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ALMA observations of NGC 6334S. II. Subsonic and Transonic Narrow Filaments in a High-mass Star Formation Cloud

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ABSTRACT

We present a study of narrow filaments toward a massive infrared dark cloud, NGC 6334S, using the Atacama Large Millimeter/submillimeter Array (ALMA). Thirteen gas filaments are identified using the $H^{13}CO^+$ line, while a single continuum filament is revealed by the continuum emission. The filaments present a compact radial distribution with a median filament width of ∼0.04 pc narrower than the previously proposed 'quasi-universal' 0.1 pc filament width. The higher spatial resolution observations and higher-density gas tracer tend to identify even narrower and lower mass filaments. The filament widths are roughly twice the size of embedded cores. The gas filaments are largely supported by thermal motions. The nonthermal motions are predominantly subsonic and transonic in both identified gas filaments and embedded cores, which may imply that stars are likely born in environments of low turbulence. A fraction of embedded objects show a narrower velocity dispersion compared with their corresponding natal filaments, which may indicate that the turbulent dissipation is taking place in these embedded cores. The physical properties (mass, mass per unit length, gas kinematics, and width) of gas filaments are analogous to those of narrow filaments found in low- to high-mass star-forming regions. The more evolved sources are found to be farther away from the

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filaments, a situation that may have resulted from the relative motions between the YSOs and their natal filaments.

Keywords: Interstellar filaments (842), Protoclusters (1297), Interstellar medium (847), Interstellar line emission (844), Star formation (1569), Star forming regions (1565), Early-type stars (430), Infrared dark clouds (787)

1. INTRODUCTION

Filamentary structures of interstellar medium (ISM) are prevalent in nearby Gould Belt molecular clouds and also more distant molecular clouds as seen in recent Galactic plane surveys from far-infrared to centimeter wavelengths and in both continuum and molecular line emission (Churchwell et al. 2009; André et al. 2010; Molinari et al. 2010; Arzoumanian et al. 2011; Goodman et al. 2014; Wang et al. 2015; Zucker et al. 2015; Contreras et al. 2016; Li et al. 2016; Soler et al. 2020; Wang et al. 2020). These filaments show wide ranges of physical properties (e.g., length, width, mass, length-to-width aspect ratios, and masses per unit length) that can vary over an order of magnitude across the revealed filaments.

Similar filamentary structures are also commonly seen in both numerical hydrodynamic (HD) and magneto-hydrodynamic (MHD) simulations of the ISM (e.g., Padoan et al. 2007; Heitsch et al. 2008; Gong & Ostriker 2011; Hennebelle 2013; Gómez & Vázquez-Semadeni 2014). Several mechanisms have been proposed for the formation of filaments in molecular clouds, such as gravitational instability (gravitational fragmentation and collapse) of sheet-like and elongated clouds (Miyama et al. 1987; Nagai et al. 1998; Hartmann & Burkert 2007; Hennebelle 2013; Gómez & Vázquez-Semadeni 2014; Van Loo et al. 2014), cloud collision (Padoan et al. 2001), and shocked flows (Gong & Ostriker 2011; Chen et al. 2020).

In dense and self-gravitating clouds, filaments often exhibit cylindrical morphologies. (e.g.,Taurus B213; Li & Goldsmith 2012). Large scale filaments often harbor parsec-scale dense massive clumps that become the fertile ground of massive star and cluster formation (Zhang et al. 2009; Jiménez-Serra et al. 2014; Wang et al. 2014; Busquet et al. 2016), although not all filaments show signs of star-formation activity (e.g., only pre-stellar cores are detected in Polaris flare; Miville-Deschênes et al. 2010). The embedded dense cores that are precursors of stars can be formed in the highest density regions of the filament via contraction by self-gravity and local kinematic processes (Inutsuka & Miyama 1992; Hartmann & Burkert 2007; Heitsch et al. 2008, 2009; Nakamura & Li 2008; Myers 2009; Gong & Ostriker 2011). The prestellar cores and protostellar cores are primarily found to reside in dense filamentary structures with supercritical mass per unit length in both low- and high-mass star-forming molecular clouds (André et al. 2014; Chung et al. 2019; Treviño-Morales et al. 2019), and most of them are believed to have formed by cloud collapse and/or fragmentation along filaments (Men'shchikov et al. 2010; André et al. 2014; Henshaw et al. 2014; Peretto et al. 2014; Beuther et al. 2015; Könyves et al. 2015; Clarke et al. 2017). The gas flows along filaments can continuously supply the material for cores to grow in mass (Liu et al. 2012; Kirk et al. 2013; Lin et al. 2017; Yuan et al. 2018; Lu et al. 2018; Liu et al. 2019; Treviño-Morales et al. 2019; Sanhueza et al. 2021).

Recently, ALMA high angular resolution observations reveal that narrow (i.e., filament widths of a few 0.01 pc) filamentary structures (or "fibers" in Hacar et al. 2018), are found in some high-mass star-forming clouds (e.g., Orion, G035.39-00.33, and G14.225-0.506; Henshaw et al. 2014; Hacar et al. 2018; Monsch et al. 2018; Chen et al. 2019b, and references therein). These filaments are much narrower than the 'quasi-universal' 0.1 pc filament width proposed by previous studies using *Herschel* observations (e.g., André et al. 2014; Arzoumanian et al. 2019, and references therein), and appear to be intimately linked to dense cores (Hacar et al. 2018). However, whether such narrow filamentary structures are ubiquitous in high-mass star formation clouds, and what their properties are remain controversial topics to be more fully explored.

To understand the nature of filaments and embedded dense cores in massive star formation regions, we have carried out high angular resolution observations toward a filamentary infrared dark cloud, NGC 6334S, using the Atacama Large Millimeter/submillimeter Array (ALMA). NGC 6334S is located at the southwestern end of the NGC 6334 molecular cloud complex (Figure 1), which is a nearby (1.3 kpc) young and massive "mini-starburst" region (Chibueze et al. 2014; Willis et al. 2013). In contrast to the well-known infrared bright OB cluster-forming clumps NGC 6334I/I(N)/II/III/IV/V (Persi & Tapia 2008; Russeil et al. 2013), NGC 6334S in some areas is dark in the infrared at wavelengths up to 70 μm (see Figure 1 of Li et al. 2020a, hereafter Paper I), signalling its youth. NGC 6334S has a mass of ∼1390 $M_\odot$ (Paper I), which is comparable to the clumps with embedded massive protostars and protoclusters elsewhere in the complex, and therefore has the potential to form massive stars together with lower-mass star clusters. Thus NGC 6334S provides an ideal laboratory to investigate the early evolutionary stages of cluster formation in filamentary clouds. We will use dense gas tracers and continuum emission not only to identify the filamentary structures in the position-position-velocity (PPV) space but also to study the physical properties (e.g., gas kinematics, mass, structure profile) of both filaments and dense cores, in order to understand the initial cloud environment of filament-based cluster formation.

We recently identified 49 continuum dense cores (hereafter continuum cores, named respectively #1, #2, #3 ...) using our 3 mm continuum image (Paper I) and found 17 starless cores (hereafter NH_2D cores, namely M1, M2, M3 ...) using the NH_2D line emission (Li et al. 2021, hereafter Paper II). These NH_2D cores are neither associated with continuum cores nor with Class I/II young stellar objects (YSOs; Willis et al. 2013). For simplicity, we refer to continuum cores and NH_2D cores as dense cores. The derived masses of dense cores range from 0.13 to 14.1 $M_\odot$, with the mean and median values of 1.8 and 0.8 $M_\odot$, respectively. The sizes of dense cores are between 0.01 and 0.04 pc, with the mean and median values of 0.018 and 0.017 pc, respectively. Paper I also shows that the nonthermal motions are predominantly subsonic and transonic throughout NGC 6334S and that the external pressure is important in confining the embedded objects. Paper II reported the presence of a cluster of low-mass starless and pre-stellar cores that show small velocity dispersions, a high fractional abundance of NH_2D, high NH_3 deuterium fractionation, and are dark at infrared wavelengths to 70 μm. In at least some of the NH_2D cores, turbulence seems dissipated and the gas kinematics is dominated by thermal motions.

In this work, we focus on filaments and investigate their properties as well as the relationship between filaments and dense cores. The observations are described in Section 2. Then, we describe the filament identification and the properties of identified filaments in Section 3. We discuss in detail the properties of filaments and dense objects in Section 4. Finally, we summarize our main findings in Section 5.

2. OBSERVATION

We have carried out a 55-pointings mosaic observation with ALMA 12m array towards the massive infrared dark cloud (IRDC) NGC 6334S between March 13 and 21 of 2017 (ID: 2016.1.00951.S). Two 234.4 MHz wide spectral windows were employed to cover the $H^{13}CO^+$ (1-0, 86.7 GHz) and NH_2D ($1_{1,1} - 1_{0,1}$, 85.9 GHz) lines with a 0.061 MHz spectral resolution (∼0.21 km s^{-1} at 86 GHz). In addition, three 1.875 GHz wide spectral windows centered at 88.5 GHz, 98.5 GHz, and 100.3 GHz with a spectral resolution of 0.977 MHz (∼3.0 – 3.3 km s^{-1}) were used to take broad band continuum data. More details on the observations can be found in Paper I.

Data calibration was performed using the CASA 4.7.0 software package (McMullin et al. 2007). Both continuum and line images were iteratively cleaned with manual masking via the *clean* task down to ∼3σ using the multiscale deconvolver and a robust weighting of 0.5. The resultant continuum and line images have a synthesized beam of $\theta_{\rm maj} \times \theta_{\rm min} = 3''.6 \times 2''.4$ (or 0.023 × 0.015 pc, with a position angle P.A = 81°) and $\theta_{\rm maj} \times \theta_{\rm min} = 4''.1 \times 2''.8$ (or 0.026 × 0.018 pc, P.A = 83°), respectively. The achieved 1σ root mean square (rms) noise levels are 0.3 mJy beam^{-1} for the continuum image and ∼6 mJy beam^{-1} per 0.21 km s^{-1} for the spectral line images. The maximum recoverable scale (MRS) of single pointing reaches up to ∼30″ in the ALMA data. All images shown in this paper are prior to primary beam correction. The measured fluxes for mass estimation have the primary beam correction applied.

3. RESULTS AND ANALYSIS

NGC 6334S is mostly dark at infrared wavelengths to 70 μm indicating its early evolutionary stage. (e.g., Sanhueza et al. 2013, 2019; Tan et al. 2013; Contreras et al. 2018; Sanhueza et al. 2017; Li et al. 2019a; Morii et al. 2021). Figure 1 shows an overview of the NGC 6334 molecular cloud complex in the far-infrared and the location of NGC 6334S.

3.1. *Molecular Lines Emission*

The rotational transitions of several molecular species (i.e., HCO^+ (1–0), HCN (1–0), CS (2–1), HNCO ($4_{0,4} - 3_{0,3}$), $H^{15}NC$ (1–0), CH_3OH ($5_{1,4} - 4_{1,3}$), SO ($2_2 - 1_1$), HC_3N (11–10)) were detected with a coarse spectral resolution of 0.977 MHz (or ∼3.0 – 3.3 km s^{-1}). However with these low spectral resolution data we are not able to determine the kinematic properties of the molecular gas. Therefore, only the high spectral resolution (0.061 MHz ∼ 0.21 km s^{-1}) data of the $H^{13}CO^+$ (1-0) and NH_2D ($1_{1,1} - 1_{0,1}$) lines will be used as diagnostics of the kinematic properties of the filaments in this work.

Figures 1 and 2 show the $H^{13}CO^+$ line, continuum, and NH_2D line emission. The $H^{13}CO^+$ (1-0; critical density $n_{\rm cr} \sim 10^5$ cm^{-3}) line traces spatially much more

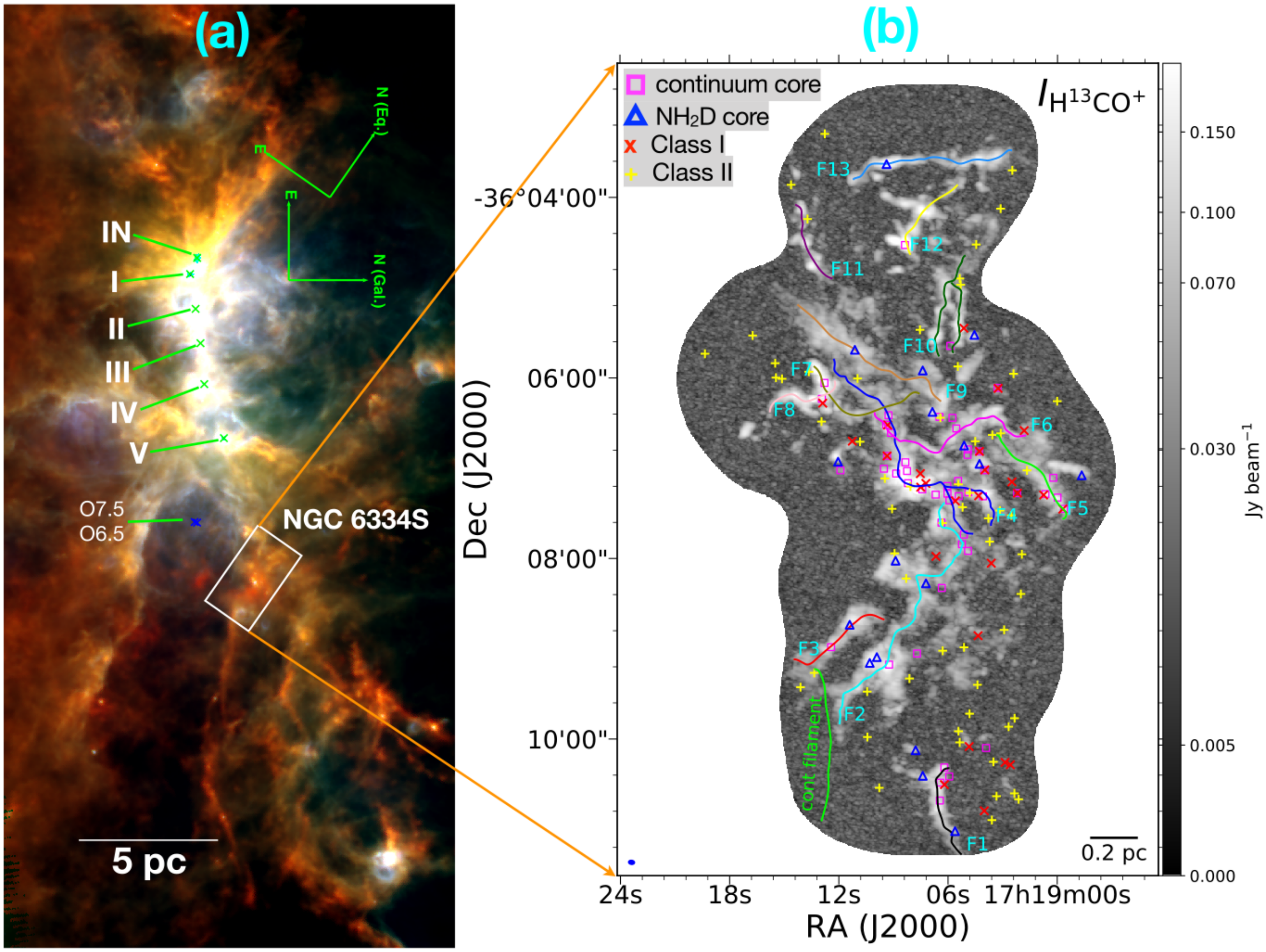

Figure 1. Panel a: three-color *Herschel* composite image of NGC 6334 molecular cloud complex with blue, green, and red for $\lambda = 70$, 160, and 350 μm, respectively. The scale bar (5 pc at the distance of 1.3 kpc), the Equatorial and the Galactic cardinal directions are shown on the upper right hand of the image. The white box presents the NGC 6334S region. Six bright infrared (IR) clumps (I, IN, II, III, IV, and V) are marked in the image (McBreen et al. 1979). Two O type stars (O7.5 and O6.5) are marked with blue cross "x" symbols (Persi & Tapia 2008). Panel b: the filament spines (color solid curves) overlaid on the peak intensity ($I_{\mathrm{H^{13}CO^+}}$; the maximum intensity of the spectrum) image of $\mathrm{H^{13}CO^+}$ line emission. Magenta open squares correspond to the 49 continuum cores identified by the ALMA 3mm continuum image (Paper I). Blue open triangles show the 17 $\mathrm{NH_2D}$ cores revealed by the $\mathrm{NH_2D}$ line emission (Paper II). The red cross "x" and yellow plus "+" symbols correspond to the 25 Class I and 58 Class II YSOs (Willis et al. 2013), respectively. The beam size (blue filled ellipse) of the $\mathrm{H^{13}CO^+}$ image is shown in the bottom left of the panel.

extended gaseous structures than the $\mathrm{NH_2D}$ ($1_{1,1} - 1_{0,1}$; $n_{\mathrm{cr}} \sim 10^6$ cm^{-3}) line since their critical densities are different by nearly an order-of-magnitude. The $\mathrm{NH_2D}$ emission appears preferentially toward the location of dense cores. In addition, the $\mathrm{H^{13}CO^+}$ emission is in a better agreement with the *Spitzer* dark and *Hershcel* bright filamentary structures than that of $\mathrm{NH_2D}$ (see also Paper I). These all suggest that the $\mathrm{H^{13}CO^+}$ emission is a better tracer of filamentary structures than $\mathrm{NH_2D}$. In what follows, the $\mathrm{H^{13}CO^+}$ will be therefore used to identify the velocity-coherent filamentary structures. There is the continuum filamentary structure in the south-eastern part of the map (see Figures 1 and 2), which continuum emission is unlikely dominated by dust emission (See discussions below in Section 4.1).

