THE HIGH-VELOCITY MOLECULAR OUTFLOWS IN MASSIVE CLUSTER-FORMING REGION G10.6–0.4

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ABSTRACT

We report the arcsecond resolution Submillimeter Array observations of the 12CO (2−1) transition in the massive cluster-forming region G10.6−0.4. In these observations, the high-velocity 12CO emission is resolved into individual outflow systems, which have a typical size scale of a few arcseconds. These molecular outflows are energetic and are interacting with the ambient molecular gas. By inspecting the shock signatures traced by CH3OH, SiO, and HCN emissions, we suggest that abundant star formation activities are distributed over the entire 0.5 pc scale dense molecular envelope. The star formation efficiency over one global free-fall timescale (of the 0.5 pc molecular envelope, ∼10^3 years) is about a few percent. The total energy feedback of these high-velocity outflows is higher than 10^{47} erg, which is comparable to the total kinetic energy in the rotational motion of the dense molecular envelope. From order-of-magnitude estimations, we suggest that the energy injected from the protostellar outflows is capable of balancing the turbulent energy dissipation. No high-velocity bipolar molecular outflow associated with the central OB cluster is directly detected, which can be due to the photoionization.

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

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1. INTRODUCTION

Theoretical studies suggest that high-velocity molecular outflows play important roles in massive cluster-forming regions. Massive molecular outflows associated with the accretion of the OB stars can create cavities with low molecular densities. The efficient photon leakage through the cavities potentially reduces the radiation pressure exerted on the molecular gas by a factor of 10 (Krumholz et al. 2005), and therefore enhances the radiation pressure exerted on the molecular gas by the radiation pressure and the pressure of the ionized gas. The efficient photon leakage through the cavities potentially reduces the radiation pressure exerted on the molecular gas by a factor of 10 (Krumholz et al. 2005), and therefore enhances the radiation pressure exerted on the molecular gas by the radiation pressure and the pressure of the ionized gas. These results suggest that the pressure of the ionized gas is an important feedback mechanism in the initially low-density region. In the plane of rotation, the dense gas is marginally centrifugally supported (Liu et al. 2010b), and its global dynamics is not yet severely disturbed by the radiation pressure and the pressure of the ionized gas. Observationally, extensive single dish surveys of the 12CO emissions found high detection rates of massive molecular outflows around the massive cluster-forming regions (Shepherd & Chuchwell 1996b; Beuther et al. 2002; Zhang et al. 2005; Wu et al. 2005; López-Sepulcre et al. 2009) suggest that the magnetically regulated accretion similar to that in low-mass star formation plays a role in OB star formation. Besides the massive bipolar outflows, however, owing to the great complexity of the OB cluster-forming regions, identifications of outflows from individual intermediate mass or solar mass stars have been difficult, and the improvements rely on detailed analysis of interferometric data.

G10.6−0.4 is a well-studied massive cluster-forming region at a 6 kpc distance (Caswell et al. 1975; Ho & Haschick 1981; Ho et al. 1983, 1986, 1994; Keto et al. 1987, 1988, 2008; Guilloteau et al. 1988; Keto 1990, 2002; Omordaka et al. 1992; Sollins et al. 2005; Sollins & Ho 2005; Keto & Wood 2006; Klaassen et al. 2009). In this region, a high bolometric luminosity (9.2 × 10^5 L_☉) and bright free–free continuum emission (≥2.4 Jy within a 0.05 pc radius at 1.3 cm band) were detected, suggesting that a cluster of O-type stars (O6.5–B0; Ho and Haschick 1981) has formed. Our previous Submillimeter Array (SMA) observations in CH3OH J = 5 transitions trace a massive rotating envelope (∼1000 M_☉ in the central 0.3 pc × 0.1 pc region) which shows a biconical cavity (Liu et al. 2010b). The biconical cavity may be initially created by powerful (proto-)stellar outflows, and clues may be provided by sensitive molecular line observations to detect the high-velocity emissions.

