THE ORIGIN OF OB CLUSTERS: FROM 10 pc TO 0.1 pc

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ABSTRACT

We observe the 1.2 mm continuum emission around the OB cluster-forming region G10.6-0.4, using the MAMBO-2 bolometer array of the IRAM 30 m telescope and the Submillimeter Array (SMA). Comparison of the Spitzer 24 μm and 8 μm images with our 1.2 mm continuum maps reveal an ionization front of an HII region, the photon-dominated layer, and several 5 pc scale filaments that follow the outer edge of the photon-dominated layer. The filaments, which are resolved in the MAMBO-2 observations, show regularly spaced parsec-scale molecular clumps, embedded with a cluster of dense molecular cores as shown in the SMA 0.87 mm observations. Toward the center of the G10.6-0.4 region, the combined SMA+IRAM 30 m continuum image reveals several parsec-scale protrusions. They may continue down to within 0.1 pc of the geometric center of a dense 3 pc scale structure, where a 200 M⊙ OB cluster resides. The observed filaments may facilitate mass accretion onto the central cluster-forming region in the presence of strong radiative and mechanical stellar feedback. Their filamentary geometry may also facilitate fragmentation. We did not detect any significant polarized emission at 0.87 mm in the inner 1 pc region with SMA.

Key words: H II regions – ISM: individual objects (G10.6-0.4) – ISM: kinematics and dynamics – stars: evolution – stars: formation – stars: massive

Online-only material: color figures

1. INTRODUCTION

Accretion and clustering are the most fundamental aspects of OB star formation (see Garay & Lizano 1999; Mckee & Ostriker 2007; Zinnecker & Yorke 2007 for reviews). OB stars are observed to form in very special regions of molecular clouds—massive molecular clumps, typically of parsec-scale in size. Large mass and high density are needed for the accretion flow to feed the forming massive stars as well as the associated stellar cluster at a high enough rate. How the massive clumps form, whether their internal conditions facilitate the accretion process, and how they fragment into clusters are still open questions. In the present work, we improve our understanding of these issues observationally, using the Submillimeter Array11 (SMA; Ho et al. 2004) and the IRAM 30 m telescope.12 We focus on the well-studied ultra-compact (UC) HII region G10.6-0.4, for which a wealth of complementary data is available to help address these questions.

G10.6-0.4 is a well-studied OB-cluster-forming region at a 6 kpc distance (Caswell et al. 1975; Downes et al. 1980).

In the central <1 pc region, high bolometric luminosity (9.2 \times 10^5 L☉) and bright free–free continuum emission (\geq 2.6 Jy within a 0.05 pc radius at 1.3 cm band) were detected (Ho & Haschick 1981; Sollins et al. 2005; Sollins & Ho 2005), suggesting that a cluster of O-type stars has formed (O6.5–B0; Ho & Haschick 1981). Observations of the 20 cm continuum emission using the NRAO13 Very Large Array (VLA) reveal a ~5 pc scale ionized bubble to the north of the brightest OB cluster, which suggests that the evolution of the cloud can be affected by the impact of the HII region projected close to G10.6-0.4 (Ho et al. 1986). Interferometric observations with high resolution detected groups of water and OH masers (Genzel & Downes 1977; Ho & Haschick 1981; Ho et al. 1983; Hofner & Churchwell 1996; Fish et al. 2005), and multiple high-velocity12CO outflows (Liu et al. 2010a), which indicate ongoing and in situ star formation. Observations of various molecular transitions (Ho & Haschick 1986; Kato et al. 1987, 1988; Guilloteau et al. 1988; Omodaka et al. 1992; Ho et al. 1994; Klaffen et al. 2009; Liu et al. 2010b, 2011; Beltrán et al. 2011) suggest that the general motion of the molecular gas at the 1 pc scale is dominated by gravity and shows rotation along a flattened geometry. The overall geometry and the excitations of the molecular gas in the central ~1 pc region resemble a scaled-up low-mass star-forming core (Liu et al. 2011), implying that the global contraction is efficient. A similar geometry in the central 1 pc scale is also resolved in the luminous...
The Astrophysical Journal, 745:61 (13 pp), 2012 January 20

Liu et al.

\((L \sim 6.6 \times 10^6 L_\odot)\) massive cluster-forming region G20.08-0.14 N (Galván-Madrid et al. 2009).

The high-resolution spectral line observations further show the clumpiness and the spatial asymmetry of the mass and the velocity field at a scale of 0.5 pc (Liu et al. 2010b, 2011). This asymmetric flow appears to have a spin-up rotational motion, and might continue to the highly clumpy 0.1 pc scale, flattened, hot toroid, which was first resolved by the NH\(_3\) optical depth studies. The hot toroid has a high temperature and should immediately surround the central 200 \(M_\odot\) OB cluster (Sollins & Ho 2005; Liu et al. 2010b; Beltrán et al. 2011), implying that massive stars may accrete from the very clumpy and geometrically thick molecular materials. Observations of the radio recombination lines suggest that part of the material that is ionized by the embedded OB stars can continue across the H\(_2\) boundary to feed the embedded OB stars (Keto 2002; Keto & Wood 2006).

Despite the rich literature on the kinematics in the inner 1 pc region, how the parsec-scale massive molecular clump connects to the external structures, how the massive clumps form, and how the detailed morphology and dynamics lead to the fragmentation and the formation of a cluster remain unanswered questions. To improve understanding of these aspects, we observed the 1.2 mm continuum emission in a 10 pc scale area using the IRAM 30 m telescope. At such a large scale, the 1.2 mm continuum emission is dominated by thermal dust emission. The large dish of the IRAM 30 m telescope allows us to resolve the dust emission, and simultaneously provides the short-spacing information to complement the SMA data. This yields high-resolution and high-dynamic range images for our morphological studies. In addition, we observed the dust polarization properties at the 0.87 mm wavelength using SMA to gauge the role of the magnetic field in the formation of the massive molecular clump. For a few 1.2 mm clumps resolved in the IRAM 30 m observations, we followed up with the SMA at 0.87 mm in order to resolve their internal structures and subsequent fragmentation.

We also compare the large-scale 1.2 mm continuum emission with the Spitzer MIPS GAL 24 \(\mu m\) map and the GLIMPSE 8 \(\mu m\) map. The diffuse 24 \(\mu m\) and 8 \(\mu m\) emissions mainly trace the ionized gas and the photon-dominant regions (PDRs) at the boundary of the neutral material. These comparisons help to define the locations and the effects of both the embedded and the external ionizing sources. We retrieved the archived VLA 20 cm continuum data and the 3.6 cm and 1.3 cm continuum data to trace the diffuse and confined ionized gas in the observed area.

