Fragmentation of star-forming filaments in the X-shape Nebula of the California molecular cloud

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ABSTRACT

Aims. We aim to further investigate the fragmentation of star-forming filaments in the X-shape Nebula of the California molecular cloud, so as to better understand the exact role of filaments in the early stages of star formation.

Methods. We applied getsource and getfilaments extraction methods to the multi-wavelength images observed with Herschel in order to produce background-subtracted images of candidate cores and filaments, respectively. The properties of the filaments and cores were determined from such an analysis. A map of \(^{13}\)CO(2 – 1) emission from the SMT 10m telescope was also used to constrain the dynamical state of the filaments.

Results. We obtained a complete sample of filamentary structures and dense cores from the Herschel high-resolution (18.2") \(\text{H}_2\) column density map of the region. We selected 10 filaments with elongation factors \(E > 4\) and column density contrasts \(C > 0.5\) from the filamentary network identified with getfilaments. All 10 filaments have roughly the same deconvolved FWHM width, with a median value of 0.12 ± 0.03 pc, independently of their column densities ranging from \(< 10^{21} \text{ cm}^{-2}\) to \(> 10^{22} \text{ cm}^{-2}\). We also identified 2 protostellar cores, 20 robust prestellar cores, 11 candidate prestellar cores, and 27 unbound starless cores. Two star-forming filaments stand out based on the Herschel data: Filaments 8 and 10 harbor quasi-periodic chains of dense cores with a typical projected core spacing of \(\sim 0.15\) pc. These two filamentary structures have supercritical line masses and are not static. Filament 8 exhibits a prominent transverse velocity gradient, suggesting that it is accreting gas from the parent cloud gas reservoir. The estimated mass accretion rate is \(\sim 40 \pm 10 M_\odot\) Myr\(^{-1}\) pc\(^{-1}\). Filament 10 includes two embedded protostars with outflows and is likely at a later evolutionary stage than filament 8. Our findings support the notion that dense molecular filaments play a crucial role in the star formation process. We suggest that accretion onto the two star-forming filaments, as well as geometrical bending, explains why the observed core spacing along them is significantly shorter than the canonical separation of \(\sim 4\) times the filament width predicted by classical cylinder fragmentation theory.

Key words. stars: formation – ISM: clouds – (ISM:) dust, extinction – ISM: kinematics and dynamics

1. Introduction

The early phases of star formation are poorly understood to date. One of the most intriguing questions in astrophysics is how filaments fragment into cores at the early evolutionary stages. It is crucial to understand the initial conditions for star formation (cf. André et al. 2010).

Observations with the Herschel space observatory have revealed that filaments are truly ubiquitous in the cold interstellar medium (ISM), with lengths ranging from \(\sim\) pc to \(\sim 10^2\) pc in the Galactic plane (Menshchikov et al. 2010, Wang et al. 2015). Most (> 75\%) prestellar cores lie inside filaments with column densities \(N_H^2 > 7 \times 10^{21} \text{ cm}^{-2}\) (Könyves et al. 2015), implying that filaments play a key role in the star formation process (André et al. 2014). The typical inner width of filaments in nearby molecular clouds is \(\sim 0.1\) pc (Arzoumanian et al. 2011, 2019), but the origin of this characteristic width is still a controversial topic. The typical value may come from supersonic turbulence in the ISM (Pudritz & Kevlahan 2013, Federrath 2016), or the balance of quasi-equilibrium structure with ambient ISM pressure (Fischera & Martin 2012). Filaments serve as highly efficient routes for feeding material into star-forming cores (André et al. 2014). The material around filaments is not at all static. For instance, a pronounced transverse velocity gradient provides good kinematic evidence for accretion flows of ambient gas material into the B211/B212 filament of the Taurus molecular cloud (MC) (Palmeirim et al. 2013, Shimajiri et al. 2019). Other dense filaments such as infrared dark clouds or the Serpens South filament exhibit both transverse and longitudinal velocity gradients, suggesting that, gas is not only accreted by, but also flowing along these filaments (e.g. Kirk et al. 2013). In most cases, the transverse gradients appear to dominate over the longitudinal gradients (Dhabal et al. 2018). In the Serpens South case, for instance, the mass flow rate along the filament is estimated to be \(\sim 1/4\) of the accretion rate in the transverse direction (Kirk et al. 2013). The critical line-mass \(M_{\text{cr, line}} \equiv 2 c_s^2 / G\) for an isothermal cylinder at a gas temperature of 10 K is \(\sim 16 M_\odot\) pc\(^{-1}\) (see e.g. Ostriker 1964, Inutsuka & Miyama 1997). Recently, Arzoumanian et al. (2019) divided observed filaments into three families according their line-mass.
$M_{\text{line}}$: thermally supercritical filaments ($M_{\text{line}} \gtrsim 2 M_{\text{line, crit}}$), transcritical filaments ($0.5 M_{\text{line, crit}} \lesssim M_{\text{line}} \lesssim 2 M_{\text{line, crit}}$), thermally subcritical filaments ($M_{\text{line, crit}} \lesssim 0.5 M_{\text{line, crit}}$). For an infinitely long and static equilibrium cylindrical filament, core spacing is predicted to be $\sim 4 \times$ the filament diameter by fragmentation models (e.g. Inutsuka & Miyama 1992), or $\sim 0.4 \, \text{pc}$ taking the typical filament width into account. However, this does not match the actual core spacing found in observations. We will try to explain this discrepancy in the present paper.