The VLA/eVLA observations of the centimeter free–free continuum emission and the CS (1−0) emission suggest that the biconical cavity is undergoing expansion with a velocity of a few km s^{-1}, which may be powered by ionized gas pressure. These results suggest that the pressure of the ionized gas is an important feedback mechanism in the initially low-density region. In the plane of rotation, the dense gas is marginally centrifugally supported (Liu et al. 2010a), and its global dynamics is not yet severely disturbed by the radiation pressure and the pressure of the ionized gas.
In the central 0.1 pc region, a fast rotating hot toroid encircling an OB cluster is detected (Keto et al. 1988; Sollins & Ho 2005; Liu et al. 2010a), which is consistent with dense core formation via a global contraction of a massive envelope. The overall geometry and the dynamics qualitatively resemble the standard magnetically regulated core collapse in the low-mass star-forming region.

To improve the understanding of how the envelope is shaped by the (proto-)stellar outflows, and how the global contraction is regulated, we carried out the interferometric observations of the $^{12}$CO (2−1) line in G10.6−0.4. We estimate the mass, energy, and momentum budgets in the detected outflow systems. In addition, by comparing the distribution of the high-velocity energy, and momentum budgets in the detected outflow systems, the role of the molecular outflow and compare it with the role of the feedback from the radiation pressure, stellar wind, and the pressure of the ionized gas. A brief conclusion is provided in Section 5.

2. OBSERVATIONS

We observed multiple molecular line transitions from 2005 until 2009. The properties of the observed molecular transitions are summarized in Table 1 and the observational parameters are summarized in Table 2. We also perform high-resolution observations of 3.6 cm continuum emissions. Details about calibrations and data reduction are introduced as follows.

2.1. The 1.3 mm Band Observation

We observed the $^{12}$CO (2−1) line toward G10.6−0.4 using the SMA in the compact configuration and the very extended configuration on 2009 June 10 and 2009 July 12, respectively, and observed the HCN (3−2) line with the SMA in the compact configuration on 2005 June 21 and in the extended configuration on 2005 May 9. We also observed the $^{12}$CO (2−1) lines in the SMA subcompact configuration on 2009 February 09. The frequency resolutions in these observations are 390 kHz ($\sim$0.5 km s$^{-1}$).

The basic calibrations are carried out in MIRIAD, the self-calibration and imaging of these data are carried out in AIPS. Continuum emissions are averaged from the line free channels and then subtracted from the line data. We construct the continuum band visibility data at 1.3 mm from the line-free channels in the SMA subcompact, compact, and very extended array data. We combined the data of all three array configurations, which yield a synthesized beam of $0.079 \times 0.058$ with position angle of 60$^\circ$. The 1.3 mm continuum image is shown in Figure 1. The discussions of this continuum image are postponed to Section 3.3.

We combine the $^{12}$CO data of all three array configurations, which yield a synthesized beam of $1.2 \times 1.2$ with a position angle of 87$^\circ$, and we perform averaging per three velocity channels to enhance the signal-to-noise ratio. The observed rms noise of the $^{12}$CO (2−1) line channel maps is 0.03 Jy beam$^{-1}$ (0.48 K) in each 1.5 km s$^{-1}$ channels, where there is no extended strong line emissions. We combine the compact array and the very extended array $^{12}$CO data, which yield $1.5 \times 1.5$ angular resolution and rms noise level of 0.06 Jy beam$^{-1}$ (0.64 K) in each 0.5 km s$^{-1}$ velocity channel. We combine the compact-array and the extended-array HCN (3−2) data, yielding $1.3 \times 1.1$ resolution, and rms noise of 0.24 Jy beam$^{-1}$ (3.03 K) in each 0.5 km s$^{-1}$ channel.

2.2. The 0.85 mm Band Observation

We observed the SiO (8−7) line using the SMA in the compact configuration on 2008 October 8. The frequency resolution in this observation is 812.5 kHz ($\sim$0.7 km s$^{-1}$).