We used the $\sim$7$''$ resolution $\mathrm{NH_3}$ rotational temperatures ($T_{\mathrm{NH_3}}$) derived in paper I. For the regions where the $\mathrm{NH_3}$ data are not available, we assume a gas kinematic temperature of $\langle T_{\mathrm{NH_3}} \rangle = 15$ K, the average gas temperature derived from the observed $\mathrm{NH_3}$ data.

3.2. *Velocity Structures*

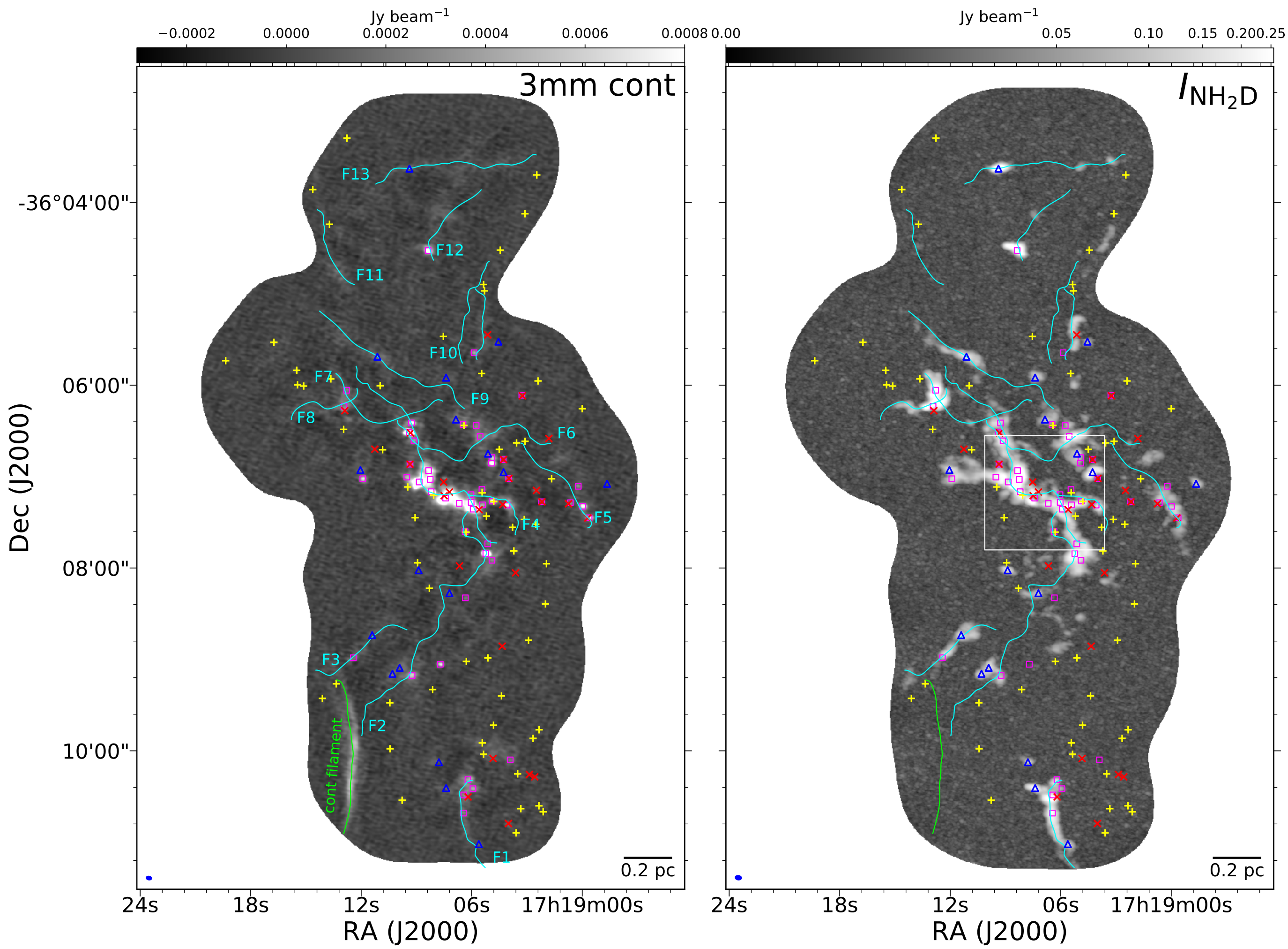

Figure 2. Magenta open squares, blue open triangles, red cross "x", and yellow plus "+" symbols show the continuum cores, NH_2D cores, Class I, and Class II, respectively. Left: the filament spines (cyan and green solid curves) overlaid on the 3 mm continuum image. Right: the filament spines (cyan and green solid curves) overlaid on the peak intensity map ($I_{\mathrm{NH_2D}}$) of the NH_2D line emission. White box shows the region where outflows are identified, with zoomed-in views presented in Figures 9. The beam size is shown in the bottom left of each panel.

Paper I found that multiple velocity components were detected in some areas where significant $H^{13}CO^+$ emission was detected. Since the majority ($\sim$85%) of $H^{13}CO^+$ emission appears as a single velocity component, we show the intensity-weighted velocity (1st-moment) and intensity-weighted dispersion (2nd-moment) of the $H^{13}CO^+$ line emission in Figure 3. We note that there are complex velocity structures across NGC 6334S, especially toward the central region which appears to be associated with multiple velocity components.

We fit Gaussian line profiles to the $H^{13}CO^+$ data pixel by pixel with multiple velocity components, under the assumption that the $H^{13}CO^+$ emission is optically thin. The detailed fitting process of molecular lines is summarized in the Paper I. The observed velocity dispersions (σ_{obs}) derived from the Gaussian fitting are between 0.10 and 0.80 km s^{-1}, with mean and median values of 0.23 and 0.20 km s^{-1}, respectively. The observed σ_{obs} is composed of the thermal and nonthermal components. Paper I shows that the nonthermal velocity dispersion σ_{nth} is dominated by subsonic and transonic motions throughout NGC 6334S. The σ_{obs} of the dense cores is greater than in the quiescent regions; the σ_{nth} and the σ_{obs} toward the central region of NGC 6334S, have generally larger values than that measured in the outer regions (see Paper I).

3.3. *Filament Identification*

3.3.1. *Friend-of-Friend Algorithm*

The results from the Gaussian fitting as described above in Section 3.2 were used to identify gas fila-

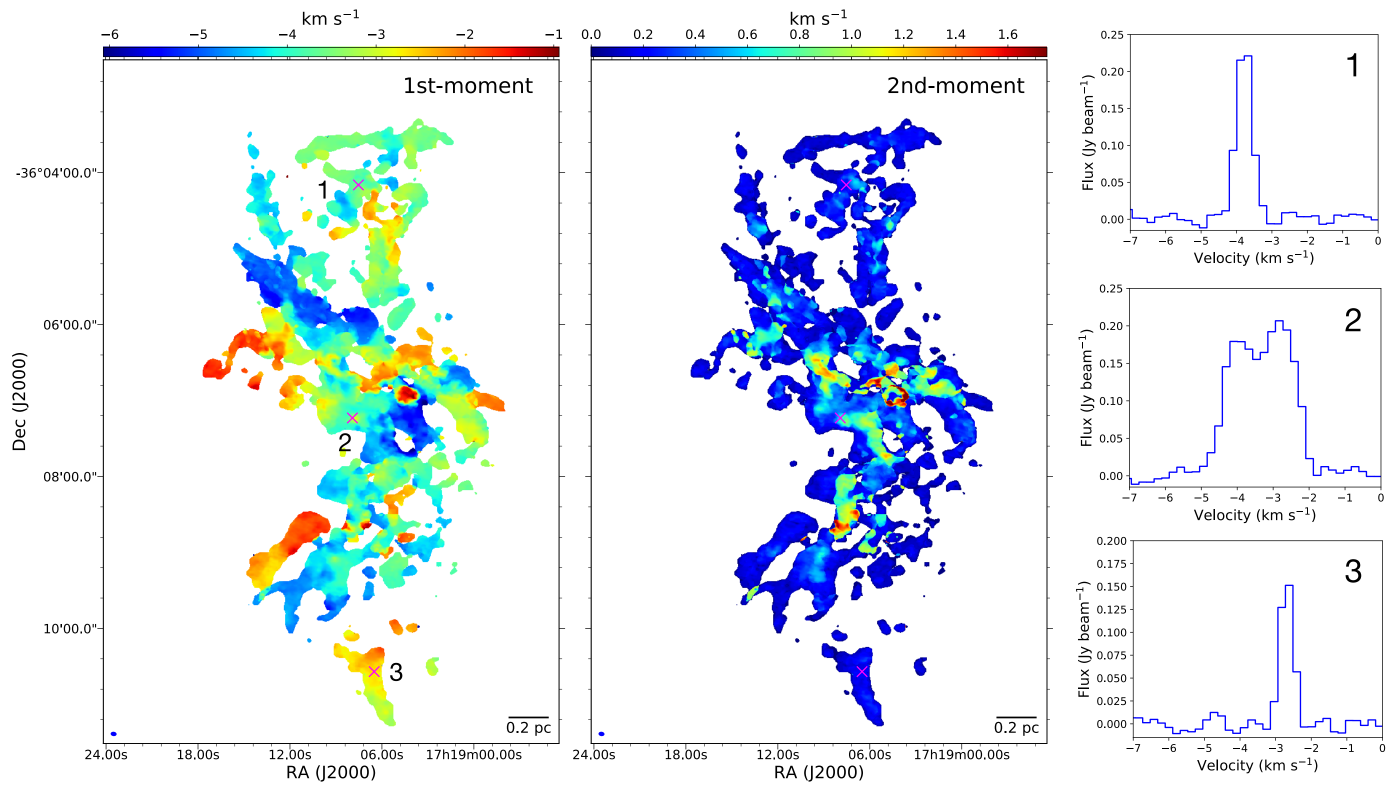

Figure 3. Left and middle panels show the $H^{13}CO^+$ intensity-weighted velocity (1st-moment) and intensity-weighted dispersion (2nd-moment) maps, respectively. The beam size is shown in the bottom left of each panel. Right panel shows the spectra of $H^{13}CO^+$ extracted from positions 1, 2, and 3. Three selected positions are marked with red cross "x" in both left and middle panels.

ments. Following similar procedures as Hacar et al. (2013, 2018), we used the python-based friend-of-friend (fof) algorithm[1] (Huchra & Geller 1982) to identify the velocity-coherent filaments, i.e., no abrupt change of sign of the gradient along the filament in PPV space.

We first used the fof algorithm to identify the seed points, those that have peak intensities (I, the maximum intensity of the spectrum) above a certain threshold I_0 (7σ), of each individual structure. In total, about $\sim$70% of the data points are above I_0. The spatial criterion between nearby points to be considered as friends is $\Delta r \leqslant 0.023$ pc ($\sim$1 beam size linear scale), while the velocity criterion uses an adaptive velocity gradient $\nabla v_{\mathrm{LSR},i} = \frac{1}{2}\frac{\triangle v_i}{\theta_{\mathrm{FWHM}}}$ similar to the definition in Hacar et al. (2018). Here, $\triangle v_i$ is the line full width half maximum (FWHM) of $H^{13}CO^+$ of the ith pixel and θ_{FWHM} is the beam size. Only structures that contain more than 150 data points (the area of a structure larger than 3 times the beam size) were considered. Second, we ran fof again to search for new friend points of each group identified in the first step, where the new friend points come from the remaining data points, in which the low intensity points ($\leqslant I_0$) are encompassed; the same spatial and velocity criteria are used. After the second fof run, there are about 20% of points that are not included within any group. The majority of them have relatively low intensities and/or appear to unaffiliated with the identified filaments.

We employed the `FilFinder`[2] algorithm to compute the filament spine. The `FilFinder` package reduces the masking area to identify a skeleton that represents the topology of the area, using a Medial Axis Transform. The masking area is delineated by the spatial distribution of the identified filaments; we refer to the derived skeletons as the filament spines. The derived filament spines are shown in Figure 1. In total, 13 velocity-coherent filaments have been identified by the fof algorithm from the PPV space of $H^{13}CO^+$ data. Filaments are named F1, F2, F3 ... in order from south to north. Filaments F4 and F10 have additional branches and they are named as F4b and F10b. The physical

[1] https://github.com/ShanghuoLi/pyfof

[2] https://github.com/e-koch/FilFinder

lengths of these identified filaments ($L_{\rm fil}$) range between 0.4 and 1.3 pc.

3.3.2. *Velocity-Coherent Filaments*

The filament spines overlaid on the channel maps of $H^{13}CO^+$ are shown in Figure 4, which shows that the line emission exhibits a filamentary distribution and that the identified filaments are consistent with the majority of the $H^{13}CO^+$ emission. This provides further evidence that the python-based fof algorithm can accurately recover the gas filamentary structures that are connected in both velocity and space (see also Figure 5).

Several small regions show significant $H^{13}CO^+$ emission but are not grouped into any identified filament. For instance, there is a small $H^{13}CO^+$ emission region on the west of F2 at velocity range of between -4.20 and 3.78 km s^{-1}, which is marked with red arrows in Figure 4. Two separated substructures appear in this small region, implying the emission is not connected in the spatial space. There are also some isolated small regions separated from the identified filaments in spatial space. These isolated regions fail to be considered as an independent filament because their emission is too weak and/or the number of total data points are lower than the criteria of identification. We stress that the identified filaments are likely to be incomplete. Potential low density and diffuse molecular filamentary structures could have been missed if their $H^{13}CO^+$ line emission is not significant and/or the detection suffers from severe missing flux.

The $H^{13}CO^+$ line emission of identified filaments generally spans $\geqslant 4$ channels (a velocity range of $\geqslant 0.84$ km s^{-1}). The filament with the largest spread in velocity is F4, which spans from -6.52 to -2.3 km s^{-1}. The majority of the filaments are spatially distinct, while several filaments partly overlap in position, such as F2–F4, F4–F6, F4–F7, and F7-F8. The overlapping regions tend to show complex velocity structures as characterized by multiple velocity components along the line of sight.

3.4. *Filament Profile*

We employed the `RadFil`[3] package (Zucker & Chen 2018), a radial density profile building and fitting tool for interstellar filaments, to construct the filament radial profile from the velocity integrated intensity of $H^{13}CO^+$ inside the mask of a given filament. We used the `RadFil` tangent to the filament spine at 7 or 8 pixel (about 1 beam size; 1 pixel = $0''.43$) intervals along the filament, then took the radial cut perpendicular to each tangent. The radial profile has been shifted along each cut in order to ensure that it is centered on the pixel with the peak intensity. Figure 6 shows the radial cut and the pixels (blue points) of the peak in the radial cut for F1. Along each cut, the radial distance is calculated as the projected distance from the peak intensity. Prior to fitting the profile, the background was subtracted using the background subtraction estimator of `RadFil`. The background is estimated by a first-order polynomial to all profiles at the given radial distance range, and then subtracts it from each cut; the background subtraction radii vary slightly from filament to filament, with a typical range of 0.08–0.15 pc.

To compute the filament widths (FWHM), we performed a Gaussian fitting to the average profile of the $H^{13}CO^+$ intensity of each filament. The Gaussian function is given by

$$A(r) = A_0 \exp\left(\frac{-(\mathrm{r}-\mu)^2}{2\sigma_{\rm G}^2}\right), \quad (1)$$

where r is the radial distance, A is the profile amplitude at the radial distance r, A_0 is the amplitude, σ_G is the standard deviation, and μ is the mean. Here, μ is fixed to zero. The best-fit Gaussian of each filament profile is listed in Table 1. An example of the fit is shown in Figure 6, where the red solid line is the best fit, the black dots correspond to the averaged integrated intensity of $H^{13}CO^+$ and the error bars are the standard deviation of the radial profile of all cuts perpendicular to the filament. The best-fit filament widths range from 0.036 to 0.074 pc, with the mean and median values of 0.046 and 0.045 pc, respectively. We also estimated the beam-deconvolved FWHM with $\mathrm{FWHM_{decon}} = \sqrt{\mathrm{FWHM}^2 - \mathrm{FWHM}_{\rm bm}^2}$, where $\mathrm{FWHM_{bm}}$ is the half-power beam width. The $\mathrm{FWHM_{bm}}$ is about $3''.4$ ($\sim$0.021 pc) in our observations. The $\mathrm{FWHM_{decon}}$ is between 0.029 and 0.071 pc, with the mean and median values of 0.041 and 0.039 pc, respectively.

