FILAMENTARY STAR FORMATION: OBSERVING THE EVOLUTION TOWARD FLATTENED ENVELOPES

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ABSTRACT

Filamentary structures are ubiquitous from large-scale molecular clouds (a few parsecs) to small-scale circumstellar envelopes around Class 0 sources (\(\sim\)1000 AU to \(\sim\)0.1 pc). In particular, recent observations with the Herschel Space Observatory emphasize the importance of large-scale filaments (a few parsecs) and star formation. The small-scale flattened envelopes around Class 0 sources are reminiscent of the large-scale filaments. We propose an observationally derived scenario for filamentary star formation that describes the evolution of filaments as part of the process for formation of cores and circumstellar envelopes. If such a scenario is correct, small-scale filamentary structures (0.1 pc in length) with higher densities embedded in starless cores should exist, although to date almost all the interferometers have failed to observe such structures. We perform synthetic observations of filaments at the prestellar stage by modeling the known Class 0 flattened envelope in L1157 using both the Combined Array for Research in Millimeter-wave Astronomy (CARMA) and the Atacama Large Millimeter/Submillimeter Array (ALMA). We show that with reasonable estimates for the column density through the flattened envelope, the CARMA D array at 3 mm wavelengths is not able to detect such filamentary structure, so previous studies would not have detected them. However, the substructures may be detected with the CARMA D+E array at 3 mm and the CARMA E array at 1 mm as a result of more appropriate resolution and sensitivity. ALMA is also capable of detecting the substructures and showing the structures in detail compared to the CARMA results with its unprecedented sensitivity. Such detection will confirm the new proposed paradigm of non-spherical star formation.

Key words: dust, extinction – ISM: clouds – radio continuum: ISM – stars: formation

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1. INTRODUCTION

It is becoming clear that filamentary structures (a few parsecs to 10 pc in length and typically 0.1 pc in width) in molecular clouds are common and need to be understood. One clear example is the Integral-Shaped Filament region in the north of Orion-A, comprising OMC 1–4, where prestellar cores and protostars are forming (e.g., Chini et al. 1997; Johnstone & Bally 1999; Aso et al. 2000; Nutter & Ward-Thompson 2007; Ikeda et al. 2007; Takahashi et al. 2008). Taurus also consists of several large filaments, each with ongoing star-forming activity (e.g., Mizuno et al. 1995; Onishi et al. 1998; Kenyon et al. 2008). The large-scale filaments are even more evident in recent observations from the Herschel Space Observatory (e.g., Andrè et al. 2010; Men’shchikov et al. 2010; Arzoumanian et al. 2011; Hill et al. 2011), and these observations further suggest a tight connection between the formation of dense cores and gravitationally unstable filaments. While the mechanisms for forming these filamentary structures are still under debate (e.g., Mac Low & Klessen 2004; Heitsch et al. 2008; Nakamura & Li 2008; Myers 2009, 2011; Pon et al. 2011), an observationally derived process has been suggested: first, the filamentary structures at large-scales form, possibly as a result of magneto-hydrodynamic turbulence in the interstellar medium (ISM), and second, the prestellar cores form from the fragments of a subset of filaments through gravitational instability.

As the role of large-scale filaments in molecular clouds has received significant attention, a number of the latest observations have unveiled filamentary structure at smaller scales (\(\sim\)a few tenths of parsecs in length and hundredths of parsecs in width). For instance, Hacar & Tafalla (2011) observed four subsonic, velocity-coherent filaments in L1517 (\(\sim\)0.5 pc in length) that are possibly condensed out from the more turbulent natal cloud and lead to the quasi-static fragmentation of cores. In addition, Pineda et al. (2011) probed the Barnard-5 star-forming core with high angular resolution and discovered filamentary structures with \(\sim\)0.1 pc in length. The filaments in Barnard-5 are possibly the result of fragmentation in a coherent region where subsonic motions dominate, and are likely to form stars via future gravitational collapse.

