Molecular filament formation and filament-cloud interaction: Hints from Nobeyama 45m telescope observations

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Abstract

We present Nobeyama 45m telescope C¹⁸O, ¹³CO, and ¹²CO(1−0) mapping observations towards an interstellar filament in the Taurus molecular cloud. We investigate the gas velocity structure along the filament and in its surrounding parent cloud. The filament is detected in the optically thin C¹⁸O emission as a single velocity component, ∼1 pc long, ∼0.06 pc wide structure. The C¹⁸O emission traces dust column densities larger than ∼5×10²¹ cm⁻². The line-of-sight (LOS) velocity fluctuates along the filament crest with an average amplitude of ∼0.2 km s⁻¹. The ¹⁳CO and ¹²CO integrated intensity maps show spatially extended emission around the elongated filament. We identify three extended structures with LOS velocities redshifted and blueshifted with respect to the average velocity of the filament identified in C¹⁸O. Based on combined analyses of velocity integrated channel maps and intensity variations of the optically thick ¹²CO spectra on and off the filament, we propose a 3-dimensional structure of the cloud surrounding the filament. We further suggest a multi-interaction scenario where sheet-like extended structures interact, in space and time, with the filament and are responsible for its compression and/or disruption, playing an important role in the star formation history of the filament. We also identify, towards the same field, a very faint filament showing a velocity field compatible with the filament formation process proposed by Inoue et al. (2017), where a filament is formed due to convergence of a flow of matter generated by the bending of the ambient magnetic field structure induced by an interstellar shock compression.

Key words: Stars: formation — ISM: clouds, filaments — Observations: dust and gas

1 Introduction

Molecular clouds are observed to be filamentary (e.g., Andrè et al. 2010; Molinari et al. 2010; Umemoto et al. 2017). Filamentary molecular clouds are proposed to be formed out of dense and cold atomic clouds as a result of multiple compressions from propagating shock waves through the interstellar medium (e.g., Hennebelle et al. 2008; Inoue & Inutsuka 2009; Inutsuka et al. 2015). The typical timescale of such shock compressions is estimated to be on average ∼1 Myr (McKee & Ostriker 1977). After each passage of a wave, the properties of the shocked molecular interstellar medium (ISM) are modified. Thus the present morphologies of the density, velocity, and magnetic field structures, are usually not those corresponding to the initial conditions at the molecular cloud formation.

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epoch, but are probably the result of their sequential alteration due to interactions with multiple propagating ISM waves.

Hence, in order to describe the formation and evolution of structures in molecular clouds, one should take into account the reorganization of interstellar matter, as a function of time, due to the propagation of waves through the filamentary clouds.

In the context of star formation, these propagating shock waves, may as a consequence be responsible for the assembly of dense molecular matter in the form of "thermally supercritical" filaments where the bulk of star formation is observed to take place (e.g., Andrê et al. 2010; Könyves et al. 2015; Marsh et al. 2016). These thermally supercritical filaments are characterized with a mass per unit length, \( M_{\text{line}} \), of the order or larger than the critical line mass of nearly isothermal, long cylinders, \( M_{\text{line, crit}} = 2c_s^2/E \sim 16 M_\odot/\text{pc} \) (Stodolkiewicz 1963; Ostriker 1964, where \( c_s \sim 0.2 \text{ km s}^{-1} \) for gas temperature of \( \sim 10 \text{ K} \), and are unstable for radial collapse and fragmentation (cf. Inutsuka & Miyama 1997). This critical mass per unit length corresponds to a column density of \( N_{\text{HI}} \sim 8 \times 10^{21} \text{ cm}^{-2} \) or a surface density of \( \Sigma_{\text{HI}} \sim 116 M_\odot/\text{pc}^2 \) for 0.1 pc wide filaments (Arzoumanian et al. 2011). These latter values are comparable to the proposed column density threshold for star formation (Lada et al. 2010; Shimajiri et al. 2017). Hence, the column density threshold for star formation can now be understood as the threshold in filament \( M_{\text{line}} \) equivalent to a critical value of hydrostatical equilibrium above which filaments are unstable to radial collapse and fragmentation into star forming cores (cf. André et al. 2014).

The analyses of Herschel observations towards the Aquila star forming region suggest that a relatively small fraction of the matter, about 15% on average, of the mass of supercritical filaments is in the form of prestellar cores (Könyves et al. 2015). Understanding this observed fraction, in the light of star formation along supercritical filaments, may give us a hint on the origin of the observed star formation efficiency in molecular clouds and in the Galaxy.

Molecular filaments are observed to span a wide range in central column density, mass per unit length, length, while they all share the same central width of about 0.1 pc (as derived in nearby regions from Herschel dust continuum observations, Arzoumanian et al. 2011; Juvela et al. 2012; Alves de Oliveira et al. 2014; Koch & Rosolowsky 2015; Arzoumanian et al. 2018, sub., and others). The origin of this filament property is not yet understood. Arzoumanian et al. (2011) suggested that the characteristic filament width may be linked to the sonic scale of turbulence in the cold (~10K) ISM, observed to be around 0.1 pc (Larson 1981; Goodman et al. 1998). The latter appears to be roughly the scale at which supersonic magnetohydrodynamic (MHD) turbulence dissipates (Federrath et al. 2010; Vázquez-Semadeni et al. 2003), compatible with the observed subsonic to transonic velocity dispersions of subcritical/critical filaments (Arzoumanian et al. 2013; Hacar et al. 2013, 2016). These results suggest that the dissipation of large-scale shock waves in the ISM may be important for the formation of the observed filamentary web (Inutsuka et al. 2015; Inoue et al. 2017).