In previous studies, observed filaments have been considered as cylindrical structures that can be described by a Plummer-like function of the form (e.g., Nutter et al. 2008; Arzoumanian et al. 2011; Palmeirim et al. 2013; Smith et al. 2014; Liu et al. 2018):

$$\int f dv(r) = \frac{A_0}{\left[1+\left(\frac{r}{R_{\rm flat}}\right)^2\right]^{\frac{p-1}{2}}}, \quad (2)$$

where $\int f dv$ is the integrated intensity, A_0 is the peak profile amplitude, $R_{\rm flat}$ is the flattening radius, and p is the power-law index of the density profile at large radii

[3] https://github.com/catherinezucker/radfil

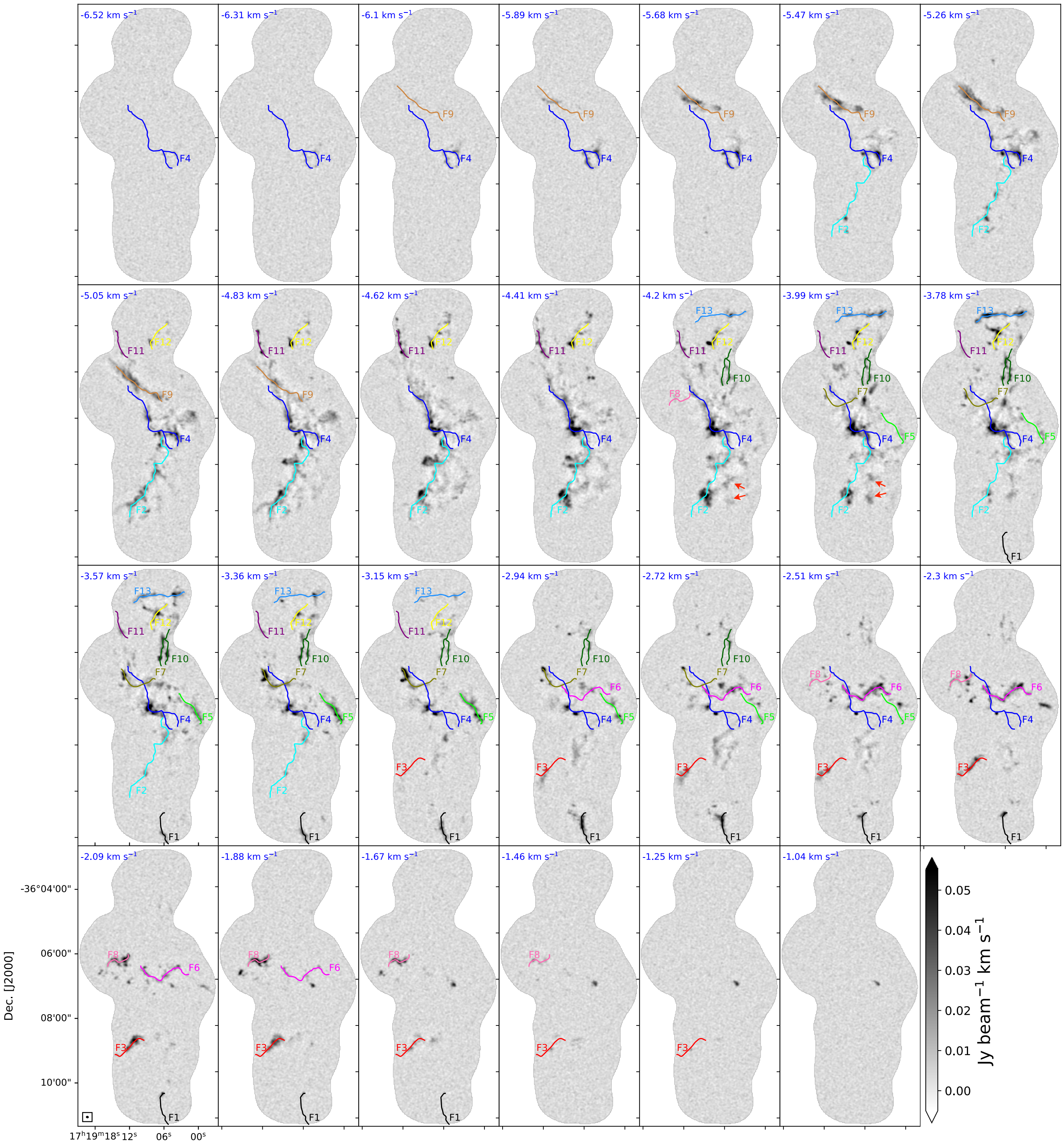

Figure 4. The filament spines (solid curves) overlaid on the channel map of $H^{13}CO^{+}$. The velocity value is presented in the top left of each panel.

(Cox et al. 2016; Zucker & Chen 2018). We also performed a Plummer fitting to the identified filaments in NGC 6334S. The best Plummer fit is shown in dashed green line in Figure 6. The filament widths derived by the Plummer fitting are similar to those of the Gaussian fitting, and FWHM ranges from 0.03 to 0.066 pc, with the mean and median values of 0.045 and 0.042 pc, respectively. The $\mathrm{FWHM_{decon}}$ is between 0.023 and 0.062 pc, with the mean and median values of 0.039 and 0.037 pc (Table 1), respectively. $R_{\rm flat}$ is between 0.012

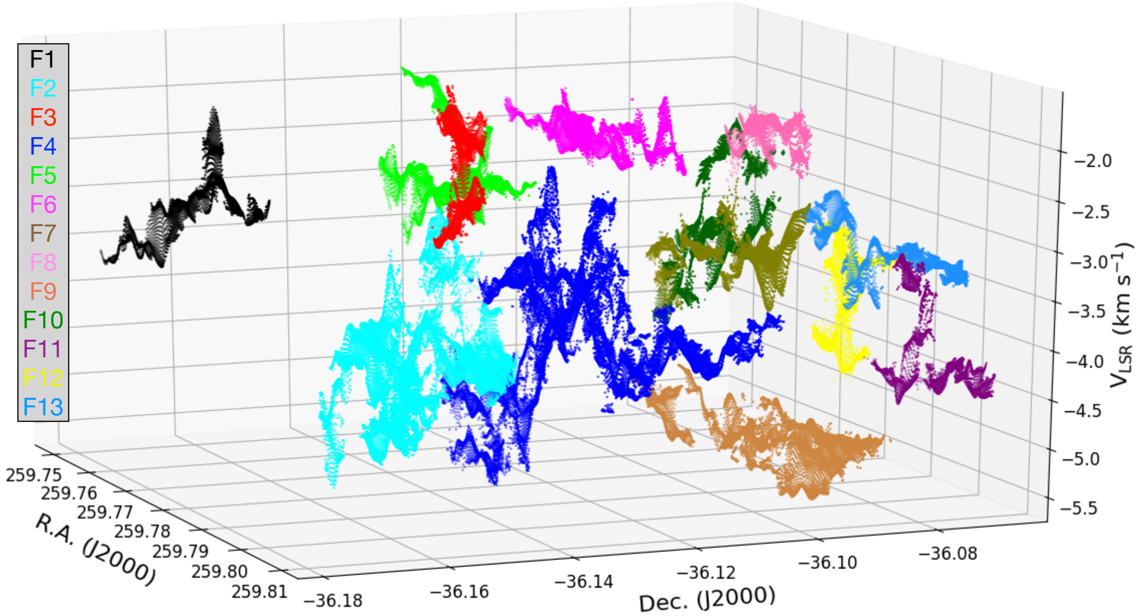

Figure 5. Position-position-velocity (PPV) cube shows the centroid velocity of the identified filaments. (The animated version of the PPV cube is available in https://github.com/ShanghuoLi/NGC6334S-filament.)

and 0.081 pc, with a mean and median values of 0.033 and 0.027 pc, respectively. Figure 6 shows that some of the filament profiles have relatively large dispersions due to non-uniform line intensities throughout the filaments. The significant variations of $H^{13}CO^+$ emission across the filaments results in a poor fit in their profiles, e.g., F4 and F9.

The derived filament widths are similar to those of Musca ($\sim$0.07 pc; Kainulainen et al. 2016), Aquila/Polaris ($\sim$0.04 pc; Men'shchikov et al. 2010), Orion ($\sim$0.02 – 0.05 pc for OMC-1/2 and ISF; Hacar et al. 2018), G14.225-0.506 ($\sim$0.05 – 0.09 pc; Chen et al. 2019b), G035.39-00.33 ($\sim$0.028 pc; Henshaw et al. 2017), and L1287 ($\sim$0.03 pc; Sepúlveda et al. 2020). In contrast, the derived filament widths are narrower than those of *Herschel* filaments studied toward IC 5146 ($\sim$0.1 pc; Arzoumanian et al. 2019), Taurus ($\sim$0.1 pc; Palmeirim et al. 2013), NGC 6334IN and NGC 6334I ($\sim$0.24 pc; Russeil et al. 2013). But note that the spatial resolution of *Herschel* observations (beam size $\sim$ 36$''$) is much poorer than that of the ALMA observations. This supports the idea that higher spatial resolution observations and higher-density gas tracers can identify narrower filaments. In addition, the dust continuum emission cannot be resolved into separate filaments when they overlap, whereas velocities measurements generally can do so. Spatially blended filaments might broaden the measured filament widths (see also Henshaw et al. 2017). This also indicates that filaments identified with different procedures might show deviating filament widths.

3.5. *Filament Mass*

The mass per unit length is one important indicator for assessing the stability of filaments. The continuum emission from dust is one of the most frequently used measurement to compute the mass. Figure 2 shows the filament spines overlaid on the 3 mm continuum image. Unfortunately, only 2 gas filaments (F4 and F1) have significant continuum emission detection (Figure 2); the remaining 11 gas filaments are either only partly detected in continuum emission or not detected at all above 5σ. An alternative way to estimate the filament mass is to make use of molecular gas emission; in this work we use $H^{13}CO^+$. With the fractional abundance of $H^{13}CO^+$ relative to H_2, $X(H^{13}CO^+) = N(H^{13}CO^+)/N(H_2)$, the filament mass can be computed as follows:

$$M_{\rm fil} = \mu_{\rm H_2}\, m_{\rm H} \sum \frac{N({\rm H^{13}CO^+})}{X({\rm H^{13}CO^+})}\, \Omega, \tag{3}$$

where $N(H^{13}CO^+)$ is the column density of $H^{13}CO^+$, $\mu_{H_2} = 2.8$ is the mean molecular weight of the interstellar medium (ISM; Kauffmann et al. 2008), m_H is the hydrogen mass, and Ω is the solid angle of the $H^{13}CO^+$ emission. Assuming local thermodynamic equilibrium (LTE), the molecular column densities can be estimated from the velocity-integrated intensity (see Appendix A1), and finally leads to $M_{\rm fil}$ (see Eq.3).

In order to estimate $X(H^{13}CO^+)$ for NGC 6334S, we have focused on F4 because both $H^{13}CO^+$ line

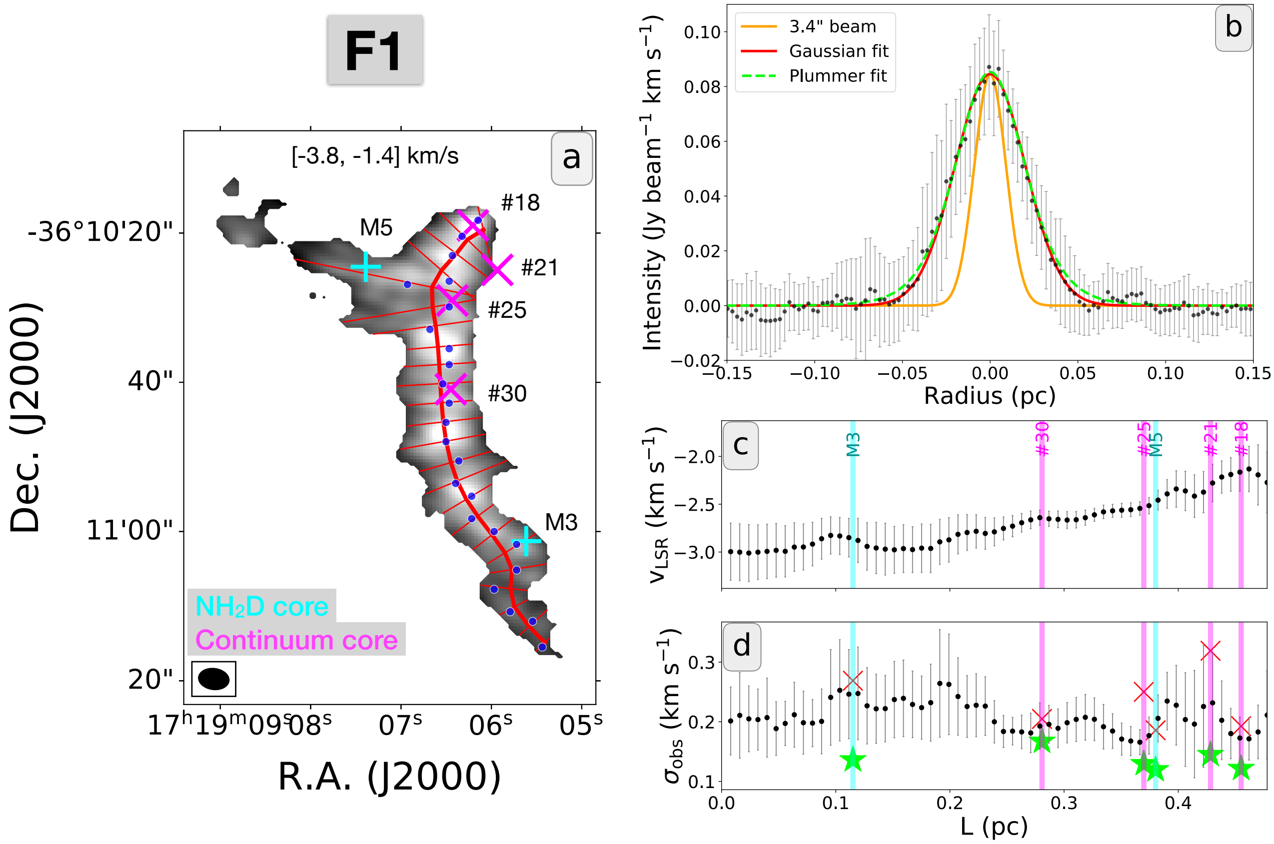

Figure 6. Panel a: the filament spine (red solid curves) of F1 overlaid on the velocity-integrated intensity map of $H^{13}CO^{+}$. Magenta cross "x" and cyan plus "+" symbols are continuum cores and NH_2D cores, respectively. The velocity range of this filament is presented in the upper middle of the panel. The beam size is shown in the bottom left of the panel. Panel b: mean integrated intensity profile of $H^{13}CO^{+}$ (black dots) was built by sampling radial cuts (short red solid lines) every 8 pixels (which corresponds to $3''.44$ or $\sim$0.019 pc at the source distance of 1.3 kpc) along the spine. The radial distance is the projected distance from the peak emission at a given cut (blue dots in panel a). The error bar represents the standard deviation of the cuts at each radial distance. The orange solid line shows the beam response with a FWHM of $\sim3''.4$. The red solid and green dashed lines present the best-fit results of Gaussian and Plummer fitting, respectively. Panel c and d: the mean centroid velocity $\langle v_{\rm LSR}\rangle$ and mean observed velocity dispersion $\langle \sigma_{\rm obs}\rangle$ of $H^{13}CO^{+}$ line variation along the filament. The error bars show the standard deviation of corresponding $v_{\rm LSR}$ and $\sigma_{\rm obs}$. Vertical magenta and cyan lines indicate the positions of associated continuum cores and NH_2D cores, respectively. The red cross "x" and green filled star symbols mark the core mean $\sigma_{\rm obs}$ derived from the $H^{13}CO^{+}$ and NH_2D lines, respectively. The complete figure set (4 images, see Figure 13) is available in the online journal.

and continuum emission are significantly detected (Figures 1 and 2). The derived $N(H^{13}CO^{+})$ ranges from 7.2×10^{11} cm^{-2} to 1.4×10^{13} cm^{-2} and N_{H_2} is between 1.3×10^{22} cm^{-2} and 6.1×10^{23} cm^{-2}. The resulting values of $X(H^{13}CO^{+})$ extend from 7.7×10^{-12} to 3.1×10^{-10}, with a median value of 5.4×10^{-11}. The derived $X(H^{13}CO^{+})$ is similar to the reported values of 3.0×10^{-11} – 4.0×10^{-10} in Butner et al. (1995), 4.5×10^{-11} in Gerner et al. (2014), 4.8×10^{-10} in Sanhueza et al. (2012), and 1.3×10^{-10} in Hoq et al. (2013).

Using the median $X(H^{13}CO^{+}) = 5.4\times10^{-11}$, we estimated the gas mass ($M_{\rm fil}$) for each filament. The derived masses are in the range of 4 – 82 $M_\odot$ (see Table 1) and the total gas mass in the filaments is about 342 $M_\odot$. The total gas mass estimated from $H^{13}CO^{+}$ in the observed region is about 395 $M_\odot$, which indicates that these filaments contain most of the dense gas (87% = 342/395), as revealed by the total $H^{13}CO^{+}$ line emission (see Section 4.5 below). The masses per unit length ($M_{\rm line} = M_{\rm fil}/L_{\rm fil}$) of filaments range between 14 and 64 $M_\odot$ pc^{-1}, with a median value of 29 $M_\odot$ pc^{-1} (see Table 1).