In addition to the filamentary structures in molecular clouds at the early stage of star formation, typical lengths of a few parsecs and widths of 0.1 pc, small-scale filamentary structures, typical lengths of a few thousand AU to 0.1 pc, and widths of a few hundred to a few thousand AU have also been observed in the envelopes around Class 0 protostars (Tobin et al. 2010). These filamentary structures in the protostellar envelopes are mostly irregular and non-axisymmetric in morphology, suggesting an initial non-equilibrium from the prestellar stage. The filamentary structure presented near the Class 0 source is reminiscent of the large Herschel observed structures, although the size scales of the two are distinct and the properties are presumably different.

The relationship between the large-scale filaments in molecular clouds and small filamentary envelopes around young protostars still requires further investigation. Several numerical simulations have shown that large-scale filaments in molecular clouds are prone to fragmentation leading to prestellar cores (e.g., Inutsuka & Miyama 1997; Hartmann 2002), and filaments are possibly the most favorable mode for fragmentation (Pon et al. 2011, 2012). Moreover, studies have also demonstrated that
filamentary geometries at large scales have a significant impact on the geometries and symmetries of the subsequently collapsing cores (Smith et al. 2011). These observations and numerical simulations deliver a clear message: filamentary structures from large to small scales are clearly playing an important role in the star formation process. In this paper, we suggest an observational evolution between filaments at the large scale and filaments on the small scale. The proposed scenario suggests that the small-scale filamentary structure (a few thousand AU) in protostellar envelopes originates from the filamentary structure (0.1 pc) embedded in the larger envelopes of starless cores instead of being produced by the protostellar collapse. We will further show why the filamentary structures in starless cores have not been observed to date.

2. EVOLUTION OF PROTOSTELLAR STRUCTURE

It has been well known that dust emission maps of Class 0 sources show very spherical emission (e.g., Looney et al. 2000; Shirley et al. 2000; Motte & André 2001). Although molecular surveys of dense cores showed non-spherical structures (e.g., Myers et al. 1991), these non-symmetric structures were often considered to be material not directly involved in the star formation process, i.e., part of the larger-scale molecular cloud or clump, so these components were rarely used in the observational modeling of these sources. Instead many authors assumed that the spherical dust emission indicated spherical collapse (e.g., Shu 1977; Terebey et al. 1984) and used this symmetry to derive envelope properties and place constraints on any embedded disk components (e.g., Keene & Masson 1990; Looney et al. 2003; Harvey et al. 2003; Jørgensen et al. 2009). However, recent studies haveshown the envelope structures to be more complex.

2.1. Changing the Paradigm for the Inner Envelope of Class 0 Protostars

The ability to use 8 μm absorption against polycyclic aromatic hydrocarbon background emission allows the decoupling of the dust density and temperature for the first time in Class 0 sources (e.g., Looney et al. 2007; Tobin et al. 2010). With these measurements, it was realized that the dense portions of the envelope are complex, filamentary, and often non-axisymmetric structures (~1000 AU to 0.1 pc). Figure 1 illustrates the diversity of structures seen in the Tobin sample. IRAS 16253-2429 is what one would expect to see in a spherical envelope case. The 8 μm absorption is not a good tracer at the central source or in the outflow cavity, since in both cases there is emission in addition to the background. In stark contrast, L673 is a clear example of the main point of Tobin et al. (2010), which is that flattened, filamentary, and non-axisymmetric envelopes are the typical envelope structure.

How does this result reconcile with interferometric dust emission observations which show spherical emission in these sources (e.g., Looney et al. 2000)? It is important to remember that dust emission depends on both dust density and temperature. With flattened or non-axisymmetric envelopes and/or outflow cavities in young sources, the heating will be inhomogeneous; the lower density material near the central source is heated more, leading to temperature and density gradients, and the dust emission will appear more spherical even if the dust distribution is not. A good example, shown in Figure 2 from Chiang et al. (2010), is the source L1157. Although there is a flattened and filamentary envelope detected in both N_2H^+ and the 8 μm absorption (also seen in Figure 6), the dust emission is very spherical and typical of a Class 0 protostar. Chiang et al. (2012) constructed a model that has a flattened geometry similar to the N_2H^+ and 8 μm absorption features and yet still predicts the...
observed spherical dust continuum when non-spherical, self-consistent temperature solutions are used.