In this paper we present Nobeyama 45m telescope C\(^{18}\)O(1 - 0), \(^{13}\)CO(1 - 0), and \(^{12}\)CO(1 - 0) molecular line observations towards a prominent ~1 pc long filament identified with Herschel in the Taurus molecular cloud (Fig. 1). In Sect. 2, we present our mapping observations with the Nobeyama 45m telescope. Section 3 details the results derived from the analysis of the velocity cubes, the spectra, the channel maps, the position-velocity maps, along, across and around the filament. In Sect. 4, we discuss the implication of our results in the understanding of filament formation, evolution, and interaction with the surrounding cloud. We summarize the results presented in this
paper and conclude in Sect. 5. Three appendices complement the analyses presented in the main text.

2 Molecular line mapping observations with the Nobeyama 45m telescope

We used the Nobeyama 45m telescope to map a molecular filament previously identified by Herschel, and its surrounding parent cloud (see Fig. 1). The target region is located on the west of the star forming L1495 hub in the Taurus molecular clouds at a distance of 140 pc (Elias 1978; Myers 2009; Ward-Thompson et al. 2016). The observations were carried out in February 2017. We mapped a 0.14 deg$^2$ region around the filament in $^{12}$CO(1 – 0), $^{13}$CO(1 – 0), and C$^{18}$O(1 – 0) with the FOREST receiver (Minamidani et al. 2016). All molecular line data were obtained simultaneously. At 115 GHz, the telescope has a beam size of ~ 15$''$ (HPBW). As backend, we used the SAM45 spectrometer which provides a bandwidth of 31 MHz and a frequency resolution of 7.63 kHz. The latter corresponds to a velocity resolution of ~0.02 km s$^{-1}$ at 115 GHz. The standard chopper wheel method was used to convert the observed signal to the antenna temperature $T_A^*$ in units of K, corrected for atmospheric attenuation. To estimate the main beam brightness temperature, $T_{MB}$, we mapped a small area of the OMC-2/FIR 4 region with strong dust continuum emission in the OMC-2/3 region (Shimajiri et al. 2008, 2015b, 2015a) once or twice per observing day. We scaled the FOREST intensity ($T_A^*$) to the intensity of the BEARS data ($T_{MB}$) obtained in (Shimajiri et al. 2011, 2014) by comparing the FOREST intensity with the BEARS intensity in the OMC-2/FIR 4 region. During the observations, the system noise temperatures ranged from 150 K to 580 K. The telescope pointing was checked every hour by observing the SiO maser source NML-tau, and was better than 3$''$ throughout the entire observing run. We used the on-the-fly (OTF) mapping technique. The central position of our final map is: (RA$_{2000}$, DEC$_{2000}$) = (04:16:49.711, 28:35:42.35). We have chosen line-of-sights of (RA$_{2000}$, DEC$_{2000}$) = (04:11:48.691, 26:46:25.59) as the off position for baseline removal. We obtained OTF maps with two different scanning directions along the RA and Dec axes and combined them into a single map (using the Emerson & Graeve (1988) PLAIT algorithm) to reduce the scanning effects. We then smoothed spatially and spectrally all the three cubes to the same effective HPBW size of 28$''$ and velocity resolution of 0.07 km s$^{-1}$. The 1$\sigma$ noise level of the final data at 28$''$ and 0.07 km s$^{-1}$ are 0.48 K, 0.22 K, and 0.20 K in $T_{MB}$ for $^{12}$CO(1 – 0), $^{13}$CO(1 – 0), and C$^{18}$O(1 – 0), respectively.

3 Analyses and results

3.1 Integrated intensity maps of $^{12}$CO(1 – 0), $^{13}$CO(1 – 0) and C$^{18}$O(1 – 0)

We derived velocity integrated intensity maps for the three lines of the observed region (Fig. 2). The emission is integrated for the local standard of rest (LSR) velocity range between 4 and 9 km s$^{-1}$, which encompasses the bulk of the emission of the observed region, as can be seen on the $^{12}$CO(1 – 0), $^{13}$CO(1 – 0) and C$^{18}$O(1 – 0) spectra averaged across the whole field (Fig. 3).

The C$^{18}$O(1 – 0) integrated emission traces the elongated structure of the filament (Fig. 2) with column densities $N_{HI} \gtrsim 5 \times 10^{21}$ cm$^{-2}$ as derived from Herschel data (Fig. 1, see also Appendix 1). The $^{13}$CO and $^{12}$CO integrated intensity maps show more extended emission around the filament for column densities $N_{HI} \gtrsim 1 \times 10^{21}$ cm$^{-2}$. In the following we re-
the mean beam brightness temperature of the $^{12}\text{CO}(1-0)$, $^{13}\text{CO}(1-0)$, and $^{13}\text{CHO}(1-0)$ emission. The $^{13}\text{CO}$ and $^{13}\text{CHO}$ spectra are multiplied by a factor 2 and 10, respectively. The five colored vertical rectangles show the five velocity channels, which we use to divide the total integrated emission based on position-velocity diagrams as explained in Sect. 3.2. The Five channels are as follow: B[4-5.4]km s$^{-1}$, F1[5.4-6.2]km s$^{-1}$, R1[6.2-7.2]km s$^{-1}$, R2[7.2-8.1]km s$^{-1}$, F2[8.1-8.7]km s$^{-1}$.