The uncertainties in the distance, assumed gas temperature, and variations of the $H^{13}CO^{+}$ fractional abundance introduce uncertainties in the estimates of the filament masses and masses per unit length. The typical uncertainties in the temperatures derived from NH_3 is $\sim$15% (see Paper I). The uncertainty in distance

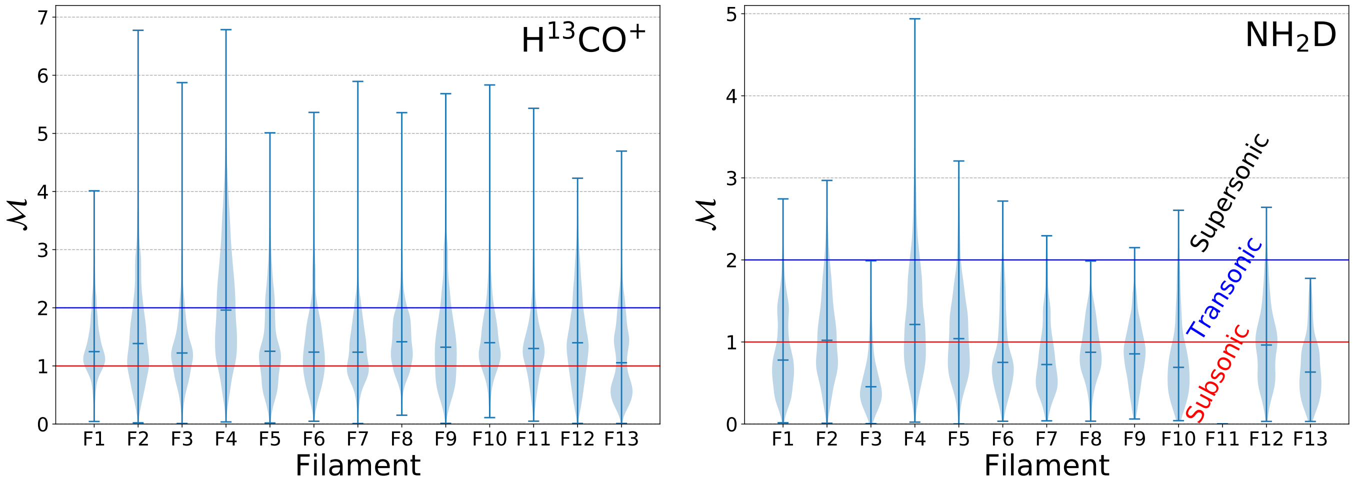

Figure 7. Left and right: violin plots of the Mach number distributions derived from $H^{13}CO^+$ and NH_2D for each filament. The blue bars from the top to bottom represent the maximum, mean, and minimum values, respectively. The red and blue solid lines are the Mach number of 1 and 2, respectively.

from the trigonometric parallax measurement is $\sim$20% (Chibueze et al. 2014). The standard deviation (std) of $X(H^{13}CO^+)$ for F4 is about 3.7×10^{-11}, which corresponds to 1σ uncertainty of $70\% = \frac{3.7\times10^{-11}}{5.4\times10^{-11}}$. We settle on an uncertainty estimate of a factor of $\sim$2 for both filament mass and mass per unit length according to the propagation of error. Considering of the inclination angle is unknown, the uncertainties in the mass per unit length could be larger.

3.6. *Subsonic and Transonic Filaments*

The three-dimensional (3D) Mach number is $\mathcal{M} = \sqrt{3}\sigma_{\rm nth}/c_{\rm s}$, where $\sigma_{\rm nth} = \sqrt{\sigma^2_{\rm obs} - (\triangle_{\rm ch}/2\sqrt{2\ln 2})^2 - \sigma^2_{\rm th}}$ is the nonthermal velocity dispersion, $c_{\rm s}$ is the sound speed, and $\triangle_{\rm ch}$ is the channel width. The molecular thermal velocity dispersion can be estimated by $\sigma_{\rm th} = \sqrt{(k_{\rm B}T)/(\mu m_{\rm H})} = 0.098\,{\rm km\,s^{-1}}\,(\frac{T}{\rm K})^{0.5}\mu^{-0.5}$, where $\mu = m/m_{\rm H}$ is the molecular weight, m is the molecular mass, $m_{\rm H}$ is the hydrogen mass, and T is the gas temperature (see also Paper I). The sound speed $c_{\rm s}$ was estimated using a mean molecular weight per free particle of $\mu_{\rm p}$=2.37 (Kauffmann et al. 2008). Figure 7 shows the Mach number ($\mathcal{M}$) distributions derived from $H^{13}CO^+$ and NH_2D for each filament, except for F11 which has no significant NH_2D detection. Some filaments are partially overlapping but the corresponding NH_2D line emission shows only one velocity component clearly. This NH_2D emission is assigned to a particular filament based on the minimum velocity differences between NH_2D emission and that filament. The Mach number distributions derived from both $H^{13}CO^+$ and NH_2D lines reveal that the majority of filaments are subsonic ($\mathcal{M} \leqslant 1$) and transonic ($1 < \mathcal{M} \leqslant 2$) in nonthermal motions. In general, the $\mathcal{M}$ derived from NH_2D tends to be smaller than those from $H^{13}CO^+$. This is because NH_2D emission traces colder, denser gas and it is less affected by the protostellar feedback (e.g., outflows) as compared to the $H^{13}CO^+$ emission; this is confirmed by the fact that the observed line widths of the former narrower than those of the latter. The subsonic and transonic features imply a quiescent nature of these filaments. The subsonic and transonic nonthermal line widths found here in dense filaments and dense cores have been seen previously in low-mass star-forming regions (e.g., Perseus, Pineda et al. 2010; Serpens, Gong et al. 2021; Ophiuchus and Taurus, Chen et al. 2019a; L1478 in the California, Chung et al. 2019), intermediate- and high-mass star-forming regions (e.g., Orion, Hacar et al. 2018; Monsch et al. 2018; Yue et al. 2021; IRDC G035.39-00.33, Sokolov et al. 2018; IRDC G14.225–0.506, Chen et al. 2019b).

4. DISCUSSION

4.1. *Continuum Filament*

The majority of the continuum emission structures have a significant line emission counterparts. One exception is the continuum filamentary structure in the south-eastern part of the map (see Figures 1 and 2), which has no line emission counterpart except for a small area near the middle that shows weak emission in the $H^{13}CO^+$, CS, HCN and HCO^+ lines. If this filamentary structure's continuum emission was dominated by free-free or synchrotron emission rather than dust emission, the stellar feedback from O type stars (O7.5 and O6.5, see Figure 1; Persi & Tapia 2008) on the north-eastern side of NGC 6334S are most likely responsible.

We used the `FilFinder` to extract this filamentary structure and its filament spine (see Figure 8). The fil-

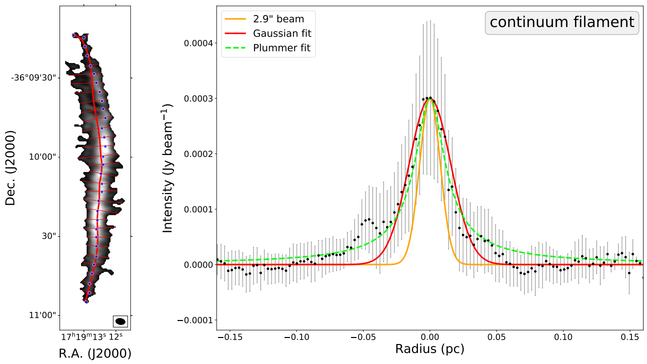

Figure 8. Left: the filament spine (red solid curve) of continuum filament overlaid on the 3 mm continuum image. Right: mean integrated intensity profile (black dots) was built by sampling radial cuts (short red solid lines) every 8 pixels (3″.44 corresponds to ∼0.019 pc at the source distance of 1.3 kpc) along the spine. The radial distance is the projected distance from the peak emission at a given cut (blue dots in the left panel). The error bar represents the standard deviation of the cuts at each radial distance. The orange solid line shows the beam response with a FWHM of ∼2.9″. The red solid and green dashed lines present the best-fit results of Gaussian and Plummer fitting, respectively.

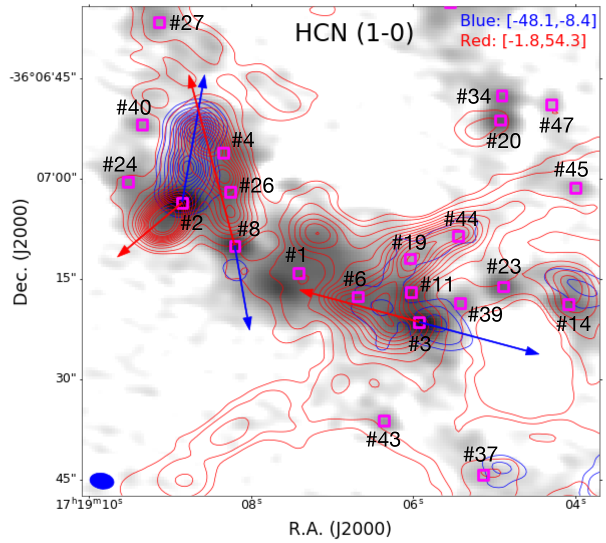

Figure 9. Magenta open squares show the continuum cores. The blue-shifted (blue contours) and red-shifted (red contours) of HCN (1-0) line emission overlaid on the continuum image. The arrows show the outflow directions. The beam size is shown in the bottom left of each panel.

ament length is about 0.8 pc. Using `Radfil`, the filament widths are about 0.032 pc and 0.023 pc derived by Gaussian and Plummer fitting based on the continuum emission (Table 1), respectively. The gas mass cannot be reliably estimated because of the unknown fraction of dust emission.

4.2. *The Kinematics of Filaments*

Figure 6 shows the variations of $v_{\rm LSR}$ and $\sigma_{\rm obs}$ derived from the H^{13}CO$^+$ line emission along the filament. Only one filament (F1) shows monotonic changes along the filament in $v_{\rm LSR}$. In contrast, the $\sigma_{\rm obs}$ shows small fluctuations along F1 rather than monotonic change. Four continuum cores and two NH$_2$D cores are associated with this filament. The core mean $\sigma_{\rm obs}$ derived from the H^{13}CO$^+$ line is comparable to the $\sigma_{\rm obs}$ of filament, however continuum cores #25 and #21 have slightly larger $\sigma_{\rm obs}$. Line widths may be broadened by active star formation. In contrast, some cores show much narrower $\sigma_{\rm obs}$ than their respective filament; e.g., #31/#36/#49 in F2, #4/#24 in F4, M11 in F5, M10 in F6, M14 in F10. The measured $\sigma_{\rm obs}$ of NH$_2$D is always narrower than those of H^{13}CO$^+$ toward the continuum cores and NH$_2$D cores, and this feature is also seen in the filaments (see Figure 7). In Section 4.4, we will discuss the properties of $\sigma_{\rm obs}$ in both continuum cores and NH$_2$D cores.

Some filaments show only small $v_{\rm LSR}$ variations along their spine (F4b, F5, F7, F8, F10, F10b, F12), while others display significant variations (F2, F3, F4, F6, F9, F11, F13). The $\sigma_{\rm obs}$ also shows irregular variations in all of filaments, except for F1 and F13. The latter shows roughly an increasing trend from east to west (Figure 13). There is another gaseous structure seen in the CS (1-0), HCO$^+$ (1-0), and HCN (1-0) lines, which runs northwest to southeast through the western part of F13. The interaction between two gas flows can broaden the H^{13}CO$^+$ line widths around the intersection regions. On the other hand, the star formation activity is responsible for some of the $v_{\rm LSR}$ and $\sigma_{\rm obs}$ variations in some filaments. For instance, F4 shows $v_{\rm LSR}$ and $\sigma_{\rm obs}$ variations at positions in which several strong molecular outflows are detected in the HCN, HCO$^+$, and CS lines (see Figure 9). These molecular outflows can inject energy and momentum into the immediate surroundings of protostars and affect the gas kinematics, and then the turbulence (or line width) will be increased and the gas velocity will be modified (Li et al. 2019b, 2020b; Lu et al. 2021). Filament F4 encompasses the highest number of continuum cores and YSOs among the filaments (Figures 1 and 13), and therefore the $v_{\rm LSR}$ and $\sigma_{\rm obs}$ of the H^{13}CO$^+$ line emission in F4 is most likely significantly affected by protostellar feedback. Overall, both protostellar activity and interaction between gas flows can significantly alter the local gas kinematics.

4.3. *Velocity Gradient Along F1*

As shown in Figure 6, F1 presents a smooth velocity change in H^{13}CO$^+$ emission from the south (-3.3 km

s^{-1}) to the north (-1.8 km s^{-1}) along the filament, resulting in a projected velocity gradient of ∼1.8±0.1 km s^{-1} pc^{-1}. The NH_2D line emission also shows a similar velocity gradient along F1. The velocity gradient along F1 could be attributed to the ongoing accretion flow in F1 (e.g., Kirk et al. 2013), whereas we cannot completely rule out the possibility that the gas kinematics is affected by the external feedback from the western YSOs, such as molecular outflows and/or expanding shells.

If the velocity gradient comes from the accretion flow along the F1 filament, one can estimate the mass flow rate using the derived velocity gradient and filament mass. Assuming that the filament has a cylindrical geometry, the mass flow rate, $\dot{M}$, can be calculated as (see Kirk et al. 2013)

$$\dot{M} = \frac{M\,\nabla_{||}v_{\rm obs}}{\tan(\alpha)} \tag{4}$$

where M is the filament mass, $\nabla_{||}v_{\rm obs}$ is the observed velocity gradient along the filament, and α is the angle of inclination to the plane of sky. Using the derived filament mass of 14 $M_\odot$, the observed velocity gradient of 1.8 km s^{-1} pc^{-1}, and assuming a moderate inclination angle of $\alpha = 45°$, the mass flow rate is estimated to be about 26 $M_\odot$ Myr^{-1} for F1. This result indicates that the F1 filament will double its mass in several free-fall time; $\sim 1\times10^5$ yrs assuming a density of 10^{5-6} cm^{-3} that is the typical value of continuum cores in the F1 (see Paper I).

Considering the uncertainties of the derived mass and inclination angle, the estimated flow accretion is roughly comparable to the values of 70±40 $M_\odot$ Myr^{-1} in the IRDC G035.39–00.33 (Henshaw et al. 2014), and 17 – 72 $M_\odot$ Myr^{-1} in the Monoceros R2 (Treviño-Morales et al. 2019), and 20 – 130 $M_\odot$ Myr^{-1} in the IRDC G14.225–0.506 (Chen et al. 2019b). The estimated mass flow rate could be treated as a lower limit, because the $H^{13}CO^+$ only traces relatively high dense gas and F1 filament is only a small part of a much large filamentary structure seen in the infrared image (see Figure 1).

A velocity gradient is also detected in sections of the other filaments (e.g., F7 and F13) and around some embedded cores (e.g., #29 in the F3; see Figure 13). Unfortunately, in these cases we cannot distinguish whether the velocity gradient is the result of gas flow or some other physical process, e.g., molecular outflow or rotation. Thus, we refrain from estimating the mass flow rate for other filaments.

4.4. *The Kinematics of Embedded Cores*

As mentioned in Section 4.3, some cores show smaller $\sigma_{\rm obs}$ compared to their immediate surrounding. This is probably because the surrounding gas is affected by the protostellar activity (e.g., molecular outflows) for some cores. For instance, there is a molecular outflow emanating from #2 in the immediate vicinity of cores #4 and #24, thus the $H^{13}CO^+$ line widths around both #4 and #24 can be broadened by this outflow activity (see Figure 2). The outflow driven by core #8 also affects the molecular gas around the core #4. The details of molecular outflow analysis is beyond the scope of this paper but is the topic of a followup paper.

Furthermore, some of the cores indeed have narrow line widths as revealed by the NH_2D line, which is less affected by the molecular outflows than $H^{13}CO^+$ as mentioned above. In addition, there are no outflow signatures around these cores. For instance, the observed velocity dispersion appears to decrease toward the center of M1 (See Figure 10). A trend of $\sigma_{\rm obs}$ decreasing with decreasing radial distance ($R_{\rm dist}$) from the center of core is found in 16 cores (see Figure 10), including 6 continuum cores (#5, #10, #22, #25, #35, and #37) and 10 NH_2D cores (M1, M4, M6, M7, M8, M9, M13, M10, M15, and M17; see also Figure 3 in Paper II for M1). Note that the annularly averaged $\sigma_{\rm obs}$ has relatively large uncertainties toward the outer edges of the cores due to the low S/N. The decreasing trend of $\sigma_{\rm obs}$ toward these core centres may indicate that turbulent dissipation from the filaments to the embedded objects is ongoing, enabling the dense precursors to collapse to form protostars. Alternatively, a number of of theoretical studies suggest that for pre-stellar cores the line width will be smaller in the more central regions if the infall speed decreases toward the center because of an outside-in collapse (e.g., Whitworth & Summers 1985; Lai 2000; Gómez et al. 2021). In summary, some dense cores indeed have narrower observed velocity dispersion compared to their natal filaments. This may indicate that turbulent dissipation is taking place in these embedded cores.