However, with enough sensitivity, the filamentary structures can still be seen in dust emission. Figure 3 is the dust emission toward L1157 with the Submillimeter Array (SMA) at $\lambda = 1.3$ mm (J. J. Tobin et al. 2013a, in preparation). In this case, the authors detected the extension along the flattened envelope and even an extension along the outflow (also see I. W. Stephens et al. 2013, in preparation). The extension along the outflow illustrates how the heating is facilitated by lower density material (in this case in the outflow cavity). In other words, the heating in these sources is not uniform, which can lead to a distortion in the structure suggested by only the dust continuum.

Indeed, when comparing the observations of L673 and L1157 with the traditional view of spherical star formation, we need to change the schematics of star formation. Figure 4 demonstrates our suggestion of moving from spherical star formation structures to filamentary star formation structures in Class 0 protostars to be more consistent with observations. The left panel presents the traditional model assuming sphericity that has impacted our theoretical understanding for decades. In this model, protostellar collapse is axisymmetric and spherical based on a singular isothermal sphere (Shu 1977). With the inclusion of rotation (Terebey et al. 1984), the density structure is slightly flattened and mostly remains spherical beyond the centrifugal radius. On the other hand, the right panel in Figure 4 shows the axisymmetric and filamentary envelopes that are often seen in our Class 0 observations (e.g., Tobin et al. 2010). The filamentary envelopes with higher density are forming inside the ambient cloud at lower density.

The change from a spherical view of star formation to a filamentary view certainly has important consequences, as several analysis techniques are based on the assumption of sphericity.
Filamentary structures appear to be ubiquitous from large molecular clouds to small-scale circumstellar envelopes. These filamentary structures are also observed to be tightly connected to the star formation process, as prestellar cores and young protostars are located within these filaments. From these observations, we propose an observationally derived scenario of filamentary collapse in star formation that is summarized in Figure 5. As we propose an observationally derived scenario of filamentary collapse in star formation that is summarized in Figure 5. As shown in the schematic, there are approximately five steps in our observational-based picture of the filamentary collapse process. Among the five steps, Steps I, II, IV, and V are from observations, and Step III is a prediction of high-density filamentary structures in starless cores, to connect Steps II and IV.

In Step I, molecular clouds are formed as filaments with a few parsecs to 10 pc in length and a characteristic width of 0.1 pc (Schneider & Elmegreen 1979; Bally et al. 1987; Johnstone & Bally 1999; André et al. 2010). These large-scale filaments are probably turbulent and prone to fragmentation, leading to subsequent velocity-coherent, higher density filaments (few tenths of parsecs in length) that are considered to be the birthplaces of prestellar cores (Inutsuka & Miyama 1997; Hartmann 2002; Pon et al. 2011). In Step II, the fragmented filaments collapse along the long and short axes while feeding material along the filament (e.g., Hacar & Tafalla 2011), enhancing the mass in a location and forming a higher density oblate (or prolate) starless core as observed with single-dish observations (Curry 2002; Jones & Basu 2002; Tassis 2007; Tassis et al. 2009). The core formation may be related to the flows from large-scale motions along the larger filaments and is kinematically coupled with the parental cloud (Hacar & Tafalla 2011). This would form a higher density filamentary structure embedded inside of the starless core as seen in Step III. This substructure is the kinematic descendant of the flow along the larger filament and the origin of the filamentary envelopes seen in the Class 0 objects. As the collapse continues in Step IV, material infalls along the smaller filament (J. J. Tobin et al. 2013b, in preparation) and the oblate (or prolate) starless core continues to collapse into a centrally condensed envelope of a Class 0 protostar. A Class 0 source is created (∼5000 AU in size), while the large-scale filamentary structure (∼1000 AU to 0.1 pc) remains behind containing an appreciable fraction of the total mass of the envelope plus source. In Step V, the Class 0 source evolves to a Class I source with a protostellar disk and the larger structure dissipates.