### Table 1
Selected Molecular Transitions

| Transition | Frequency (GHz) | $E_u/k$ (K) | Einstein A Coefficient (s$^{-1}$) |
|------------|----------------|------------|---------------------------------|
| CO (2−1)   | 230.538        | 16.68      | $6.91 \times 10^{-7}$           |
| HCN (3−2)  | 265.886        | 25.33      | $8.36 \times 10^{-4}$           |
| CH$_3$OH 5(0, 5)−4(0, 4) E | 241.700      | 47.68      | $6.04 \times 10^{-5}$           |
| CH$_3$OH 5(−2, 4)−4(−2, 3) E | 241.904      | 60.38      | $5.09 \times 10^{-5}$           |
| SiO (8−7)  | 347.331        | 74.62      | $2.20 \times 10^{-3}$           |

Notes. The quantum number of the transitions are listed in the first column. Their frequencies and upper-level-energy ($E_u$) are listed in the second and the third column. The Einstein A coefficient of each transition is listed in the fourth column.

### Table 2
Observational Parameters

| Transition | Beam | Channel Width (km s$^{-1}$) | rms (Jy/beam) | SMA Array Configuration | Observed Date |
|------------|------|----------------------------|--------------|-------------------------|--------------|
| CO (2−1)   | 1″\’\’ × 1″\’\’ | 1.5           | 0.05         | Subcompact + Compact + Vex | 2009 Feb 9/2009 Jun 10/2009 Jul 12 |
| CH$_3$OH J = 5 | 1″5 × 1″3 | 0.53         | 0.06         | Compact + Vex           | 2009 Jun 10/2009 Jul 12 |
| HCN (3−2)  | 1″3 × 1″1 | 0.46         | 0.24         | Compact + Extended      | 2005 Jun 21/2005 Sep 9 |
| SiO (8−7)  | 4″9 × 1″5 | 0.7          | 0.24         | Compact                 | 2008 Oct 4   |
Calibrations are carried out in miriad and imaging is carried out in AIPS. Owing to a non-uniform uv coverage in this observation, using natural weighting, we obtain a 4.9′ × 1.5′ synthesized beam with a position angle of 21°. The rms noise in each 0.7 km s\(^{-1}\) channel is 0.24 Jy beam\(^{-1}\) (0.33 K).

2.3. 3.6 cm Continuum Observation

The X-band continuum emission toward G10.6−0.4 was observed in the Very Large Array (VLA) A-configuration including the VLBA Pie-Town antenna on 2005 January 2. The sources 1331+305 and 1820−254 were observed as absolute flux and gain calibrators.

The basic calibrations, self-calibration, and imaging of these data are done in AIPS package. The synthesized beam of the image is 0′.34 × 0′.19 with a position angle of −7.5. The observed rms noise of the 3.6 cm continuum image is about 0.1 m Jy beam\(^{-1}\) (~27 K in brightness temperature). We note that the 3.6 cm continuum emission is free–free emission from spectral index measurements (Keto et al. 2008).

3. RESULTS

In the following sections, we inspect the spatial distribution of the high-velocity \(^{12}\)CO outflows, with reference to the overall distribution of the dense gas in G10.6−0.4. We trace the dense molecular gas by the emission of the CH\(_3\)OH J = 5 transitions (Liu et al. 2010b). The CH\(_3\)OH 5(0, 5)−4(0, 4) A+ transition, the CH\(_3\)OH 5(0, 5)−4(0, 4) E transition, and the blended CH\(_3\)OH 5(2, 3)−4(2, 2) E and 5(−2, 4)−4(−2, 3) E transitions trace an extended 0.5 pc scale massive envelope. The highest excitation CH\(_3\)OH 5(−3, 3)−4(−3, 2) E transition exclusively trace a <0.1 pc scale hot toroid, which is revealed as a white compact ellipse in the middle of the CH\(_3\)OH RGB image (Figure 2). As will be discussed in the position–velocity (pv) diagram (Figure 3), the CH\(_3\)OH emission shows an integrated rotational motion, and trace the warm and dense accretion flow around the OB cluster. By comparing the outflows with the CH\(_3\)OH emission, we try to emphasize the formation of a cluster of stars in the self–gravitational accretion flow.