4.5. *Filament Stability*

The comparison between the $M_{\rm line}$ and the corresponding critical line-mass $M_{\rm crit} = 2\sigma_{\rm eff}^2/G$ can be used to evaluate the stability of the filament; where $\sigma_{\rm eff}$ is the effective velocity dispersion and G is the gravitational constant (see Appendix B for the estimation of critical line-mass.). Ignoring external pressure and magnetic fields, we computed the $M_{\rm crit}$ for thermally supported ($\sigma_{\rm eff} = c_{\rm s}$), nonthermal motions supported ($\sigma_{\rm eff} = \sigma_{\rm nth}$), and total motions supported (i.e. including both thermal and nonthermal contributions, $\sigma_{\rm eff} = \sqrt{c_{\rm s}^2 + \sigma_{\rm nth}^2}$) filaments. As shown in Figure 11, $M_{\rm line}$ is larger than the thermal critical mass ($M_{\rm crit,th}$), except for F4b, F6

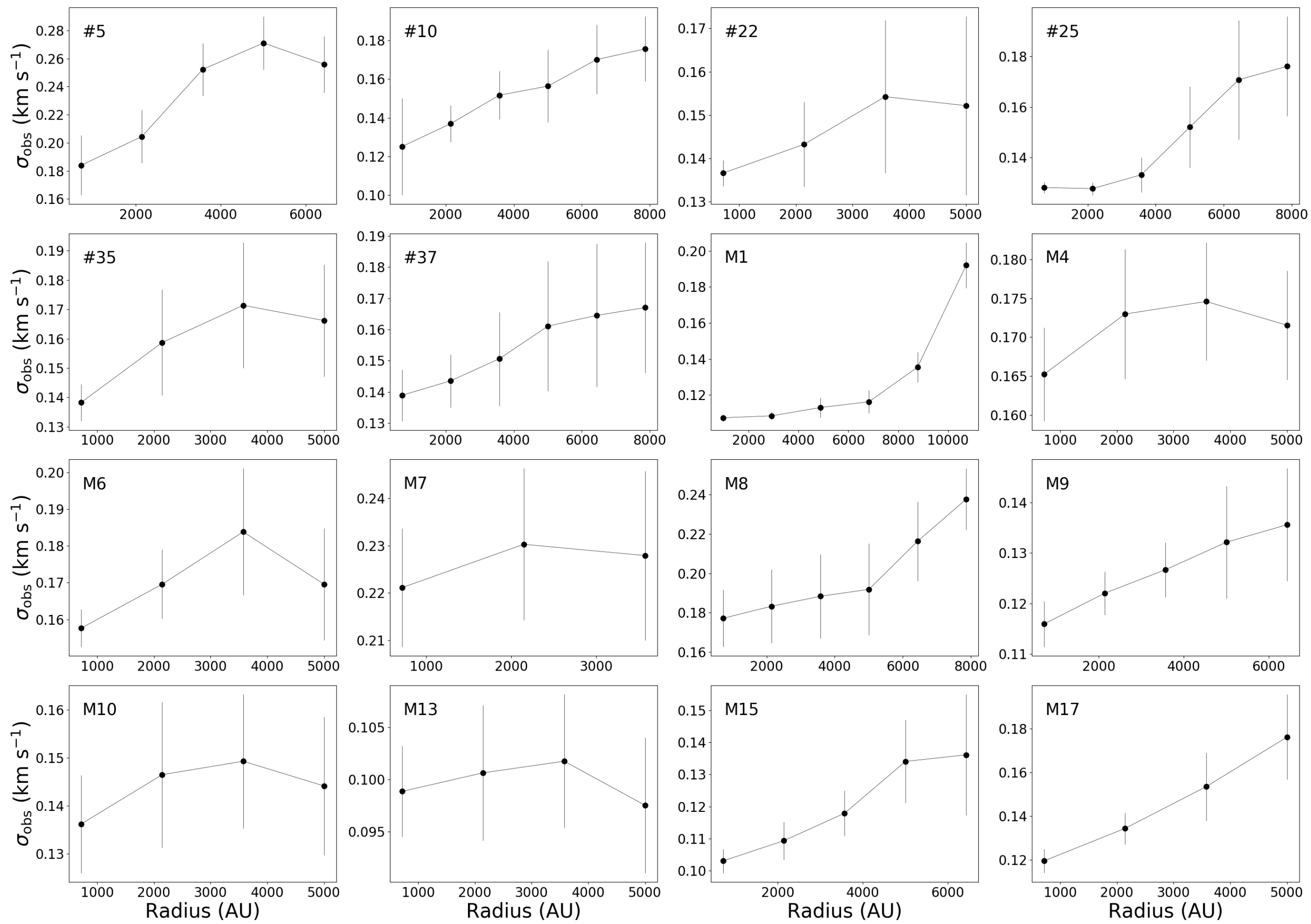

Figure 10. The annularly averaged observed NH_2D velocity dispersions ($\sigma_{\rm obs}$) as a function of radial distance from the center of cores. The error bars show the statistical standard deviation inside each ring divided by the square root of the length of the ring. M1 is modified from Paper II. The name of each core is shown in the top left of each panel.

and F13 that are smaller than the $M_{\rm crit,th}$. This indicates that the filaments would be gravitationally bound (except for F4b, F6 and F13) in the purely thermally supported case. $M_{\rm line}$ is about 2 times the nonthermal critical mass ($M_{\rm crit,nth}$), which suggests that nonthermal support alone cannot prevent gravitational collapse. The ratios of $M_{\rm crit,nth}/M_{\rm crit,th}$ are in the range 0.4–1.4 with a mean value of 0.7, which suggests that the filaments are mostly supported by thermal motions. The estimated $M_{\rm line}$ is smaller than the total critical ($M_{\rm crit,tot}$) mass in all the filaments, except for F4.

Although most of the filaments at the current evolutionary state are gravitationally unbound when considering only the balance between self-gravity and the thermal plus nonthermal support, the presence of dense cores suggests that in fact star formation has already started. Note that by neglecting external pressure, magnetic field, mass uncertainty, and inclination angle uncertainty might bring an addition error into the $M_{\rm line}/M_{\rm crit,tot}$. Being gravitationally bound is not the sole prerequisite for forming stars in a filament. The fragmentation may have occurred already very early in the evolution of the filaments, if these dense cores originate from filament fragmentation. In addition, the subsonic and transonic dominated filaments and embedded cores indicate that there are low turbulence environments (Paper II); this is analogous to the situation in low-mass star-forming clouds (e.g., Hartmann 2002; Pineda et al. 2010; Hacar & Tafalla 2011; Hacar et al. 2016, 2017). The similarity suggests that similar turbulent conditions may apply in the very early evolutionary phases of low- and high-mass star formation at clump scales ($\leqslant$ of a few pc) where turbulence inherited from larger scales (e.g., giant molecular clouds) has already decayed or dissipated in a short timeframe (Mac Low 1999; Mac Low & Klessen 2004).

Figure 11 shows $M_{\rm line}$ as a function of $\sigma_{\rm nth}/c_{\rm s}$. The derived masses per unit length are similar to those of narrow filaments in B213-L1495 (24±19 $M_\odot$ pc^{-1}), Musca (26 $M_\odot$ pc^{-1}), NGC 1333 (34±22 $M_\odot$ pc^{-1}), and Orion

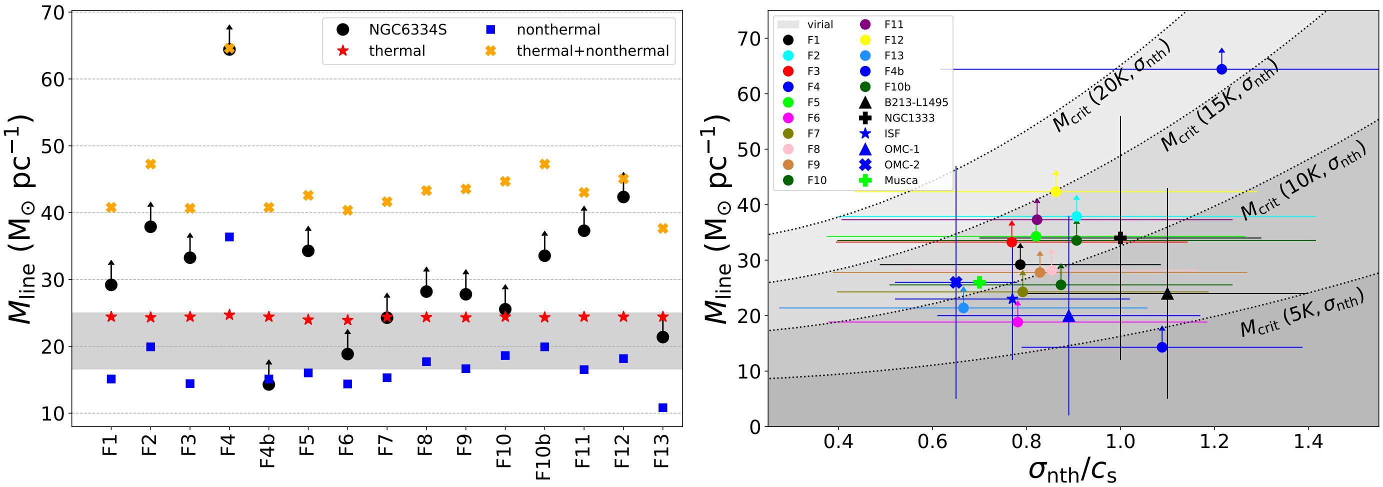

Figure 11. Left: the line-mass for each filament. The black filled circles, red filled stars, blue filled squares, and orange filled crosses show the estimated mass per unit length, thermal critical line-mass, nonthermal critical line-mass, and total (thermal + nonthermal) critical line-mass, respectively. The shaded gray region shows the thermal critical line-mass of 16.6 – 25 $M_\odot$ pc^{-1} corresponding to the gas temperature of 10 – 15 K. The arrows indicate that the estimated mass per unit length could be treated as a lower limit. Right: mass per unit length vs. $\sigma_{\rm nth}/c_{\rm s}$. The error bars indicate the standard deviation of the parameters. The dashed lines show the expected total critical line-mass for an infinite filament in hydrostatic equilibrium at temperatures of 5 K, 10 K, 15 K, and 20 K, respectively (see Appendix B). The data points of B213-L1495, NGC1333, ISF, OMC1, OMC2, and Musca are retrieved from Hacar et al. (2018).

(23±11 $M_\odot$ pc^{-1} for ISF, 20±18 $M_\odot$ pc^{-1} for OMC-1, and 26±21 $M_\odot$ pc^{-1} for OMC-2; Hacar et al. 2013, 2016, 2017, 2018). The measured $\sigma_{\rm nth}/c_{\rm s}$ are also comparable to those narrow filaments in the B213-L1495, Musca, NGC 1333, and Orion (OMC-1/2 and ISF; see Figure 11). These results indicate that the masses per unit length and gas kinematics of narrow filaments in NGC 6334S are comparable to those found in various other environments, from low-mass to high-mass star-forming molecular clouds.

The total gas mass computed from $H^{13}CO^+$ is about 395 $M_\odot$, which is larger than the total gas mass of 160 $M_\odot$ estimated from continuum emission. The $H^{13}CO^+$ recovers about 28% of the accumulated mass (1389 $M_\odot$) derived from H_2 column density map (derived in Paper I; see Appendix A in Paper I for detailed derivation of H_2 column density.) This indicates that the extended flux, which contains a significant amount of mass, is not fully recovered by the $H^{13}CO^+$ line toward NGC 6334S in this ALMA observation. The estimated filament masses should thus be treated as lower limits because $H^{13}CO^+$ (1-0; $n_{\rm cr}$ $\sim$ 10^5 cm^{-3}) only probes higher density gas components; moreover, the data suffer from missing flux due to the lack of short spacing observations.

4.6. *Population of Embedded Cores and YSOs*

The continuum cores are likely at protostellar or prestellar evolutionary phases, while the NH_2D cores seem at the starless/pre-stellar phases (see Paper II). Figure 1(b) shows the distribution of identified dense objects and filaments toward NGC 6334S. The majority of the 45 continuum cores are associated with filaments, while only 4 continuum cores (#22, #28, #33 and #48) are not associated with any identified filament. In addition, 15 out of 17 NH_2D cores are associated with filaments. These results indicate that the majority of dense cores are closely related with filaments in NGC 6334S; as noted earlier, this situation is also found in nearby low-mass star-forming regions (e.g., André et al. 2010).

Figure 1(b) also shows the YSOs spatial distributions toward NGC 6334S. There are 25 Class I and 58 Class II YSOs in the NGC 6334S. The Class I and II YSOs are identified with the near-IR (NEWFIRM) and mid-IR (IRAC) data (see Willis et al. 2013). Among the 49 identified continuum cores, 12 cores are spatially associated with Class I objects, 5 cores are spatially associated Class II objects, and the remaining 32 cores do not have YSOs counterparts. This indicates that these 32 cores could be younger compared to those cores associated with Class I and Class II YSOs. The majority of YSOs have no continuum core counterparts, perhaps because their continuum emission is too faint (1σ $\sim$ 0.03 mJy beam^{-1}, or $\sim$0.04 $M_\odot$ at a temperature of 10 K). Furthermore, the YSOs are not associated with NH_2D cores counterparts, because the NH_2D line emission is in cold dense gas still in its extremely early evolutionary stages (e.g., starless and/or pre-stellar).

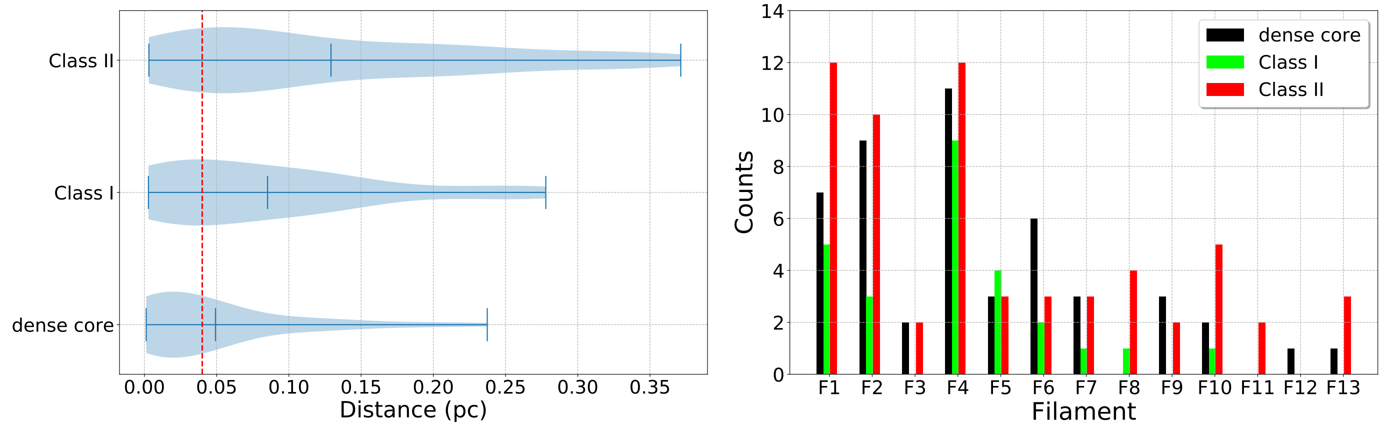

Figure 12. Left: violin plot of the distance distributions for each type object, where the distances are the objects to the nearest filament spine. The shape of each distribution shows the probability density of the data smoothed by a kernel density estimator. The blue bars from the top to bottom represent the maximum, mean, and minimum values, respectively. The vertical red dashed line is the mean beam-convolved filament width of ∼0.04 pc. Right: the number of the nearest dense cores, Class I and Class II objects for each filament.

The majority of continuum cores, NH_2D cores, and Class I objects reside in or close to a filament, while the majority of Class II objects are far away (see Figures 1 and 2). We computed the distance of these objects to their nearest filament spine, in order to search for possible correlations between the evolutionary stages and the distance from the filament. Based on the distance distribution of each type of object shown in Figure 12(a), Class II objects have larger distances than Class I, while Class I objects have larger distance than the distribution of continuum cores and NH_2D cores. Continuum cores and NH_2D cores are classified as the same type of object in this analysis because the majority of them are embedded in filaments and their evolutionary stages (pre-stellar or protostellar) are earlier than Class I/II (Paper II). The median distances are 0.09 pc, 0.06 pc, and 0.03 pc for Class II, Class I, and dense cores, respectively. Overall, Figure 12(a) indicates that the more evolved objects are further away from the dense gas filaments in NGC 6334S.

One possible explanation for the different distance distributions is that the evolved objects are moving away from their parental dense filament due to the kinematical motions (e.g., slingshot mechanism and ejection; Stutz & Gould 2016; Russeil et al. 2020). Assuming the Class II are moving 1 km s^{-1} relative to the filaments (the typical moving velocity of Class II in Orion; Stutz & Gould 2016), the estimated moving timescales are between $3{\times}10^3$ and $4{\times}10^5$ yr, with a median value of $9{\times}10^4$ yr. We would like to stress the fact that the actual moving distances may be much smaller than the estimated distances because the YSOs might not necessarily form in the centre of the filament. Therefore, the actual dynamical timescales could be smaller than the estimated values. Another possibility is that NGC 6334S has experienced star formation before, and the parental molecular structures of Class II have already been moved away from the YSOs (e.g., Vázquez-Semadeni et al. 2017; Kumar et al. 2020) or dispersed/destroyed by star formation feedback. Finally, we cannot rule out the possibility that a few Class II objects may have originated outside of NGC 6334S; especially those objects that are distant from the filaments.

The number of nearest dense cores, Class I, and Class II for each filament is presented in Figure 12(b). The number of dense cores and Class I around F4 is much higher than for the rest of filaments, while the number of Class II around F1, F2, and F4 is comparable and higher than in the other filaments. F4 is located at the central region where encompasses a significant fraction of dense gas and thus it has potential to form more stars as evidenced by the numerous continuum cores and YSOs. F2 has the longest physical length in NGC 6334S, and thus, it is expected to be associated with more YSOs. As shown in Figure 1, a cluster of YSOs is forming on the western side of F1, resulting in a large number of nearest YSOs. We note that F1 is only a small part of a much larger filamentary structure seen in the infrared image (see Figure 1), implying that it has a large dense gas reservoir from which to form more stars.

