The straight and isolated G350.54+0.69 filament: density profile and star formation content

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ABSTRACT
We investigate the global properties of the straight and isolated filamentary cloud G350.54+0.69 using Herschel continuum and APEX molecular line data. The overall straight morphology is similar to two other well studied nearby filaments (Musca and Taurus-B211/3) while the isolated nature of G350.54+0.69 appears similar to Musca. G350.54+0.69 is composed of two distinct filaments with a length \(\sim 5.9\) pc for G350.5-N (\(\sim 2.3\) pc for G350.5-S), a total mass of \(\sim 810\ M_\odot\) (\(\sim 110\ M_\odot\)), and a mean temperature of \(\sim 18.2\) K (\(\sim 17.7\) K). We identify 9 dense and gravitationally bound cores in the whole cloud G350.54+0.69. The separations between cores and the line mass of the whole cloud appear to follow the predictions of the “sausage” instability theory, which suggests that G350.54+0.69 could have undergone radial collapse and fragmentation. The presence of young protostars is consistent with this hypothesis. The line masses of the two filaments (\(\sim 120\ M_\odot\) pc\(^{-1}\) for G350.5-N, and \(\sim 45\ M_\odot\) pc\(^{-1}\) for G350.5-S), mass-size distributions of the dense cores, and low-mass protostars collectively suggest that G350.54+0.69 is a site of ongoing low-mass star formation. Based on the above evidence, we place G350.54+0.69 in an intermediate evolutionary state between Musca and Taurus-B211/3. We suggest that investigations into straight (and isolated) versus those distributed inside molecular clouds may provide important clues into filament formation and evolution.

Key words: ISM: individual objects: G350.5 – ISM: clouds – ISM: structure – ISM: molecules – stars: formation – infrared: ISM

1 INTRODUCTION
Filamentary structures in the ISM have long been recognized (e.g., Barnard 1905, Schneider & Elmegreen 1979). However, their role in the process of star formation has received renewed and focused attention recently thanks to long-wavelength data provided by the Herschel Observatory. These data demonstrate the ubiquity of the filaments in the cold interstellar medium (e.g., Molinari et al. 2010; Andrè et al. 2010, 2014; Stutz & Kainulainen 2015). Combined with multi-wavelength information, these data reveal a close connection between filamentary clouds and star formation. For example, Könyves & Andrè (2015) and Stutz & Kainulainen (2015) demonstrate that most cores are located on the filaments within clouds. Moreover, using gas velocity information, Stutz & Gould (2016) show that protostellar cores are also kinematically coupled to the dense filamentary environments in Orion; that is, the protostellar cores have similar radial velocities as the gas filament as well as being located on or very near the filament ridgelines.

On scales larger than cores, Herschel results have focused on the column density profiles of the filaments themselves. Arzoumanian et al. (2011) found that the filaments in the low mass IC5146 molecular cloud have an approximately uniform inner width of 0.1 pc (assuming a distance of 460 pc; see their appendix A). This result was later confirmed in other nearby and low mass clouds in the Gould Belt (Koch & Rosolowsky 2015). A proposed explanation for this observation is that the common width may be attributed to the sonic scale below which the interstellar turbulence becomes subsonic in diffuse, and non star-forming molecular gas (Padoan et al. 2001; Federrath 2016; Andrè et al. 2016; Andrè 2017). Another possibility is that the approximately uniform widths may be rooted in the dissipation of magneto-hydrodynamic (MHD) waves (Hennebelle & Andrè 2013; Andrè et al. 2016; Andrè 2017).

Interestingly, claims of a “universal” and constant width for filaments is being challenged by analysis in other more distant (and sometimes higher mass) clouds, most of which lie beyond the Gould Belt. Wider widths (between 0.26 pc and 0.34 pc) have been reported in both the DR 21 ridge and Cygnus X (Hennemann et al. 2012). In addition, on the basis of a large sample of low and
high-mass filaments within the Planck cold clumps, Juvela et al. (2012) find filament widths of 0.1 to 1 pc, with a typical value of $\sim 0.2 - 0.3$ pc. This large variation may be a result of inconsistencies both in the definition of filament widths and in the methodology adopted for measuring this parameter (e.g., Juvela et al. 2012; Smith, Glover, & Klessen 2014; Panopoulou et al. 2017). In further tension with the results inferred in low-mass Gould Belt cloud, the Orion A Integral Shaped Filament (ISF) has an average profile that is extremely well represented by a power-law down to 0.05 pc, the resolution limit of the Herschel observations (Stutz & Gould 2016; see their Figure 5). This profile is inconsistent with a $\sim 0.1$ pc width since such a width would require a flattening or softening of the density profile inside that radius. Stutz & Gould (2016) propose that the differences in the ISF density profile and properties may be rooted in two distinct, if related, physical parameters in this filament: its high mass and the action of the magnetic field. One thing is clear: this varied patchwork of inconsistent results are difficult to interpret even though Andrè (2017) argues that the 0.1 pc width may be physically meaningful. It is, therefore, necessary to investigate the properties, including the density profile shape, of star forming gas filaments beyond the Gould Belt.

The purpose of this paper is to investigate the evolutionary and physical state of the star forming filamentary cloud G350.54+0.69 (G350.5 afterwards). This filament is very interesting because of its straight and isolated nature (see Fig. 1), similar in morphology to B211/3 (Palmeirim et al. 2013) and in both morphology and isolation to Musca (e.g., Cox et al. 2016). In contrast, most well-studied filaments in nearby clouds appear as curved and intertwined structures embedded in the larger molecular cloud material. One example includes the Orion Integral Shaped Filament (ISF), which completely dominates the cloud structure in the north of Orion A, has a high line-mass, and a curved wave-like morphology (Stutz & Gould 2016; Stutz 2018). Other examples are the lower line-mass filaments embedded within clouds; these exhibit a “noodle soup”-like morphology, e.g., Polaris (André et al. 2010), IC5146 (Arzoumanian et al. 2011), Pipe (Peretto et al. 2012), Orion B (Schneider et al. 2013), and Aquila (Könnyves & André 2015). Determining the physical nature of these two classes of filaments (i.e., straight and isolated versus curved and intertwined) requires detailed investigation of such straight and isolated filament, of which there are few examples in the literature.