The observations and data reductions are introduced in Section 2. The observational results are presented in Section 3. The physical implications of the results are discussed in Section 4. A brief summary and our plan for follow-up research are given in Sections 5 and 6. We will follow up the studies of the kinematics in a future publication. We use the coordinate system of Epoch J2000 throughout the present paper.

2. OBSERVATIONS AND DATA REDUCTION

2.1. The Millimeter and Submillimeter Continuum Data

IRAM 30 m Telescope. We performed a 7′ × 7′ on-the-fly scanning observation using the IRAM 30 m telescope MAMBO-2 array receiver on 2011 January 20. The observation was carried out at a frequency of 250 GHz (1.2 mm) with a primary beam size of 10″.5. We made three maps (map-1, 2, and 3 hereafter), with 1 hr on-source time for each, centered at R.A. = \(18^h10^m30^s14\), decl. = \(-19°55′29″70\), using the wobbler switching mode. The wobbler throw is 120″; the scanning directions of these three maps have different position angles relative to the R.A. axis, due to the rotation of the sky. Basic data reduction was carried out using the Mopscie software. Map-1 is observed in a low sky noise condition, while map-2 and map-3 showed higher noise and stripes in the image before the sky noise subtraction was performed.

Without performing the sky noise subtractions, we consistently obtain a peak flux of 9.5 Jy beam\(^{-1}\) for all three maps. This value is comparable to the previous SMA measurement of \(\sim10\) Jy at 1.3 mm in the central 10° region (Liu et al. 2010b).

A few percents error in estimating the flux distribution in the brightest central region will couple to the uncertainties in the modeling of the local zero flux level. This can propagate significant (~100 mJy beam\(^{-1}\)) repetitive artifacts in the scanning direction. We formed the final image based on map-1. We used the measurements in map-2 and map-3 to amend the pixels in map-1 which are corrupted by the repetitive artifacts. However, because of the sky subtraction effects noted above, the replaced pixels may still bias the local brightness distribution in certain areas. These effects, however, are limited to a level that does not affect the discussions in the present paper. The rms noise level of map-1 (without sky noise subtraction) is about 7 mJy beam\(^{-1}\).

SMA. We performed the 1.3 mm band observations using the 6 m dishes of SMA in the subcompact configuration, the compact configuration, and the very extended configuration on 2009 February 9, 2009 June 10, and 2009 July 12, respectively. In the compact configuration and the very extended configuration observations, the observing frequencies were centered on 231 GHz (1.30 mm) in the lower sideband and centered on 241 GHz (1.24 mm) in the upper sideband, respectively; in the subcompact configuration observation, the observing frequencies of the two sidebands were centered on 221 GHz (1.36 mm) and 231 GHz (1.30 mm). These observations were carried out with eight antennas. The pointing center of these observations is R.A. = \(18^h10^m28^s683\), decl. = \(-19°55′49″07\). The primary beam size of these observations is 55″. The basic calibrations were carried out using the MIRIDL and the Miriad software packages; the self-calibrations of these data were carried out using the AIPS package. We constructed the continuum band visibility data at 1.3 mm from the line-free channels. The combined SMA data sets cover a uv-sampling range of 5–410 kλ. We detect \(\sim14\) Jy of Stokes I emission in the field of view of the SMA observations. The continuum image of this combined SMA data set \((\theta_{\text{maj}} \times \theta_{\text{min}} = 0′79 \times 0′58)\) has been published in Liu et al. (2010a).

We performed follow-up 0.87 mm band observations using SMA on 2011 March 15 in the subcompact array configuration with seven antennas, and on 2011 March 25 in the compact array configuration with eight antennas. The observing frequencies of the two sidebands were centered on 336 GHz (0.89 mm) and 348 GHz (0.86 mm). The pointing centers of these observations are R.A. = \(18^h10^m41^s10\), decl. = \(-19°57′1′′30\) (P1 region hereafter), and R.A. = \(18^h10^m36′80\), decl. = \(-19°57′03″20\) (P2 region hereafter). The observations were carried out in snapshot.
mode, with 20 minute on-source integration per pointing in the subcompact configuration, and 16 minute on-source integration per pointing in the compact configuration (after flagging the bad data). The theoretical rms noise level after combining the subcompact array and the compact array data is about 3.4 mJy beam\(^{-1}\). We provide two versions of the continuum map. In one version, we limit the uv-sampling range to 8–45 kλ to optimize the sensitivity and the shape of the synthesized beam (4.8 \(\times\) 3′′). Without limiting the uv-sampling range (8–80 kλ), we obtain a higher resolution 0.87 mm continuum image with a 2′9 \(\times\) 1′9 synthesized beam to resolve the detailed structures in the brighter P1 region.

**IRAM 30 m Telescope + SMA.** We approximate the SMA observations at 1.2 mm using the SMA data taken at 1.24 mm and at 1.30 mm. The IRAM 30 m observations detect \(\sim\)30 Jy of Stokes I emission within the SMA primary beam. We convert the IRAM 30 m image into a uv-visibility data set by using the Miriad tasks *demos, uvrandom*, and *uvmodel*. We limit the uv-sampling range of the IRAM 30 m visibility to 0–4 kλ to fill in the missing short-spacing information in the SMA data. We note that in such a small uv-sampling range, the visibility model of the IRAM data is minimally affected by the attenuation of the single-dish primary beam. We have inspected the data and confirm the consistent absolute flux levels of the SMA data and the visibility model of the IRAM 30 m data. We limit the uv-sampling range of the SMA data to within 0–220 kλ to optimize the sensitivity to the extended structures and the angular resolution. By applying *invert* and (non-box) *clean* to the SMA and IRAM 30 m visibility data sets with 5000 iterations in Miriad, we obtain a synthesized beam of 3′4 \(\times\) 3′1 (P.A. = 15°), and an rms noise level of 5 mJy beam\(^{-1}\). The flux recovered by *clean* is 29.93 Jy. The final combined 1.2 mm image is formed by the Miriad task *restor*.

### 2.2. The 0.87 mm Polarization Observation

We performed observations in the 0.87 mm band in polarization mode using SMA in the compact-north array on 2010 July 31 and in the extended array on 2010 September 12. The observing frequencies of the two sidesbands were centered on 336 GHz (0.89 mm) and 348 GHz (0.86 mm). The pointing center of both observations is R.A. = \(18^h10^m28^s\), decl. = \(-19°55′49″\). The primary beam size of these observations is 40″. These observations cover the uv-sampling range of 10–135 kλ and 20–220 kλ, respectively. The recovered Stokes I fluxes are 15 Jy and 10 Jy, respectively. Calibrations and imaging were carried out using the Miriad software package.