Fig. 3. Positionally averaged spectra (across the whole observed region) of $^{12}\text{CO}(1-0)$, $^{13}\text{CO}(1-0)$, and $^{13}\text{CHO}(1-0)$ emission. The $^{13}\text{CO}$ and $^{13}\text{CHO}$ emission are optically thin for all channels, the $^{12}\text{CO}$ emission is mostly optically thin. The mean PV diagram, we identify four velocity components. While the $^{13}\text{CHO}(1-0)$ emission which is not strong to detect extended $^{13}\text{CHO}(1-0)$ emission which is not strong enough to be detected otherwise, e.g., on the channel maps (Figs. 6 and 7).

3.2 Position velocity diagrams and channel maps

Figure 5 shows position-velocity (PV) diagrams perpendicular to the main axis of the filament MF, and averaged along its length. In practice, the cubes have first been rotated by 25$^\circ$ (corresponding to the mean orientation of MF on the plane of the sky) from North to East. Second, the PV-cuts in the horizontal direction have been averaged in the vertical direction along the 1 pc length of the filament. Averaging the emission increases the signal to noise ratio ($S/\sigma$), which makes it possible to detect extended $^{13}\text{CHO}(1-0)$ emission which is not strong enough to be detected otherwise, e.g., on the channel maps (Figs. 6 and 7).

These PV diagrams show multiple velocity components towards the filament MF and its surroundings. From the $^{13}\text{CHO}(1-0)$ mean PV diagram, we identify four velocity compo-
Fig. 6. Velocity channel maps in units of K km s\(^{-1}\). From left to right, velocity integrated intensity maps for \(^{12}\)CO(1 -- 0), \(^{13}\)CO(1 -- 0), and \(^{18}\)O(1 -- 0) emission. From top to bottom, channel maps derived by integrating the intensity for the following velocity ranges: Channel B [4--5.4] km s\(^{-1}\), Channel F1 [5.4--6.2] km s\(^{-1}\), and Channel R1 [6.2--7.2] km s\(^{-1}\). The velocity ranges of the channel maps are indicated on the top left of each panel. The spatial and spectral resolution of the maps are 28" and 0.07 km s\(^{-1}\), respectively. The blue contours correspond to column densities of 4, 6, and \(6 \times 10^{21}\) cm\(^{-2}\) derived from Herschel data, and are the same as those in Fig. 1. Note that the range of the color scale (indicated with the bar in the top of each panel) is different for each plot. This scale has been chosen to represent the dynamical range of the emission for each velocity channel map.
ponents: $\text{B}[4.5-5.4] \text{ km s}^{-1}, \text{F1}[5.4-6.2] \text{ km s}^{-1}, \text{R1}[6.2-7.2] \text{ km s}^{-1}, \text{R2}[7.2-8.1] \text{ km s}^{-1}$. The velocities given in the brackets correspond to the velocity ranges considered for each of the four components. The F1 velocity range corresponds to that of the filament MF (cf. below Sect. 3.4 and Fig. 6). A fifth velocity component, F2[8.1-8.7] km s$^{-1}$, is identified on the $^{13}$CO$(1-0)$ channel map as can be seen in Fig. 7 (bottom middle panel).

The analysis of the $^{12}$CO$(1-0)$ and $^{13}$CO$(1-0)$ velocity cubes indicate that the gas structures emitting at the velocity ranges, B, R1, and R2, introduced above, have different spatial distributions towards and around MF. We name SB, SR1, SR2, the structures associated to the velocity ranges B, R1, R2, respectively. In the following, we describe the spatial distributions of these different emitting structures that can be seen on the channel maps of Figs. 6 and 7.

As already mentioned, the filament MF is traced in $^{18}$O$(1-0)$ at the velocity range F1, while at this same velocity range, the $^{12}$CO emission shows an extended emission around MF, with some decrease of the intensity towards the filament crest (see also Sect. 3.3). Similarly the $^{13}$CO emission, albeit tracing MF, has a more extended structure on both sides of the filament crest. The $^{13}$CO emission of the SB structure, associated to the B velocity range, is mostly located on the eastern part of MF. While the $^{12}$CO emission is also partly detected on the western side of MF. SR1 is mostly traced towards the South and North-West of the field in both $^{12}$CO and $^{13}$CO. SR2 covers mostly the northern part of the field in $^{13}$CO, while $^{12}$CO emission is also seen in the South. At velocities between F2[8.1-8.7] km s$^{-1}$, a
second filament appears very bright in the North-East part of the field (see bottom-middle panel of Fig. 7). We identify this filament as YF (young filament, see Sect. 4.2 and Fig. 1).

The three extended structures, SB, SR1, and SR2, identified from the PV diagram of the C^{18}O emission, do not have sharp boundaries in space and in velocity but are interconnected spatially with continuous velocity fields. We can see on Fig. 5, velocity gradients across MF from the B to the R1 velocity ranges, traced by both the C^{18}O and the $^{13}$CO emission. These velocity bridges suggest that both structures, SB and SR1, may be physically connected to MF with partly mixed velocities. On the other hand, SR2 may not be presently directly connected to MF neither in velocity and probably nor in space.

