CO in less dense regions (Bergin et al. 2001). However, the similarity between the structures traced by N$_2$H$^+$ and H$_2$CO$^+$ at the CLASSy resolution scale implies that the morphology and kinematics determined from these maps truly represent the dense gas distribution and are unlikely to be arising from chemical selectivity. There are some differences in the relative intensities of the structures traced by HNC, which...
could be an effect of relative abundance, temperature, density, or a combination of them.

5.1. Morphology

The different regions studied in this paper indicate that despite the variety of filament structure, there are many common features. In this subsection, we discuss the different aspects of filament morphologies and their implications. In some cases, rigorous analysis is only possible for the well-isolated filaments, i.e., for Serpens South—NW filament and Serpens Main—E filament.

5.1.1. Physical Parameters of Tracers

Single transitions can be used to determine physical parameters like column density in molecular clouds only if we assume thermalization. Thus, if we assume that a single excitation temperature \( T_{\text{ex}} \) defines the level populations of a molecule, we can use the integrated intensity to calculate the total column density in the optically thin limit using the formula (Goldsmith & Langer 1999)

\[
N_{\text{thin}}^\text{thin} = \frac{Q}{g_i e^{-E_i/kT_{\text{ex}}}} \sum \int_{-\infty}^{\infty} \int \frac{Q}{g_i e^{-E_i/kT_{\text{ex}}}} \int_{-\infty}^{\infty} T_{\text{obs}} \, dv.
\]

where \( c \), \( k \), and \( h \) are the speed-of-light constant, the Boltzmann constant, and the Planck constant, respectively. The transition frequency is \( \nu \), and \( A_{\text{vd}} \) is the Einstein A coefficient corresponding to the transition. \( Q \) is the partition function, which is assumed to be a function of a single variable \( T_{\text{ex}} \). Parameters \( g_i \) and \( E_i \) are the degeneracy and energy,
respectively, of the \(i\)th energy level. The subscripts \(u\) and \(l\) represent the upper and lower levels of the transition, respectively. The integral represents the integrated line intensity, with \(T_b\) as the observed brightness temperature in K and \(dv\) as the channel width in km s\(^{-1}\). Here we assume a unity beam filling factor. Further, a correction factor of \(\tau/(1 - e^{-\tau})\) is multiplied if the transition is optically thick. This opacity \(\tau\) can be determined using the radiative transfer equation

\[
T_b = \frac{h\nu}{k} \left( \frac{1}{e^{h\nu/kT_{bg}} - 1} - \frac{1}{e^{h\nu/kT_{bg}} - 1} \right) [1 - e^{-\tau}],
\]

(2)

where \(T_{bg}\) is the background radiation of 2.73 K.

Because of the limitations of the analysis and the presence of overlapping structures in many regions further complicating the analysis, we present the results only for the Serpens South—NW filament ridge in H\(^{13}\)CO\(^+\) and N\(_2\)H\(^+\). The lower limit of \(T_{ex}\) for N\(_2\)H\(^+\) is estimated from the observed brightness temperature (∼6 K). This \(T_{ex}\) limit is also applicable to H\(^{13}\)CO\(^+\) since it has a critical density similar to that of N\(_2\)H\(^+\). For the upper limit of \(T_{ex}\), we use the maximum kinetic temperature from the dust temperature maps. Based on this, we use representative \(T_{ex}\) values in the range of 6–15 K. Using these equations and the assumed range of \(T_{ex}\) values, we obtained column densities of (0.9–1.1) × 10\(^{12}\) cm\(^{-2}\) for H\(^{13}\)CO\(^+\) and (7.9–10.3) × 10\(^{12}\) cm\(^{-2}\) for N\(_2\)H\(^+\) along the ridge of the isolated filament in Serpens South—NW region. The column density values can be averaged over areas equal to the Herschel beam size and compared to the \(H_2\) column densities of ∼2.0 × 10\(^{22}\) cm\(^{-2}\) obtained from Herschel maps to get molecular abundances. By this method, we calculate abundances of (2.7–4.6) × 10\(^{-11}\) for H\(^{13}\)CO\(^+\) and (2.2–3.3) × 10\(^{-10}\) for N\(_2\)H\(^+\).