The high-velocity outflows are interacting with the ambient dense gas. We diagnose the interactions between the high-velocity outflows and the ambient dense gas via the broad CH\(_3\)OH emission and also the distribution of the water maser sources (Hofner & Churchwell 1996). From the flux of the \(^{12}\)CO emission, we estimate the mass, energy, and momentum feedback. We constrain the feedback rate from the outflow dynamical timescale.

In addition, we report the detection of significantly enhanced HCN (3−2) emission, which has the distribution and the velocity range that are consistent with one of the strongest blueshifted \(^{12}\)CO outflow components near the central hot toroid (we call this blueshifted outflow component HCN outflow hereafter). We also detect localized broad SiO (8−7) emission and geometrically elongated 3.6 cm free–free continuum emissions around HCN outflow. The physical implications of these observed signatures are discussed.

For the sake of clarity, the discussion in the following sections are mostly based on the velocity integrated maps. The \(^{12}\)CO (2−1) and the HCN (3−2) channel maps are presented in Appendix A.

3.1. The Spatial Distribution and Morphology of the \(^{12}\)CO Emission

Figure 2 shows the velocity integrated maps of the \(^{12}\)CO (2−1) emission in the blueshifted, redshifted, and the intermediate velocity ranges, superposed on the dense molecular envelope as traced by the velocity integrated emission of CH\(_3\)OH J = 5 transitions. The intermediate velocity range is defined as −15.25−8.75 km s\(^{-1}\). In this range, the rms noise in channel maps is significantly worse owing to the difficulties in imaging the strong and extended emission. The blueshifted (−124.75 to −15.25 km s\(^{-1}\)) and the redshifted (8.75−46.25 km s\(^{-1}\)) velocity ranges are defined relative to the intermediate velocity range. The system velocity of G10.6−0.4 is −3 km s\(^{-1}\), which is about the midpoint of the intermediate velocity range. We integrate the emission in these three limited velocity ranges such that the significant features are not diluted in the velocity space. Some highly redshifted \(^{12}\)CO emissions marginally detected in the velocity channels of 48.5 km s\(^{-1}\)−57.5 km s\(^{-1}\) will be discussed separately. Outside of these selected velocity ranges, we do not see significant detection of \(^{12}\)CO emission. According to the galactic rotation curve (Caswell et al. 1975; Corbel & Eikenberry 2004), the \(^{12}\)CO emission in the velocity range of v\(_{\text{lsr}}\) = −3−45 km s\(^{-1}\) is potentially confused with the foreground molecular gas emission/absorption, which may explain why the velocity integrated map of the redshifted \(^{12}\)CO shows more diffuse emission than that of the blueshifted \(^{12}\)CO (see also the discussions in Appendix A).