The PV diagrams perpendicular to YF (Fig. 8) show two extended structures, one at velocities ~ 5 km s^{-1} and another at around ~ 8 km s^{-1}. These two velocity components correspond to the channels B and R2, respectively (see Fig. 8). The filament YF is identified on these PV diagrams in both C^{18}O(1−0) and $^{13}$CO(1−0), as a compact structure at a velocity ~ 8.3 km s^{-1}. On the $^{12}$CO(1−0) PV diagram an extended structure is detected at velocities between ~ 7.5 and 8.5 km s^{-1}, with a bent around the position of YF (Fig. 8, see Sect. 4.2).

### 3.3 Analysis of $^{12}$CO(1−0) spectra

The velocity channel maps (Figs. 6 and 7) and the PV diagrams (Fig. 5) show the presence of extended structures (with respect to the compact, elongated shape of the main filament MF). These extended structures have different velocity components at redshifted and blueshifted LOS velocities with respect to the mean velocity detected in C^{18}O(1−0) along MF.

To get a hint on the relative position of the different extended structures surrounding MF, we analyse the $^{12}$CO(1−0) spectra. To do so, we compare the optically thick $^{12}$CO(1−0) spectra at different positions “on” and “off” MF searching for signatures of absorption that may be used as an indication of the relative position of the different emitting structures along the LOS. Figure 9 shows $^{12}$CO(1−0) spectra integrated in 2′ x 2′ boxes on and off the filament, towards the North (a) and South (b) of the observed region. The color coding is indicated in the top right of the panels. The dotted spectra show integrated C^{18}O(1−0) emission within the same 2′ x 2′ boxes observed on the filament. The five colored polygons correspond to the 5 channels defined in Sect. 3.4: [5.4-6.2] km s^{-1}, [6.2-7.2] km s^{-1}, [7.2-8.1] km s^{-1}, [8.1-8.7] km s^{-1}.
3.4 Velocity structure along and around MF

The analysis of the $^{12}$CO(1–0) and $^{13}$CO(1–0) velocity cubes indicate several velocity components in the surroundings of the filament MF. These various velocity structures have different spatial distributions in the observed field (Figs. 6 and 7).

The filament MF is detected in $^{18}$O(1–0) as a velocity coherent structure with mostly a single velocity component all along the crest (Fig. 10). Towards the North section of MF the $^{18}$O(1–0) spectra show a second velocity component at $\sim 8$ km s$^{-1}$. The structure emitting at this systemic velocity is probably not connected neither spatially nor in velocity to MF (cf. Fig. 5).

Figure 10 shows a large scale velocity gradient of $\sim 1$ km s$^{-1}$ pc$^{-1}$ along the filament. In the southern part, for $0 < x_{\text{crest}} < 0.4$ pc, where $x_{\text{crest}}$ is the position along the filament crest, MF has a velocity in between the velocities of the extended structures SB and SR1, detected at velocity ranges blueshifted and redshifted, respectively, with respect to that of MF. Towards the North, for $x_{\text{crest}} > 0.4$, MF has a velocity compatible with the velocity of the extended structure SB detected at velocity ranges B, corresponding to blueshifted velocities with respect to that of MF. On top of this large scale velocity gradient, along the southern part of MF we can see small scale velocity fluctuations with an amplitude of about 0.13 km s$^{-1}$ for $0 < x_{\text{crest}} < 0.4$ pc. Along the northern part of MF the velocity fluctuations have larger amplitudes of about 0.34 km s$^{-1}$ for $x_{\text{crest}} > 0.4$ pc, as can be seen in the middle panel of Fig. 11.

The velocity fluctuations, as traced with the $^{18}$O(1–0) emission along MF, are compared to the column density fluctuation as derived from dust continuum using Herschel data. We can see velocity gradients towards the cores observed in dust continuum along the filament (Fig. 11). These may indicate converging motions towards the over-densities and prestellar cores identified with Herschel. The analysis of the velocity structure towards the core is not the scope of this present paper. Figure 11-bottom shows the velocity dispersion derived from Gaussian fitting of the optically thin $^{18}$O(1–0) spectra observed along the crest of MF. The total velocity dispersion (cf., e.g., Arzoumanian et al. 2013) is about $0.27$ km s$^{-1}$, with...
some larger values observed at a few positions along the crest of MF. We notice an anti-correlation between column density and velocity dispersion, where some of the column density deeps (e.g., around $x_{\text{crest}} \sim 0.45$) are associated with an increase of the velocity dispersion.

### 4 Discussion

In this section, we first discuss the implications of the observed velocity structures towards MF and YF, and their surroundings in our understanding of filament interaction with the parent cloud gas (Sect. 4.1). Second, we present our observations towards YF in the context of the detection of an early stage of filament formation supported by a theoretical understanding of filament formation in a magnetized ISM (Sect. 4.2).