We can also use the LVG approximation to get a lower bound on the density of the region. Using the H\(^{13}\)CO\(^+\) observed brightness temperature and a maximum value of \(\tau = 0.8\) (from Equation (2)) corresponding to \(T_{ex} = 6\) K, we get a minimum gas density of 3.0 × 10\(^3\) cm\(^{-3}\) along the Serpens South—NW filament ridge. From the LVG model, we also obtain a minimum H\(^{13}\)CO\(^+\) column density of 0.9 × 10\(^{12}\) cm\(^{-2}\) corresponding to the mean brightness temperature of 1.9 K. This estimate matches well with the analytically obtained column density in the previous paragraph.

5.1.2. Filament Widths in Comparison with Herschel Dust Maps

Publications from the Gould Belt survey argued that all filaments have a similar width of about 0.1 pc (André et al. 2010; Arzoumanian et al. 2011; Palmeirim et al. 2013) with a narrow distribution. Other authors like Juvela et al. (2012) and Hennemann et al. (2012) have, however, reported larger widths of about 0.3 pc, while Panopoulou et al. (2016) reported a lesser width of 0.06 ± 0.04 pc. Ysard et al. (2013) reported widths varying by a factor of 4, while Panopoulou et al. (2017) concluded that a single characteristic width of filaments is inconsistent with observations and that the narrow distribution is an averaging effect.

Earlier in Section 4, we reported the widths for the individual filamentary structures. Here we use a more systematic approach to calculate the widths of filaments using H\(^{13}\)CO\(^+\) and dust column density maps and compare between them. Since H\(^{13}\)CO\(^+\) is optically thin, the integrated intensity map scales directly with the column density (Equation (1)). Hydrogen column density maps were obtained from the Herschel Gould Belt archive. We take parallel cuts across the filaments at multiple points along its length, about 7" apart (comparable to beam size), average over the cuts, and fit a Gaussian to get the FWHM. The deconvolved width, \(W_{de}\), is obtained using the expression

\[
W_{de} = \sqrt{\text{FWHM}^2 - (\text{HPBW})^2},
\]

where HPBW is the half-power beam width for the maps (Könnyves et al. 2015).

5.1.3. Multiple Structures

Except for the Serpens South—NW filament, all the remaining regions have partially overlapping multiple structures in the line of sight. The regions in Serpens Main have a line-of-sight velocity difference of as much as 1.4 km s\(^{-1}\). Assuming timescales comparable to the cloud free-fall times (~1 Myr) for motion governed by gravity (which also includes turbulence in a bound molecular cloud), these structures should be separated by about 1.5 pc. This is comparable to the size of the molecular clouds and is much larger than the filament widths. Alternatively, if they are assumed to be in closer physical proximity, then they have proportionately lesser free-fall times and therefore represent transient structures that may be forming from or evolving into larger structures. This
discussion does not take into account effects of magnetic fields, which can also affect the timescales.

These velocity-coherent structures are also distinct from each other in their morphology, velocity gradients, and HNC absorption characteristics. Many of the subfilaments are parallel to each other. Additionally in Serpens South—E region and NGC 1333—SE region, the parallel subfilaments have a fairly constant velocity difference of about 0.5 km s\(^{-1}\) at the nearer edge between the filaments. In both these regions, there is a velocity gradient across one of the filaments.