Star formation activity is generally found only in high-extinction parts of MCs, but the mass of high-extinction material with $A_K > 1.0$ mag in the California MC is only 10% of that in Orion A MC (Lada et al. 2009), and the star formation rate is accordingly much lower. The number of young stellar objects (YSOs), which may be taken as an indicator of star-formation activity, is only 177/2980– 6% of that observed in the Orion A MC (Lada et al. 2017; Grohschedl et al. 2019). Only one B-type main-sequence star is found in the south-eastern part of the California MC and is associated with relatively intense star formation in a local region around it (Andrews & Wolk 2008). The global star formation efficiency estimated by Zhang et al. (2018) for the California MC is only $\sim 1\%$, which is half of the typical value ($\sim 2\%$) in the molecular clouds of the Milky Way (Evans 1991). The California MC is therefore an ideal place to study star formation at early stages. The X-shape region lies at the center of the California MC. Gaia DR2 (Gaia Collaboration et al. 2018) parallaxes of the stars with G band extinction measurements give a distance of 500 ± 7 pc (Yan et al. 2019), which is 50 pc farther than the distance (450 ± 23 pc) estimated by Lada et al. (2009) through comparison of foreground star counts with Galactic models. Considering that Gaia measures distances at an accuracy level never before achieved, we adopt the Gaia distance of 500 pc in our study. The most distinctive feature of this region is that it resembles an ‘X’. Two low-density filaments meet at the north dense hub region and extend to the southeast and southwest with an intersection angle of $\sim 60\degree$ in the plane of sky. The velocity gradients along the southeast and southwest filaments are 0.1 and 0.2 km s$^{-1}$ pc$^{-1}$ (Imara et al. 2017). There are two YSOs in the region. One is a Class II YSO and the other is a Class I YSO (Harvey et al. 2013; Broekhoven-Fiene et al. 2014). The two YSOs may be the driving sources of a low-mass low-velocity outflow (Imara et al. 2017).

The outline of the paper is as follows. In Sect. 2 we describe the Herschel submillimeter dust emission data and SMT 10m molecular line observations of the X-shape region. Data analysis and results are presented in Sect. 3. In Sect. 4 we discuss evidence of accretion onto an early-stage filament, as well as the detailed fragmentation properties of the same filament. We summarize our conclusions in Sect. 5.

2. Observations and data reduction

2.1. Herschel data

The Herschel imaging observations of the California MC (Harvey et al. 2013), include PACS 70 and 160 $\mu$m (Poglitsch et al. 2010) and SPIRE 250, 350 and 500 $\mu$m (Griffin et al. 2010). The beam sizes of the PACS at 70 and 160 $\mu$m are 8.4 and 13.5 $\arcsec$, respectively. The beam sizes of the SPIRE at 250, 350 and 500 $\mu$m are 18.2, 24.9 and 36.3 $\arcsec$, respectively. The SPIRE/PACS parallel-mode was used to make scan maps with speed of 60$''$ s$^{-1}$. We downloaded Herschel maps from the NASA/IPAC Infrared Science Archive1 and extract X-shape Nebula from the California MC with an area about 40x40$'$.

1 https://irsa.ipac.caltech.edu/data/Herschel/ACMC/
2.2. SMT 10m single-dish observations

$^{12}\text{CO}(2-1)$ and $^{13}\text{CO}(2-1)$ maps towards the X-shape Nebula come from an ongoing ESO Public Survey sampling observed with the 10m submillimeter telescope (SMT) of the Arizona Radio Observatory. Observations with the SMT were carried out in on-the-fly mode with Nyquist sampling, on 13.5 $\times$ 5' small fields along filamentary skeletons of the X-shape. We used GILDAS$^1$ to detect bad channels and calibrate the data. The main beam efficiency of 0.7 is adopted for conversion from the measured antenna temperature ($T_A$) scale to the main beam temperature ($T_{mb}$). The molecular spectra effective resolution is 36'', corresponding ~0.9 pc at the distance of 500 pc. The channel width is 0.33 km s$^{-1}$, the RMS noise is less than 0.2 K, and pixel size of final data cubes in fits format is 8''.