Although this scenario fits together, there is one serious problem with our proposed evolution of filaments in star formation: no one has detected the substructure (e.g., filamentary structure) predicted in Step III in starless cores to date. Unfortunately, there is some difficulty in detecting these structures. One could use molecular line tracers such as N2H+ or NH3, which often correspond to the 8 μm absorption (e.g., Chiang et al. 2010; Tobin et al. 2011). However, in starless cores, N2H+ could still have chemical effects such as depletion (e.g., Bergin et al. 2002), although several studies (Tafalla et al. 2002) showed less depletion for N2H+ than for other molecules. Since the depletion usually occurs at the center of the core, the filament could appear fragmented in the map depending on the size of the central depletion. In addition, the molecular distribution could originate from chemistry and not trace the dense material well. Thus, to confirm the detection of substructure, we must rely on dust continuum emission. Dust emission at millimeter wavelengths presumably is more appropriate than 8 μm emission because of the low optical depth. 8 μm extinction shows detection in the outer regions only if the background signal-to-noise is high enough.

In order to resolve the structures, we must have a resolution of ∼5 arcsec, which implies the use of interferometers. For example, Schnee et al. (2010) performed dust continuum observations at 3 mm toward 11 starless cores in Perseus with the Combined Array for Research in Millimeter-wave Astronomy (CARMA). Although two sources were detected, they were later
Table 1  
Synthesized Beam Sizes and Noise Levels for the Synthetic Observations

| Array Configuration       | Beam Size (3 mm) | 3 mm | 1 mm |
|---------------------------|------------------|------|------|
| CARMA D Array             | $5.14 \times 4.76$ | 0.3 mJy beam$^{-1}$ | 0.15 mJy beam$^{-1}$ | 0.35 mJy beam$^{-1}$ |
| CARMA D+E Array           | $7.92 \times 7.23$ | 0.15 mJy beam$^{-1}$ | 0.35 mJy beam$^{-1}$ |
| CARMA E Array             | $4.21 \times 3.65$ | 0.35 mJy beam$^{-1}$ | |

Figure 5. Illustration of filamentary collapse in five steps. In Step I, molecular clouds are formed with filamentary shapes (a few parsecs in length and 0.1 pc in width) that are prone to fragmentation. In Step II, the subsequently fragmented filaments (a few tenths of parsecs in length) collapse and form prolate or oblate starless cores (0.1 pc in size). In Step III, embedded in the starless core is a filamentary structure of higher density that arises from the flow along the large-scale filament axis. In Step IV, the starless core continues to infall into a centrally condensed envelope of a Class 0 protostar ($\sim 5000$ AU). In Step V, the Class 0 source evolves to a Class I source with a protostellar disk (a few hundred AU) and outflow (the arrows). The orientation of the protostellar disk depends on the detailed kinematics of collapse and is not necessarily along the filament as shown in this schematic. Note in each step the structures with lower density are indicated with dashed lines.

3. SYNTHETIC OBSERVATIONS

To examine the likelihood of our proposed structures in starless cores, we make synthetic observations with CARMA, directly comparing these to the observations of Schnee et al. (2010), and the Atacama Large Millimeter/Submillimeter Array (ALMA), using the flattened envelope around L1157 as a model. The result will show that the expected structures are below the CARMA D array’s detection threshold at 3 mm, but they should be detectable with CARMA D+E array observations at 3 mm, the CARMA E array at 1 mm, and ALMA at 1 mm observations. This implies that there is not yet a disagreement between our observational-based proposed evolutionary scheme in Step III for low-mass star formation and current observations, and an exciting observational future is suggested.