#### 4.1 Filament and sheet-like-cloud interaction

The region studied in this paper is located in the west of the L1495 star forming hub in the Taurus molecular cloud (Fig. 1). A number of starless and prestellar cores are observed along the crest of the main filament MF (Marsh et al. 2016). This filament has $M_{\text{line}} \sim 16 M_{\odot} < M_{\text{line,crit}}$, a central width of $\sim 0.06$ pc and a power law profile at large radii, as derived from Herschel observations (cf. Table 2, Fig. 13 and, e.g., Arzoumanian et al. 2011; Palmeirim et al. 2013; Cox et al. 2016). It has a column density contrast with respect to the local background of $\sim 2$ (see Table 2 for the adopted definition). The second filament discussed in this paper, the young filament, YF, is thermally subcritical with $M_{\text{line}} \sim 1 M_{\odot} < M_{\text{line,crit}}$. It has a column density contrast with respect to the local background of $\lesssim 0.3$, a width of $\sim 0.08$ pc, and its profile is well described by a Gaussian function (Fig. 13).

Table 2 summarizes the properties of these two filaments as derived from Herschel observations.

These two filaments show coherent, one component velocity structures along their crests, while other velocity components detected towards the filaments are part of more extended structures of the surrounding parent cloud (cf. Sect. 3.4). Our results (as opposed to the case of the B211/3 filament, cf., Hacar et al. 2013) suggest that not all velocity components detected towards MF and YF have filamentary, i.e., elongated shape. These extended structures may however contribute 1) to the total column density observed in dust continuum towards the filament and 2) to the power-law wings of the filament radial profile at radii larger than the inner width (cf. Fig. 13). Mapping observations at scales larger than the filament width, tracking both dense and low density gas, are thus necessary to describe accurately the structure of the emitting gas (e.g., filament vs. extended structure).

From the analysis of the velocity integrated channel maps (as described in Sect. 3.4) we propose a representation of the environment of MF, attempting to constrain the relative positions of the emitting gas structures observed in the five different velocity ranges, B, F1, R1, R2, and F2. From the observed column densities and densities derived from the detection of molecular emission we estimated LOS depths of the three extended structures SB, SR1, and SR2 that vary between $\sim 0.2$ pc and $\sim 0.4$ pc for the $^{13}\text{CO}(1-0)$ emission and $\sim 0.1$ pc and $\sim 0.3$ pc for the

| Structure | Velocity range [km s\(^{-1}\)] | $\tau_{^{13}\text{CO}}$ | FWHM$^{13}\text{CO}$ [km s\(^{-1}\)] | $^{13}\text{N}_2$ | $^{13}\text{LOS}$ | $\tau_{^{18}\text{O}}$ | FWHM$^{18}\text{O}$ [km s\(^{-1}\)] | $^{18}\text{N}_2$ | $^{18}\text{LOS}$ |
|-----------|---------------------------------|-----------------------|-------------------------|-------------|----------------|-----------------------|-------------------------|-------------|-------------------|
| SB        | B[4.4 – 5.4]                    | 0.80                  | 0.68                    | 1.73        | 0.28           | 0.68                  | 1.73                    | 0.28        | 1.73              |
| MF        | F1[5.4 – 6.2]                   | 0.75                  | 0.51                    | 1.31        | 0.21           | 0.66                  | 1.76                    | 0.29        | 1.76              |
| SR1       | R1[6.2 – 7.2]                   | 0.79                  | 0.68                    | 1.76        | 0.29           | 0.79                  | 1.76                    | 0.29        | 1.76              |
| SR2       | R2[7.2 – 8.1]                   | 1.09                  | 0.66                    | 2.45        | 0.40           | 0.97                  | 0.97                    | 0.40        | 0.97              |
| YF        | F2[8.1 – 8.7]                   | 0.67                  | 0.42                    | 0.97        | 0.16           | 0.67                  | 0.42                    | 0.16        | 0.42              |
| All*      |                                | 0.79                  | 0.66                    | 1.73        | 0.28           | 0.67                  | 0.97                    | 0.28        | 0.97              |

Col. 1: Name of the structure identified in the given velocity range.
Col. 2: Velocity range identified from the PV diagrams (see Fig. 5 and Sect. 3.2).
Col. 3: Optical depth of the $^{13}\text{CO}$ emission calculated using equation (1) from Shimajiri et al. (2014), assuming an excitation temperature of 10K in local thermodynamic equilibrium (LTE) conditions, and a filling factor of 1. The peak brightness temperature of the $^{13}\text{CO}$ emission over the observed region have been derived using the MOMENT task in MIRIAD for each velocity range.
Col. 4: FWHM line width of the $^{13}\text{CO}$ spectra derived using the MOMENT task in MIRIAD for each velocity range.
Col. 5: H$_2$ molecular gas column density derived from $^{13}\text{CO}$ column densities calculated using equation (2) from Shimajiri et al. (2014), assuming a fractional abundance of $^{13}\text{CO}$ with respect to H$_2$ of $1.7 \times 10^{-6}$ (Freundling et al. 1982).
Col. 6: Extend of the emitting structure along the line of sight estimated from the column density given in Col. 5 for a critical density of $2 \times 10^3$ cm\(^{-3}\).
Col. 7 to Col. 10: Same as Col. 3 to Col. 6 for the $^{18}\text{O}$ emission, with a fractional abundance of $^{18}\text{O}$ with respect to H$_2$ of $1.7 \times 10^{-7}$ and a critical density of $5 \times 10^3$ cm\(^{-3}\).