3. Data analysis and results

3.1. Source and filament extraction

We apply source and filament extraction method of getsources and getfilaments (Men'shchikov et al. 2012, Men'shchikov 2013, 2017). We use SMT 2020 in prep.) to the multi-wavelengths images with Herschel, in order to produce separate images of sources, protostars, background and filaments.

3.1.1. Preparing images for extraction

Seven images, including the Herschel 70, 160, 250, 350, 500 $\mu$m dust maps, temperature-corrected 160 $\mu$m map (13.5'' resolution), and H$_2$ column density map at 250 $\mu$m resolution (18.2'') were converted to registered detection and observed images. In particular, all images were reprojected onto the same grid covering the same area of $\sim$ 0.7 deg$^2$ with the same pixel size of 3'' and the same coordinate system. The detection images come from the observed images by using detection quality improvement methods such as convolution, subtraction of baseline images, etc. The aligned detection images were used to detect the filaments and sources, and the aligned observed images were only used to measure properties of detected filaments and sources. The temperature-corrected 160 $\mu$m map is obtained by converting the original observed 160 $\mu$m map to an approximate column density image using the color-temperature map derived from the intensity ratio between 160 and 250 $\mu$m (see Könyves et al. 2015). Pixel-by-pixel SED fitting for Herschel 160 to 500 $\mu$m for a modified blackbody function was used to create high-resolution H$_2$ column density map with the method described in Appendix A of Palmeirim et al. (2013). The dust optical law $\kappa_\lambda = 0.1 (\lambda/300 \mu$m)$^\beta$ cm$^{-2}$ g$^{-1}$ with fixed $\beta = 2$ in this thin gray-body model was used (Roy et al. 2014).

3.1.2. Source extraction process

The getsources and getfilaments methods are fully automated. Men'shchikov et al. (2012, 2013) and Men'shchikov (2020 in prep.) provide full technical details about this extraction method. We only summarize it briefly here. Before running getsources and getfilaments, we first run getimages to produce background-subtracted and flattened images, remove large-scale intensity changes and equalize the fluctuation levels globally at small-scale (Men'shchikov 2017). Second getsources and getfilaments decompose detection images in many spatial scales. In the third step, the clean high-resolution column density image (18.2'') reconstructed over the entire range of spatial scales are used to measure and catalog the properties of filaments. For compact sources, the combined clean single-scale images at all wavelengths are used to detect and catalog sources, and the clean images reconstructed over the entire range of spatial scales at each wavelength were used to catalog and measure the fluxes at all wavelengths. To identify the self-luminous point-like objects, we ran getsources again only with 70 $\mu$m image for detection, and measured the fluxes at all wavelengths.

3.2. Filamentary structure selection

Molecular filaments are elongated structures of gas and dust in molecular clouds (e.g. Andre et al. 2011, 2017). We define the elongation factor $E$ of a filamentary structure as

$$E = L/W,$$

where $L$ is length of the crest and $W$ is the full width at half maximum (FWHM) of the radial column density profile. We use the median FWHM measured along the crest in the present study. The column density contrast $C$ of the filamentary structure is defined as

$$C = N_{H_2}/N_{H_2}^{bg},$$

where $N_{H_2}$ is median filament crest value of the column density, $N_{H_2}^{bg}$ is the background around the filament. $N_{H_2}^{bg}$ is measured in the source-subtracted filament map. And $N_{H_2}^{bg}$ is measured in the background map. Using getfilaments, a network of filaments and its corresponding skeleton was traced in the column density map. From this network, we extracted 10 filamentary structures with elongation factors $E > 4$ and column density contrasts $C > 0.5$. The line mass $M_{line}$ of each filament was estimated as follows:

$$M_{line} = \mu_\text{H}_2 m_\text{H}_2 N_{H_2}^{0} \times W,$$

where $\mu_\text{H}_2 = 2.8$ is the molecular weight per hydrogen molecule, $m_\text{H}_2$ is the H atom mass. Assuming that each filament is cylindrical, we took the filament diameter to be the measured filament FWHM width $W$. The filament average column density was estimated as

$$N_{H_2} = N_{H_2}^{0}/W.$$

We found 5 subcritical filaments (filament 1–4, 7), 5 supercritical (or transcritical) filaments (filament 5, 6, 8–10). The derived physical properties of the 10 filaments identified with getfilaments are given in Tab. Article number, page 3 of 9
Table 1. Physical parameters of the filaments.