In summary, all identified filaments show a narrow width and the majority of them host embedded dense core. These embedded dense cores are born in environments of low turbulence, which is similar to conditions found in low-mass star-forming regions. More evolved objects are found to be farther away from the filaments, suggesting YSOs or filaments have a tendency to move away from their natal place as they evolve.

5. CONCLUSION

In this paper, we investigated the velocity-coherent filaments in the massive IRDC NGC 6334S using ALMA observations. Using the $H^{13}CO^+$ (1-0) line emission, we have identified 13 velocity-coherent filaments. We investigated the physical properties of the identified filaments and characterized the dense objects in the NGC 6334S. Our main findings are summarized as follows:

1. The filaments show a compact radial distribution with a median $\mathrm{FWHM_{decon}}$ of $\sim$0.04 pc. The derived filament widths are narrower than the previously proposed 'quasi-universal' 0.1 pc filament width. In addition, the filament widths are roughly twice the size of embedded cores (radius $\sim$0.017 pc). The higher spatial resolution observations and higher-density gas tracer tend to identify even narrower and lower mass filaments.

2. The nonthermal motions are predominantly subsonic and transonic in all observed filaments; the single exception is F4 which has been significantly affected by protostellar feedback. The filaments are largely supported by thermal motions. The physical properties (mass, mass per unit length, gas kinematics, and width) of filaments are similar to those seen in narrow filaments found in various other kinds of environments such as low-mass, intermediate-mass, and high-mass star-forming regions (i.e., B213-L1495, Musca, NGC 1333, Orion, and G035.39-00.33).

3. A fraction of the embedded objects show narrower observed velocity dispersions (σ_{obs}) than their natal filaments, which may indicate that turbulent dissipation is taking place in these embedded cores. The subsonic and transonic dominated filaments and dense cores indicate that in NGC 6334S the stars are often born in environments of low turbulent motions. This conclusion hints that similar small turbulent conditions exist at very early evolutionary stages of low- and high-mass star formation at clump scales.

4. The median distance to the nearest filament for dense cores, Class I, and Class II, is 0.03 pc, 0.06 pc, and 0.09 pc respectively. The increasing distances suggest that the more evolved objects are farther away from the filaments in the NGC 6334S, perhaps because either YSOs or filaments tend to move away from their natal place as they evolve.

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Facilities: ALMA, Herschel.

Software: CASA (McMullin et al. 2007), APLpy (Robitaille & Bressert 2012), Matplotlib (Hunter 2007), Astropy (Astropy Collaboration et al. 2013), PySpecKit (Ginsburg & Mirocha 2011), Numpy (Harris et al. 2020).

Table 1. Physical parameters of the filaments.

Filament	$L_{\rm fil}$	$M_{\rm fil}$	$M_{\rm line}$	$M_{\rm crit,tot}$	$M_{\rm crit,nth}$	$M_{\rm crit,th}$	Gaussian A$_0$	stddev	FWHM	FWHM$_{\rm decon}$	Plummer A$_0$	$R_{\rm flat}$	p	FWHM	FWHM$_{\rm decon}$
	(pc)	($M_\odot$)	($M_\odot$ pc^{-1})	($M_\odot$ pc^{-1})	($M_\odot$ pc^{-1})	($M_\odot$ pc^{-1})	(10^{-2} Jy/beam km/s)	(pc)	(pc)	(pc)	(10^{-2} Jy/beam km/s)	(pc)		(pc)	(pc)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
F1	0.48	14	29	41	15	24	8.45±0.12	0.020	0.047	0.042	8.53±0.12	0.057±0.009	9.78±2.37	0.047	0.042
F2	1.37	52	38	47	20	24	5.20±0.06	0.026	0.061	0.057	5.16±0.14	0.081±0.030	10.05±5.74	0.066	0.062
F3	0.50	17	33	41	14	24	7.30±0.11	0.023	0.054	0.049	7.25±0.20	0.051±0.012	6.27±1.99	0.056	0.051
F4	1.27	82	64	65	36	25	8.39±0.23	0.021	0.049	0.044	8.84±0.26	0.021±0.004	2.81±0.34	0.045	0.039
F4b	0.27	4	14	41	15	24	9.90±0.21	0.019	0.045	0.040	10.05±0.29	0.014±0.003	1.84±0.17	0.057	0.053
F5	0.53	18	34	41	16	24	6.37±0.16	0.024	0.056	0.052	6.73±0.22	0.024±0.004	2.78±0.30	0.051	0.047
F6	0.86	16	19	43	14	24	5.06±0.11	0.015	0.036	0.029	5.16±0.15	0.023±0.006	3.94±1.08	0.036	0.029
F7	0.62	15	24	40	15	24	3.65±0.18	0.016	0.037	0.030	3.77±0.22	0.015±0.006	2.40±0.55	0.038	0.032
F8	0.40	11	28	42	18	24	7.46±0.22	0.015	0.036	0.029	7.62±0.19	0.034±0.007	7.16±2.05	0.034	0.027
F9	0.82	23	28	43	17	24	3.92±0.13	0.031	0.074	0.071	4.29±0.15	0.021±0.005	2.17±0.24	0.064	0.060
F10	0.53	13	26	44	19	24	8.34±0.23	0.019	0.045	0.040	9.09±0.25	0.014±0.002	2.29±0.19	0.039	0.033
F10b	0.35	12	34	47	20	24	11.09±0.23	0.018	0.042	0.036	11.21±0.25	0.050±0.018	9.85±5.34	0.041	0.036
F11	0.42	15	37	45	17	24	11.22±0.23	0.017	0.040	0.034	11.35±0.25	0.045±0.014	9.11±4.18	0.039	0.033
F12	0.43	18	42	47	18	24	7.34±0.46	0.019	0.044	0.039	7.48±0.35	0.035±0.012	5.33±2.16	0.043	0.038
F13	0.78	17	21	43	11	24	5.68±0.18	0.016	0.037	0.030	5.84±0.18	0.030±0.007	5.67±1.56	0.035	0.028
cont filament[a]	0.80						0.029±0.001	0.016	0.037	0.032	0.032±0.001	0.012±0.002	2.47±0.23	0.030	0.023
mean	0.65	22	32	45	18	24	6.84±0.18	0.020	0.046	0.041	7.03±0.20	0.033±0.009	5.24±1.78	0.045	0.039
median	0.53	16	29	43	17	24	7.32±0.18	0.019	0.045	0.039	7.37±0.21	0.027±0.006	4.64±1.32	0.042	0.037
minimun	0.27	4	14	40	11	24	0.03±0.001	0.015	0.036	0.029	0.03±0.001	0.012±0.002	1.84±0.17	0.030	0.023
maximum	1.37	82	64	65	36	25	11.22±0.46	0.031	0.074	0.071	11.35±0.35	0.081±0.030	10.05±5.74	0.066	0.062

Notes. (2) Filament length. (3) Filament mass. (4) Filament mass per unit length. (5) Total critical line-mass. (6) Nonthermal critical line-mass. (7) Thermal critical line-mass. (8) – (11) The amplitude, standard deviation σ = FWHM/$(2\sqrt{2\ln(2)})$, and width, and beam-deconvolved width derived from the Gaussian fitting. (12)–(16) The amplitude, flattening radius, density profile, width, and beam-deconvolved width derived from the Plummer fitting. a: the amplitude unit is Jy beam^{-1}.

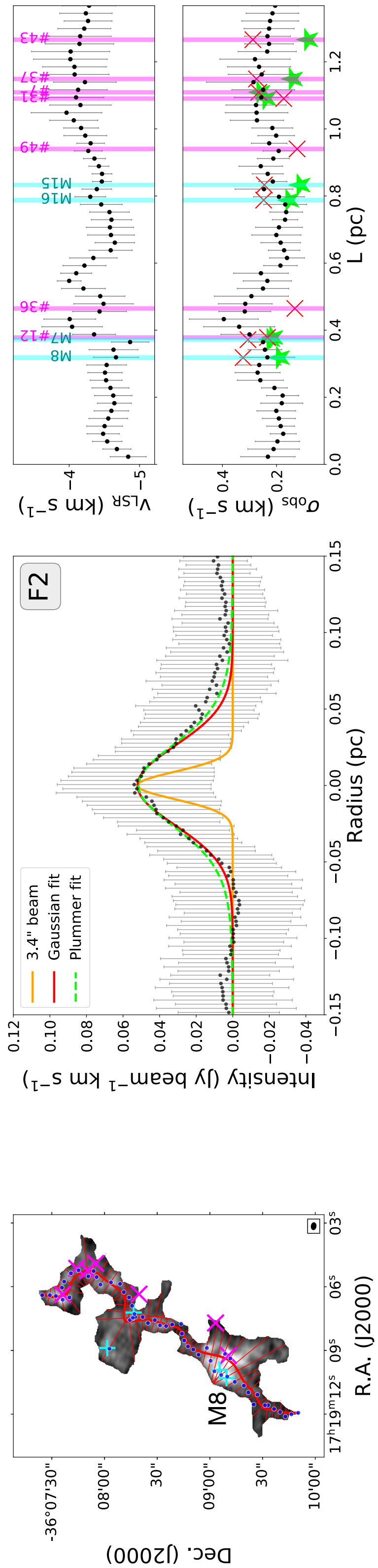


Figure 13. Left column: the filament spine (red solid curve) overlaid on the velocity-integrated intensity image. Magenta cross "x" and cyan plus "+" symbols are continuum cores and NH_2D cores, respectively. Middle column: mean integrated intensity profile and best-fit result (black dots) built by sampling radial cuts (short red solid lines) every 7 or 8 pixels ($3''.44$ corresponds to $\sim$0.019 pc at the source distance of 1.3 kpc) along the spine. The radial distance is the projected distance from the peak emission at a given cut (blue dots in the left column). The error bar represents the standard deviation of the cuts at each radial distance. The orange solid line shows the beam response with a FWHM of $\sim 3.'' 4$. The red solid and green dashed lines present the best-fit results of Gaussian and Plummer fitting, respectively. Right column: the mean $v_{\rm LSR}$ and mean $\sigma_{\rm obs}$ of $H^{13}CO^+$ line emission variation along the filament. The error bars show the standard deviation of corresponding $v_{\rm LSR}$ and $\sigma_{\rm obs}$. Vertical magenta and cyan lines indicate the positions of associated continuum cores and NH_2D cores, respectively. The red cross "x" and green filled star symbols mark the core mean $\sigma_{\rm obs}$ derived from the $H^{13}CO^+$ and NH_2D lines, respectively.

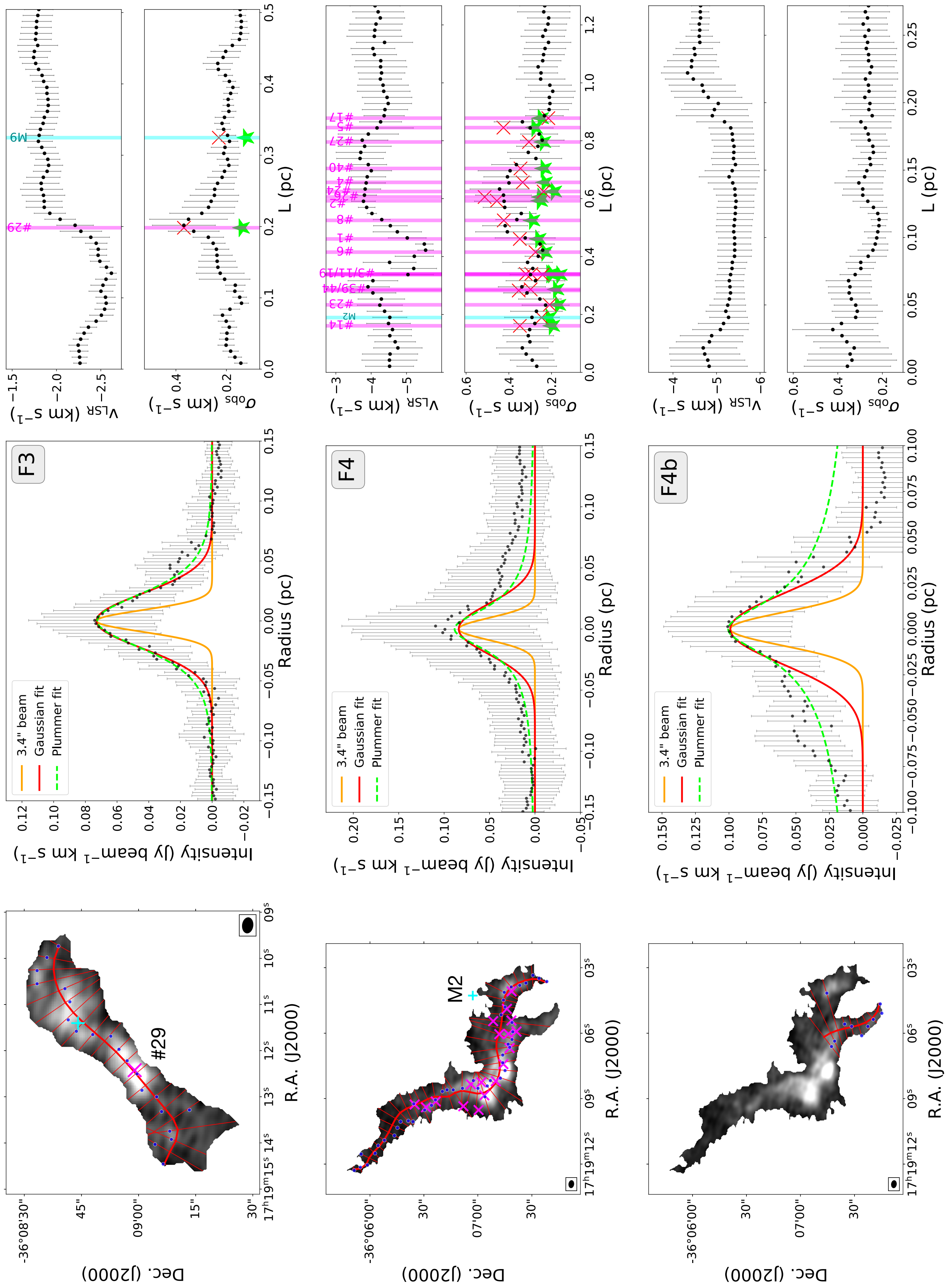


Figure 13.