* Median values for the five structures.
C$^{18}$O(1−0) emission (cf. Table 1). As for the extent of the structures on the plane of the sky we are limited by the coverage of the map of our Nobeyama observations, however a comparison with the $^{12}$CO data of Goldsmith et al. (2008) indicated that the structures identified in our maps cover a larger area (up to several parsecs) on the plane of the sky (Shimajiri et al. in prep.). The estimated LOS depth suggest that these extended structures are most probably sheet-like (and not spherical). The LOS depths estimated assuming $^{12}$CO(1−0) and C$^{18}$O(1−0) emission associated to densities $>10^3$ cm$^{-3}$ (cf. Table 1) are compatible with the detection of extended structures in $^{12}$CO(2−1), $^{13}$CO(2−1) and C$^{18}$O(2−1) towards our studied field (Tokuda et al. 2015). These latter transitions are shown to be excited at densities $>10^3$ cm$^{-3}$ (e.g., Nishimura et al. 2015).

The PV diagrams show “velocity bridge” like structures between the velocities of the SB and SR1 structures and that of MF (Fig. 5). This would suggest a physical connection between these different structures. In the northern section of MF, the correlation between the LOS velocity fluctuations and the column density fluctuations indicate that 1) the low column density parts of MF have velocities compatible with the B velocity range of the extended structure SB observed mostly towards the East of the filament, 2) while the high column density fragments are detected with velocities closer to those observed in the southern, more denser part of the filament. This would suggest that SB may be interacting with MF, dragging along its low column density parts, while the higher column density fragments are less affected and are observed at their “initial” LOS velocities, i.e, before interaction with SB. In this section of the filament, we observe a one-sided compression, with SB sweeping up the low column density parts of MF. In the southern section, MF has 1) velocities in between the B and R1 velocity ranges, 2) smaller velocity fluctuations, and 3) larger column densities. These observations suggest that SB and SR1 may be converging simultaneously towards MF, resulting in a compression (column density enhancement) of the filament. The large scale velocity gradient of about 1 km s$^{-1}$ pc$^{-1}$ observed along the filament crest (Fig. 10) may thus result from the interaction of SB and SR1 with MF. Interestingly, MF is observed at similar velocities as that of the neighboring ~6 pc long B211/3 filament in the South-East of the field (see Fig. 1-left). Using large scale $^{12}$CO and $^{13}$CO observations (from Goldsmith et al. 2008), Palmeirim et al. (2013) identified velocity gradients on both sides of the B211/3 filament with blueshifted and redshifted velocity components with respect to the velocity of the B211/3 filament. This velocity structure is discussed as tracing a matter flow, confined in a sheet, onto the filament (Palmeirim et al. 2013, Shimajiri et al. in prep.). The velocity ranges of the blueshifted and redshifted components observed around the B211/3 filament are similar to that of SB and SR1 identified towards MF, supporting our proposed picture of interaction of SB and SR1 with MF, suggesting a coherent picture within the cloud at larger scales. The converging motions of SB and SR1 towards MF, may also be in agreement with the analysis presented in Sect. 3.3, where the decrease of the $^{13}$CO intensity in the B velocity range observed towards MF, would result partly from the absorption of the optically thick $^{12}$CO emission located in the back of MF along the LOS.

This interaction between the filament and the surrounding more extended (sheet-like) structures may have implications in the evolution and the life time of filaments observed in molecular clouds. Thermally transcritical and supercritical filaments undergoing fragmentation into star forming cores may be affected by the interaction with these surrounding structures. Such interactions, which may vary as a function of relative density and velocity between the filament and the sheet, may be responsible in sweeping up matter from the filament and the surrounding of the core changing their mass accretion and final total mass. Overall, such interactions may affect/change the star formation activity along the filament. This may be an example of **resetting of star formation activity** along the filaments and might be important in our understanding of the observed star formation efficiency in molecular clouds.

### 4.2 Detection of an early stage of filament formation

The PV diagrams derived from C$^{18}$O(1−0) and $^{13}$CO(1−0) observations perpendicular to the young filament YF (Fig. 8), show the filament detected at velocities around 8.2 km s$^{-1}$, while a more extended structure is identified at velocities around 7.8 km s$^{-1}$. The presence of a velocity gradient of about 0.5 km s$^{-1}$, between YF and the extended structure, suggests matter flow onto the young filament, which evolves increasing in mass and density. This observed velocity pattern is in agreement with the formation of filamentary structures by accumulation of matter along magnetic field (B-field) lines bent by a shock compression as proposed by Inoue et al. (2017, see also, Inoue & Fukui 2013 and Vaidya et al. 2013). Appendix 3
presents a PV diagram perpendicular to the main axis of one of the filaments derived from the 3D data cubes of the simulation by Inoue et al. (2017). The schematic view of the filament formation scenario is presented in Fig. 12 and can be described as the following:

1. The initial condition corresponds to an over-density, a clump denser than its surrounding, present in the molecular cloud, formed, e.g., due to interstellar turbulence. The clump is threaded with an ordered magnetic field. This structure is about to interact with an interstellar shock front parallel to the magnetic field orientation and propagating towards it.