We place particular emphasis on the filament column density profile, the kinematics of dense cores, and the star formation content of the filaments. G350.5 is centered at $\alpha_{2000} = 17^h 18^m 13.8^s$, $\delta_{2000} = -36^\circ 29' 21".5$ and located at $1.38 \pm 0.13$ kpc (calculated using the online program Bayesian Distance Calculator) by inputing a systemic velocity of $V_{lsr} = -3.9$ km s$^{-1}$. The analysis on the column density profile can, on one hand, add to a number of previous studies of nearby filament clouds for pinpointing which properties may give rise to the inner width of a given filament. Moreover, G350.5 has not been well-studied up till now, and therefore represents a new laboratory within which to investigate the physical conditions in star forming filaments. Finally, we tentatively place G350.5 in an evolutionary context through comparison to the nearby Taurus B211/3 (Palmeirim et al. 2013) and Musca (e.g., Cox et al. 2016) filaments, which exhibit similar morphology to G350.5.

This paper is organized as follows: the Herschel and molecular line observations are described in Section 2, the data analysis results are presented in Section 3, the discussions are in Section 4, and a summary is given in Section 5.

2 OBSERVATIONS AND DATA REDUCTION

2.1 Herschel observations

Far-infrared data carried out with the Herschel Space Observatory (HSO) were used to characterize dust properties of the G350.5 filament. G350.5 was observed as part of the Hi-GAL$^2$ survey. The PACS (Poglitsch et al. 2010) and SPIRE (Griffin et al. 2010) instruments were used to carry out the survey simultaneously at 70, 160, 250, 350, and 500 $\mu$m in the parallel photometric mode. The observations were made in two orthogonal scanning directions at a scan speed of 60 arcsec s$^{-1}$. The effective angular resolutions for those five wavelength bands are $6.0', 12.0', 18.0', 24.0', and 35.0' (Molinari et al. 2016), respectively, which correspond to 0.04, 0.08, 0.12, 0.16, and 0.23 pc, respectively, at a distance of 1.38 kpc. More details about the data preprocessing up to usable high-quality images can be found in Traficante et al. (2011).

2.2 Molecular observations

The molecular observations of $^{13}$CO and C$^{18}$O (2-1) presented in this paper were made on September 24, 2017, with the Atacama Pathfinder Experiment (APEX) 12-m telescope (Güsten et al. 2006) at Llano de Chajnantor (Chilean Andes). In the observations, the frontend was equipped with the APEX-1 receiver of the Swedish Heterodyne Facility Instrument (SHEFI, Vassilev et al. 2008) and the backend was the eXtended bandwidth Fast Fourier Transform Spectrometer (XFFTS) with an effective spectral resolution of 114 KHz or 0.15 km s$^{-1}$ at a tuned central frequency of 220 GHz between $\nu = 220.39684$ GHz (i.e., $^{13}$CO (2-1)) and $\nu = 219.560358$ GHz (i.e., C$^{18}$O (2-1)). The angular resolution at these two frequencies is $\sim 28''$.

Mapping observations were made using the on-the-fly mode in the two orthogonal scanning directions along 50$^\circ$-rotated Right Ascension and Declination (see the dashed rectangle in Fig. 1). The mapping is centered on $\alpha_{2000} = 17^h 18^m 13.8^s$, $\delta_{2000} = -36^\circ 28' 21''5$ with a rectangular size of $7' \times 16'$. The observations were calibrated with the chopper-wheel technique and the output intensity scale given by the system was $T_a^*$, which represents the antenna temperature corrected for atmospheric attenuation. That intensity scale was further converted to the main-beam brightness temperature by $T_{mb} = T_a^*/\eta_{mb}$, where the main beam efficiency $\eta_{mb}$ is 0.75. All observation data were reduced using the CLASS90 programme of the IRAMs GILDAS software (Guilloteau & Lucas 2000). The reduced spectra finally present a typical rms value of 0.42 K.

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1. http://bessel.vlbi-astrometry.org/bayesian

2. Hi-GAL, the Herschel infrared Galactic Plane Survey, is an Open Time Key project on the Herschel Space Observatory (HSO) aiming to map the entire Galactic Plane in five infrared bands. This survey covers a $|b| < 1^\circ$ wide strip of the Milky Way Galactic plane in the longitude range $-60^\circ < l < 60^\circ$. 
3 RESULTS

3.1 Dust temperature and column density maps

The dust temperature ($T_{\text{dust}}$) and column density ($N_{\text{H}_2}$) maps of the filament G350.5 were created using a modified blackbody model to fit the spectral energy distribution (SED) pixel by pixel, as described in Liu et al. (2016, 2017). Before the SED fitting, all Herschel images except for the 70 $\mu$m one were convolved to the resolution of the 500 $\mu$m image, and then regridded to the same pixel size as that in the 500 $\mu$m band. Emission at 70 $\mu$m was not considered in the SED fitting for a single temperature since 70 $\mu$m radiation may trace hotter components such as very small grains (VSGs), and warmer material heated by protostars, both of which can not be interpreted properly by a single temperature. In the SED fitting, a dust opacity law of $\kappa_\nu = 0.1 \times (\nu / 1 \text{THz})^{0.5}$ was assumed with a gas-to-dust mass ratio of 100 (Beckwith et al. 1990). $\beta = 2$ was fixed to keep consistent with that used in studies of Herschel observations toward other star-forming filaments (e.g., Palmeirim et al. 2013; Cox et al. 2016). To reveal small-scale dense structures (i.e., clumps/cores), we made a high-resolution $N_{\text{H}_2}$ map using the 35$''$-resolution $T_{\text{dust}}$ map to convert the 250 $\mu$m intensity map to a column density map. This simple method has already been demonstrated to be feasible in creating a relatively high-resolution $N_{\text{H}_2}$ map (Stutz & Kainulainen 2015; Stutz & Gould 2016). Figure 1 presents the 35$''$-resolution $T_{\text{dust}}$ map, and the final 18$''$-resolution $N_{\text{H}_2}$ map.