Hacar et al. (2013) also observed multiple velocity components in the L1495/B213 filaments in Taurus. They identified shorter 0.5 pc coherent noninteracting subfilaments that have velocity separations of 0.5–1.0 km s\(^{-1}\), similar to what we observe. Tafalla & Hacar (2015) proposed a “fray and fragment” model to explain the multiple structures. This model starts with a wide filament that fragments into subfilaments, which then further fragment into cores. Hydrodynamic simulations of turbulent clouds by Moeckel & Burkert (2015) and Smith et al. (2016) also showed the presence of multiple components in filaments. However, contrary to the “fray and fragment” model, Smith et al. (2016) proposed a “fray and gather” model, in which the subfilaments are formed first and then gathered together by large-scale motions within the cloud—initially by large-scale turbulent modes and afterward gravitationally. Since the subfilaments observed by us are parallel, they are likely to be influenced by the same physical processes locally, but the observations cannot distinguish between the two models discussed above.

### 5.1.4. Absorption Features in HNC

The HNC spectrum shows absorption features in many regions. These dips result in the HNC spectrum having multiple peaks and are identified as absorption features based on the peaks in the H\(^{13}\)CO\(^+\) spectrum and the N\(_2\)H\(^+\) isolated hyperfine spectrum. In many regions, the dips correspond to similar dips in HCO\(^+\) and HCN. In regions having multiple

![Figure 13. Filament width in different regions. The dark dots represent the normalized average of the cuts over a filament section, which is fitted with one or two Gaussians. The light color spread represents the range of normalized values over a section of the filament. Top: Serpens South—NW filament, comparison of filament widths in dust (blue) and H\(^{13}\)CO\(^+\) (green). The dust map shows two parallel filaments about 75″ apart and is fitted with two Gaussians. The FWHM of the filament mapped by us is 53″ ± 3″ in dust and 29″ ± 5″ in H\(^{13}\)CO\(^+\). Bottom left: Serpens Main—E filament, comparison of filament widths in two parts of the same filament: FWHM 26″ ± 5″ near cloud center (green) and 17″ ± 5″ away from cloud center (red). Closer to the cloud core, the intensity profile across the filament departs from a Gaussian profile, even though we detect a single velocity-coherent component throughout. Bottom right: northern part of Serpens Main—S filament, two parallel subfilaments separated by about 25″ with FWHM 23″ ± 8″ and 19″ ± 7″ respectively. A two-Gaussian fit is used since two velocity-coherent subfilaments were identified using the data cube.](image-url)
structure, we see that in some cases only one structure has absorption dips, while in other cases emission from both structures has absorption dips.

Absorption features with a higher blueshifted peak and a lower redshifted peak are considered a signature of radially symmetric infall into the filament core (De Vries & Myers 2005; Friesen et al. 2013). We find that in the regions studied by us there are absorption features with both blue asymmetry and red asymmetry (see Figure 14). The generic infall models are inadequate in explaining the velocity structure of the HNC lines.

Although self-absorption within the filament is likely, an alternate possibility is absorption by lower-density clouds surrounding the main filament that are in the line of sight. This theory is supported by the observation that the absorption features in filaments are equally strong as we move from the center of the filament to the edges. Self-absorption by filament material should decrease through lesser optical depth regions near the edges of the filament.

5.1.5. Filaments in Relation to Star Formation

Filaments are known to be closely associated with star-forming regions, and many YSOs and prestellar cores are identified along some filaments (Bontemps et al. 2010; Hacar & Tafalla 2011). On comparing our regions with the Herschel 70 μm detections and the Spitzer catalog of YSOs (Dunham et al. 2015), we find that two of the filaments harbor multiple YSOs along their length: Serpens South—E filament (left panel of Figure 9) and Serpens Main—S filament (left panel of Figure 11). The YSOs in these filaments are all Class 0/I/flat-spectrum sources, indicating that they are associated with early stages of star formation. Both these filaments have parallel substructures, and it cannot be determined whether some of the YSOs are associated with one subfilament or the other, since they appear in the overlapping regions. YSOs are also detected at the filament intersection in the Serpens Main—S region and the filament–flow intersection in the Serpens Main cloud center (left panel of Figure 10), corroborating with observations by Jiménez-Serra et al. (2014) toward the IRDC G035.3900.33. This
suggests that the subfilaments may be interacting with each other and are probably in close proximity even in the line of sight. We also find that all of the regions have continuum sources close to the ends of the filaments near filamentary hubs or cloud centers.