2. The interaction between the over-density and the propagating shock front compresses the over-dense structure into a sheet like flattened structure. Due to the finite size of the initial over-dense structure, with respect to the shock front, this latter induces a bent both in the compressed sheet like structure and in the frozen in magnetic field structure. The shock front deformation along with the bending of the B-field lines increases the velocity component along the bent B-field lines, inducing a matter flow along the B-field lines and towards the maximum curvature, where matter converges as an elongated young filament (see, Sect.3.1 of Inoue et al. 2017 for more detailed explanation about this mechanism). Note that in a hydrodynamic oblique shock case velocity gradients are also induced along the oblique shock front, however the presence of an ordered and strong magnetic field is required to create a long and coherent filament.

Thanks to the ordered magnetic field structure, and the induced velocity gradients along the B-field lines, the filament is formed perpendicular to the ambient B-field lines. The filament is thus expected to be straight and uniform along its crest. The central density and total mass of the filament increase in time during the evolution of the sheet-filament system (as suggested by the numerical simulations of Inoue et al. 2017).

Our observations suggest that matter converge along the B-field lines with a rate of \( \rho_{\text{Vind}} 2\pi R \approx 48 \ M_\odot/\text{pc/Myr} \), for \( \rho = 3 \times 10^{3} \ \text{cm}^{-3} \) estimated from \( N_{\text{H}_2} = 8 \times 10^{20} \ \text{cm}^{-2} \) and a size of 0.08 pc (see Table 2), \( v_{\text{inf}} = 0.5 \ \text{km s}^{-1} \), and \( R = 0.1 \ \text{pc} \) (see Fig. 12-Right). At this estimated rate, the forming filament increases in mass per unit length and may become critical \( (M_{\text{line,cr}} \sim 16 M_\odot/\text{pc}) \) in \( \sim 0.3 \ \text{Myr} \). If there is sufficient gas mass in the parent sheet, the initially thermally subcritical young filament may increase in mass per unit length until it reaches a mass per unit length equal to the critical mass per unit length, becomes gravitationally unstable and undergoes gravitational fragmentation into prestellar cores. On the other hand, when the filament cannot accumulate enough mass to become gravitationally bound, it may disperse, or be more vulnerable to expected forthcoming collisions/interactions with the surrounding environment.

Above we compared the expected velocity pattern from this scenario with the observation of the velocity field towards and around the filament YF. This comparison suggests that YF may be a young filament being formed by the convergence of matter along the B-field lines due to a flow induced by a shock compression. The scenario proposed by Inoue et al. (2017) is based on the main role of the relatively strong magnetic field. The only available data tracing the magnetic field towards this region are the Planck dust polarization maps at 350 GHz at a nominal resolution of 5' (or 0.2 pc at the distance of 140 pc of the Taurus cloud, see, e.g., Planck Collaboration Int. XXXIII 2016). The mean B-field orientation towards YF (averaged within 20'×20') is \( \sim (112 \pm 10)° \), making an angle of \( \sim 30° \) with respect to the orientation of YF on the plane of the sky. It is however difficult to conclude on the relative orientation in 3D between the filament and the local B-field with the Planck data, because of 1) the low spatial resolution and the integration of the emission from several structure along the LOS, and 2) the projection effect which may not give the true 3D relative orientation between the B-field and the filament. From Planck dust polarization data we can only derive the plane-of-the-sky (POS) component of the line of sight average B-field.

Our results suggesting that the B-field structure towards YF, a presently subcritical, low column density filament, being perpendicular to the axis of YF may be in contradiction with the orientation of the B-field lines derived from Planck dust polarization, supporting previous results derived from dust polarization observations as well as near infrared and optical polariza-
5 Summary and conclusions

In this paper, we presented molecular line mapping observations with the Nobeyama 45m telescope towards a 10′ × 20′ field in the Taurus molecular cloud. The analyses and results derived from the OTF maps in \(^{12}\)CO(1−0), \(^{13}\)CO(1−0) and \(^{18}\)O(1−0), can be summarized as follows:

1. The \(^{18}\)O(1−0) integrated emission traces the elongated structure of the ~1 pc long thermally transcritical filament MF with column densities \(N_\text{H}_2 \geq 5 \times 10^{21} \text{ cm}^{-2}\) as derived from Herschel data. The \(^{13}\)CO and \(^{12}\)CO integrated intensity maps show more extended emission around MF with column densities \(N_\text{H}_2 \geq 1 \times 10^{21} \text{ cm}^{-2}\).

2. Using PV diagrams and velocity channel maps derived from the \(^{12}\)CO(1−0), \(^{13}\)CO(1−0) and \(^{18}\)O(1−0) emission we identified five structures at the following velocity ranges: \(B[4.5-5.4] \text{ km s}^{-1}\), \(F1[5.4-6.2] \text{ km s}^{-1}\), \(R1[6.2-7.2] \text{ km s}^{-1}\), \(R2[7.2-8.1] \text{ km s}^{-1}\), \(F2[8.1-8.7] \text{ km s}^{-1}\). The structures emitting at the velocities of B, R1, and R2 are identified as extended sheet-like structures surrounding the filament MF. The F2 velocity range corresponds to a thermally subcritical filament (YF) detected in the \(^{12}\)CO channel map.