We do not detect the collimated high-velocity bipolar outflow aligned with the rotational axis of the central hot toroid. In the blueshifted \(^{12}\)CO velocity integrated map, which is not biased by the foreground emission/absorption, we see individual compact components. These compact components have the angular size scale of a few arcseconds. From the channel maps (Appendix A), one can see that these compact blueshifted outflow systems have very different coverages in the velocity space. This morphology of the high-velocity \(^{12}\)CO emissions qualitatively look very different from the well-defined massive
Figure 2. Top left: the RGB image of the CH$_3$OH $J = 5$ transitions (R: CH$_3$OH 5(0, 5)$\rightarrow$4(0, 4) A+, B: CH$_3$OH 5(3, 3)$\rightarrow$4(3, 2) E, C: CH$_3$OH 5(2, 3)$\rightarrow$4(2, 2) E), overlaid with the velocity integrated $^{12}$CO (2–1) emission in the intermediate velocity range ($-\Delta V = 15.25$–8.75 km s$^{-1}$) CO. Contours start from 3 Jy (beam km s$^{-1}$)$^{-1}$, with 9 Jy (beam km s$^{-1}$)$^{-1}$ intervals. Note that the CO emissions in this velocity range are suffering from missing flux and the high optical depth of the foreground gas. Top right: the RGB image of the CH$_3$OH $J = 5$ transitions, overlaid with the velocity integrated $^{12}$CO (2–1) emission in the blueshifted velocity range ($-\Delta V = 124.75$ to $-15.25$ km s$^{-1}$) CO. Contours start from 1 Jy (beam km s$^{-1}$)$^{-1}$, with 1 Jy (beam km s$^{-1}$)$^{-1}$ intervals. Bottom left: the RGB image of the CH$_3$OH $J = 5$ transitions, overlaid with the velocity integrated $^{12}$CO (2–1) emission in the redshifted velocity range ($\Delta V = 8.75$–46.25 km s$^{-1}$) CO. Contours start from 0.5 Jy (beam km s$^{-1}$)$^{-1}$, with 0.5 Jy (beam km s$^{-1}$)$^{-1}$ intervals. Bottom right: the RGB image of the CH$_3$OH $J = 5$ transitions overlaid with the both the redshifted and blueshifted $^{12}$CO (2–1) emission. (A color version of this figure is available in the online journal.)

bipolar molecular outflow (see the case of G240.31+0.07 for an example; Qiu et al. 2009), and are difficult to interpret by a single wide angle wind. These results can either be explained by multiple powering sources, or can be explained by powerful non-uniform or episodic bursts. These different explanations are not mutually exclusive. Future observations with higher sensitivity and higher resolution to detect the protostellar cores and to resolve the morphology/alignment of individual outflows/jets will help to clarify the origin of the high-velocity $^{12}$CO emissions. We also note that G10.6–0.4 is a quite evolved massive cluster-forming region with extremely bright H II regions. Comparing the physical size scale of the entire dense envelope ($\sim$0.5 pc) with that of Orion$^5$, it is not surprising if multiple (proto-)stellar objects have already been formed and are widely distributed in the entire massive envelope$^6$. In active accretion phase, those (proto-)stellar objects

$^5$ The field of view of our $^{12}$CO observations in G10.6–0.4 is about 1'. The physical scales of the observed area and the resolution of this G10.6–0.4 data are comparable with those of the $^{13}$CO survey in OMC-2 and OMC-3, reported by Williams et al. (2003).

$^6$ We define the massive envelope as the region with molecular hydrogen density greater than $10^5$ cm$^{-3}$, and with temperature greater than 30 K. Such a region can be traced by the NH$_3$ main hyperfine inversion line and the CH$_3$OH 5(0, 5)$\rightarrow$4(0, 4) A+ transition (Liu et al. 2010b).
will also eject molecular outflows, which will contribute to the high-velocity $^{12}$CO emissions.

The size scale and the spatial distribution of the significantly detected compact redshifted $^{12}$CO emission are qualitatively consistent with the results of the blueshifted $^{12}$CO emission. However, from the channel maps (Figures 9–12), we see that the velocity coverage of the redshifted $^{12}$CO emission is about a factor of 2 smaller than the blueshifted emission. This can be either explained by the intrinsic asymmetry in some specific powering sources or the asymmetry of the entrained ambient molecular gas. For the sake of the convenience of the following discussions, we label several compact blueshifted and redshifted components on the velocity integrated maps, which are visually identified from the channel maps. When we mention the labels like $R_1$, $B_1$ outflow, or HCN outflow, we specifically refer to the $^{12}$CO emission in the corresponding velocity range.