| No. | L (pc) | W$_{dec}$ (pc) | E | C | T$_d$ (K) | N$_{H_2}^0$ $10^{21}$ cm$^{-2}$ | n$_{H_2}$ | M$_{fil}$ ($M_\odot$) | M$_{line}$ ($M_\odot$ pc$^{-1}$) |
|-----|--------|----------------|---|---|----------|-----------------|--------|----------------|-----------------|
| 1   | 0.53   | 0.11 (0.02)    | 4.4 (0.8) | 0.7 (0.08) | 16.4 (0.20) | 0.8 (0.1) | 2.2 (0.4) | 1.2 | 2.3 |
| 2   | 0.48   | 0.10 (0.04)    | 4.4 (1.6) | 0.9 (0.11) | 15.9 (0.28) | 1.2 (0.2) | 3.5 (0.6) | 1.4 | 2.9 |
| 3   | 0.80   | 0.11 (0.10)    | 6.8 (5.7) | 0.8 (0.10) | 16.8 (0.19) | 0.8 (0.1) | 2.3 (0.6) | 1.8 | 2.2 |
| 4   | 0.64   | 0.16 (0.09)    | 4.0 (2.2) | 1.0 (0.22) | 16.3 (0.44) | 1.2 (0.3) | 2.4 (0.8) | 2.8 | 4.3 |
| 5   | 0.93   | 0.16 (0.06)    | 5.8 (2.3) | 2.0 (0.28) | 15.1 (0.42) | 2.4 (0.3) | 4.9 (1.0) | 8.2 | 8.8 |
| 6   | 0.95   | 0.18 (0.08)    | 5.1 (2.2) | 1.3 (0.19) | 15.0 (0.69) | 1.8 (0.3) | 3.2 (0.7) | 7.2 | 7.6 |
| 7   | 1.13   | 0.13 (0.03)    | 8.4 (1.7) | 0.9 (0.19) | 16.0 (0.48) | 1.1 (0.4) | 2.7 (1.1) | 3.9 | 3.5 |
| 8   | 0.98   | 0.13 (0.03)    | 7.1 (1.7) | 5.3 (0.74) | 12.9 (0.35) | 9.5 (1) | 22.0 (3.0) | 29.1 | 29.6 |
| 9   | 0.66   | 0.10 (0.04)    | 5.9 (2.1) | 4.0 (1.03) | 13.3 (0.42) | 6.8 (1.5) | 22.7 (8.9) | 13.2 | 19.9 |
| 10  | 0.55   | 0.09 (0.03)    | 5.4 (1.6) | 7.6 (1.09) | 13.3 (0.91) | 12.1 (8) | 38.5 (7.7) | 14.8 | 27.0 |

Notes. The filament is detected and measured on Herschel high-resolution (18.2") column density map. No. is the index number of the filament. L is the length. W$_{dec}$ is the median deconvolved FWHM width. E is the elongation factor. C is the column density contrast. T$_d$ is the median centroid dust temperature. N$_{H_2}^0$ is the median centroid H$_2$ column density. n$_{H_2}$ is the average volume density. M$_{fil}$ is the mass estimated by M$_{fil}$ = M$_{line}$ * L. M$_{line}$ is the linear mass.

3.3. Selection and classification of reliable cores

Reliable cores were selected and classified according to the detailed criteria described by Kónyves et al. [2015]. This method has already been validated and applied to many molecular clouds in the Herschel Gould Belt Survey (HGBS). The core size is defined as the deconvolved FWHM of an equivalent Gaussian.

$$R_{dec} = \sqrt{H_1 H_2 - O^2}$$  \hspace{1cm} (5)

where H$_1$ and H$_2$ is the major axis and the minor axis of the equivalent Gaussian. O $\approx$ 18.2" is the angular resolution of the column density map. The integrated flux measured for each deconvolved core at each wavelength by getsources were used to fit a SED with a modified blackbody function that also was used to create column density map in Sec. [3.1]. The core mass, line of sight averaged dust temperature and peak column density were well estimated. Starless core are fundamental units of star formation. A prestellar core is gravitationally bound starless core (Ward-Thompson et al. [2007] André et al. [2014]). The critical Bonnor-Ebert (BE) mass can be expressed as (Bonnor [1956])

$$M_{BE}^{\text{crit}} \approx 2.4 R_{BE}^2 \frac{c_s^2}{G}$$  \hspace{1cm} (6)

where R$_{BE}$ is the BE radius, the deconvolved observed core radius is adopted. Assuming an ambient cloud temperature of 10 K, the isothermal sound speed c$_s$ is $\sim$ 0.19 km s$^{-1}$. G is the gravitational constant. When the ratio $\sigma_{BE} = M_{BE}^{\text{crit}} / M_{core} \leq$ 2, the starless core is deemed to be self-gravitating and classified as a robust prestellar core. Following Kónyves et al. [2015], an empirical size-dependent ratio $\sigma_{BE} / \sigma_{BE, \text{emp}} \leq 5 \times (O_{N_{H_2}} / H_{N_{H_2}})^{0.4}$, where O$_{N_{H_2}}$ and H$_{N_{H_2}}$ are the beam size (18.2") of the high-resolution column density map and the core FWHM in this map, respectively, is also considered to select additional candidate prestellar cores. Although M$_{BE}^{\text{crit}}$ differs conceptually from the virial mass, it provides a good approximation to the latter for unmagnetized, thermal cores (see, e.g., Li et al. [2013]). A protostellar core is a dense core in which there is at least one protostar in the half-power column density contour.