Different filaments can be at different stages of their star-forming life (Myers 2017), and based on our observations, it can be argued that only two of the five filaments studied by us are currently actively star-forming. The mass per unit length of filaments is often used as an indicator of the evolutionary stage of filament accretion (Heitsch 2013; Palmeirim et al. 2013; Li et al. 2014), with higher values indicating greater chances of gravitational fragmentation. We can estimate the mass per unit length of the Herschel filaments by summing over the pixels of the H$_2$ column density map over the filament and subtracting the background. On applying this method to the isolated filaments, we obtain an average mass per unit length of 21.3 $M_\odot$ pc$^{-1}$ for Serpens South—NW filament and 16.9 $M_\odot$ pc$^{-1}$ for Serpens Main—E filament. The values are comparable to or less than the critical mass per unit length of 20.9 $M_\odot$ pc$^{-1}$, calculated for isothermal ($T = 12.5$ K) self-gravitating cylinders using the formula $M_{\text{crit}} = 2c_s^3/G$, where $c_s$ is the sonic speed in the cloud and $G$ is the universal gravitational constant (Ostriker 1964). This is consistent with the observation that neither of these filaments has any Class 0/I sources along their lengths. The Serpens South—E filament and the Serpens Main—S filament, which have YSOs along their length, have mass per unit length values of 28.7 and 44.6 $M_\odot$ pc$^{-1}$, respectively, which are both greater than the critical value. However, the 36$^\circ$ column density map beam size is insufficient to resolve the contribution of individual substructures within the filament. In the NGC 1333—SE filament, the mass per unit length varies by a factor of 4; although its mean value is supercritical, it does not have any YSOs along its length. So even though the mass per unit length is a good indicator of the star formation stage for a filament, it is not a conclusive discriminator.

5.2. Kinematics

All the CLASSy-II regions have at least one filamentary structure with an evident gradient in the line-of-sight velocity: across the filament, along the filament, or both. The complete list is given in Table 3. The filaments and regions where we observe negligible velocity variations may still have gradients into the plane of the sky.

The kinematics observed in N$_2$H$^+$ match well with those in H$^{13}$CO$^+$ for the nonoverlapping regions and show similar trends in regions having multiple structures in the line of sight. This is evident from the velocity maps in Section 3. However, the hyperfine structure of N$_2$H$^+$ limits its capability of distinguishing between multiple structures and quantifying their kinematic features independently. N$_2$H$^+$ velocity maps had been generated using line fitting of all seven hyperfine components, but assuming a single velocity component for most locations on the map. In regions with multiple velocity components, such a line fitting produced a centroid velocity with a large line width. Velocity maps thus obtained were used previously to determine the kinematics of the regions (Fernández-López et al. 2014; Lee et al. 2014), which in some cases give different results from our H$^{13}$CO$^+$ analysis that allows for multiple components. Attempts to fit for multiple velocity components in the N$_2$H$^+$ spectra lead to erroneous degenerate solutions, unless the components are $\geq 1$ km s$^{-1}$ apart. For example, in Fernández-López et al. (2014) the Serpens South—E filament is reported to have an LVG of 11.9 km s$^{-1}$ pc$^{-1}$ across the filament. However, the H$^{13}$CO$^+$ data cube reveals that this is an effect of multiple velocity-coherent components in close proximity (see Figure 9), even though its velocity map matches well that of N$_2$H$^+$ (see Figure 3). Only the eastern half of one of the substructures (“A”) in this filament has a gradient across it, but in the opposite sense to that reported in Fernández-López et al. (2014).