3.2 Filament properties

As shown in Fig. 1, the filament G350.5 is composed of two discontinuous filaments in both dust temperature and column density maps. To better delineate them, the function make_fil_spine built in the algorithm FilFinder$^3$ was used to extract the main skeleton of the filaments from the column density map. For simplicity, FilFinder identifies the filamentary structures using an adaptive thresholding, which creates a mask based on local brightness (or intensity) changes in the image. The method Medial Axis Transform is then used to reduce the signal mask to a skeleton. This skeleton is finally pruned down to a filamentary network. More detailed descriptions on FilFinder can be found in Koch & Rosolowsky (2015). With that algorithm, two discontinuous filaments are well identified (see Fig. 1). Given the distance to G350.5, the northern part is estimated to be $\sim 5.9$ pc long and the southern one is $\sim 2.3$ pc long. The two parts are called G350.5-N, and G350.5-S in the following discussions, respectively.

G350.5-N, and G350.5-S are observed to be associated with each other with similar systematic velocities based on the $^{13}$CO and C$^{18}$O (2-1) observations (see Sect. 3.3). To make an approximated calculation, we define these two discontinuous filaments within a column density level of $1.8 \times 10^{22}$ cm$^{-2}$ that surrounds the majority of their masses. After subtracting an approximate background emission of $1.43 \times 10^{22}$ cm$^{-2}$, which was estimated from the column density profiles of the two filaments (see Sect. 3.2.1), we obtain the total mass, mean column density, and mean temperature to be $\sim 590 M_\odot$, $\sim 8.2 \times 10^{22}$ cm$^{-2}$, and $\sim 18.2$ K, respectively, for G350.5-N and $\sim 95 M_\odot$, $\sim 8.2 \times 10^{21}$ cm$^{-2}$, and $\sim 17.7$ K, respectively, for G350.5-S.

3.2.1 Column density profile

To better and quantitatively characterize the filaments, we construct the column density profiles for G350.5-N, and G350.5-S using the column density map with the same procedure as adopted in previous studies (e.g., Arzoumanian et al. 2011; Palmeirim et al. 2013; $^3$ https://github.com/e-koch/FilFinder

Figure 1. (Left): 35$''$-resolution $T_{\text{dust}}$ map for the filament G350.5. (Right): 18$''$-resolution $N_{\text{H}_2}$ column density map, where two discontinuous filaments (i.e., G350.5-N, and G350.5-S) are delineated with red curves. The red dashed rectangle shows the area covered by molecular line observations with APEX, which is rotated by 50 degrees relative to the RA direction. A scale bar of 1 pc is shown on the bottom left.
Cox et al. (2016). In a nutshell, we first created the individual column density profile in the local tangent direction for each pixel along the crest (i.e., the red curve in Fig. 1) of the filament. The mean column density profile was then derived by averaging the individual profiles for all pixels. The resulting column density profiles for the two filaments G350.5-N, and G350.5-S are shown in Fig. 2, where the gray dots with error bars stand for the mean measured column densities and the errors come from the standard deviation.

The Plummer-like function is commonly used to describe the column density profile of a filament. According to Cox et al. (2016), the form of the Plummer-like function can be simplified as below:

$$N_p(r) = \frac{N_{p0}^0}{\cos(i)(1 + (r/R_{flat})^2)^{p+1}}$$

where $N_{p0}^0$ is the central column density, $R_{flat}$ is the flattening radius, $p$ is the index of a power-law fall off in column density beyond $R_{flat}$, and $i$ is the inclination angle of the filament to the plane of the sky, assumed to be 0 degrees here. Before the Plummer-like function fitting, we estimated the background column density level fitting a first order polynomial to the selected radius range (1 pc $< |r| < 2$ pc) where the observed column density profile appears to be in a constant level for the two filaments. This method gives rise to $N_{H_2}^{bg} = 1.43 \times 10^{22}$ cm$^{-2}$ for G350.5-N, and $N_{H_2}^{bg} = 1.42 \times 10^{22}$ cm$^{-2}$ for G350.5-S, respectively. As a first-order approximation, the mean value $N_{H_2}^{bg} = 1.43 \times 10^{22}$ cm$^{-2}$ is used as background emission for the whole G350.5 cloud. After the background subtraction to the observed mean column density profile, the Plummer-like function fits were made in a radius range of $|r| < 0.5$ pc using the MPFIT non-linear least-squares fitting programme (Markwardt 2009), which can propagate the uncertainties in the mean observed column density profile into estimating the uncertainties in the derived parameters. The radius range $|r| < 0.5$ pc is chosen since the majority of the densities of the two filaments in that range are above the background level. The best fits as indicated with red lines in Fig. 2 yield the parameters $R_{flat} = 0.15 \pm 0.01$ pc, and $p = 3.0 \pm 0.1$ for the plummer-like fitting, and FWHM = 0.34 $\pm$ 0.01 pc for the Gaussian fitting. For the filament G350.5-S, the corresponding fitting parameters are $R_{flat} = 0.12 \pm 0.01$ pc, $p = 3.5 \pm 0.5$, and FWHM = 0.24 $\pm$ 0.01 pc.

As mentioned in Sect. 1, the inner width (FWHM) of the filament is important for constraining the density profile and filament formation scenarios. By fitting a single gaussian function (i.e., the blue solid line in Fig. 2) to the observed column density profile in an inner range of $|r| < 0.5$ pc, in which the inner part of the two filaments appears to reside as shown in Fig. 2, the inner widths are derived to be 0.34 $\pm$ 0.01 pc for G350.5-N, and 0.24 $\pm$ 0.01 pc for G350.5-S, which correspond to the deconvolved FWHMs 0.32 $\pm$ 0.01 pc, and 0.21 $\pm$ 0.01 pc, respectively, given a beam size of 0.12 pc.