By comparing the spatial distribution of the redshifted and blueshifted $^{12}$CO, we see that the compact components from these distinct velocity ranges are highly correlated. The $R_3$ outflow and the $B_3$ outflow are spatially close to each other, but are isolated from the massive envelope as traced by the CH$_3$OH emission. The averaged line-of-sight velocities of the $R_3$ outflow and the $B_3$ outflow have comparable absolute values, which are $14.6$ km s$^{-1}$ and $18.1$ km s$^{-1}$, respectively. The $B_3$ outflow is elongated in the southeast–northwest direction, which is consistent with the alignment of $B_4$ and $R_4$ outflows. These results suggest that the $R_4$ and $B_4$ outflows resemble a bipolar molecular jet, and provide indirect indications that protostars form not only in the densest center of the massive envelope, but also form in other local overdensities.

The averaged line-of-sight velocities is derived by $I/M$, where $M$ and $I$ are the mass and the line-of-sight momentum integrated in the blueshifted or the redshifted velocity range (see Table 3).
gradient from southeast to northwest. In the envelope, a significant V-shaped feature of outflow cavity can be seen north of the hot toroid. Northeast of the V-shaped feature, we detect 5″–10″ (0.15–0.3 pc) scale filamentary structures (filament NE hereafter). From the mean velocity map and the 12CO channel maps (Figure 10), we see that filament NE has brightness temperature of a few tens of Kelvin, and covers the velocity range of −16 to −10 km s\(^{-1}\), which is broad and is significantly bluer than the systemic velocity of the dense molecular envelope (−3 km s\(^{-1}\)). A population of the redshifted gas (G10–SW hereafter) is further seen southwest of the hot toroid. The morphology of G10–SW is potentially filamentary and has the northeast–southwest alignment. However, the emission from G10–SW is projected against the emission from the cavity features south of the hot toroid (Liu et al. 2010b). Some hints for the filamentary morphology of G10–SW can be seen in the velocity dispersion map, which shows broad-line emission regions with a narrowly elongated shape. The velocities of the filament NE and the G10–SW together show a gradient from the northeast to the southwest. These filamentary structures may have originated from ambient gas influenced by massive bipolar molecular outflow or the expansional motion of ionized gas. The energetics of this dynamical feature can be approximately seen from previous single dish measurement. By observing the 13CO (2−1) line using the IRAM 30 m telescope, López-Sepulcre et al. (2009) estimated the mass, momentum, and energy of the molecular line wind in the velocity range of −11.6 to −8.6 km s\(^{-1}\) and 3.9–7.9 km s\(^{-1}\) to be 200 \(M_\odot\), 1510 \(M_\odot\) km s\(^{-1}\), and 12 \times 10^{46} \text{erg}, respectively. The filament NE is also marginally detected in our CS (1−0) observations (Liu et al. 2010b); however, both the filament NE and the G10–SW are not seen in the CH\(_3\)OH images (Figure 2), which provides the limits on the density and the gas excitation temperature. The detailed physical conditions can be constrained by future sensitive observations in CO \(J = 2−1\) and \(J = 3−2\) isotopologues transitions. More discussions about the velocity dispersion of the intermediate velocity 12CO emission are postponed to Section 3.3.

We note that filamentary structures with the same spatial scale are also detected around the nearby massive cluster-forming region, the Orion KL region (Wiseman & Ho 1996, 1998). From the results of the NH\(_3\) observations, Wiseman & Ho (1998) suggested a bimodal pattern of velocity. In addition, they found that the filaments appear to be fragmenting into chains of core, which are potentially the future or current sites for low-mass star formation.