We identified 27 unbound starless cores, 20 robust prestellar cores, 11 additional candidate prestellar cores, and two protostellar cores. About 45% of the prestellar cores lie in thermally supercritical filaments, ~45% in transcritical filaments, while the rest (~10%) of the prestellar cores are observed toward clumpy cloud structures. Unbound starless cores are only observed toward subcritical filamentary structures. The derived core masses...
Fig. 3. High-resolution (18.2") column density map of filament 8 and its embedded cores. The maps are shown from $10^{21}$ to $2 \times 10^{22}$ cm$^{-2}$. Panel (a) shows the high-resolution (18.2") column density map fitted from Herschel observed bands from 160 to 500 µm. Panel (b) shows clean-background and core-subtracted filament image reconstructed over the full range of spatial scales. The crest is shown with a blue dotted line. Panel (c) shows the five robust prestellar cores on this filament. The number of the core is the core running number of the getsources. We find those cores are regularly arranged on the filament from south to north with core spacings of 0.17, 0.16, 0.15 and 0.18 pc, respectively. The typical core spacing is 0.17 ± 0.01 pc. The size of the core is FWHM of the equivalent Gaussian. Panel (d) shows the detected cores overlaying on the filament.

Fig. 4. High-resolution (18.2") column density map of filament 10 and its embedded cores. The map is shown from $10^{21}$ to $3 \times 10^{22}$ cm$^{-2}$. Two protostellar cores (core # 1, 2) and two robust prestellar cores (core # 5, 7) are detected on this filament. Four cores are regularly arranged on the filament with core spacing of 0.11, 0.12 and 0.16 pc, respectively. The average core spacing is 0.13 ± 0.02 pc.

range from 0.04 to 5.8 $M_\odot$, with a mean value of 0.8 $M_\odot$. The deconvolved core radii range from 0.02 to 0.17 pc, with a mean value of 0.06 pc. A remarkable string of five regularly-spaced robust prestellar cores is observed along the crest of filament 8 (see Fig. 3). The typical projected spacing of these five cores (# 9, 10, 11, 16, 6) is ~ 0.17 pc (see Fig. 3), and their typical mass is ~ 0.8 $M_\odot$ (see Tab. 2). Fig. 5 shows the radial profile of filament 8 as measured on the original column density map and dust temperature map, respectively. The estimated background column density toward this filament is ~ $3 \times 10^{21}$ cm$^{-2}$ and the centroid temperature is ~ 13 K. Another string of four regularly-spaced cores is observed along the crest of filament 10 (see Fig. 4), including two robust prestellar cores (core # 5 and 7) and two protostellar cores (core # 1 and 2). Here, the typical projected core spacing is ~ 0.13 pc (see Fig. 4). Fig. 6 shows the radial profile of filament 10 as measured on the original column density map and dust temperature map, respectively.
Table 2. The core physical parameters.

| Filament | No. | R.A.  | Dec.  | \(H_L\)  | \(H_S\)  | PA    | \(R_{\text{de}}\) | \(N^p_{\text{H}_2}\) | \(M_{\text{core}}\) | \(M_{\text{BE}}\) | Type |
|----------|-----|-------|-------|-----------|-----------|-------|-----------------|-----------------|-----------------|-------------|------|
|          | 9   | 04:21:14.5 | +37:37:48 | 46.2 | 18.5 | 169.9 | 0.06 | 6.4(1) | 0.9 | 1.1 | R-PRE |
|          | 10  | 04:21:14.6 | +37:36:37 | 41.2 | 20.0 | 164.1 | 0.05 | 5(1.5) | 0.9 | 1.1 | R-PRE |
|          | 11  | 04:21:17.4 | +37:35:38 | 37.8 | 20.9 | 116.5 | 0.05 | 4(1.7) | 0.7 | 1 | R-PRE |
|          | 16  | 04:21:20.7 | +37:34:51 | 39.1 | 20.5 | 165.8 | 0.05 | 2.4(1.2) | 0.5 | 1 | R-PRE |
|          | 6   | 04:21:18.2 | +37:33:44 | 37.6 | 19.8 | 4.8 | 0.05 | 11(1.4) | 2.3 | 1 | R-PRE |
|          | 5   | 04:21:37.7 | +37:35:21 | 32.5 | 18.2 | 157.4 | 0.04 | 5.6(2) | 2.8 | 0.8 | R-PRE |
|          | 1   | 04:21:38.5 | +37:34:37 | 24.1 | 18.2 | 3.0 | 0.03 | 18.7(4.3) | 3.8 | 0.5 | PRO |
|          | 2   | 04:21:41.1 | +37:33:58 | 20.3 | 18.7 | 130.3 | 0.02 | 15.3(4.5) | 1.9 | 0.3 | PRO |
|          | 7   | 04:21:45.5 | +37:33:19 | 36.6 | 18.2 | 128.2 | 0.04 | 9(3.6) | 2.9 | 0.9 | R-PRE |