5.2.1. Velocity Gradients across Filaments and Their Implications on the Filament Formation Mechanism

Four of the eight identified filamentary structures have velocity gradients perpendicular to their length in the range 3.6–12.2 km s$^{-1}$ pc$^{-1}$. They are determined from the H$^{13}$CO$^+$ maps as discussed in Section 4. These gradients are unidirectional in each filamentary structure but have variations in magnitude along the filaments. The magnitudes correspond to crossing times of $(1–3) \times 10^3$ yr. Such gradients of smaller magnitude have been observed by Peretto et al. (2014) as well. Schneider et al. (2010) also reported observations of gradients across a filament in the Cygnus molecular cloud, but it has a width of 1 pc, about 20 times wider than the filaments observed by us. Further, the gradient across the Cygnus filament changes direction at different positions along the length of the filament. Out of the regions studied by us, in addition to the four filamentary structures with gradients across their widths, we also identified line-of-sight velocity gradients across the Serpens Main—S region, but it is arguably an effect of multiple juxtaposed structures at different velocities.

The velocity gradients across the filaments support the filament formation model by C-Y. C. Chen & E. O. Ostriker (2018, private communication). According to the model, the velocity gradient is a projection effect of the accreting material in a 2D flow within the dense layer created by colliding turbulent cells. The cartoon in Figure 15 illustrates this effect. In the case of a nonaxisymmetric cylinder in the sky plane, we expect the observed centroid velocity to vary systematically for a cut across the filament. This model also corroborates with Smith et al. (2016), who report that the filament cross sections in their simulations are elongated instead of being circular, and that the largest gradients appear perpendicular to the filament. The absence of gradients across some of the filaments could be a result of close to face-on viewing angle or a different formation mechanism. More observations are required to establish the broad relevance of this model.

Alternate interpretations of the velocity gradient include filament rotation (Olmi & Testi 2002) and multiple narrow filaments that are partially overlapping in the sky viewing plane (Beuther et al. 2015). To our knowledge, the first idea is not supported by numerical simulations (Smith et al. 2016). We have seen some evidence of parallel subfilaments in a few regions masquerading as a single filament with a large gradient if we only see their velocity maps (as in Serpens South—E region and NGC 1333—SE region). However, after disentangling their individual velocity distributions using the H$^{13}$CO$^+$ maps, we see that one of the parallel subfilaments has a velocity gradient across it independent of the other subfilament (see Figure 12, bottom right). The observed gradients across filaments (which are equally or more evident than gradients along filaments) indicate that the local dynamical evolution of
In this scenario, matter from large scales is gathered to the center of a gravitational potential well, where multiple protostars are formed. It is to be noted that material does not flow along the filaments (analogous to water flowing in a river); rather, the entire filament moves down into the potential well.

In the Serpens Main cloud center, we identify a filament intersection point having the highest blueshift. We use velocities ($v_{\text{obs}}$) at different distances ($l_{\text{obs}}$) from this point to measure the gravitational potential. The line-of-sight cloud velocity ($v_{\text{cloud}}$) of 8.15 km s$^{-1}$ is subtracted from the observed line-of-sight velocities. The velocity thus obtained is a projection of the velocity along the filament $v$ in the local frame of the cloud (see Figure 16). We obtain $v$ assuming an inclination angle $i$ (positive when the filament is inclined away from the observer), using the expression $v_{\text{obs}} = v_{\text{cloud}} - v \sin i$. The observed distance $l_{\text{obs}}$ is also a projection of the radial distance $r$, and they are related as $l_{\text{obs}} = r \cos i$. Assuming a steady state, using energy conservation for a pair of points along the filament, we can write

$$v_2^2 - v_1^2 = GM \left( \frac{1}{r_2} - \frac{1}{r_1} \right),$$

(3)

where $G$ is the gravitational constant and $M$ is the mass of the core. This can be written in terms of the observables and the inclination angle as

$$(v_{\text{cloud}} - v_{2,\text{obs}})^2 - (v_{\text{cloud}} - v_{1,\text{obs}})^2 = GM \sin^2 i \cos i$$

$$\times \left( \frac{1}{l_{2,\text{obs}}} - \frac{1}{l_{1,\text{obs}}} \right).$$