We averaged the line-free channels in the individual observations to generate the continuum channels, and jointly imaged the upper 4 GHz and the lower 4 GHz sidebands. For the compact-north array observations, we obtain an rms noise level of 2.7 mJy beam\(^{-1}\) for the Stokes \(Q\) and the Stokes \(U\) images. For the extended array observations, we obtain an rms noise level of 3.0 mJy beam\(^{-1}\) for the Stokes \(Q\) and the Stokes \(U\) images. Jointly imaging the data from these observations yields a synthesized beam of 1″2 \(\times\) 1″0 and an rms noise level of 2.3 mJy beam\(^{-1}\) for the Stokes \(Q\) and Stokes \(U\) images.

### 2.3. The Centimeter Continuum Observations

We retrieved the archived 3.6 cm continuum emission toward G10.6-0.4 in the VLA A-configuration including the Very Long Baseline Array Pie-Town antenna on 2005 January 2, and we observed the 3.6 cm continuum emission in the NRAO VLA/Expanded Very Large Array (EVLA) C-configuration on 2009 July 27. The pointing center of these observations is R.A. = \(18^h10^m28^s\), decl. = \(-19°55′49″\). The primary beam size of these observations is 330″. The basic calibrations, self-calibration, and imaging of these data were carried out using the AIPS package. We combined the A-array+Pie-Town visibility data with the C-array visibility data, and applied a Gaussian taper in the uv-domain with an FWHM of 170 kλ, yielding a 2′3 \(\times\) 1′5 synthesized beam with a position angle of \(-10°9′\). The observed rms noise of the 3.6 cm continuum image is about 1 mJy beam\(^{-1}\) (\(\sim\)5 K in terms of brightness temperature). We note that the 3.6 cm continuum emission traces free–free emission based on spectral index measurements.

We retrieved the archived VLA 20 cm continuum data, taken on 1984 June 13. The primary beam size of this observation is 1833″ (\(\sim\)30′5). The basic calibrations, self-calibration, and imaging of these data were carried out using the AIPS package, yielding an rms noise level of 1 mJy beam\(^{-1}\), with a 21″ \(\times\) 14″ synthesized beam (see also Ho et al. 1986).

We retrieved the archived VLA 1.3 cm continuum data taken on 2002 February 1. The primary beam size of this observation is 2′. The basic calibrations, self-calibration, and imaging of these data were carried out using the AIPS package, yielding an rms noise level of 0.13 mJy beam\(^{-1}\), with a 0′11 \(\times\) 0′07 synthesized beam (see also Sollins et al. 2005; Sollins & Ho 2005).

### 2.4. The CS (1–0) Data

We observed the CS (1–0)–1\(\rightarrow\)0 transition using the NRAO VLA/ELVA in the DnC-configuration, on 2009 September 27. These observations had a continuous local sidereal time duration of 9 hr, with 20 available antennas after flagging. The pointing center is R.A. = \(18^h10^m28^s\), decl. = \(-19°55′49″\). The primary beam size of these observations is 55″. The observations cover the uv-sampling range of 4–245 kλ. Continuum emission is averaged from the line-free channels and then subtracted from the line data. Calibrations, self-calibrations, and imaging were carried out using the AIPS package, yielding a synthesized beam of 1′5 \(\times\) 1′1 and an rms noise level of 22 mJy beam\(^{-1}\). This CS data set was previously published in Liu et al. (2011).

### 3. RESULTS

The observations discussed in this paper cover a tremendous amount of molecular structures. These structures have a broad range of linear size scales and are embedded in different ambient environments (e.g., different molecular volume density, geometry, morphology, gravitational potential). To clarify the terminology (e.g., filaments, clumps, cores, protrusive features/structures, envelope), we present a schematic model in Figure 1, which also forecasts parts of the observational results. This model presents a filamentary, 10 pc scale molecular cloud, which may still be embedded in a giant molecular cloud. The local concentrations of mass in the filaments fragment into smaller and denser substructures on a dynamical timescale shorter than the timescale of the global contraction. Depending on the physical environments in the parent structures, these processes of fragmentation may also be hierarchical. We note that the scale bars in the schematic model reflect the physical size scales of the structures to which we will refer. Part of this schematic model, the massive molecular envelope region, has been introduced in a previous publication (Liu et al. 2011). Also refer to Zhang & Tan (2011) for the radiation transfer simulations of a scaled-down model.
3.1. The Global Environment

Figure 2 shows the 1.2 mm continuum map from the IRAM 30 m observations. In this figure, we label the significant 24 $\mu$m emission regions (a–o) as the suspected OB star-forming regions. Most of these OB star-forming regions already show 20 cm or 6 cm free–free continuum emissions (Ho et al. 1986). Five resolved UC H II regions in our 3.6 cm observations are also labeled (A–E; see also Figure 4). The UC H II region A is located at the geometric center. This UC H II region is the brightest one, and has been studied by the highest angular resolution VLA observations at 1.3 cm. Analysis of the continuum flux suggests that a 200 $M_\odot$ OB cluster is contained in this UC H II region. From the 1.2 mm continuum map presented in Figure 2, we see at least five extended ($\gtrsim$ 3 pc in the projected scale) massive molecular filaments. Some extended structures may still be blended, and remain to be resolved with higher angular resolution.

The most significant feature in Figure 2 is the clear separation between the H II region in the northeast and the neutral material in the southwest. A $>10$ pc scale ionized arc traced by the diffuse 24 $\mu$m emission is immediately followed by a slightly more extended 8 $\mu$m bright PDR shell southwest of it. Most of the dense neutral material is distributed further southwest of the PDR shell and is traced by the 1.2 mm continuum emission. The neutral material is filamentary, and is extremely clumpy, with massive stars forming in localized dense structures. Multiple 24 $\mu$m bright H II regions with significant PDR shells are seen over the $>10$ pc scale region (e.g., massive clusters a, c, d, e, f, j, m, n). UV photons from the massive cluster o appear to photoionize a filament in the south and generate a bow-shock-shaped H II region (see also Section 4.2).

The extended filament in the northwest seems to continue to the massive clusters e, f, and g. How this filament is dynamically associated with the densest structure in the center of this map is uncertain. The rest of the extended filaments appear to connect to the geometrical center, an extremely bright 1.2 mm source with a projected scale of $\sim$2–3 pc. A high concentration of 8 $\mu$m point sources is resolved in this central region, indicating the active fragmentation and the formation of a stellar cluster.
Figure 2. Spitzer MIPSGAL 24 μm image (red), Spitzer GLIMPSE survey 8 μm image (green), and IRAM 30 m 1.2 mm continuum image (blue color and contours). The beam of the 1.2 mm continuum image ($\theta_{maj} \times \theta_{min} = 10.5 \times 10.5$) is shown in the bottom left corner. A scale bar indicating the 5 pc projected length is shown, with the assumption of a 6 kpc line-of-sight distance. The suspected OB clusters associated with the bright 24 μm emission are labeled (a–o) with white arrows. The dashed circles represent the primary beam of the SMA 1.3 mm observations. The UC H ii regions in the SMA primary beam are labeled (A–E) with cyan solid arrows (see also Figure 4). Five extended elongated structures or filaments are labeled (FL–NE, E, S, SW1, NW2) with thick yellow arrows (better defined in Figure 4). We note that there might be some line-of-sight filaments, which are less extended in projection and have poorly resolved alignments in the IRAM 30 m 1.2 mm continuum image. However, we expect higher resolution maps to resolve more of these kinds of filamentary structures (Figure 4). Contours are 20 mJy beam$^{-1} \times [1, 5, 20]$ ($1\sigma = 7$ mJy beam$^{-1}$).