The fitted parameters $R_{flat}$, $p$, and FWHM should be regarded as approximate for the following reasons. The radial profile in Fig. 2 shows a very flat and wide inner profile for both filaments, implying that the central crest may not be resolved. Fitting a Gaussian or a Plummer-like function to a flattened profile would then show a larger width (i.e., $R_{flat}$, FWHM) than that of a more resolved filament. The Plummer-like parameters (e.g., $R_{flat}$, $p$) are strongly dependent on each other (e.g., Malinen et al. 2012; Juvela et al. 2012; Smith, Glover, & Klessen 2014). That is, if $R_{flat}$ is wider than it should be, it would in turn directly affect the fitted $p$ value. It is, therefore, worthwhile to carry out in the future high-resolution continuum observations, which would be very helpful for investigating the detailed density profiles of both G350.5-N and G350.5-S.
3.2.2 Line mass distribution

One of the advantages of building the column density profile is to use it to derive the mass per unit length \((M_{\text{line}})\) along the main axis of the filament. We calculated \(M_{\text{line}}\) for each position along the crest of the filament by integrating the observed column density profile over its outer width (i.e., \(|r| < 0.5\ \text{pc}\)). The resulting \(M_{\text{line}}\) distributions for G350.5-N, and G350.5-S are displayed in Fig. 3, where several sharp \(M_{\text{line}}\) peaks are related to dense cores (see Sect. 3.3) and the dashed horizontal lines represent the critical mass per unit length \((M_{\text{crit}})\). According to Inutsuka & Miyama (1997), \(M_{\text{crit}}\) is defined as \(2\sigma_{\text{th}}^2/G\) for an unmagnetized isothermal filament, where \(\sigma_{\text{th}}\) corresponds to the thermal sound speed and \(G\) is the gravitational constant. Given the mean dust temperature of each filament (i.e., 18.2 K for G350.5-N, and 17.7 K for G350.5-S, see Sect. 3.1), the critical line masses are \(\sim 30\ M_{\odot}\ \text{pc}^{-1}\) for G350.5-N, and \(\sim 29\ M_{\odot}\ \text{pc}^{-1}\) for G350.5-S. Note that we neglected the non-thermal support in the above calculation. Therefore, using the actual velocity dispersion, \(0.47 \pm 0.11\ \text{km \ s}^{-1}\) (see Sect. 4.1) instead of the thermal sound speed, we obtain the critical value \(M_{\text{line}}^{\text{crit}}\) of \(102 \pm 48\ M_{\odot}\ \text{pc}^{-1}\) for both G350.5-N and G350.5-S. As shown in Fig. 3, most parts of the two filaments have \(M_{\text{line}} > M_{\text{line}}^{\text{crit}}\). This suggests that both filaments could be supercritical on the process of fragmentation into prestellar dense cores owing to gravitational instability, which is well consistent with the picture of dense cores detected in the two filaments (see Sect. 3.3).

In addition, we calculated the total mass for these two filaments by integrating the \(M_{\text{line}}\) along the main axis of each filament, resulting in \(\sim 810\ M_{\odot}\) for G350.5-N, and \(\sim 110\ M_{\odot}\) for G350.5-S, respectively. These values are in agreement with those estimated before from the column densities as described in Sect. 3.1.

3.3 Dense cores

Nine dense cores were identified on the filaments using the column density map (see Fig. 1). We made use of the Python package astrodendro\(^4\) to identify potential dense entities within the main structure of the filaments. As requested by the source extraction algorithm, a column density of \(2.1 \times 10^{22}\ \text{cm}^{-2}\) was input to be a start level to construct the dendrogram and a threshold of 9 pixels (> 18\(^2\)) was imposed to ensure a leaf to be resolvable under current resolution. As a result, nine dense cores are identified as shown in Fig. 4 and their corresponding parameters are summarized in Table 1, including the identity number, coordinates, effective beam-deconvolved radius, dust temperature, column density, number density, and core mass.

Figure 4 presents the spectra of the transition \(J = 2 \rightarrow 1\) of \(^{13}\text{CO}\) and \(^{13}\text{C}^{18}\text{O}\) for all identified dense cores except for the C9 core not covered by our current APEX observations. It can be seen that emission of both \(^{13}\text{CO}\) and \(^{13}\text{C}^{18}\text{O}\) (2-1) is strong enough to be detected in all of the eight dense cores. Fitting a single-Gaussian function to the observed spectra with the software GILDAS, we retrieved the corresponding observed parameters for each core, including the main-beam temperature \(T_{\text{mb}}\), peak velocity \(V_{\text{mb}}\), and velocity dispersion \(\sigma\) for both spectra (see Table 2). The peak velocities derived from both \(^{13}\text{CO}\) and \(^{13}\text{C}^{18}\text{O}\) (2-1) are consistent with each other within 0.4 km s\(^{-1}\) in all eight cores but the core C2, suggesting that both tracers basically trace the same region.