**Notes.** We show the cores on filament 8 and 10. No. is the core running number of the getsources. R.A. and Dec. are the center positions of the cores in format of hh:mm:ss and dd:mm:ss. The cores are sorted from north to south along the crest of the filament. \(H_L\) and \(H_S\) are the major axis and the minor axis of the equivalent Gaussian, that are measured from Herschel high-resolution (18.2") column density map. PA is the position angle of the major axis. \(R_{\text{de}}\) is the deconvolved radius. \(N^p_{\text{H}_2}\) is the peak column density. \(M_{\text{core}}\) is the mass estimated by SED fitting. When core is protostellar core, \(M_{\text{core}}\) is protostellar envelope mass. \(M_{\text{BE}}\) is the critical Bonnor-Ebert (BE) mass. R-PRE is robust prestellar core. PRO is protostellar core.

![Figure 5](image1.png)

**Fig. 5.** Column density distribution of filament 8. We measured the filament column density along the filament crest on the real high-resolution (18.2") column density map. There are five cores in this filament. It seems core # 11 and 16 overlap together. The getsources deblended them with an iterative method. We show the possible structure of those two cores with blue dashed gauss profiles.

![Figure 6](image2.png)

**Fig. 6.** Column density distribution of filament 10. There are four cores in this filament, we can see those four core peak positions clearly.

### 3.4. Transverse velocity gradient across filament 8

We selected all SMT \(^{13}\text{CO}(2 - 1)\) spectra with a signal-to-noise ratio S/N > 4. After subtracting a baseline from each spectrum, we fitted a Gaussian profile to estimate the centroid velocity at each position and created a centroid velocity map (see Fig. 9). Based on this map, we constructed an average transverse position-velocity plot across filament 8 (Fig. 9b). To do so, we selected all \(^{13}\text{CO}(2 - 1)\) spectra observed in a 0.5-pc-wide strip around the filament crest (see Fig. 9b) and grouped them in bins of 0.05 pc to calculate a crest-averaged centroid velocity as a function of radial offset from the filament crest (Fig. 9b). The average velocity at crest position of filament 8 is \(\sim 0.36\) km s\(^{-1}\). Blue-shifted gas is distributed to the east of the filament crest. The averaged velocity at the position of 0.25 pc in the east is \(-0.87\) km s\(^{-1}\). The relative velocity with respect to the filament is \(\sim 0.51\) km s\(^{-1}\). Red-shifted gas is observed to the west of the filament crest. The averaged velocity at the position of 0.25 pc in the west is \(\sim -0.21\) km s\(^{-1}\). The relative velocity with respect to the filament is \(\sim 0.15\) km s\(^{-1}\). The best-fit velocity gradient is \(\Delta V_{\text{east}} = 2.17 \pm 0.27\) km s\(^{-1}\) pc\(^{-1}\) on the eastern side and \(\Delta V_{\text{west}} = 0.74 \pm 0.09\) km s\(^{-1}\) pc\(^{-1}\) on the western side.

### 4. Discussion

The Herschel data have revealed the presence of at least two quasi-periodic chains of dense cores (along filaments 8 and 10) in the X-shape region, with a typical projected core spacing \(\sim 0.15\) pc comparable to (or only \(\sim 30-40\%\) higher than) the filament inner width in both cases. The length of filament 8 is \(\sim 1\) pc and its line-mass is \(\sim 30\) \(M_{\odot}\) pc\(^{-1}\), roughly twice the critical line-mass \((M_{\text{line, crit}} \sim 16\) \(M_{\odot}\) pc\(^{-1}\)) for an isothermal gas cylinder at 10 K. Filament 10 has about the same mass per unit length but is about half the length of filament 8 (see Tab. [1]). In contrast to filament 8 which includes only prestellar cores, filament 10 harbors two embedded protostars and may be thus be slightly more evolved, at a somewhat later fragmentation stage. While filament 8 exhibits a pronounced transverse velocity gradient (Sect. [3] and Fig. [9]), there is no clear evidence of such a gradient toward filament 10, but this may be due to confusion of the \(^{13}\text{CO}(2 - 1)\) data by the outflows from the two embedded protostars. In this section, we discuss the implications of these results for our understanding of fragmentation in star-forming filaments.
4. Evidence of accretion into filament 8?