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

region has high extinction. There might be more embedded massive stars which are not visible in the optical and near-infrared observations. Clusters of water masers (Hofner & Churchwell 1996) and high-velocity $^{12}$CO (2–1) outflows (Liu et al. 2010a) were also reported in this region. We observe the 1.3 mm continuum emission using SMA and observe the 3.6 cm free–free continuum emission and the CS (1–0) transitions using VLA/EVLA in the center of this dense structure (Section 3.2).

3.2. The Geometrical Context of the Accretion Flow from the 5 pc Radius to the Central 0.05 pc

Figure 3 shows the IRAM 30 m 1.2 mm continuum map with much more detailed contours, overlaid with the combined IRAM 30 m+SMA 1.2 mm continuum map in the central region. Assuming $\beta = 2$, a gas-to-dust ratio of 100 (Lis et al. 1998), an average temperature of 30–50 K, and subtracting the free–free continuum flux of 4 Jy (Liu et al. 2010b), the detected 1.2 mm flux within the central 55″ SMA primary beam corresponds to $(1.8–4) \times 10^4 M_\odot$ of the molecular mass. We note that from the CS observations, Omodaka et al. (1992) estimated the mass to be $4 \times 10^4 M_\odot$ in the central 30″ region. We show the combined IRAM 30 m+SMA 1.2 mm continuum map, and the velocity-integrated CS (1–0) maps in Figure 4 to demonstrate the structures in the inner region with higher angular resolutions.

While Figure 3 shows multiple filaments on the scale of a few parsecs, in Figure 4 we see multiple protrusions in the
Figure 3. IRAM 30 m 1.2 mm continuum image (magenta contours, blue color scale) and the combined IRAM 30 m + SMA image (dark blue contours). The magenta contours are 15 mJy beam$^{-1} \times [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 30, 36, 42] (1\sigma = 7 mJy beam$^{-1}$). The dark blue contours are 16 mJy beam$^{-1} \times [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 12, 14, 16, 20, 60] (1\sigma = 5 mJy beam$^{-1}$). The beam of the IRAM 30 m image ($\theta_{\text{maj}} \times \theta_{\text{min}} = 10.5'' \times 10.5''$) and the synthesized beam of the combined IRAM 30 m+SMA 1.2 mm continuum image ($\theta_{\text{maj}} \times \theta_{\text{min}} = 3.4'' \times 3.1''$) are shown by the blue and yellow filled circles, respectively. This figure demonstrates the filamentary morphology of the molecular cloud, with embedded massive molecular clumps. The identified massive molecular clumps in FL–E and FL–S are labeled by MM 1–9. The dashed circle around the dark blue contours represents the primary beam coverage of the SMA 1.3 mm observations; two dashed circles around MM 1, 2 (P1 region), and MM 4 (P2 region) represent the primary beam coverages of the SMA 0.87 mm observations. The dotted circles mark the regions that are potentially affected by repetitive artifacts (Section 2).
(A color version of this figure is available in the online journal.)

inner parsec-scale region. These protrusions seem to have no preferred alignment, exhibiting instead a radial configuration connecting to a common center. We visually identify the protrusions in the combined 1.2 mm map (Figure 4). The identified structures are labeled by FL–NE, E, SE, S, SW2, SW1, NW2, NW1, respectively. The elongated structures FL–NW1, FL–E, and FL–SW1 are consistent with the more extended molecular filaments, which were previously detected in the NH$_3$ (Ho & Haschick 1986) and the CS (1–0) observations (Omodaka et al. 1992). We note that the velocity gradient of FL–E was marginally resolved by Ho & Haschick (1986), and was interpreted as the envelope rotational motion. The FL–S might have been detected in the previous C$^{18}$O observation (Ho et al. 1994). However, we emphasize that the 1.2 mm continuum emission presented in this paper traces the thermal dust emission, without being biased by the excitation conditions and the molecular abundances.

Some of the protrusions continue outside of the primary beam of the SMA observations, which can only be followed in the IRAM 30 m 1.2 mm continuum map, for example, FL–NE, FL–NW1, FL–NW2. Some structures around the middle of the map might be foreshortened and are only marginally resolved.
in the IRAM 30 m continuum map. There is also an apparent filament or protrusion, which continues from the central parsec region to a large scale, and is associated with the massive cluster c. We suspect another filamentary structure exists that continues to the large scale, which is related to the formation of the massive clusters m and n. These suggestions can be tested with interferometric mosaic observations.

Comparing the combined 1.2 mm continuum map with the velocity-integrated CS (1–0) map (Figure 4) suggests that some protrusions might continue directly into the central 0.05 pc, where the fast spinning hot toroid (Sollins & Ho 2005; Liu et al. 2010b; Beltrán et al. 2011) is immediately around the most massive (∼200 M⊙) OB cluster. We note that the filamentary and clumpy nature of the massive molecular envelope traced by the CS (1–0) map has been highlighted in Liu et al. (2011). Lee et al. (2011) also recently reported the clumpy nature of the high mass star-forming region IRAS 05345+3157 based on CARMA observations of CS (2–1). As an example of the continuation of the filaments, we zoom in on the FL–SE region and show the combined 1.2 mm continuum map and CS (1–0) map in Figure 5. In the figure, we see that both the 1.2 mm emission and CS (1–0) emission show a number of elongated structures. The most prominent one follows the suggested plane of rotation (Keto et al. 1988; Sollins & Ho 2005; Liu et al. 2010b). Figure 6 demonstrates the relation between the elongated CS emission and the 1.3 cm free–free continuum emission from the centrally embedded UC H II region. We note that the arc-shaped features in the east of the 1.3 cm continuum map are explained as signatures of the externally ionized molecular clumps, which are approaching the embedded OB cluster (Sollins & Ho 2005).