(4)

Using this equation and measured sets of velocities at different distances from the core for the different structures, we obtain consistent core mass values in the range of 30–37 $M_\odot$ for an inclination angle of $i = 45^\circ$. The mass varies by a factor of about 1.5 if we assume an inclination angle range of 30°–60°. Additionally, because of uncertainties in the distance and velocity measurements, there can be up to 50% error in mass estimates. As shown in the figure, from this interpretation we can also make inferences about the 3D structure of the filaments—whether the filaments are inclined toward us or...
away from us. Part for both these cases, the more blueshifted (or less redshifted) part of the filament is expected to be closer to the observer than the less blueshifted (or more redshifted) part.

6. Summary

We presented CARMA observations of H$_{13}$CO$^+$ (1–0) and HNC (1–0) for five regions in Serpens Main, Serpens South, and NGC 1333 containing filaments. For the four Serpens regions, we also obtained data on the H$^{13}$CN (1–0) emission. The observations have an angular resolution of $\sim$7$''$ and a spectral resolution of 0.16 km s$^{-1}$. We studied the morphology and kinematics of these regions, comparing them to existing maps of the dust continuum and N$_2$H$^+$ (1–0) emission. Our main conclusions are summarized below.

1. The emission distribution in the H$^{13}$CO$^+$ maps traces similar filamentary structures to the N$_2$H$^+$ maps obtained by CLASSy and corresponds to the same morphology and kinematics.

2. In many regions, multiple velocity-coherent structures are present, identifiable by multiple peaks in the H$^{13}$CO$^+$ spectrum. H$^{13}$CO$^+$ is the only species observed by us that allows us to unambiguously disentangle the overlapping components.

3. Some of these multiple structures are filament substructures that are roughly aligned with each other even though they have velocity differences of 0.5–1.0 km s$^{-1}$ between them. We identify two substructures each in three filaments, while two filaments are each found to be composed of a single velocity-coherent component. We report statistics of these eight filamentary structures.

4. The mean width of these filamentary structures is 0.05 pc, but they vary in the range of 0.03–0.08 pc. Along the same filamentary structure, the width can vary by a factor of 2. The widths of velocity-coherent filaments in the dense gas tracers are a factor of 1.5 narrower than the Herschel widths.

5. Four of the eight filamentary structures have significant velocity gradients perpendicular to the filament length, with mean values in the range of 4–10 km s$^{-1}$ pc$^{-1}$. This provides evidence for predictions from simulations, in which filaments form via inflows within the dense layer created by collapsing turbulent cells.

6. Two filamentary structures in Serpens Main have velocity gradients along their lengths, which increase closer to the cloud core. This may indicate gravitational infall of filaments into the central core.

7. Class 0/1/flat-spectrum YSOs are identified only along two of the filaments and are found to be preferably located at the overlapping regions of the filamentary structures. This suggests that the subfilaments are physically interacting with each other, which possibly plays a role in star formation.

Overall, the observations support the presence of finer structures within the Herschel filaments with systematic properties like alignment of subfilaments and presence of velocity gradients across them. These properties suggest a common formation mechanism. Features like the large distribution of widths of filamentary structures and the presence of YSOs only in some of the regions indicate their diversity.

These can arise from local effects or could be dependent on the evolutionary stage of the filaments.