The blue-shifted gas and red-shifted gas distribute on the eastern and western sides of the filament 8, respectively. There are transverse velocity gradients on both sides of the filament 8. This physical phenomenon has been reported before in other filaments, such as the Taurus B211/B213 (Palmeirim et al. 2013), the Serpens cloud (Fernández-López et al. 2014; Dhabal et al. 2018), IRDC 18223 (Beuther et al. 2015), and it suggests the filament density curve starts to fluctuate irregularly, where we define as the background. $R_{\text{out}}$ estimated from high-resolution ($18.2''$) H$_2$ column density map is $0.18 \pm 0.1$ pc (see Fig.7). The background column density of the filament is $N_{\text{Background}} \sim 3 \times 10^{21}$ cm$^{-2}$. The observed relative velocity of the east blue-shift gas at $R_{\text{out}}$ to the filament center velocity is $V_{E} = \left| V_{\text{east},R_{\text{out}}} - V_{E} \right| = 0.38$ km s$^{-1}$. The observed relative velocity of the west red-shift gas at $R_{\text{out}}$ to
the filament center velocity \( V_c = |V_{\text{west}, R0} - V_c| \approx 0.13 \text{ km s}^{-1} \). Assuming that the ambient gas of cylindrical filament is in free-fall motion in the radial direction under self-gravity, the free-fall velocity at \( R_{\text{out}} \) is \( V_f = 2 \sqrt{GM_{\text{line, crit}}(R_{\text{init}}/R_{\text{out}})} \) \citep{Palmeirim2013}, where \( R_{\text{init}} \) is gas accretion range in radial direction. After we checked the continuity distribution of the red-shifted and blue-shifted gas on either side of the filament, we estimated \( R_{\text{max}} \approx 0.4 \text{ pc} \). \( V_f \) at \( R_{\text{out}} \) is \( 0.32 \text{ km s}^{-1} \). The gas accretion from both sides is \( M_{\text{ff}} = \mu_{\text{H}_2} m_{\text{H}_2} N_{\text{Background}} V_f \times 2 \). \( M_{\text{ff}} \approx 43 M_{\odot} \text{ Myr}^{-1} \text{ pc}^{-1} \). If we do not consider inclination angle, the observed \( M_{\text{obs}} \) can be estimated by \( M_{\text{obs}} = \mu_{\text{H}_2} m_{\text{H}_2} N_{\text{Background}}(V_c + V_f) \approx 35 M_{\odot} \text{ Myr}^{-1} \text{ pc}^{-1} \). Finally, we estimate \( M_{\text{line}} \approx 35-43 M_{\odot} \text{ Myr}^{-1} \text{ pc}^{-1} \), corresponding to a typical accretion timescale, \( M_{\text{line}}/M_{\odot} \approx 0.7 \pm 0.2 \text{ Myr}, \) for filament 8.

4.2. Fragmentation manner of filaments 8 and 10

The presence of two quasi-periodic chains of dense cores in the X-shape region with a projected spacing similar to the width of the parent filaments is quite remarkable. A few other examples of quasi-periodic configurations of roughly equally-spaced dense cores have recently been reported in the literature. ALMA dust continuum emission at 870 \( \mu \text{m} \) show a chain of dense cores spaced with a separation of \( \approx 0.023 \text{ pc} \) on a filamentary structure: G35.20-0.74N \citep{Sanchez-Monge2014}, \citep{Jackson2010} mapped filamentary infrared dark cloud (IRDC) of “Nessie” Nebula in HNC (1–0) emission with ATNF Mopra Telescope and found that the cores spacing separation is \( \approx 4.5 \text{ pc} \) \citep{Tafalla2015} found a chain of dense cores with a separation of \( \approx 0.1 \text{ pc} \) in the L1495/B213 filament of Taurus MC (see also \citealt{Bracco2017}). \citep{Wang2011} found a similar separation of \( \approx 0.16 \text{ pc} \) in the G28.34+0.06 IRDC, but the line-mass of this filamentary IRDC is eight times larger than the line-mass of filament 8 here. It is likely that the same underlying physical mechanism has produced quasi-periodic core patterns in all of these filaments.