3.1. CARMA Observations

We simulate CARMA imaging with parameters used by Schnee et al. (2010): heterogeneous array (six 10 m antennas and nine 6 m antennas) imaging with the CARMA-D array configuration at 3 mm continuum. We use the Miriad tasks $uvgen$, $demos$, and $uvmodel$, based on Wright (2010) without the 3.5 m telescopes. To find the detection limit of such a structure, we also simulate CARMA D+E array observations at 3 mm and the CARMA E array at 1 mm. Baselines range from $3k\lambda$ to $38k\lambda$ for the D array at 3 mm, $2k\lambda$ to $19k\lambda$ for the E array at 3 mm, and $5k\lambda$ to $47k\lambda$ for the E array at 1 mm. The observing rest frequency is centered at 90 GHz for 3 mm observations and 230 GHz for 1 mm observations with a total bandwidth of 4 GHz for continuum observations. The total observing time on the target is 6 hr for each synthetic observation (for the one with the CARMA D+E array; the observing time is 3 hr for the D array and 3 hr for the E array). In the analysis (Section 3.3), we perform a small mosaic (standard seven pointings) around the source to capture all of the extended structure. Table 1 summarizes the synthesized beam sizes and noise levels for the simulated CARMA observations.

3.2. ALMA Observations

We used the tasks $sim\_observe$ and $sim\_analyze$ in the package casapy to perform the simulated observations with ALMA. The angular resolution is requested to be 1.2 in the simulation to observe detailed structures, and a small mosaic is applied to capture all possible structures. The observing time for each mosaic pointing is 100 s, and the total observing time is 2 hr. The observing frequency is centered at 90 GHz with the bandwidth of 8 GHz for continuum observations. Thermal noise is added with a typical precipitable water vapor of 2.8 mm. The clean threshold is set to 1.5 times the noise rms, and the pixel size is set to 0.12 arcsec.
3.3. Modeling and Results

As described in Steps III and IV in Figure 5, the flattened protostellar envelopes around Class 0 sources are speculated to be highly connected to the filamentary structure at the previous stage, the prestellar phase. Therefore, the envelopes around Class 0 sources best describe the morphology of the high-density filamentary structures in Step III. To simulate the structure in Step III, we modify the flattened envelope in the Class 0 source L1157 by the physical conditions expected at the prestellar stage, in order to examine if CARMA and ALMA are able to detect filamentary structure at the prestellar stage. Figure 6 (left) shows the extinction map of L1157 from the Spitzer 8 μm observation (Looney et al. 2007). We chose L1157 to model as it has an obvious filamentary envelope structure seen in the 8 μm absorption against the background emission, and the symmetric structure can be approximated with a radial density power law (Looney et al. 2007). The spatial scale of the filamentary envelope is 0.1 pc, too large for a circumstellar disk or a pseudo-disk (e.g., Galli & Shu 1993). The L1157 dark cloud is located ∼250 pc away6 with an edge-on view concealing the Class 0 source embedded in the flattened envelope nearly perpendicular to a large powerful outflow from the north to the south. The distance to L1157 is approximately the same as to Perseus (also at ∼250 pc) and thus it remains an excellent proxy for Perseus when compared with Schnee et al. (2010).

If the proposed scenario of filamentary collapse is correct, the flattened envelope is expected to be related to the filamentary structures on larger scales, and thus this source is suitable for modeling the transient phase in the prestellar stages with appropriate physical conditions.

To better concentrate on the filamentary envelope, we removed the emission from the outflow and the scattered light from the central object. We then filled the inner regions with the averaged value from the envelopes on the two sides, as shown in Figure 6 (right). The total mass calculated from the extinction increased by about 10% by filling the inner region with this method. The extinction map was compared toward background stars measured in the near-IR to an optical-depth image generated with or without the zodiacal correction (Tobin et al. 2010).

We next generated the brightness map at millimeter wavelengths (at 3 mm in our model) by assuming that L1157 is optically thin at 3 mm. We first calculated the mass contained in each pixel from the extinction map,

\[
M = d\Omega \times D^2 \times (1.496 \times 10^{13} \frac{\text{cm}}{\text{AU}})^2 \times \frac{\tau}{\kappa_{8\mu m}},
\]

where \(d\Omega\) is the pixel solid angle (\(1.2''\)^2), \(D\) is the distance in parsecs (250 pc for L1157), and \(\kappa_{8\mu m}\) is the dust plus gas opacity at 8 μm. The 3 mm flux in each pixel is then determined from the mass, opacity, and temperature,

\[
F = \frac{M \times B_\nu(T) \times \kappa_{3\text{mm}}}{D^2},
\]

where \(B_\nu(T)\) is the Planck function and \(\kappa_{3\text{mm}}\) is the dust plus gas opacity at 3 mm.