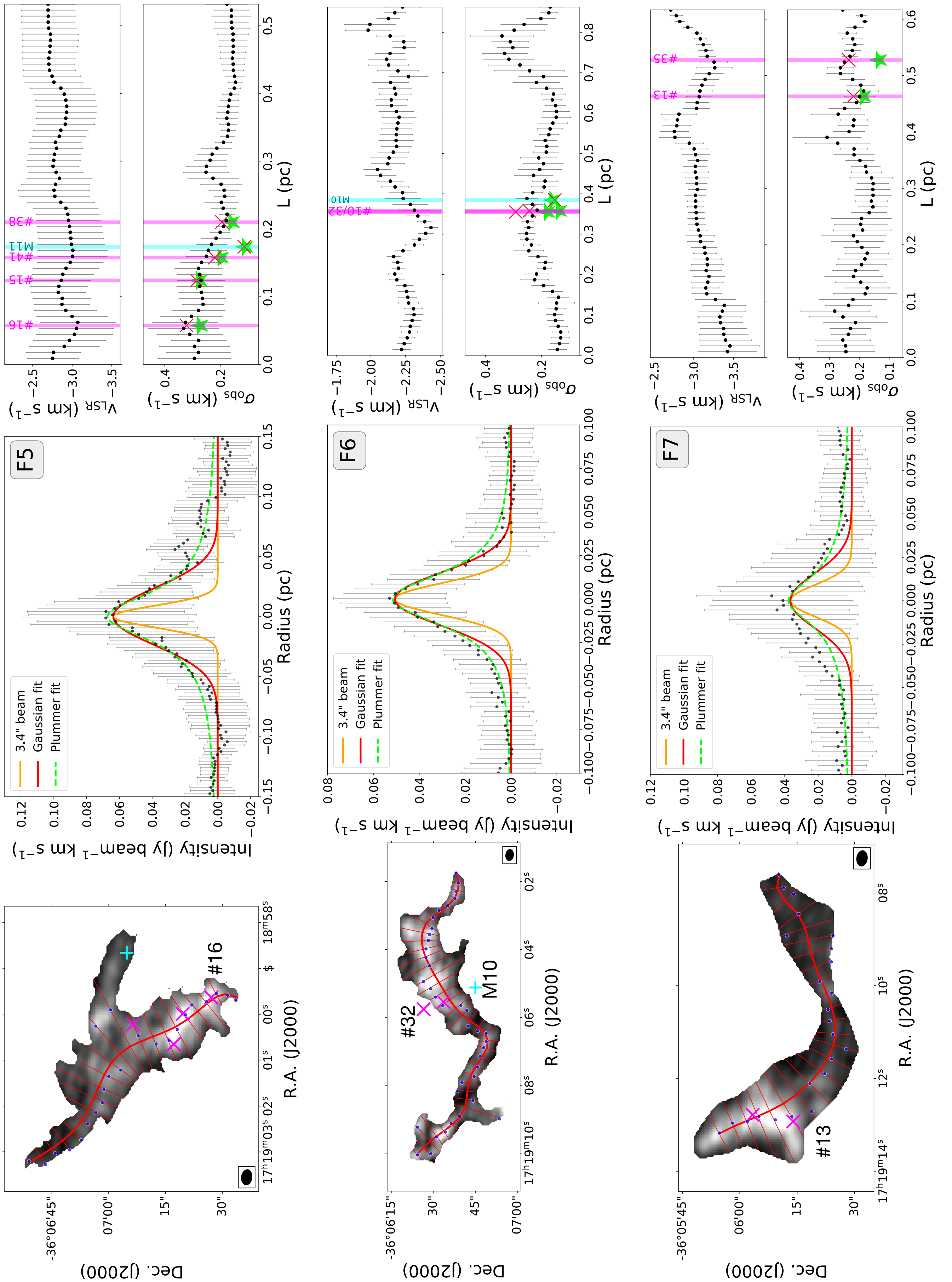
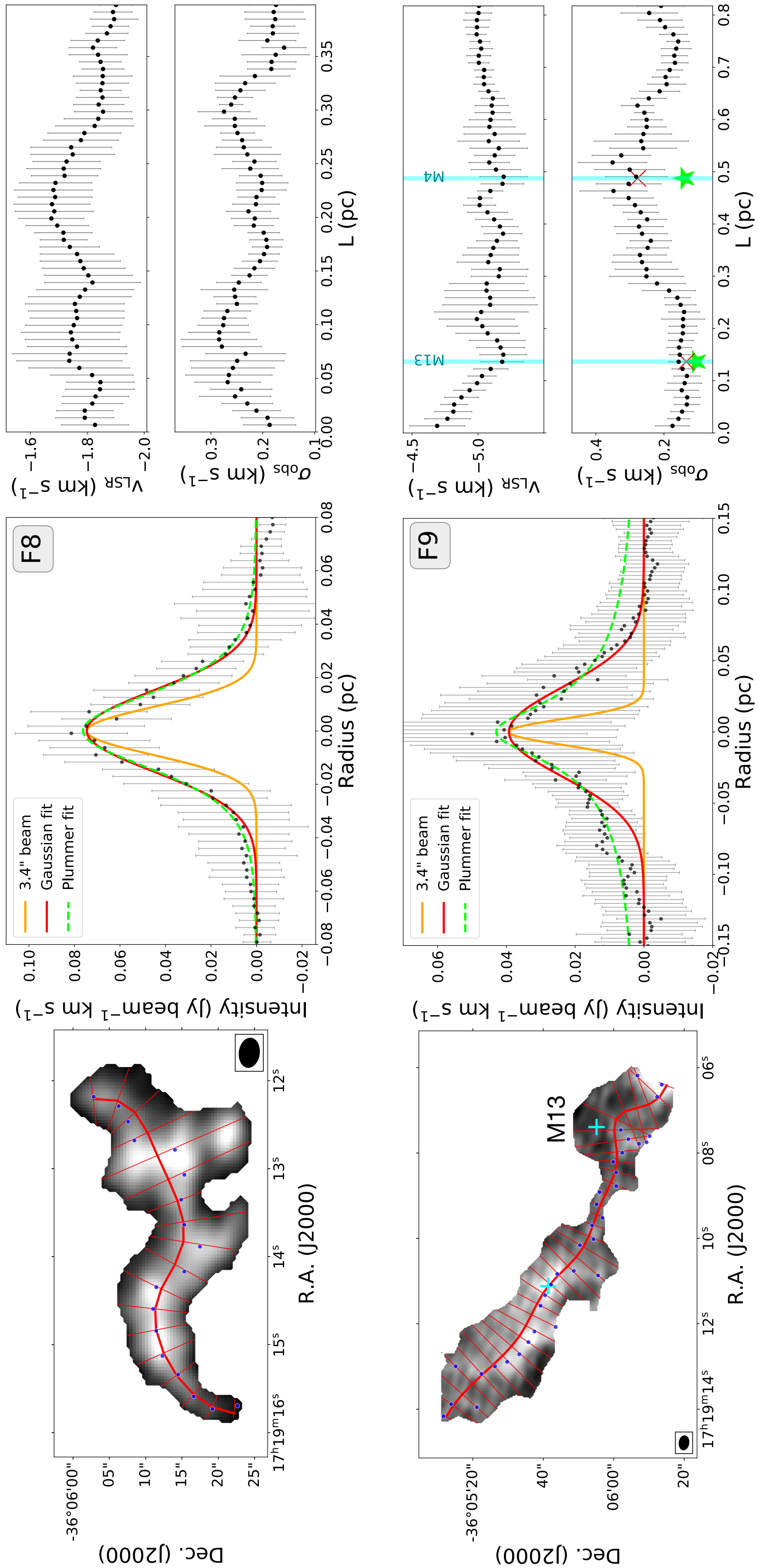
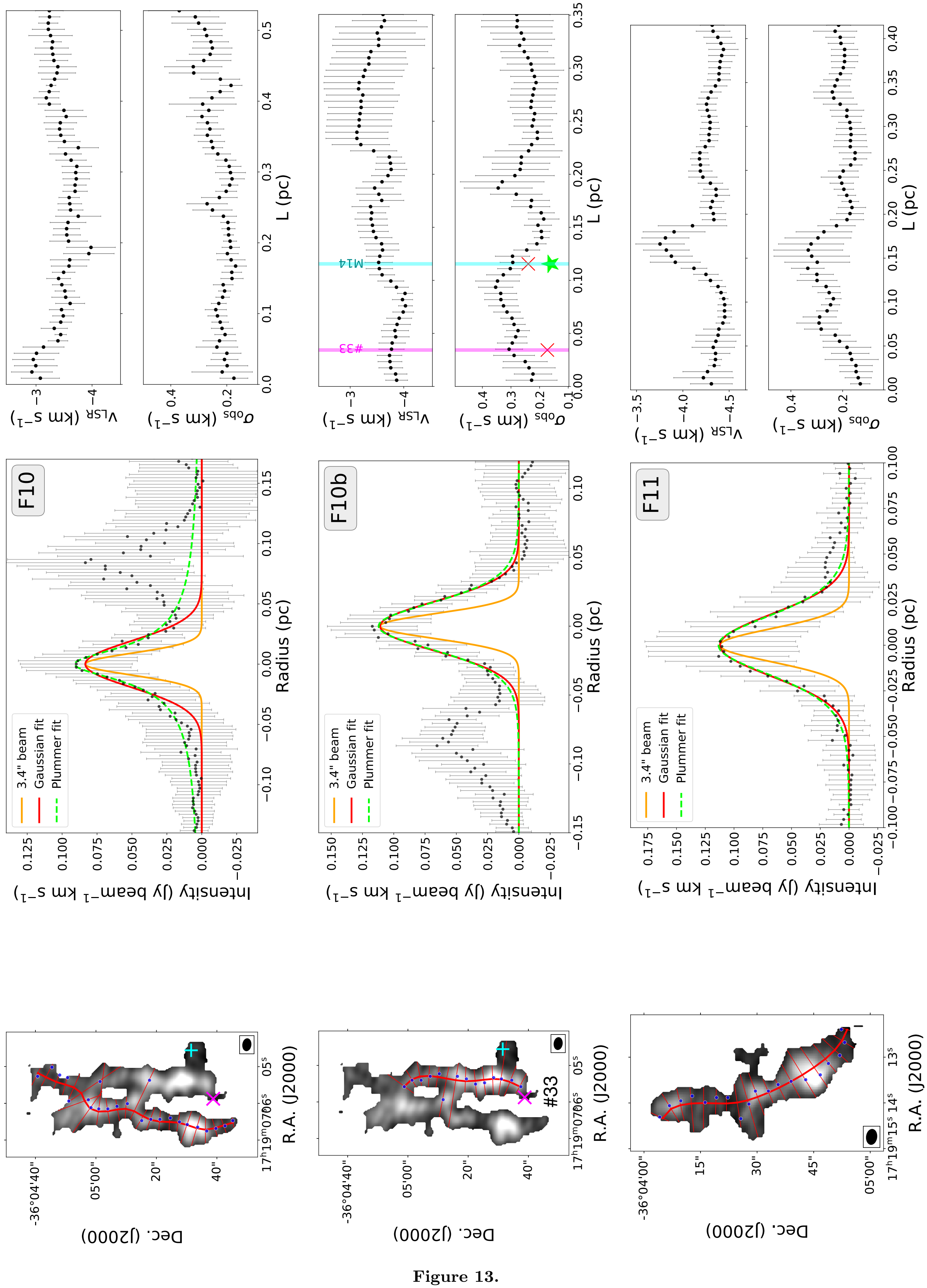

F5
F6
F7
3.4" beam
Gaussian fit
Plummer fit
Intensity (Jy beam^{-1} km s^{-1})
Radius (pc)
L (pc)
V_{LSR} (km s^{-1})
σ_{obs} (km s^{-1})
R.A. (J2000)
Dec. (J2000)
#16
#15
#41
#38
M11
#32
M10
#10/32
#13
#35

Figure 13.



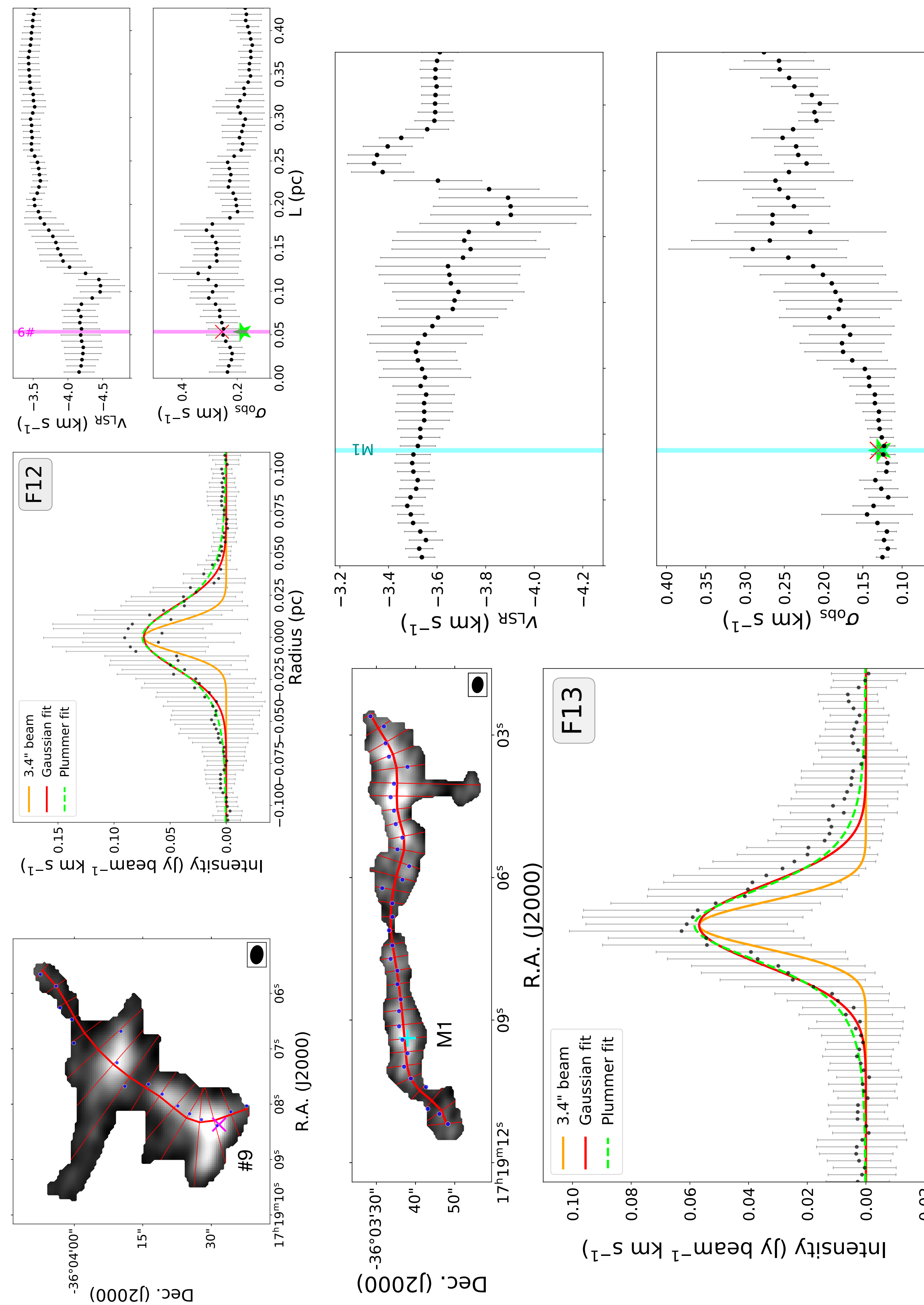
F8
F9
M13
M4
3.4" beam
Gaussian fit
Plummer fit
Radius (pc)
Intensity (Jy beam^{-1} km s^{-1})
L (pc)
V_{LSR} (km s^{-1})
σ_{obs} (km s^{-1})
R.A. (J2000)
Dec. (J2000)

Figure 13.



F10
F10b
F11
3.4" beam
Gaussian fit
Plummer fit
Radius (pc)
Intensity (Jy beam−1 km s−1)
L (pc)
VLSR (km s−1)
σobs (km s−1)
#33
M14
R.A. (J2000)
Dec. (J2000)

Figure 13.



F12
F13
#9
M1
3.4" beam
Gaussian fit
Plummer fit
R.A. (J2000)
Dec. (J2000)
Radius (pc)
Intensity (Jy beam^{-1} km s^{-1})
L (pc)
V_{LSR} (km s^{-1})
σ_{obs} (km s^{-1})

Figure 13.

REFERENCES

André, P., Di Francesco, J., Ward-Thompson, D., et al. 2014, in Protostars and Planets VI, ed. H. Beuther, R. S. Klessen, C. P. Dullemond, & T. Henning, 27, doi: 10.2458/azu_uapress_9780816531240-ch002

André, P., Men'shchikov, A., Bontemps, S., et al. 2010, A&A, 518, L102, doi: 10.1051/0004-6361/201014666

Arzoumanian, D., André, P., Didelon, P., et al. 2011, A&A, 529, L6, doi: 10.1051/0004-6361/201116596

Arzoumanian, D., André, P., Könyves, V., et al. 2019, A&A, 621, A42, doi: 10.1051/0004-6361/201832725

Astropy Collaboration, Robitaille, T. P., Tollerud, E. J., et al. 2013, A&A, 558, A33, doi: 10.1051/0004-6361/201322068

Beuther, H., Ragan, S. E., Johnston, K., et al. 2015, A&A, 584, A67, doi: 10.1051/0004-6361/201527108

Busquet, G., Estalella, R., Palau, A., et al. 2016, ApJ, 819, 139, doi: 10.3847/0004-637X/819/2/139

Butner, H. M., Lada, E. A., & Loren, R. B. 1995, ApJ, 448, 207, doi: 10.1086/175953

Chen, C.-Y., Mundy, L. G., Ostriker, E. C., Storm, S., & Dhabal, A. 2020, MNRAS, 494, 3675, doi: 10.1093/mnras/staa960

Chen, H. H.-H., Pineda, J. E., Goodman, A. A., et al. 2019a, ApJ, 877, 93, doi: 10.3847/1538-4357/ab1a40

Chen, H.-R. V., Zhang, Q., Wright, M. C. H., et al. 2019b, ApJ, 875, 24, doi: 10.3847/1538-4357/ab0f3e

Chibueze, J. O., Omodaka, T., Handa, T., et al. 2014, ApJ, 784, 114, doi: 10.1088/0004-637X/784/2/114

Chung, E. J., Lee, C. W., Kim, S., et al. 2019, ApJ, 877, 114, doi: 10.3847/1538-4357/ab12d1

Churchwell, E., Babler, B. L., Meade, M. R., et al. 2009, PASP, 121, 213, doi: 10.1086/597811

Clarke, S. D., Whitworth, A. P., Duarte-Cabral, A., & Hubber, D. A. 2017, MNRAS, 468, 2489, doi: 10.1093/mnras/stx637

Contreras, Y., Garay, G., Rathborne, J. M., & Sanhueza, P. 2016, MNRAS, 456, 2041, doi: 10.1093/mnras/stv2796

Contreras, Y., Sanhueza, P., Jackson, J. M., et al. 2018, ApJ, 861, 14, doi: 10.3847/1538-4357/aac2ec

Cox, N. L. J., Arzoumanian, D., André, P., et al. 2016, A&A, 590, A110, doi: 10.1051/0004-6361/201527068

Gerner, T., Beuther, H., Semenov, D., et al. 2014, A&A, 563, A97, doi: 10.1051/0004-6361/201322541

Ginsburg, A., & Mirocha, J. 2011, PySpecKit: Python Spectroscopic Toolkit, Astrophysics Source Code Library. http://ascl.net/1109.001

Gómez, G. C., & Vázquez-Semadeni, E. 2014, ApJ, 791, 124, doi: 10.1088/0004-637X/791/2/124

Gómez, G. C., Vázquez-Semadeni, E., & Palau, A. 2021, MNRAS, 502, 4963, doi: 10.1093/mnras/stab394

Gong, H., & Ostriker, E. C. 2011, ApJ, 729, 120, doi: 10.1088/0004-637X/729/2/120