4 DISCUSSIONS

4.1 Column density profile analysis

The mean column density profiles of G350.5-N, and G350.5-S are described in a Plummer-like function with a power law index of \(p \sim 3\) (see Fig. 2). This index is in a reasonable previously observed range. For example, a range of \(p \sim 1.5 - 3\) has been reported in several filaments, such as \(p = 1.5 - 2.5\) observed towards the filaments in the IC5146 cloud (Arzoumanian et al. 2011), \(p = 2.0 \pm 0.4\) in the Taurus B211/3 filament (Palmeirim et al. 2013), \(p = 2.2 \pm 0.3\) in high-mass star-forming ridge of the NGC6334 cloud (André et al. 2016), \(p = 2.7 \pm 0.2\) in the cloud Vela C (Hill et al. 2012), \(p = 2.7 - 3.4\) in L1517 (Hacar & Tafalla 2011), and \(p = 3\) in L1495 (Tafalla & Hacar 2015). Theoretically, the radial equilibrium of filamentary molecular clouds can be described by treating filaments as isothermal cylinders and using either pure hydrostatic models (Ostriker 1964) or magnetohydrodynamic models (e.g., Fiege & Pudritz 2000). The former models can lead to a typical density profile of \(\rho \propto r^{-p}\) and the latter ones can give a characteristic density profile approaching to \(\rho \propto r^{-2}\). From the observation point of view, the theoretical models with magnetic fields can produce more realistic density profiles than those without magnetic fields based on at least two facts: 1) most of observed column density profiles are shallower than predicted for a pure gravitationally bound filament without magnetic fields (Ostriker 1964), and 2) magnetic fields have already been observed to be important over largely dynamical scales from 100 pc to 0.01 pc (e.g., Li et al. 2013, 2014, 2015). Filaments G350.5-N and G350.5-S have steeper column density profiles than those expected for the case of a magnetized isothermal cylinder filament (i.e., \(\rho \propto r^{-2}\)). Keeping in mind the uncertainties of the fitted \(p\) (see Sect. 3.2.1), we suggest that the steeper column density profiles of both G350.5-N, and G350.5-S might be a result of the radially gravitational contraction of the filament, which is consistent with the supercritical mass per unit length of both filaments, an indicator of filament fragmentation induced by gravitational instability (see Fig. 3).

Nearby filamentary clouds in the Gould Belt have been observed to be characterized with an almost constant inner width of 0.1 pc (e.g., Arzoumanian et al. 2011). As analyzed in Sect. 3.2.1, the FWHMs of G350.5-N, and G350.5-S are 0.28 ± 0.01 pc, and 0.22 ± 0.01 pc, respectively. These values agree with those found between 0.26 to 0.34 pc for the filaments observed in Cygnus X, and others found in the literature (see Sect. 1), suggesting that the inner width 0.1 pc is not necessarily universal for the filaments beyond the Gould Belt. According to Larson’s velocity dispersion-size relationship, \(\sigma_{10}\) (km s\(^{-1}\)) = \(0.63 \times L_{\text{pc}}^{0.38}\) (Larson 1981), the FWHMs, 0.34 pc (0.24 pc) for G350.5-N(S), lead to a predicted velocity dispersion of 0.42 km s\(^{-1}\) (0.37 km s\(^{-1}\)). As mentioned in Sect. 3.2.1, the fitted FWHMs of the two filaments are probably overestimated due to the flat density profiles caused by our current poor spatial resolution. In turn, the predicted velocity dispersion values could be overestimated. Figure 5 presents the veloc-

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\(^4\) http://dendrograms.org/
Figure 3. Mass per unit length ($M_{\text{line}}$) along the filament main axis for G350.5-N (Left), and G350.5-S (Right). The thick dashed lines show the critical $M_{\text{line}} \sim 102 \ M_\odot \, \text{pc}^{-1}$ for both G350.5-N and G350.5-S, and the thin dashed lines an uncertainty of $\sim 48 \ M_\odot \, \text{pc}^{-1}$. Several peaks are related to dense cores (see Fig. 4) as indicated by vertical lines. It can be seen that most parts of the two filaments have $M_{\text{line}} \sim M_{\text{line}}^{\text{critical}}$, suggesting fragmentation processes taking place on both filaments due to gravitational instability.

Figure 4. Left: nine identified dense cores. The column density map (color scale) is shown on the log scale. Right: spectra of $J = 2 - 1$ of $^{13}$CO (in red) and $^{18}$O (in blue) for the nine dense cores. The Gaussian fitting is indicated with the black curve.

4.2 Fragmentation of filaments

As discussed in Sect. 3.2.2, the filamentary cloud G350.5 is gravitationally unstable. Therefore, nine dense cores detected on the main structure of the filament should be a result of the fragmentation of G350.5. The projected separations between these cores are measured to be in the range $\sim 0.4 - 1.7 \, \text{pc}$ at the cloud distance. The mean separation of these cores is $\sim 0.9 \pm 0.4 \, \text{pc}$. The shortest two separations are found in two pairs of cores, C3 and C4, C5 and C6. Regardless of these two pairs, other separations appear to be periodic.

We take advantage of “sausage” instability theory to examine the fragmentation of the filamentary cloud G350.5 in more details. The keystone of this theory is that the fragmentation of a self-gravitating fluid cylinder can give rise to distinct dense cores with...
For an incompressible fluid, perturbation analysis shows that the critical wavelength appears at $\lambda_{\text{crit}} = 11R_{\text{cyl}}$, where $R_{\text{cyl}}$ is the cylinder’s radius (e.g., Chandrasekhar & Fermi 1953). In an infinite isothermal gas cylinder, the characteristic wavelength becomes $\lambda_{\text{crit}} = 22H$, where $H = c_s(4\pi G \rho_c)^{-1/2}$ is the isothermal scale height with $\rho_c$ the central mass density along the axis of the cylinder (e.g., Nagasawa 1987; Imotsuka & Miyama 1992; Jackson et al. 2010). For a finite isothermal gas cylinder surrounded by uniform medium, $\lambda_{\text{crit}}$ is determined by the ratio of the cylinder radius to isothermal scale height, $R_{\text{cyl}}/H$. If $R_{\text{cyl}}/H \gg 1$, the characteristic separation will approach that for the infinite isothermal gas cylinder model, $\lambda_{\text{crit}} = 22H$, but if $R_{\text{cyl}}/H \ll 1$, it will decrease to $\lambda_{\text{crit}} = 11H$ for the incompressible case (see Jackson et al. 2010) for a review.