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6 The L1157 cloud is estimated to have a galactic latitude similar to the absorbing clouds with 200 pc and 300 pc in Cepheus (Kun 1998) and therefore we adopted a distance of 250 pc in this paper. By comparison, Kirk et al. (2009) adopted a distance of 325 pc for the region around L1157.
Figure 7. Simulated observations with the CARMA D array at 3 mm for 6 hr with different values of $\kappa_{\mu m}$. The center is positioned at 20$^\text{h}$39$^\text{m}$05$^\text{s}$2 (R.A.) and 68$^\circ$02$'$15$''$3 (decl.) (J2000). The synthesized beam size is 5$''$14 by 4$''$76 shown in the bottom-right corner. The noise level $\sigma$ is 0.3 mJy beam$^{-1}$, and the contours are $\pm 3, \pm 4, \pm 6, \pm 8, \pm 10, \pm 12, \pm 14 \times \sigma$ (in step of $\sqrt{2}\sigma$). The color scale shows flux in Jy beam$^{-1}$. With the reasonable value for $\kappa_{\mu m}$ (10.96 cm$^2$ g$^{-1}$) in the left panel, no structures are detected. For the structures to be clearly detected (the right panel), $\kappa_{\mu m}$ needs to be an almost impossibly small value (2.0 cm$^2$ g$^{-1}$).

(A color version of this figure is available in the online journal.)

Figure 8. Simulated observations with the CARMA D+E array at 3 mm for 6 hr in total (3 hr for the D array and 3 hr for the E array). The value for $\kappa_{\mu m}$ is 10.96 cm$^2$ g$^{-1}$. The center is positioned at 20$^\text{h}$39$^\text{m}$05$^\text{s}$2 (R.A.) and 68$^\circ$02$'$15$''$3 (decl.) (J2000). The synthesized beam size is 7$''$92 by 7$''$23 shown in the bottom-right corner. The noise level $\sigma$ is 0.28 mJy beam$^{-1}$, and the contours are $\pm 3, \pm 4, \pm 5, \pm 6, \pm 7, \pm 8, \pm 9, \pm 10 \times \sigma$. The color scale shows flux in Jy beam$^{-1}$.

(A color version of this figure is available in the online journal.)

We used 0.00169 cm$^2$ g$^{-1}$ for $\kappa_{3\text{mm}}$ by assuming 100 for the gas to dust ratio (e.g., Schnee et al. 2010). The temperature was assumed to be a constant at 10 K for starless cores (e.g., Schnee et al. 2009). After obtaining the brightness map at 3 mm, we simulated the CARMA D array observations with our model. Since the opacity in the infrared is poorly constrained, we generated models with varying values for $\kappa_{\mu m}$, which also modifies the derived mass in the flattened envelope structure. The equation above indicates that the observed millimeter brightness decreases with increasing $\kappa_{\mu m}$, since less mass is required to produce the IR extinction. In the left panel of Figure 7, we show that with an expected value of $\sim 10.96$ cm$^2$ g$^{-1}$ for $\kappa_{\mu m}$ (Tobin et al. 2010; Butler & Tan 2009) toward L1157, the CARMA D array is not able to detect the filamentary structures at the prestellar stage. For the structures to be clearly detected (the right panel of Figure 7), the dust opacity at 8$\mu$m would have to be an unphysically small value.
Figure 9. Simulated observations with the CARMA E array at 1 mm for 6 hr in total. The value for $\kappa_\mu m$ is 10.96 cm$^2$ g$^{-1}$. The center is positioned at 20$^h$39$^m$05$^s$2 (R.A.) and 68$^\circ$02$^\prime$15$^\prime\prime$3 (decl.) (J2000). The synthesized beam size is 4.21 by 3.65 shown in the bottom-right corner. The noise level $\sigma$ is 0.49 mJy beam$^{-1}$, and the contours are $\pm$3, $\pm$4, $\pm$5, $\pm$6, $\pm$7, $\pm$8, $\pm$9, $\pm$10 $\times$ $\sigma$. The color scale shows flux in Jy beam$^{-1}$. (A color version of this figure is available in the online journal.)