3. We compared the optically thick \(^{12}\)CO(1−0) spectra “on” and “off” MF. In the B velocity range, we identify a decrease of \(^{12}\)CO intensity “on” MF, that may results from absorption, suggesting that the structure emitting at these velocities may be located, at least partly, in the back of MF with respect to the LOS. Similar analysis suggested that the structures emitting at velocity ranges of R1 and R2 may be located in the front of MF with respect to the LOS. We use these analysis to describe the relative positions of the sheet-like structures surrounding the filament MF.

4. We detect a velocity gradient along the crest of MF with velocity oscillations of ~ 0.2 km s\(^{-1}\) on average, increasing towards the North part of the filament. We compare the velocity and column density structures along the filament crest. In the South part MF has 1) larger column densities, 2) velocities in between that of SB and SR1, and 3) small velocity fluctuations. These suggest that MF may be compressed on both sides by SB and SR1. In the northern part, the velocities observed towards the low column density sections of MF are compatible with that of the SB structure emitting at the B velocity range. We suggest that, in the northern section, SB is interacting with MF dragging its low column density parts. The higher column density fragments resist the sweeping and are observed at the LOS velocity of MF before interaction with SB.

5. The PV diagrams of \(^{13}\)CO and \(^{18}\)O towards YF show an elongated structure at velocities that differ by ~ 0.5 km s\(^{-1}\) with respect to the velocity of YF. We compare the observed velocity structure with that expected from the filament formation model presented in Inoue et al. (2017, see also Appendix 3). We suggest that our observations are compatible with the formation of a filament from the accumulation of matter along magnetic field lines induced by a shock compression due to a propagating wave. The observations suggest that a YF-like filament may form at a mass accretion rate of ~ 50 M_\odot pc/Myr and become thermally critical in ~ 0.2 Myr.

6. The propagation of interstellar shock waves, creating sheet-like molecular gas structures may play an important role in the formation of filamentary structure in molecular clouds. These filaments increase in mass per unit length accreting matter from the surrounding sheet until reaching the critical mass per unit length and becoming gravitationally unstable, fragmenting into star forming cores. The same propagating shock waves may interact with already formed filaments resulting in the compression of additional matter onto the filaments or the removal/disruption of low column density parts. We suggest that such interactions may play an important role in the life time of filaments and their star formation activity.

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Appendix 1 Column density structure derived from Herschel observations

We present here the properties of the two filaments discussed in this paper as derived from Herschel dust continuum observations. The column density map shown in Fig. 13 is derived as explained in Palmeirim et al. (2013) (see also, http://gouldbelt-herschel.cea.fr/archives, and, e.g., Marsh et al. 2016). We convolve the column density map to the 28″ resolution, the same as that of the molecular line maps studied in this paper.

We trace the crest of the filaments using the DisPerSE algorithm Sousbie (2011). The MF filament is traced on the column density map, while the YF filament is traced on the 13CO(1 − 0) F2 channel map (Fig. 8-right). We derive radial column density profiles perpendicular to the filament crests and measure the filament properties as explained in Arzoumanian et al. (2011, 2018).

Figure 13 shows the column density map derived from Herschel observations and the radial column density profiles perpendicular to the MF and YF filaments and averaged along their crests. Table 2 summarizes the main properties of the filaments.

Appendix 2 Analysis of the observed spectra over the field

In this appendix we extend the analysis discussed in Sect. 3.3 presenting averaged 12CO(1 − 0), 13CO(1 − 0), and C18O(1 − 0) spectra overlaid on the Herschel column density map (see Fig. 14). The spectra have been averaged over 2′ × 2′ squares and centered at different location over the observed field on the filament MF as well as on its East and West sides. Figure 14, complements the spectra of Fig. 9 showing the variation of the spectra in the B velocity range suggesting possible absorption of the optically thick emission, while such features are not observed towards the R1 and R2 velocity ranges. We have used this analysis to suggest a 3D structure of the observed portion of the cloud (see Sect. 4).

Appendix 3 Position-velocity diagram derived from the numerical simulation of filament formation by Inoue et al. (2017)

In this section we present the column density map and the PV diagram towards a filament extracted from the numerical simulation of Inoue et al. (2017), which studied the formation and evolution of filamentary structures induced by a shock propagation in a turbulent molecular cloud. The numerical simulation is an isothermal MHD simulation using an adaptive mesh refinement technique. The simulation has been particularly tuned to study the formation of massive filaments forming high mass stars, thus the densities and the velocity of the shock propagation...
Fig. 14. *Herschel* column density map at the resolution of 28′′ (same as Fig. 1), overlaid with spectra averaged in 2′ × 2′ squares over the observed region. The velocity range is [4-10] km s\(^{-1}\), and the intensity range is from -1 to 18 K. Black, red, and blue spectra correspond to \(^{12}\)CO(1 − 0), \(^{13}\)CO(1 − 0), and C\(^{18}\)O(1 − 0) emission respectively. The \(^{13}\)CO line is multiplied by a factor of 2 and the C\(^{18}\)O line by a factor of 5. The shaded area on the plots for each spectrum show the same velocity ranges as the 5 channels discussed in the paper (see, e.g., Fig. 9).

Fig. 15. Background subtracted column density structure of a filament from the simulation data by Inoue et al. (2017).

Fig. 16. Position-velocity diagram perpendicular to the filament shown in Fig. 15 from the simulation by Inoue et al. (2017). This diagram is derived by averaging the simulated cubes along the filament length as described by Eq. (A1). The unit of the color scale of the map is given by Eq. (A1).

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