This is the first time we resolve the geometry of the massive accretion flows in the distant (few kpc) OB cluster-forming regions, on such a large scale and with such a high spectral dynamic range. However, the resolved structures mentioned here are all projected onto the two-dimensional images.
3.3. The Millimeter Clumps and the Submillimeter Cores

The parsec-scale filaments have complicated internal structures. As an example, Figure 7 shows the IRAM 30 m 1.2 mm continuum map in FL–E, overlaid with the saturated 24 μm and 8 μm Spitzer images. Some infrared dark regions with complicated structures are consistently traced by the 1.2 mm emission and the near-infrared opacity suggest a structure continuing from the southwest, which may still contain substructures. More detailed structures are suggested by the near-infrared opacity, although it is hard to distinguish if those structures are physically associated or a mere projection along the line of sight. In such an evolved region, the distribution of the foreground and background extended infrared emissions severely confuse the structure identification. The local structures can best be recognized from the millimeter and submillimeter thermal dust emission. However, the IRAM 1.2 mm continuum map has much poorer angular resolution as compared to the 24 μm and 8 μm Spitzer images.

Here, we define the millimeter clumps as compact structures identified in the IRAM 1.2 mm map, which have size scales of ~0.5 pc. We define the submillimeter cores as compact structures identified in the SMA 0.87 mm Stokes I image, which have size scales ≲0.2 pc. We identify the millimeter clumps as well as the submillimeter cores in regions where the fluxes are predominantly contributed by FL–E and FL–S, since structures in other regions, particularly in the east, appear to be blended due to the still insufficient angular resolution. In addition, the millimeter and the submillimeter continuum emissions in FL–E and FL–S are minimally contaminated by the free–free continuum emission, and are therefore good tracers of the molecular mass (Figures 3 and 8; see also Ho et al. 1986 for the free–free continuum emission). Note that these observationally defined features are still limited

![Figure 6](image1.png)

![Figure 7](image2.png)

![Figure 8](image3.png)
of 100, and assuming an average temperature of 25 K, the gas-to-dust ratio
optically thin dust emission formulation in Lis et al. (1998), we simply sum the flux within the ellipses as defined by the
distribution of the identified structures may be non-Gaussian
the emission from the filaments. The profiles of the brightness
Gaussian fits of the fainter cores are biased by the confusion with
is limited by the (synthesized) beam of the observations. The
IMFIT
observations, with likely unresolved substructures.

by the insufficient angular resolution and sensitivity of our
observations, with likely unresolved substructures.

We perform two-dimensional Gaussian fit using the AIPS task
IMFIT to obtain the size. We note that the size from the fitting
is limited by the (synthesized) beam of the observations. The
Gaussian fits of the fainter cores are biased by the confusion with
the emission from the filaments. The profiles of the brightness
distribution of the identified structures may be non-Gaussian
due to the internal structures. Hence, to obtain the total flux,
we simply sum the flux within the ellipses as defined by the
Gaussian fits.

We provide the preliminary mass estimates based on the
optically thin dust emission formulation in Lis et al. (1998),
assuming an average temperature of 25 K, the gas-to-dust ratio
100, and \( \beta = 2 \). We approximate the volume of each of the
clumps and cores by assuming a spherical geometry, with the
radius being the average of their projected major and minor
axes. The estimated flux and mass of the clumps and cores can
be biased to be factors of 2–3 higher, due to the uncertainties in
the Gaussian fits. However, while estimating the density, these
biases will be compensated by the similar bias in the volume.

The coordinates, size, millimeter or submillimeter flux, mass,
and the average density are summarized in Tables 1 and 2. With
similar assumptions, the overall molecular mass in FL–E and
FL–S, without including the structures in the central 3 pc dense
region, are \( 6 \times 10^3 \, M_\odot \) and \( 4.5 \times 10^3 \, M_\odot \), respectively.

The identified structures are also labeled (MM 1–9, SMM
1–6, and SMM 1–5 a, b, c) in Figures 3, 8, and 9. The millimeter
clumps in FL–E have an average projected separation of 0.82 pc,
and the millimeter clumps in FL–S have an average projected
separation of 0.54 pc. Our follow-up submillimeter Stokes I
observations focus on the millimeter clumps MM1, MM2, and

| Table 1 |
| --- |
| The Millimeter Clumps Identified from the IRAM 30 m MAMBO-2 1.2 mm Continuum Observation |
| Object | R.A. (J2000) | Decl. (J2000) | Size (arcsec × arcsec) | Flux (mJy) | \( H_2 \) Mass (\( M_\odot \)) | Volume Density (\( 10^3 \, n_{H_2} \, (\text{cm}^{-3})^{-1} \)) |
| MM1 | 18°10′41″59 | −19°57′41″4 | 15 × 13 | 168 | 263 | 1.5 |
| MM2 | 18°10′40″41 | −19°57′41″4 | 15 × 13 | 154 | 241 | 1.4 |
| MM3 | 18°10′38″61 | −19°57′21″7 | 27 × 19 | 335 | 525 | 0.68 |
| MM4 | 18°10′56″84 | −19°57′03″8 | 15 × 12 | 122 | 191 | 1.2 |
| MM5 | 18°10′34″61 | −19°58′42″2 | 27 × 16 | 242 | 379 | 0.60 |
| MM6 | 18°10′34″61 | −19°58′24″7 | 25 × 16 | 224 | 351 | 0.69 |
| MM7 | 18°10′33″86 | −19°58′17″7 | 27 × 21 | 354 | 555 | 0.63 |
| MM8 | 18°10′33″37 | −19°58′00″2 | 30 × 19 | 351 | 550 | 0.59 |
| MM9 | 18°10′32″62 | −19°57′39″2 | 27 × 14 | 192 | 301 | 0.55 |

| Table 2 |
| --- |
| The Submillimeter Cores Identified from the SMA 0.87 mm Stokes I Images |
| Object | R.A. (J2000) | Decl. (J2000) | Size (arcsec × arcsec) | Flux (mJy) | \( H_2 \) Mass (\( M_\odot \)) | Volume Density (\( 10^3 \, n_{H_2} \, (\text{cm}^{-3})^{-1} \)) |
| SMM1a | 18°10′41″75 | −19°57′38″2 | 3.4 × 2.0 | 56 | 37 | 30 |
| SMM1b | 18°10′42″04 | −19°57′39″8 | 3.5 × 2.7 | 28 | 19 | 10 |
| SMM1c | 18°10′41″97 | −19°57′36″5 | 3.7 × 1.7 | 22 | 15 | 12 |
| SMM2a | 18°10′41″52 | −19°57′38″7 | 2.9 × 2.3 | 24 | 16 | 14 |
| SMM2b | 18°10′41″31 | −19°57′38″7 | 2.7 × 1.9 | 20 | 13 | 16 |
| SMM3a | 18°10′40″76 | −19°57′40″9 | 3.4 × 2.9 | 49 | 32 | 25 |
| SMM3b | 18°10′40″98 | −19°57′44″3 | 5.0 × 2.7 | 45 | 30 | 8.2 |
| SMM4 | 18°10′40″53 | −19°57′38″9 | 3.6 × 2.6 | 37 | 25 | 13 |
| SMM5a | 18°10′40″36 | −19°57′37″5 | 5.9 × 2.7 | 69 | 46 | 9.1 |
| SMM5b | 18°10′40″22 | −19°57′36″1 | 3.8 × 2.2 | 26 | 17 | 9.9 |
| SMM6 | 18°10′40″43 | −19°57′36″7 | 6.9 × 5.0 | 43 | 28 | 2.1 |

Note. We note that the volume densities in the last column are the averaged values for unresolved structures, which can be underestimated.