Figure 10. Simulated observations with ALMA for $\kappa_\mu m = 10.96$ cm$^2$ g$^{-1}$. The noise level $\sigma$ is 0.15 mJy beam$^{-1}$. The contours indicate $\pm$10, $\pm$15, $\pm$20, $\pm$25, $\pm$30, $\pm$40, $\pm$50, $\pm$60 $\times$ $\sigma$. The color scale shows flux in Jy beam$^{-1}$. The synthesized beam size is 1$^\prime$.2 shown in the bottom-right corner. (A color version of this figure is available in the online journal.)

To fully explore CARMA’s capability, we performed the synthetic observation with CARMA D+E array at 3 mm since the E array is more compact and sensitive to emission at larger scales than the D array. The total observing time was 6 hr (3 hr with the D array and 3 hr with the E array). The value for $\kappa_\mu m$ used is 10.96 cm$^2$ g$^{-1}$ to compare with the result from the D array only, since it produces the weakest emission (contains the least mass). As shown in Figure 8, the filamentary structure is detected with a similar noise level (0.28 mJy beam$^{-1}$) as the D array (0.3 mJy beam$^{-1}$), although only the structures with stronger emissions close to the center could be seen and the structures are not in detail. The detection suggests that non-detection with the D array is due to a combination of spatial resolution and sensitivity. Furthermore, we shift the observation from 3 mm to 1 mm assuming that the dust opacity is 0.9 cm$^2$ g$^{-1}$ at 1 mm (Ossenkopf & Henning 1994) and $\kappa_\mu m$ is still 10.96 cm$^2$ g$^{-1}$. Again, the CARMA E array is able to show detection on the structure as shown in Figure 9, as the brightness increases toward the short wavelengths.

We further ran the synthetic observations with ALMA also for the case of $\kappa_\mu m = 10.96$ cm$^2$ g$^{-1}$. Figure 10 shows the result from the synthetic observation (the contours are plotted by percentages of the peak flux instead of the noise levels due to the artificial effects from resolving out large structures).
As can be clearly seen, ALMA is able to detect most of the structure in the flattened envelope. Comparing the results from CARMA and ALMA for $\kappa_{\text{mm}} = 10.96 \, \text{cm}^2 \, \text{g}^{-1}$, ALMA’s unprecedented sensitivity greatly improves the appearance of filamentary structures and should provide a powerful tool for uncovering any hidden filamentary profiles at the starless/prestellar stage. Located in the southern hemisphere, ALMA is not able to look at L1157; these results are, however, indicative of the ALMA observations with other starless cores.

4. CONCLUSION

In this paper, we posit an observationally derived scenario for filament-driven star formation that incorporates the evolution of star-forming cores with filaments into filamentary envelopes from large to small scales. Molecular clouds are formed as filaments (a few parsecs to 10 pc) and then fragment to smaller filaments (a few tenths of parsecs), which eventually collapse to form triaxial starless cores. As collapse continues, the material infalls along the filament into a centrally condensed filamentary envelope of a spherical Class 0 source, which keeps evolving to a Class I source with a protoplanetary disk.

If such a scenario is correct, filamentary structures should exist at the prestellar stage. The only reason that they have not yet been detected is because of sensitivity to large-scale emission in the surveys. They are possible to detect with the CARMA D+E array at 3 mm due to more appropriate resolution and the CARMA E array at 1 mm as a result of the higher brightness at 1 mm; however, ALMA is even more capable of clearly detecting detailed structures of the filamentary envelopes. In fact, the very high sensitivity of ALMA will allow for much shorter integrations (less than 2 hr for L1157-like prestellar cores) and thus we will be able to conduct quick and efficient surveys of the geometry of the envelopes around starless cores. The proposed scenario can be immediately tested by observations with the current instruments.

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