Gong, Y., Belloche, A., Du, F. J., et al. 2021, A&A, 646, A170, doi: 10.1051/0004-6361/202039465

Goodman, A. A., Alves, J., Beaumont, C. N., et al. 2014, ApJ, 797, 53, doi: 10.1088/0004-637X/797/1/53

Hacar, A., Kainulainen, J., Tafalla, M., Beuther, H., & Alves, J. 2016, A&A, 587, A97, doi: 10.1051/0004-6361/201526015

Hacar, A., & Tafalla, M. 2011, A&A, 533, A34, doi: 10.1051/0004-6361/201117039

Hacar, A., Tafalla, M., & Alves, J. 2017, A&A, 606, A123, doi: 10.1051/0004-6361/201630348

Hacar, A., Tafalla, M., Forbrich, J., et al. 2018, A&A, 610, A77, doi: 10.1051/0004-6361/201731894

Hacar, A., Tafalla, M., Kauffmann, J., & Kovács, A. 2013, A&A, 554, A55, doi: 10.1051/0004-6361/201220090

Harris, C. R., Millman, K. J., van der Walt, S. J., et al. 2020, Nature, 585, 357, doi: 10.1038/s41586-020-2649-2

Hartmann, L. 2002, ApJ, 578, 914, doi: 10.1086/342657

Hartmann, L., & Burkert, A. 2007, ApJ, 654, 988, doi: 10.1086/509321

Heitsch, F., Ballesteros-Paredes, J., & Hartmann, L. 2009, ApJ, 704, 1735, doi: 10.1088/0004-637X/704/2/1735

Heitsch, F., Hartmann, L. W., Slyz, A. D., Devriendt, J. E. G., & Burkert, A. 2008, ApJ, 674, 316, doi: 10.1086/523697

Hennebelle, P. 2013, A&A, 556, A153, doi: 10.1051/0004-6361/201321292

Henshaw, J. D., Caselli, P., Fontani, F., Jiménez-Serra, I., & Tan, J. C. 2014, MNRAS, 440, 2860, doi: 10.1093/mnras/stu446

Henshaw, J. D., Jiménez-Serra, I., Longmore, S. N., et al. 2017, MNRAS, 464, L31, doi: 10.1093/mnrasl/slw154

Hildebrand, R. H. 1983, QJRAS, 24, 267

Hoq, S., Jackson, J. M., Foster, J. B., et al. 2013, ApJ, 777, 157, doi: 10.1088/0004-637X/777/2/157

Huchra, J. P., & Geller, M. J. 1982, ApJ, 257, 423, doi: 10.1086/160000

Hunter, J. D. 2007, Computing in Science Engineering, 9, 90

Inutsuka, S.-I., & Miyama, S. M. 1992, ApJ, 388, 392, doi: 10.1086/171162

Jiménez-Serra, I., Caselli, P., Fontani, F., et al. 2014, MNRAS, 439, 1996, doi: 10.1093/mnras/stu078

Kainulainen, J., Hacar, A., Alves, J., et al. 2016, A&A, 586, A27, doi: 10.1051/0004-6361/201526017

Kauffmann, J., Bertoldi, F., Bourke, T. L., Evans, N. J., I., & Lee, C. W. 2008, A&A, 487, 993, doi: 10.1051/0004-6361:200809481

Kirk, H., Myers, P. C., Bourke, T. L., et al. 2013, ApJ, 766, 115, doi: 10.1088/0004-637X/766/2/115

Könyves, V., André, P., Men'shchikov, A., et al. 2015, A&A, 584, A91, doi: 10.1051/0004-6361/201525861

Kumar, M. S. N., Palmeirim, P., Arzoumanian, D., & Inutsuka, S. I. 2020, A&A, 642, A87, doi: 10.1051/0004-6361/202038232

Lai, D. 2000, ApJ, 540, 946, doi: 10.1086/309361

Li, D., & Goldsmith, P. F. 2012, ApJ, 756, 12, doi: 10.1088/0004-637X/756/1/12

Li, G.-X., Urquhart, J. S., Leurini, S., et al. 2016, A&A, 591, A5, doi: 10.1051/0004-6361/201527468

Li, S., Zhang, Q., Pillai, T., et al. 2019a, ApJ, 886, 130, doi: 10.3847/1538-4357/ab464e

Li, S., Wang, J., Fang, M., et al. 2019b, ApJ, 878, 29, doi: 10.3847/1538-4357/ab1e4c

Li, S., Zhang, Q., Liu, H. B., et al. 2020a, ApJ, 896, 110, doi: 10.3847/1538-4357/ab84f1

Li, S., Sanhueza, P., Zhang, Q., et al. 2020b, ApJ, 903, 119, doi: 10.3847/1538-4357/abb81f

Li, S., Lu, X., Zhang, Q., et al. 2021, ApJL, 912, L7, doi: 10.3847/2041-8213/abf64f

Lin, Y., Liu, H. B., Dale, J. E., et al. 2017, ApJ, 840, 22, doi: 10.3847/1538-4357/aa6c67

Liu, H. B., Jiménez-Serra, I., Ho, P. T. P., et al. 2012, ApJ, 756, 10, doi: 10.1088/0004-637X/756/1/10

Liu, H.-L., Stutz, A., & Yuan, J.-H. 2018, MNRAS, 478, 2119, doi: 10.1093/mnras/sty1270

—. 2019, MNRAS, 487, 1259, doi: 10.1093/mnras/stz1340

Lu, X., Zhang, Q., Liu, H. B., et al. 2018, ApJ, 855, 9, doi: 10.3847/1538-4357/aaad11

Lu, X., Li, S., Ginsburg, A., et al. 2021, ApJ, 909, 177, doi: 10.3847/1538-4357/abde3c

Mac Low, M.-M. 1999, ApJ, 524, 169, doi: 10.1086/307784

Mac Low, M.-M., & Klessen, R. S. 2004, Reviews of Modern Physics, 76, 125, doi: 10.1103/RevModPhys.76.125

Mangum, J. G., & Shirley, Y. L. 2015, PASP, 127, 266, doi: 10.1086/680323

McBreen, B., Fazio, G. G., Stier, M., & Wright, E. L. 1979, ApJL, 232, L183, doi: 10.1086/183061

McMullin, J. P., Waters, B., Schiebel, D., Young, W., & Golap, K. 2007, in Astronomical Society of the Pacific Conference Series, Vol. 376, Astronomical Data Analysis Software and Systems XVI, ed. R. A. Shaw, F. Hill, & D. J. Bell, 127

Men'shchikov, A., André, P., Didelon, P., et al. 2010, A&A, 518, L103, doi: 10.1051/0004-6361/201014668

Miville-Deschênes, M. A., Martin, P. G., Abergel, A., et al. 2010, A&A, 518, L104, doi: 10.1051/0004-6361/201014678

Miyama, S. M., Narita, S., & Hayashi, C. 1987, Progress of Theoretical Physics, 78, 1051, doi: 10.1143/PTP.78.1051

Molinari, S., Swinyard, B., Bally, J., et al. 2010, A&A, 518, L100, doi: 10.1051/0004-6361/201014659

Monsch, K., Pineda, J. E., Liu, H. B., et al. 2018, ApJ, 861, 77, doi: 10.3847/1538-4357/aac8da

Morii, K., Sanhueza, P., Nakamura, F., et al. 2021, arXiv e-prints, arXiv:2109.01231. https://arxiv.org/abs/2109.01231

Müller, H. S. P., Schlöder, F., Stutzki, J., & Winnewisser, G. 2005, Journal of Molecular Structure, 742, 215, doi: 10.1016/j.molstruc.2005.01.027

Myers, P. C. 2009, ApJ, 700, 1609, doi: 10.1088/0004-637X/700/2/1609

Nagai, T., Inutsuka, S.-i., & Miyama, S. M. 1998, ApJ, 506, 306, doi: 10.1086/306249

Nakamura, F., & Li, Z.-Y. 2008, ApJ, 687, 354, doi: 10.1086/591641

Nutter, D., Kirk, J. M., Stamatellos, D., & Ward-Thompson, D. 2008, MNRAS, 384, 755, doi: 10.1111/j.1365-2966.2007.12750.x

Ostriker, J. 1964, ApJ, 140, 1056, doi: 10.1086/148005

Padoan, P., Juvela, M., Goodman, A. A., & Nordlund, Å. 2001, ApJ, 553, 227, doi: 10.1086/320636

Padoan, P., Nordlund, Å., Kritsuk, A. G., Norman, M. L., & Li, P. S. 2007, ApJ, 661, 972, doi: 10.1086/516623

Palmeirim, P., André, P., Kirk, J., et al. 2013, A&A, 550, A38, doi: 10.1051/0004-6361/201220500

Peretto, N., Fuller, G. A., André, P., et al. 2014, A&A, 561, A83, doi: 10.1051/0004-6361/201322172

Persi, P., & Tapia, M. 2008, Star Formation in NGC 6334, ed. B. Reipurth, Vol. 5, 456

Pineda, J. E., Goodman, A. A., Arce, H. G., et al. 2010, ApJL, 712, L116, doi: 10.1088/2041-8205/712/1/L116

Robitaille, T., & Bressert, E. 2012, APLpy: Astronomical Plotting Library in Python, Astrophysics Source Code Library. http://ascl.net/1208.017

Russeil, D., Zavagno, A., Nguyen, A., et al. 2020, A&A, 642, A21, doi: 10.1051/0004-6361/202037674

Russeil, D., Schneider, N., Anderson, L. D., et al. 2013, A&A, 554, A42, doi: 10.1051/0004-6361/201219971

Sanhueza, P., Jackson, J. M., Foster, J. B., et al. 2012, ApJ, 756, 60, doi: 10.1088/0004-637X/756/1/60

—. 2013, ApJ, 773, 123, doi: 10.1088/0004-637X/773/2/123

Sanhueza, P., Jackson, J. M., Zhang, Q., et al. 2017, ApJ, 841, 97, doi: 10.3847/1538-4357/aa6ff8

Sanhueza, P., Contreras, Y., Wu, B., et al. 2019, ApJ, 886, 102, doi: 10.3847/1538-4357/ab45e9

Sanhueza, P., Girart, J. M., Padovani, M., et al. 2021, ApJL, 915, L10, doi: 10.3847/2041-8213/ac081c

Sepúlveda, I., Estalella, R., Anglada, G., et al. 2020, A&A, 644, A128, doi: 10.1051/0004-6361/202037895

Smith, R. J., Glover, S. C. O., & Klessen, R. S. 2014, MNRAS, 445, 2900, doi: 10.1093/mnras/stu1915

Sokolov, V., Wang, K., Pineda, J. E., et al. 2018, A&A, 611, L3, doi: 10.1051/0004-6361/201832746

Soler, J. D., Beuther, H., Syed, J., et al. 2020, A&A, 642, A163, doi: 10.1051/0004-6361/202038882

Stutz, A. M., & Gould, A. 2016, A&A, 590, A2, doi: 10.1051/0004-6361/201527979

Tan, J. C., Kong, S., Butler, M. J., Caselli, P., & Fontani, F. 2013, ApJ, 779, 96, doi: 10.1088/0004-637X/779/2/96

Treviño-Morales, S. P., Fuente, A., Sánchez-Monge, Á., et al. 2019, A&A, 629, A81, doi: 10.1051/0004-6361/201935260

Van Loo, S., Keto, E., & Zhang, Q. 2014, ApJ, 789, 37, doi: 10.1088/0004-637X/789/1/37

Vázquez-Semadeni, E., González-Samaniego, A., & Colín, P. 2017, MNRAS, 467, 1313, doi: 10.1093/mnras/stw3229

Wang, K., Testi, L., Ginsburg, A., et al. 2015, MNRAS, 450, 4043, doi: 10.1093/mnras/stv735

Wang, K., Zhang, Q., Testi, L., et al. 2014, MNRAS, 439, 3275, doi: 10.1093/mnras/stu127

Wang, Y., Beuther, H., Schneider, N., et al. 2020, A&A, 641, A53, doi: 10.1051/0004-6361/202037928

Whitworth, A., & Summers, D. 1985, MNRAS, 214, 1, doi: 10.1093/mnras/214.1.1

Willis, S., Marengo, M., Allen, L., et al. 2013, ApJ, 778, 96, doi: 10.1088/0004-637X/778/2/96

Yuan, J., Li, J.-Z., Wu, Y., et al. 2018, ApJ, 852, 12, doi: 10.3847/1538-4357/aa9d40

Yue, N.-N., Li, D., Zhang, Q.-Z., et al. 2021, Research in Astronomy and Astrophysics, 21, 024, doi: 10.1088/1674-4527/21/1/24

Zhang, Q., Wang, Y., Pillai, T., & Rathborne, J. 2009, ApJ, 696, 268, doi: 10.1088/0004-637X/696/1/268

Zucker, C., Battersby, C., & Goodman, A. 2015, ApJ, 815, 23, doi: 10.1088/0004-637X/815/1/23

Zucker, C., & Chen, H. H.-H. 2018, ApJ, 864, 152, doi: 10.3847/1538-4357/aad3b5

APPENDIX

A. COLUMN DENSITY

Assuming local thermodynamic equilibrium (LTE), the column density of molecules can be calculated following (Mangum & Shirley 2015)

$$N = C_\tau \frac{3h}{8\pi^3 R} \frac{Q_{\rm rot}}{S\mu^2 g_{\rm u}} \frac{\exp(\frac{E_{\rm u}}{kT_{\rm ex}})}{\exp(\frac{h\nu}{kT_{\rm ex}}) - 1} \left(J_\nu(T_{\rm ex}) - J_\nu(T_{\rm bg})\right)^{-1} \int \frac{T_{\rm R} dv}{f}, \tag{A1}$$

where $C_\tau = \tau/(1-\exp(-\tau))$ is the optical depth correction factor, h is the Planck constant, $S\mu^2$ is the line strength multiplied by the square of dipole moment, R is the line intensity, $g_{\rm u}$ is the statistical weight of the upper level, $T_{\rm ex}$ is the excitation temperature, $T_{\rm bg}$ is the back ground temperature, $E_{\rm u}$ is the energy of the upper state, ν is the transition frequency, $\int T_{\rm R} dv$ is the velocity-integrated intensity, f is the filling factor, and $Q_{\rm rot}$ is the partition function. Here f is assumed to be 1 and the $T_{\rm NH_3}$ approximates the $T_{\rm ex}$ of molecular lines (see Section 3.1). Both $H^{13}CO^+$ and NH_2D emission are generally optically thin. The NH_2D partition function is $Q_{\rm rot} = 0.73T_{\rm ex}^{3/2} + 6.56$ that is the best-fit result from a fit to the partition function obtained from CDMS catalogues at the different excitation temperatures of 10–300 K (Müller et al. 2005), while the $H^{13}CO^+$ partition function can be estimated from $Q_{\rm rot} \approx kT_{\rm ex}/hB + 1/3$ that is a approximation for diatomic linear molecules (Mangum & Shirley 2015). For NH_2D, the molecular parameters are 15 for $g_{\rm u}$; 11.91 D for $S\mu^2$; 20.68 K for $E_{\rm u}$; 85.926 GHz for ν; 1/2 for R that is the relative intensity of the main hyperfine transition with respect to the other hyperfine transitions. For $H^{13}CO^+$, the molecular parameters are 3 for $g_{\rm u}$; 15.21 D^2 for $S\mu^2$; 15.21 K for $E_{\rm u}/k$; 86.754288 GHz for ν; 1 for R.

The $N_{\rm H_2}$ is derived from the continuum emission with

$$N_{\rm H_2} = \eta \frac{S_\nu}{\Omega\, B_\nu(T_{\rm dust})\, \kappa_\nu\, \mu\, m_{\rm H}}, \tag{A2}$$

where η=100 is the gas-to-dust ratio, S_ν is the peak flux density, Ω is the beam solid angle, $m_{\rm H}$ is the proton mass, μ=2.8 is the mean molecular weight of the interstellar medium (Kauffmann et al. 2008), and κ_ν is the dust opacity at a frequency of ν. We used $\kappa_\nu = 0.235$ cm^{-2} g^{-1} by assuming $\kappa_\nu = 10(\nu/1.2{\rm THz})^\beta$ cm^{-2} g^{-1} and $\beta = 1.5$ (Hildebrand 1983).

B. FILAMENT CRITICAL LINE-MASS

Assuming the filament is an infinite self-gravitating isothermal cylinder in hydrostatic equilibrium, the critical line-mass of filament can be estimated by (Ostriker 1964)

$$M_{\rm crit} = \frac{2\sigma_{\rm eff}^2}{G}, \tag{B3}$$

where $\sigma_{\rm eff}$ is the effective velocity dispersion and G is the gravitational constant. If the thermal gas pressure is the only force opposing gravity, the $\sigma_{\rm eff} = c_{\rm s}$. If the turbulence is the only force against gravity, $\sigma_{\rm eff} = \sigma_{\rm nth}$. If both thermal and turbulence supports are considered, $\sigma_{\rm eff} = \sqrt{\sigma_{\rm nth}^2 + c_{\rm s}^2}$. In the last case, the Equation B3 can be written as (see also Hacar et al. 2018):

$$M_{\rm crit}(T, \sigma_{\rm nth}) = \frac{2\, c_{\rm s}^2}{G} \left(1 + \left(\frac{\sigma_{\rm nth}}{c_{\rm s}}\right)^2\right). \tag{B4}$$