Figure 9. IRAM 30 m 1.2 mm continuum image (magenta contours), and the high-resolution SMA 0.87 mm continuum image (blue contours and color scale; \( \theta_{\text{maj}} \times \theta_{\text{min}} = 2′′9 \times 1′′9, \text{P.A.} = 0′′9 \)) in the P1 region. The magenta contours are 15 mJy beam
\( ^{-1} \) \times \([1, 2, 3, 4, 5, 6]\). The blue contours are 10 mJy beam
\( ^{-1} \) \times \([-1, 1, 2, 3, 4]\) \times \(3.4 \, \text{mJy beam}^{-1} \). The synthesized beam of the high-resolution SMA 0.87 mm continuum image is shown in the bottom left corner.

The identified submillimeter cores are labeled by SMM 1–5 (a, b, and c). These submillimeter cores seem to be aligned linearly.

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

MM4. We resolved six submillimeter substructures in the lower resolution versions of the 0.87 mm Stokes I image (SMM 1–6, Figure 8). SMM 1 and SMM 2 have a projected separation of...
0.27 pc; and SMM 3, 4, 5 have an average projected separation of 0.15 pc. We note that the Jeans length is 0.14 pc, assuming an average temperature of 25 K, and an average density of $n_H = 10^3$ cm$^{-3}$.

Without limiting the uv-sampling (Section 2.2), we made a higher angular resolution (2$''/9 \times 1''/9$) 0.87 mm Stokes I image. We find that the core SMM1 is resolved into three independent submillimeter cores, while SMM 2, 3, and 5 are also each resolved into two further submillimeter cores (Figure 9). This implies smaller actual sizes and average separations of submillimeter cores in MM1 and MM2. We label the resolved substructures of SMM 1–5 with suffixes a, b, c. The submillimeter cores SMM 1a, 1b, 1c, 2a, and 2b seem to follow one elongated distribution; the submillimeter cores SMM 3a, 3b, 4, 5a, 5b are aligned in another elongated distribution. With the still insufficient angular resolution of the SMA 0.87 mm Stokes I image (Section 2.2), we may underestimate the volume density (Table 2) of the submillimeter cores. The submillimeter core SMM 6 has an elongated shape (Figure 8), which may indicate further internal structures, but is too faint to be resolved.

3.4. Dust Polarization

We do not detect the Stokes Q and Stokes U emissions at the 3$\sigma$ level in any combination of the compact-north array and the extended array data. We note that our polarized intensity maps have achieved comparable resolutions and lower rms noise levels as compared with the previous SMA studies of distant OB star formation regions (G31.41+0.31: Girart et al. 2009; G5.89-0.39: Tang et al. 2009a; W51 e2/e8 cores: Tang et al. 2009b). Our non-detection suggests that G10.6-0.4 is less than 2.8% polarized. Possible explanations for the lower level of the polarized emission and the physical implications are discussed in Section 4.6.

3.5. The Ionized Bubble and the Patchy Surrounding Molecular Gas

The early VLA 20 cm observations show an ionized bubble to the north of the central OB cluster. This ionized bubble can be seen in the 24 $\mu$m emission (Figure 2), and also with the 8 $\mu$m bright PDR shell external to it. The 24 $\mu$m emission additionally shows some patchy structures on the eastern edge of the ionized bubble. Those patchy structures have high opacities and are dark in the 24 $\mu$m and 8 $\mu$m maps.

The observed area has strong diffuse infrared emission. The structures in the background infrared brightness distributions and the foreground infrared emission can confuse the identifications of structures. We report the patchy dust emission from the same area in the 1.2 mm band. A blown-up view of the IRAM 30 m 1.2 mm continuum map overlaid with the VLA 20 cm continuum map is provided in Figure 10.

The distribution of the 20 cm continuum emission suggests that the 1.2 mm emission from the patchy molecular gas are not contaminated by the free–free emission. This patchy molecular gas shows rich subparsec-scale structures. With our current data, how these patchy structures form, and if they are interacting with the ionized bubble or the H II region, are unclear. We suspect that they are naked dense cores which lost their ambient gas through interactions or they can be some foreground, isolated, subparsec-scale molecular cloudlets. These have to be distinguished in future observations.

4. DISCUSSION

4.1. The Impulse-driven or Regulated Structure Formation?

From Figure 2, we see the formation of the OB stars over the entire $\geq$10 pc projected area. The formation of these OB stars seems to be synchronized on a time interval which is short in the sense that it takes $\geq 10^7$ years to propagate the sound wave in this $\sim$10 pc cloud. This propagation timescale is much longer than the collapsing timescale plus the lifetime of the massive stars. The Alfvén waves can propagate supersonically. However, they will be restricted by the detailed magnetic field line configurations and the magnetic field strength.

Are there large-scale physical phenomena which are globally regulating or triggering the local structure formations (e.g., the formation of the massive core or the collapsing of the massive cores)? The impulse from the H II region in the northeast might be a candidate for such a global mechanism, which was suggested by Ho et al. (1986) with their VLA 20 cm continuum observations. This scenario has to be tested by the numerical hydrodynamical simulations.

4.2. The Ionizing Pattern as Evidence of the Filamentary Nature

With the 1.2 mm dust continuum maps, one may argue that the filamentary geometry of the neutral material could be a projection effect. In this section, we present the case of the ionizing pattern around the parsec-scale filament in the south and the massive cluster o (Figure 2) to argue in favor of the elongated geometry of the parsec-scale structures. While fragmentation in filamentary infrared dark clouds is ubiquitously seen, we argue that our result provides hints for their evolutionary context. We cannot rule out the possibility that there are edge-on sheets which in projection appear like filaments. However, it is questionable whether a $\geq 5$ pc scale sheet is likely at such a late evolutionary stage where clusters of smaller structures and massive stars are already present.
The idea is that if there is an OB cluster located close to the parsec-scale massive filaments (with a gradient of volume density along the radius), its ionizing photons and stellar wind will be blocked in the direction of the dense neutral material. The UV photons emanating from the OB stars will only efficiently ionize the outer edges of the filament. If the filament presents a small solid angle to the OB cluster, most of the UV photons, the stellar wind, and the ionized gas will flow around the filament, and form a U-shaped free–free continuum emission region. Such a U-shaped illumination pattern is seen around the massive filament in the south (Figure 8). If that filament were just filamentary in projection but an extended smooth sheet in reality, we would not expect to see the ionized gas penetrating to the northeast of it; instead, the free–free emission should be limited to the southwest. Alternatively, the U-shaped illumination pattern can also be explained by the addition of two photoionized molecular filaments. This scenario can be examined by deeper observations of thermal dust emission with higher angular resolution.