To compare our observations with the “sausage” instability theory, the filament cloud G350.5 is assumed to be a uniform isothermal cylinder. The outer radius of G350.5 is $\sim 0.5\,\text{pc}$ as almost periodic separations (e.g., Chandrasekhar & Fermi 1953; Nagasawa 1987; Jackson et al. 2010). This separation corresponds to the characteristic wavelength ($\lambda_{\text{crit}}$) where the stability grows the fastest. For an incompressible fluid, perturbation analysis shows that the critical wavelength appears at $\lambda_{\text{crit}} = 11R_{\text{cyl}}$, where $R_{\text{cyl}}$ is the cylinder’s radius (e.g., Chandrasekhar & Fermi 1953). In an infinite isothermal gas cylinder, the characteristic wavelength becomes $\lambda_{\text{crit}} = 22H$, where $H = c_s(4\pi G \rho_c)^{-1/2}$ is the isothermal scale height with $\rho_c$ the central mass density along the axis of the cylinder (e.g., Nagasawa 1987; Imotsuka & Miyama 1992; Jackson et al. 2010). For a finite isothermal gas cylinder surrounded by uniform medium, $\lambda_{\text{crit}}$ is determined by the ratio of the cylinder radius to isothermal scale height, $R_{\text{cyl}}/H$. If $R_{\text{cyl}}/H \gg 1$, the characteristic separation will approach that for the infinite isothermal gas cylinder model, $\lambda_{\text{crit}} = 22H$, but if $R_{\text{cyl}}/H \ll 1$, it will decrease to $\lambda_{\text{crit}} = 11H$ for the incompressible case (see Jackson et al. 2010) for a review.

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measured in Sect. 3.2.1. In addition, the Plummer-like function fitting to the column density profiles results in a central gas volume density of $\rho_c = 2.7 \times 10^4$ cm$^{-3}$ given $\rho_c = n_c \mu m_H$, where $n_c = 2 N_c/\pi R_{\text{flat}}$ (see Eqs. 1, and Eq. 2 of Smith, Glover, & Klessen 2014). This central gas density represents an underestimate because at the resolution (0.12 pc) of our observations the central filament density profile may be unresolved. Given an average dust temperature of $\sim 18$ K, which is derived from the temperature map (see Fig. 1), a thermal sound speed of 0.25 km s$^{-1}$ can be estimated, leading to the scale height $H \sim 0.03$ pc. With only thermal turbulence considered in the above calculation, that scale height should be underestimated since the observed velocity dispersion is greater than the thermal sound speed (see Fig. 5), which suggests non-thermal turbulent pressure dominant over thermal pressure in the entire cloud G350.5. With the typical turbulent velocity 0.47 km s$^{-1}$ for the entire cloud, one can get the scale height $H \sim 0.05$ pc, which is much less than the typical radius of G350.5 and hence follows $H_{\text{crit}} \sim 22 H \sim 1.1$ pc. This theoretically predicted value is comparable to the observed separation, $\sim 0.9$ pc. Note that the underestimated central gas volume density can increase the estimate of the scale height. Apart from central gas volume density, the idealized assumption of a uniform, isothermal cylinder should cause uncertainties on the calculation of the critical wavelength, which could explain the observed separation range $\sim 0.4 - 1.7$ pc.

The “sausage” instability theory also predicts the critical maximum line mass, above which self-gravitating cylinders would collapse radially into a line. That maximum line mass can be expressed as $M_{\text{line}}^{\text{max}} = 2 \pi^2 G$. As analyzed in Sect. 3.2.2, $M_{\text{line}}^{\text{max}} = \sim 102 M_\odot$ pc$^{-1}$ is consistent with the average observed line mass $\sim 101 M_\odot$ pc$^{-1}$. Therefore, according to the comparisons between the observed separation, line mass and the theoretically predicted counterparts, we suggest that the whole filamentary cloud G350.5 could have undergone radial collapse and fragmentation into distinct small-scale dense cores through the “sausage” instability.

### 4.3 Dense cores in fragments

Given the filamentary cloud G350.5 fragmenting into dense cores, it is worthwhile to assess the gravitational stability of dense cores. We compare thermal masses with Bonnor-Ebert critical masses ($M_{\text{BE}}$) for the eight cores towards which C$^{18}$O (2-1) emission is detected using the relation from Kauffmann, Pillai, & Goldsmith (2013):

$$M_{\text{BE}} = 2.43 \frac{\sigma_v^2 R_{\text{eff}}}{G} \quad (2)$$

where $R_{\text{eff}}$ is the effective radius of the dense cores, $\sigma_v$ is the velocity dispersion of gas, and $G$ is the gravitational constant. The significance of Eq. 2 is that supercritical cores with $M_{\text{BE}} < M_{\text{core}}$ will collapse, while subcritical cores with $M_{\text{BE}} > M_{\text{core}}$ will expand or must be confirmed by additional forces (e.g., external pressures Kauffmann, Pillai, & Goldsmith 2013).

Figure 7 shows the core masses versus the Bonnor-Ebert critical masses for the eight cores. It can be seen that five out of eight cores (i.e., C1, C2, C3, C6, and C7) are gravitationally bound and the other three (i.e., C4, C5, and C8) are marginally bound by the gravity. The ability of those cores to gravitationally collapse is actually consistent with the picture of star formation already taking place in some of them (see Sect. 4.4). As shown in Fig. 3, these dense cores have conspicuous $M_{\text{line}}$ corresponding to the peaks of the $M_{\text{line}}$ distribution of both G350.5-N, and G350.5-S, which are far above the critical values around $30 M_\odot$. Therefore, the eight dense cores are actually located within the supercritical filaments which are in a position to fragment and collapse to form new stars.
4.4 Star formation in the filaments