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References

André, P., Men'shchikov, A., Bontemps, S., et al. 2010, A&A, 518, L102
Arzoumanian, D., André, P., Didelon, P., et al. 2011, A&A, 529, L6
Astropy Collaboration, Robitaille, T. P., Tollerud, E. J., et al. 2013, A&A, 558, A33
Bally, J., Langer, W. D., Stark, A. A., & Wilson, R. W. 1987, ApJL, 312, L45
Banerjee, R., Pudritz, R. E., & Anderson, D. W. 2006, MNRAS, 373, 1091
Bechtel, H. A., Steeves, A. H., & Field, R. W. 2006, ApJL, 649, L35
Bergin, E. A., Ciardi, D. R., Lada, C. J., Alves, J., & Lada, E. A. 2001, ApJ, 557, 209
Beuther, H., Ragan, S. E., Johnston, K., et al. 2015, A&A, 584, A67
Boldyrev, S., Nordlund, A., & Padoan, P. 2002, PdRvL, 89, 031102
Bontemps, S., André, P., Könyves, V., et al. 2010, A&A, 518, L85
Chini, R., Reichardt, B., Ward-Thompson, D., et al. 1997, ApJL, 474, L135
Clarke, S. D., Whitworth, A. P., Duarte-Cabral, A., & Hubbard, D. A. 2017, MNRAS, 468, 2489
Csengeri, T., Bontemps, S., Schneider, N., Motte, F., & Dib, S. 2011, A&A, 527, A135
Davis, C. J., Matthews, H. E., Ray, T. P., Dent, W. R. F., & Richer, J. S. 1999, MNRAS, 309, 141
De Vries, C. H., & Myers, P. C. 2005, ApJ, 620, 800
Demouchel, F., Faure, A., & Liége, F. 2010, MNRAS, 406, 2488
Dunham, M. M., Allen, L. E., Evans, N. J., II, et al. 2015, ApJS, 220, 11
Federrath, C. 2016, MNRAS, 457, 375
Fernández-López, M., Arce, H. G., Looney, L., et al. 2014, ApJL, 790, L19
Flower, D. R. 1999, MNRAS, 305, 651
Friesen, R. K., Bourke, T. L., Di Francesco, J., Gutermuth, R., & Myers, P. C. 2016, ApJ, 833, 204
Friesen, R. K., Medeiros, L., Schnie, S., et al. 2013, MNRAS, 436, 1513
Furuya, R. S., Kitamura, Y., & Shinnaga, H. 2014, ApJ, 793, 94
Goldsmith, P. F., Heyer, M., Narayanan, G., et al. 2008, ApJ, 680, 428
Goldsmith, P. F., & Langer, W. D. 1999, ApJ, 517, 209
Gómez, G. C., & Vázquez-Semadeni, E. 2014, ApJ, 791, 124
Gong, H., & Ostriker, E. C. 2011, ApJ, 729, 120
Green, S., & Thaddeus, P. 1974, ApJ, 191, 653
Gutermuth, R. A., Bourke, T. L., Allen, L. E., et al. 2008a, ApJL, 673, L151
Gutermuth, R. A., Myers, P. C., Megeath, S. T., et al. 2008b, ApJ, 674, 336
Hacar, A., & Tafalla, M. 2011, A&A, 533, A34
Hacar, A., Tafalla, M., Kaufmann, L., & Kovács, A. 2013, A&A, 554, A55
Heitsch, F. 2013, ApJ, 769, 115
Heitsch, F., Ballesteros-Paredes, J., & Hartmann, L. 2009, ApJ, 704, 1735
Hennebelle, P., & André, P. 2013, A&A, 560, A68
Hennebelle, P., Motte, F., Schneider, N., et al. 2012, A&A, 543, L3
Henshaw, J. D., Caselli, P., Fontani, F., et al. 2013, MNRAS, 428, 3425
Henshaw, J. D., Caselli, P., Fontani, F., et al. 2016, MNRAS, 463, 146
Hunter, J. D. 2007, CSIE, 9, 90
Jiménez-Serra, I., Caselli, P., Fontani, F., et al. 2014, MNRAS, 430, 1996