We note that the cloud with a filamentary morphology may be self-shielded from an OB cluster deeply embedded in the geometrical center of the cloud. While the parsec-scale filament in the south is illuminated by the massive cluster o and shows significant 8 \mum emission (Figure 2), the filament in the east remains dark at 8 \mum. If there are smaller and denser filaments continuing to the centrally embedded OB cluster, the small cross-sections of the filamentary accretion flow is minimally affected by the radiation from the luminous OB cluster, and the pressure force of the ionized gas. Therefore, it is conducive for the accretion of the massive stars.

Previous observations have suggested that the major, massive filaments can be formed from the merging of the smaller ones (Jiménez-Serra et al. 2010). The filaments may also collide with each other, which is conducive for the formation of cores and massive stars (Galván-Madrid et al. 2010).

At a 10 pc scale, the filamentary morphology has a low volume filling factor, or a high porosity even after being projected onto a two-dimensional observing area. The intensity ratios of molecular gas tracers (e.g., HCN/CO) can then be easily converted to volume filling factors (e.g., dense gas volume filling factor) as in extragalactic studies. From Figures 3, 8, and 9, we see concentration of dense gas in the form of massive molecular clumps and molecular cores. The volume densities of these clumps and cores (Tables 1 and 2) are high enough to excite the dense gas tracers CS, HCO+, HCN, and H2CO.

4.3. A Geometrically Regulated Fragmentation in Parsec-scale Filaments

The parsec-scale filaments, especially the two in the south and in the east, show rich marginally resolved 1.2 mm substructures, the millimeter clumps (Figure 3). The clumps in the eastern filament show a generally stronger 1.2 mm emission than those in the southern filament, which can be due to their difference in mass, temperature, or dust properties. This can be further examined by observing the NH3 emission with multiple transitions, and by observing the dust continuum emission in multiple frequency bands. At least three massive clumps in the eastern filament may be forming massive stars and show bright 8 \mum point sources around the region we label cluster 1 (Figure 2).

Clumps in the southern and the eastern filaments seem to be regularly separated by 0.5–1 pc, implying a scale length for the local contractions which may be related to the length and width of the filaments. In the clumps MM1 and MM2, our follow-up SMA observations have resolved much more submillimeter cores, which have an averaged projected separation comparable to the thermal Jeans length (Section 3.3, Figure 9). Compared with other high-resolution interferometric observations of filamentary infrared dark clouds, it is likely that hierarchical fragmentation is common. Undoubtedly, there will be more blended substructures in our IRAM 30 m map due to the still insufficient angular resolution such as in the case study of the infrared dark cloud G28.34+0.06 (d \sim 4.8 kpc; Wang et al. 2008, 2011; Zhang et al. 2009), the 1.3 mm continuum observation of five SMA resolved cores within a single local maximum in the IRAM 30 m 1.2 mm continuum map.

We note that the submillimeter cores in the molecular clumps MM 1 and MM 2 (Figure 9) are not randomly distributed, but are aligned linearly, forming the main axis of the filament. That the successive fragmentation at even smaller scales continues to be aligned along the filaments suggests a common process.

The process of fragmentation into clumps can be regulated by the density, mass concentration, the geometry or the morphology of the clump, the local magnetic field structure, the local feedback and the ambient pressure, the velocity field, interactions, and so on. Successive fragmentation takes place as the local conditions change. Furthermore, collision or merging of filaments may also be an important process. We postpone the detailed statistical studies of these cores until we obtain follow-up observations that achieve a physical resolution of \ll 0.1 pc, and achieve a much better sensitivity to recover the solar mass or smaller substructures.

Some of the parsec-scale filaments appear to converge into the geometric center of a 2–3 pc scale densest structure. The abundance of protrusions in both the IRAM 30 m 1.2 mm continuum map and the combined IRAM 30 m + SMA 1.2 mm continuum map (Figure 3) supports such a scenario. We note, however, that the massive stars are distributed over the entire 10 pc area. Hence, it appears that the star formation process may be driven by local processes and may not be related to inflow from large scales via the filaments.

4.4. Morphologically Regulated Cluster Formation

We provide simple arguments based on the global and the local free-fall timescale to justify that the filamentary accretion flows with a radial alignment will allow efficient fragmentation during the quick global contraction (Miyama et al. 1987). Theories about how contractions depend on morphology, geometry, and initial conditions are described by Ledoux (1951), Ostriker (1964), Larson (1985), Vishniac (1994), Whitworth et al. (1994), Curry (2000), and Myers (2009). Our estimates specifically focus on the materials in the central 2 pc region (i.e., inside the SMA primary beam shown in Figure 4), in which we see a concentration of bright infrared point sources (Figure 2). We do not consider the magnetic field in our estimates, which is consistent with our observations that strong and organized magnetic fields may not be present at the sampled size scales (see also Section 4.6). With some rescaling, the same calculations can be applied to the more extended area while a lack of understanding of the large-scale initial turbulence brings large uncertainties.

The free-fall timescale is inversely proportional to the square root of the averaged density \rho. The value of \rho can be estimated
by
\[ \rho = \frac{M(R)}{\frac{4}{3} \pi R^3}, \]

while \( R \) is the radius around a “local” center of mass and \( M(R) \) is the total mass enclosed in the radius \( R \). For the case of G10.6-0.4, in the central 2 pc region, we have resolved \( \sim 8 \) protrusions (Figure 4). Assuming a filamentary geometry for those protrusions, of which the width is a fraction of a parsec, say 0.1–0.3 pc, the volume occupied by each filament can be approximately estimated as the volume of a 2 pc rod, which is \( (\pi/4) \times (0.1–0.3)^2 \times 2 \times 0.016–0.14 \) pc\(^3\). The volume filling factor in the inner 2 pc region can be approximately estimated by
\[ \frac{8 \times (0.016–0.14)}{\frac{4}{3} \pi \times (1 \text{ pc})^3} = 3.0–27\%. \]

If we project all structures along the line of sight, we can also estimate the surface filling factor, which is \( \geq 50\% \). We note that the smaller beam filling factor of 30% reported in the previous low-resolution NH\(_3\) observations (Keto et al.) suggests that most of the mass is concentrated in narrower filaments or in the central massive core.