The filaments G350.5-N, and G350.5-S could be on the process of star formation as suggested by their mean line masses, $\sim 120 \pm 60 \, M_\odot \, \text{pc}^{-1}$ for G350.5-N, and $\sim 45 \pm 50 \, M_\odot \, \text{pc}^{-1}$ for G350.5-S, greater than the critical line masses around $30 \, M_\odot \, \text{pc}^{-1}$. Actually, G350.5-N, and G350.5-S do not have a large difference in line mass from the well-known Taurus B211/3. The filament G350.5-N is more or less twice as massive as B211/3 ($\sim 50 \, M_\text{line}$, Palmeirim et al. 2013) and G350.5-S's line mass is comparable to that of B211/3. This comparison suggests that G350.5-N and G350.5-S could be sites of low-mass star formation. To quantitatively demonstrate this conjecture, we take advantage of an empirical mass-size relationship, $m(r) \lesssim 870M_\odot (r/\text{pc})^{1.33}$, which was suggested to be an approximate threshold between low- and high-mass star formation.
Table 3. Derived parameters of young stellar objects

| ID | R.A., Dec. | N_{data} | \chi^2/N_{data} | A_V | M_\star | Log(M_{env}) | Log(M_{disk}) | L_{bol} | Stage | Association |
|----|------------|----------|----------------|-----|--------|-------------|-------------|---------|-------|-------------|
| Y1 | 259.513 -36.491 | 4 | 5.0 ± 5.0 | 120.0 ± 0.0 | 0.7 ± 0.1 | -3.3 ± 0.1 | -1.7 ± 0.5 | 10 ± 2 | 0I | C7 |
| Y2 | 259.556 -36.454 | 6 | 22.4 ± 22.1 | 93.3 ± 0.0 | 0.7 ± 0.0 | -3.4 ± 0.0 | -3.0 ± 0.0 | 13 ± 4 | 0I | C6 |
| Y3 | 259.568 -36.449 | 10 | 35.0 ± 34.8 | 88.9 ± 16.0 | 1.5 ± 0.6 | -4.7 ± 0.1 | -1.0 ± 0.2 | 238 ± 83 | 0I | C5 |
| Y4 | 259.611 -36.429 | 10 | 38.2 ± 3.0 | 65.4 ± 16.7 | 2.3 ± 0.9 | -3.3 ± 0.1 | -2.5 ± 0.6 | 49 ± 30 | 0I | C4 |
| Y5 | 259.628 -36.422 | 5 | 19.6 ± 19.3 | 120.0 ± 0.0 | 0.9 ± 0.3 | -3.5 ± 0.1 | -1.9 ± 1.0 | 14 ± 5 | 0I | C3 |
| Y6 | 259.648 -36.398 | 8 | 12.6 ± 12.5 | 99.0 ± 0.0 | 0.7 ± 0.0 | -3.4 ± 0.0 | -3.0 ± 0.0 | 13 ± 4 | 0I | C2 |

NOTE: Col. 1 is the source identity. Cols. 2-3 the coordinates, Col. 4 the count of data points used in the SED fitting, Col. 5 the reduced \chi^2, Col. 6 the visual extinction, Col. 7 the stellar mass, Col. 8 the envelope accretion rate, Col. 9 the disk mass, Col. 10 the bolometric luminosity, Col. 11 the evolutionary stage, Col. 12 the spatial association of the YSO candidate with the dense core. The parameters in Cols 5-10 were constrained with the normalized relative probability distribution of the well-fitted models of each source (Yuan et al. 2014). \( P(\chi^2) = \frac{e^{-\frac{(\chi^2 - \chi^2_{best})}{2N_{data}}}}{\sum_{i} e^{-\frac{(\chi^2 - \chi^2_{best,i})}{2N_{data}}}} \). Here, the well-fitted models are assumed to be those satisfying \( (\chi^2 - \chi^2_{best})/N_{data} < 3 \).

(Kaufmann & Pillai 2010). Figure 8 shows the mass versus size relation for the observed nine dense cores. One can notice that all of the nine cores are below the threshold as indicated by the dashed line, indicative of low mass star formation most likely occurring in these dense cores. For further comparison, we collected part of dense cores in the Taurus-L1495 cloud extracted from Herschel observations (green circles, André et al. 2010; Marsh et al. 2016), and molecular dense cores from \(^{13}\)CO (2-1) observations toward the entire Taurus cloud (blue diamonds, Qian, Li, & Goldsmith 2012). Figure 8 shows that all of the dense cores in this work are basically located close to the Taurus dense cores. Therefore, the mass-size distribution of the nine dense cores suggests that they most likely form low-mass stars, which can also be consolidated by several low-mass YSOs detected in some of the dense cores (see below).

Six bright point sources at 70 m are found to be spatially coincident with six out of the nine cores, as shown in Fig. 6. These sources may be similar in nature to the 70 m protostars (Stutz et al. 2013; see also Ragan et al. 2012). These authors concluded that protostars with very red 70 m to 24 m colors are consistent with having denser envelopes and thus are younger than the bulk of the Class 0 and Class I protostars in Orion (Furlan et al. 2016; Fischer et al. 2017). To examine if these bright sources are YSO candidates, we conducted the fitting of spectral energy distribution (SED) with the tool developed by Robitaille et al. (2006). This tool invokes a grid of 200,000 two-dimensional Monte Carlo radiation transfer models, working as a linear regression method to fit these models to the multi-wavelength photometry measurements of a given source. We first retrieved the photometry data matched within 5″ from the center coordinates of each bright source (see Fig. 6) by surveying the Spitzer-Glimpse, Spitzer-Mipsgal, and Herschel-HiGal archives from the IRSA data base.\(^5\) Then we performed the YSO SED fitting for the six sources following the procedures as described in Liu et al. (2016). The resulting fitting plots are presented in Fig. 9. Following the descriptions by Yuan et al. (2014), we calculated several key parameters, which are tabulated in Table 3. As shown in Fig. 9, the fitting performances are not being perfect. This can be attributed to at least the following three aspects. Firstly, for the Herschel photometry data, poor resolutions at wavelengths of \( \approx 160 \) m make it difficult to accurately measure the photometry fluxes that really represent radiation from YSOs. Secondly, the YSO models in the SED fitting tool can not interpret the photometry fluxes at longer wavelengths very well (Robitaille, private communication). Thirdly, as a result of the previous two problems, the more the data points included, the larger the goodness of the SED fitting. As defined in Liu et al. (2016), the goodness \( (\chi^2 - \chi^2_{best})/N_{data} \) where \( N_{data} \) is the number of samples included in the fitting) of the SED fitting for the six bright sources ranges from 5 to 38 (see Table 3). Despite the goodness of the fitting not perfect, some of the resulting fitting parameters can still be used to get some hints from the statistical point of view.