Juvela, M., Ristorcelli, I., Pagani, L., et al. 2012, A&A, 541, A12
Kirk, H., Klassen, M., Pudritz, R., & Pillsworth, S. 2015, ApJ, 802, 75
Kirk, H., Myers, P. C., Bourke, T. L., et al. 2013, ApJ, 766, 115
Klessen, R. S., Heitsch, F., & Mac Low, M.-M. 2000, ApJ, 535, 887
Könyves, V., André, P., Men'shchikov, A., et al. 2015, A&A, 584, A91
Koumpia, E., van der Tak, F. F. S., Kwon, W., et al. 2016, A&A, 595, A51
Kritsuk, A. G., Lee, C. T., & Norman, M. L. 2013, MNRAS, 436, 3247
Lee, K. I., Fernández-López, M., Storm, S., et al. 2014, ApJ, 797, 76
Li, D. L., Esimbek, J., Zhou, J. J., et al. 2014, A&A, 567, A10
Moeckel, N., & Burkert, A. 2015, ApJ, 807, 67
Molinari, S., Swinney, B., Bally, J., et al. 2010, A&A, 518, L100
Myers, P. C. 2009, ApJ, 706, 1341
Myers, P. C. 2017, ApJ, 838, 10
Olmi, L., & Testi, L. 2002, A&A, 392, 1053
Ortiz-León, G. N., Dzib, S. A., Kounkel, M. A., et al. 2017, ApJ, 834, 143
Ostriker, J. 1964, ApJ, 140, 1056
Palmeirim, P., André, P., Kirk, J., et al. 2013, A&A, 550, A38
Panopoulou, G. V., Psaradaki, I., Skalidis, R., Tassis, K., & Andrews, J. J. 2017, MNRAS, 466, 2529
Panopoulou, G. V., Psaradaki, I., & Tassis, K. 2016, MNRAS, 462, 1517
Peretto, N., Fuller, G. A., André, P., et al. 2014, A&A, 561, A83
Peretto, N., Fuller, G. A., Duarte-Cabral, A., et al. 2013, A&A, 555, A112
Peters, T., Schleicher, D. R. G., Klessen, R. S., et al. 2012, ApJL, 760, L28
Pezzuto, S., Elia, D., Schisano, E., et al. 2012, A&A, 547, A54
Roccatagliata, V., Dale, J. E., Ratzka, T., et al. 2015, A&A, 584, A119
Sault, R. J., Teuben, P. J., & Wright, M. C. H. 1995, in ASP Conf. Ser. 77, Astronomical Data Analysis Software and Systems IV, ed. R. A. Shaw, H. E. Payne, & J. J. E. Hayes (San Francisco, CA: ASP), 433
Schlafly, E. F., Green, G., Finkbeiner, D. P., et al. 2014, ApJ, 786, 29
Schneider, N., Csengeri, T., Bontemps, S., et al. 2010, A&A, 520, A49
Schneider, S., & Elmegreen, B. G. 1979, ApJS, 41, 87
Schoier, F. L., van der Tak, F. F. S., van Dishoeck, E. F., & Black, J. H. 2005, A&A, 432, 369
Seifried, D., & Walch, S. 2015, MNRAS, 452, 2410
Smith, R. J., Glover, S. C. O., & Klessen, R. S. 2014, MNRAS, 445, 2900
Smith, R. J., Glover, S. C. O., Klessen, R. S., & Fuller, G. A. 2016, MNRAS, 455, 3640
Stephens, I. W., Dunham, M. M., Myers, P. C., et al. 2017, ApJ, 846, 16
Storm, S., Mundy, L. G., Fernández-López, M., et al. 2014, ApJ, 794, 165
Tafalla, M., & Hacar, A. 2015, A&A, 574, A104
Tafalla, M., Myers, P. C., Caselli, P., Walmsley, C. M., & Comito, C. 2002, ApJ, 569, 815
Tanaka, T., Nakamura, F., Awazu, Y., et al. 2013, ApJ, 778, 34
Teixeira, P. S., Takahashi, S., Zapata, L. A., & Ho, P. T. P. 2016, A&A, 587, A47
Ysard, N., Abergel, A., Ristorcelli, I., et al. 2013, A&A, 559, A133