Interstellar turbulence is believed to seed a whole spectrum of density fluctuations along filaments, and subcritical filaments are indeed observed to harbor a Kolmogorov-like spectrum of linear density fluctuations \citep{Roy2015}. In the case of thermally transcritical and supercritical filaments, self-gravity can amplify some of these density fluctuations beyond the linear regime, leading to prestellar core formation and protostellar collapse. Linear fragmentation models for the growth of density perturbations on infinitely long, isothermal equilibrium cylinders with \( M_{\text{lin}} = M_{\text{line, crit}} \) show that density perturbations with wavelengths greater than \( 2 \text{ times the filament diameter} \) can grow and predict a characteristic core spacing of \( \sim 4 \times \) the filament width (e.g., \citealt{Inutsuka1992}). Here, the \( FWHM_{\text{obs}} \) widths of filaments 8 and 10 are \( 0.13 \pm 0.03 \text{ pc} \) and \( 0.09 \pm 0.03 \text{ pc} \), respectively, so we would expect characteristic core spacings \( S_{\text{lin}}^{\text{crit}} \sim 0.52 \pm 0.12 \text{ pc} \) and \( S_{\text{lin}}^{\text{crit}} \sim 0.36 \pm 0.12 \text{ pc} \) in the two filaments according to these models. For these predictions to match the observed (projected) spacings, \( S_{\text{lin}}^{\text{crit}} \sim 0.17 \pm 0.01 \text{ pc} \) and \( S_{\text{lin}}^{\text{crit}} \sim 0.13 \pm 0.03 \text{ pc} \), the two filaments would have to be seen almost “head-on”, with a viewing angle \( \alpha \) of only \( 20 \pm 5^\circ \) between the filament axis and the line of sight in both cases. Such extreme values of \( \alpha \) are quite unlikely, especially for two independent filaments. Assuming random inclinations to the line of sight, the probability of observing a cylindrical filament with a viewing angle \( \alpha \leq \alpha_0 \) is \( \rho = 1 - \cos \alpha_0 \) or \( \rho \approx 6\% \) for \( \alpha_0 = 20^\circ \). The probability of observing two filaments (such as filaments 8 and 10 here) with \( \alpha \leq \alpha_0 \approx 20^\circ \) in a sample of 5 transcritical or supercritical filaments (\#5, 6, 8, 9, 10 in Tab.1) is only \( P = \binom{\delta}{\frac{5}{2}} p(1-p)^{\frac{5}{2}} \approx 3.6\% \) according to binomial statistics. The null hypothesis that the fragmentation pattern observed in filaments 8 and 10 is consistent with the predictions of classical cylinder fragmentation theory (e.g., \citealt{Inutsuka1992}) can thus be rejected at the \( > 2\sigma \) confidence level.

At least two explanations can be proposed to account for this discrepancy. First, filaments 8 and 10 are clearly not perfect, straight cylinders as they exhibit rather pronounced bends along their lengths (cf. Figs. 3 and 4). Using numerical simulations, \citep{Gritschneder2017} investigated the fragmentation properties of filaments including sinusoidal bends or longitudi-
nal oscillations and showed that bending filaments are prone to “geometrical fragmentation”, a process which generates cores at the turning points of the geometrical oscillation, separated by half the wavelength of the initial sinusoidal perturbation. Such a process may be partly at work here, although the geometrical deformations observed in filaments 8 and 10 (compared to straight filaments) are not purely sinusoidal, and some of the detected cores are apparently not located at clear bends along the filaments (cf. Figs. 3 and 5).

Second, neither filament 8 nor filament 10 is an isolated cloud structure in perfect hydrostatic equilibrium. As discussed in Sect. 4.1, the transverse velocity gradient seen across filament 8, the presence of quasi-periodic spacing of its cores on a scale comparable to its width, and feature bends along their crests which likely a

5. Conclusions

We performed a detailed study of filaments and cores in the X-shape Nebula of the California MC using a high-resolution (18.2") column density map constructed from Herschel data, along with 12CO(2–1) and 13CO(2–1) data from the SMT 10m telescope. Our main findings may be summarized as follows:

1. We selected 10 robust filamentary structures with elongation factors $E > 4$ and column density contrasts $C > 0.5$ from a skeleton network obtained with the getfilaments algorithm. The dust temperatures of the filaments are anti-correlated with their column densities ($N_{H_2}$). The deconvolved FWHM widths ($W_{\text{dec}}$) of the 10 filaments range from 0.09 to 0.18 pc and are independent of their column densities ($N_{H_2}$). The derived median filament width, 0.12±0.03 pc, is consistent with the inner core width of ~ 0.1 pc measured by [Arzoumanian et al. 2011, 2019] for Herschel filaments in nearby molecular clouds.

2. We identified two thermally supercritical filaments: filament 8 and 10, which both exhibit quasi-periodic chains of dense cores. The typical projected core spacing is ~ 0.15 pc, close or only ~ 30–40% higher than the filament inner width. Five prestellar cores form the central structure of filament 8. There is a transverse velocity gradient across filament 8, suggesting that this filament is accreting gas from a surrounding gas reservoir with an accretion rate $M \sim 40 \pm 10 M_\odot$ Myr$^{-1}$ pc$^{-1}$. Filament 10 is ~ 0.5 pc away from filament 8 and at a later fragmentation stage than filament 8. Two prestellar cores and two protostellar cores form the core structure of this filament.

3. We emphasize that classical cylinder fragmentation theory cannot account for the observed fragmentation properties of filaments 8 and 10. We suggest that two key factors may explain why the observed core spacing is shorter than the standard fragmentation length scale of equilibrium filaments. First, filaments 8 and 10 are not straight cylinder structures and feature bends along their crests which likely affect the fragmentation process. Second, at least in the case of filament 8, the presence of external accretion from the ambient cloud may enhance initial density perturbations lead to a shorter core spacing compared to an isolated filament.

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