According to the scheme of YSO classification by Robitaille et al. (2006), all six sources can be classified as Stage 0/I YSO candidates (see Table 3). Their spatial associations with the dense cores are commented in Table 3. Such associations are well supportive of star formation ongoing in some of the dense cores. In addition, these YSO candidates have masses ranging from 0.7 to 2.3 \( M_\odot \). This mass range demonstrates that there are already histories of low-mass star formation in some of nine dense cores. All in all, the mass-size distributions of the nine dense cores, and the low-mass YSOs associated with some cores collectively suggest that both filaments could be sites of ongoing low-mass star formation.

4.5 Comparison with other two filaments

G350.5 appears basically straight and isolated, with similarities to both Musca and Taurus B211/3. Moreover, G350.5 is surrounded by thin perpendicular striations, especially in the G350.5-N part (see Fig. 6, A1), which resembles the dust emission morphologies in Musca, and Taurus B211/3 (e.g., Palmeirim et al. 2013; Cox et al. 2016). This resemblance indicates that G350.5 might have a similar formation mechanism to Musca, and Taurus B211/3. Based on magnetically-aligned striations observed in Taurus B211/3, and Musca, Hennebelle & André (2013) and Cox et al. (2016) proposed a possible filament formation mechanism. That is, the filament grows in mass by accreting background material channeled by magnetic fields, leading to accretion-driven MHD turbulence within the main filament structure (Hennebelle & André 2013; Cox et al. 2016). The accretion transfers gravitational energy to the system, which sequentially turns into turbulent kinetic energy (Cox et al. 2016). During the accretion, a supercritical filament could provide us with a hint on the evolution of the filaments. Due to the absence of complicated intertwined velocity-coherent fibers in Musca (Kainulainen et al. 2016; Hacar et al. 2016) as observed

\(^5\) http://irsa.ipac.caltech.edu/frontpage/
in Taurus B211/3 (Hacar et al. 2013; Tafalla & Hacar 2015). Cox et al. (2016) suggested that Musca is at an earlier stage of evolution than Taurus B211/3 filament, which is further supported by a very low present-day star-formation efficiency of \(\ll\) than Taurus B211/3 filament, which is further supported by a very low present-day star-formation efficiency of \(\ll\) \(\%\) derived from a candidate young low-mass T Tauri star located at the most northeast end of the Musca filament.

Figure 10 shows the velocity integrated intensity map of the cloud G350.5 over the two velocity ranges \(-7 \to -5\) \(\text{km s}^{-1}\) and \(-5 \to -3\) \(\text{km s}^{-1}\). G350.5 does not seem to have a complicated network of velocity-coherent intertwined fibers within the main filament structure, suggestive of the cloud G350.5 being likely less evolved than Taurus B211/3. Note that our current molecular line observations with the resolution \(28''\) probably do not resolve the intrinsically complicated network of velocity-coherent fibers in G350.5. Therefore, future dense gas observations with higher resolutions would be helpful for dissecting the internal velocity structures within the main filament structure of the cloud G350.5. Regardless of the velocity-coherent structures, the presence of different stages of YSOs in the two clouds where G350.5 has Stage 0/I YSOs only but the Taurus B211/3 cloud has YSO candidates evolved up to T Tauri stars, also supports that G350.5 could be in an intermediate evolutionary state between Musca and Taurus-B211/3.

5 CONCLUSIONS

We have investigated the column density profiles of the two filaments G350.5-N and G350.5-S, the gravitational stability of the dense cores on the filaments, possible fragmentation process, and star formation in the two filaments, combing Herschel data with our molecular line observations by APEX. The main findings are summarized here:

- The filamentary cloud G350.5 appears rather straight and basically isolated, composed of two discontinuous filaments, G350.5-N and G350.5-S. G350.5-N (S) has a length of \(\sim 5.9\) pc (\(\sim 2.3\) pc), a total mass of \(\sim 810 M_\odot (\sim 110 M_\odot)\), and a mean temperature of \(\sim 18.2 K (\sim 17.7 K)\). Both filaments have a similar mean column density of \(\sim 8.2 \times 10^{22} \text{cm}^{-2}\).
- The mean column density profiles of G350.5-N, and G350.5-S are described in a Plummer-like function with a power law index of \(p \sim 3\). This index is only a first-order approximation. Dust continuum observations with higher spatial resolutions deserve to reveal the detailed density profiles of both filaments.
- Nine dense cores are identified with \(M_{\text{core}} \gg M_{\text{BE}}\). That is, the cores are gravitationally bound and have the potential to further collapse to form protostars.
- The separation (\(\sim 0.9\) pc) among nine cores and the average line mass (\(\sim 101 M_\odot\) \(\text{pc}^{-1}\)) of the whole cloud appear to follow the predictions of the “sausage” instability theory. This suggests that G350.5 could have undergone radial collapse and fragmentation.
- The mass-size relation of the nine cores, and the appearance of six low-mass YSOs associated with the cores together provide strong evidence that G350.5 is a site of ongoing low-mass star formation.
- The presence of young protostars (i.e., Stage 0/I) indicates that the G350.5 filament may be in an evolutionary state between Musca, with no protostars, and Taurus B211/3, with evolved young stars (i.e., class II YSOs).

The filamentary cloud G350.5 has not been well-studied until now. Its rather straight and isolated feature may be very helpful for dissecting the filament and understanding the nature of isolated and straight filament formation. Our forthcoming paper (Liu et al., 2018, in prep.), will be devoted to further investigation of kinematics of this system, which will allow us to understand the connection between those two filaments and core formation therein.

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APPENDIX A: CONTINUUM EMISSION AT 160, 250, 350, AND 500 µm

This paper has been typeset from a TEX/LATEX file prepared by the author.
Figure A1. Same as Fig. 6 but for Herschel 160, 250, 350, 500 μm from left to right. The main structure of G350.5 appears to be surrounded by thin perpendicular striations. This scenario seems to be clearer at both 160 and 250 μm than at both 350 and 500 μm, which could be a consequence of lower spatial-resolution at longer wavelengths.