The estimated small volume filling factor implies potentially a much higher local volume density than the averaged volume density in that region. Within the region enclosed by the 1 pc radius, the free-fall contraction timescale of the local perturbations can be a factor of 1.9–5.8 times shorter than the global free-fall contraction timescale. Depending on the support of the rotational velocities, the timescale of the large-scale contraction could be a few times longer than the global free-fall contraction timescale (Ho & Haschick 1986; Keto et al. 1987, 1988; Keto 1990; Liu et al. 2010b, 2011). Thus we suggest that although the system may have a quick global contraction (see also the clump-fed scenario in Wang et al. 2010), the existence of small-scale structures implies that efficient fragmentation and subsequent star formation may have already occurred. The accretion flows are clearly highly clumpy, and have been resolved in the high-resolution NH\(_3\) absorption experiment (Sollins & Ho 2005), and the position–velocity (PV) diagram of \(^{13}\)CS (5–4) (Liu et al. 2010b). The fragmentation of the accretion flows is consistent with the observed clusters of UC H\(_\text{ii}\) regions, multiple water masers and high-velocity \(^{12}\)CO outflow sources (Figure 4), many dusty cores with strong 1.3 mm emission, all external to the centrally located, compact, fast spinning, hot toroid (Liu et al. 2010a, 2011). The earliest epoch of star formation generates turbulence, which helps regulate the subsequent star formation efficiency and the accretion of the centrally embedded massive star (G10.6-0.4: Liu et al. 2010a; Simulations: Li & Nakamura 2006; Nakamura & Li 2007; Carroll et al. 2009; Wang et al. 2010).

From the three-color image (Figure 2), we see a higher concentration of the 8 \( \mu \text{m} \) sources in the central parsec region than in the extended region, which may be explained by the faster fragmentation and contraction of the filamentary structures in the higher density environment. We note that the interferometric observations of the nearby massive cluster-forming region, the Orion–KL central core, have also demonstrated the highly filamentary nature of the molecular gas, as well as the fragmentation in those filaments, in the inner \( \sim 1 \) pc region (Wiseman & Ho 1996, 1998). Note that on such a small scale, the filaments do not need to be primordial or a continuation of the outer structures. The interactions between the ambient gas and the (proto-)stellar feedback can also lead to the formation of filaments in the later evolutionary stages. Of course, the filaments can also be destroyed by the same feedback mechanisms (Wang et al. 2010). The process of infall and fragmentation is highly dynamical and chaotic.

4.5. Spin-up Signature of the Filamentary Accretion Flow

The red excess of the velocity field in G10.6-0.4 was previously reported in the NH\(_3\) absorption line experiments, which is consistent with a high-velocity infall (Ho & Haschick 1986; Keto et al. 1987, 1988; Keto 1990; Sollins & Ho 2005). From 1" resolution emission line observations, Liu et al. (2010b) confirmed the red excess in the central \( \sim 0.06 \) pc (2") region, and further saw the high spatial asymmetry and the clumpiness in the mass distribution from the PV diagram. Motivated by the resolved protrusions in the present work (Figure 4), we propose that the spin-up rotational motions of the accretion flow with a filamentary morphology may coherently explain the red excess, the spatial asymmetry, and the clumpiness in those PV diagrams. Detailed modeling will be provided in our follow-up kinematics studies.

4.6. The Magnetic Field

SMA observations of luminous massive star-forming regions (G31.41+0.31: Girart et al. 2009; G5.89-0.39: Tang et al. 2009a; W51 e2/e8 cores: Tang et al. 2009b) have shown that the polarization percentage of the 0.87 mm thermal dust emission ranges from a few percent (e.g., 4\% in G31.41+0.31) to up to \( \sim 8\% \) in the W51 e2/e8 regions, and up to \( \sim 22\% \) in the G5.89-0.39 region. The polarization observations of G10.6-0.4 achieved an improved sensitivity over the previous SMA studies of similar types of targets. While those previous cases all show significant detections of polarized flux, in the present work, we do not detect polarized emission above the 3\( \sigma \) rms noise level.

In G10.6-0.4, the polarization percentage of the dust emission at 0.87 mm is constrained to be less than 2.8\%. Such a polarization percentage is lower than the reported polarization percentages in previous cases. If G10.6-0.4 is a strongly magnetized case, the low polarized flux can be interpreted by some differences in the dust properties from the other targets which produce less polarized flux, the relatively inefficient dust alignment in G10.6-0.4, and/or the canceling of the polarized emission from structures overlapping along the line of sight. The feedback of the high-velocity molecular outflows and the expansions of the H\(_\text{ii}\) regions may, but not necessarily, disturb the magnetic field and lead to the non-detection of the polarized flux. Tang et al. (2009a) interpreted the configuration of the polarized dust emission detected in the region G5.89-0.39 as the result of magnetic field structures strongly affected by the expanding UC H\(_\text{ii}\) region and multiple molecular outflows. In G10.6-04, the magnetic field might also be more important on a much smaller scale, which is unresolved in our SMA observations.

The radial morphology of the filamentary structures in the central core suggests contraction by gravity to be dominant over all possible sources of support. This needs to be confirmed via modeling of the kinematics. The absence of detectable magnetic field structures is consistent with this scenario. We note that Li et al. (2010), using numerical magnetic hydrodynamical simulations, suggest that cluster-forming regions with weaker magnetic fields will have higher characteristic stellar mass.
Comparing our high-resolution 1.2 mm continuum maps and the CS \((1-0)\) observations suggests that the massive molecular clump containing a luminous \((\gg 10^5 L_\odot)\) OB cluster is part of a \(\geq 10\) pc scale organized structure. The extended molecular gas has a filamentary geometry, starting from a \(\sim 5\) pc extent in radius to a geometrical center of a 2–3 pc scale dense structure. The parsec-scale filaments show regularly spaced molecular clumps, each containing massive molecular cores that are associated with the local massive star formations. Part of these parsec-scale filaments might directly continue into the central 0.05 pc radius hot toroid, which encircles the mass of the central OB cluster. High-resolution molecular line and dust polarization observations might help to address this question.

In the present work, we suggest that the convergence of the massive filamentary structures is one very important aspect in OB cluster formation. However, how such filaments of a few parsec-scale form is still uncertain and should be a very fundamental aspect in the study of the interstellar medium. The very sensitive high-resolution and high-dynamic-range spectral line and dust polarization observations might help to address this question.

Another aspect which cannot be addressed by our present research is how the 0.1 pc scale hot toroid converges to form the embedded OB clusters. High-resolution molecular and recombination line observations with ALMA will certainly address this issue.

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