3.2. The Mass, Energy, and Momentum of the High-velocity CO Outflows

For the blueshifted and the redshifted outflows, we assume optically thin emission with LTE conditions. We estimate the mass, momentum, and energy traced by the 12CO emission by adopting the gas excitation temperature of \(T = 100\) K and the interstellar abundance ratio [12CO]/[H\(_2\)] = 10\(^{-4}\). Our estimate does not explicitly consider the inclination angle, which statistically biases the total outflow momentum lower by a factor of order 1. The optically thin assumption on average may also bias the estimate lower by a factor of order 1. The angular size scale of the synthesized beam of our 12CO images is 1″/2. The emissions from isolated structures with angular size scale much smaller than that of the synthesized beam are potentially beam diluted and therefore cannot be detected. In nearby clouds, the molecular outflows/jets typically have the physical size scale
of a few times 0.1 pc, which corresponds to a few times 3\(^{\circ}\) at the distance of G10.6–0.4. This typical angular size scale is greater than the 1\(^{\prime\prime}\) synthesized beam of our 12CO images. Therefore, we do not consider the effect of beam dilution as a dominant bias in our estimates. The diffuse emission may not be robustly imaged in the high-resolution maps. To check this effect, we image the 12CO (2–1) emission with the subcompact-arc array data alone, yielding 4\(^{\prime}\)7 × 2\(^{\prime\prime}\)4 synthesized beam and rms noise of 0.17 Jy beam\(^{-1}\) (0.44 K) in each velocity channel of 0.5 km s\(^{-1}\) width. By averaging the subcompact-arc array channels in the blueshifted and the redshifted velocity ranges, we do not find significantly more diffuse high-velocity emission, thus suggesting that our estimates based on the 1\(^{\prime}\)2 × 1\(^{\prime\prime}\)2 high resolution images (Section 2) are representative of the total mass, momentum, and energy feedback.

The 12CO outflows in the intermediate velocity range may be some energetic systems with small inclination angles, and observationally, systems in this velocity range are severely confused with the global dynamics of the dense gas (Liu et al. 2010a, 2010b). Therefore, the direct analysis of the 12CO outflow momentum and energy in the intermediate velocity range is difficult. In addition, the 12CO emission is optically thick in this velocity range. Without the complementary information of the 13CO or C\(^{18}\)O observations, the optical depth is uncertain. Statistically, we expect the outflow feedback from those systems with low inclination angle has quantitatively the same order of magnitude as the feedback from outflows which have high inclination angles and are detected in the blueshifted and the redshifted velocity ranges. Or, there can be some less energetic outflow systems, as those detected in OMC-2 and OMC-3 (see Williams et al. 2003 and references therein). The contribution of such systems are not as significant compared with the energetic high-velocity outflows.

We estimate the deconvolved size scale of each outflow system by performing two-dimensional Gaussian fitting of the velocity integrated maps. The outflow dynamical timescale is estimated by dividing the major axis of the fitted Gaussian with the averaged velocity. The dominant uncertainties in the estimation of the dynamical timescale are caused by the inclination, which is not measured in these observations. Also, owing to the limited angular resolution, we are only able to measure the dynamical timescale greater than 1700 years\(^8\), assuming a typical outflow velocity of 20 km s\(^{-1}\).

The dynamical timescale, mass, momentum, and energy of each significant and compact outflow system in G10.6–0.4 are summarized in Table 3. The individual outflow systems have a typical mass of \(~1\) M\(_\odot\), and momentum of a few tens of M\(_\odot\) km s\(^{-1}\). Since we only estimate the physical properties of the outflow systems in the blueshifted and the redshifted velocity ranges while the real outflow systems continue into the intermediate velocity range, these quantities can be underestimated. To provide the sense of how much bias is made by considering only the limited velocity ranges, we estimate the physical properties of the HCN outflow both in the blueshifted velocity range and in the entire velocity range with 12CO (2–1) detection. By including the intermediate velocity range, the dense gas in the massive envelope significantly contributes to the 12CO flux, and the estimated mass should be treated as the upper limit of the molecular mass in the outflow system. From Table 3, we see that the results with the inclusion of the intermediate velocity range has a factor of 10 higher mass, a factor of 4 higher momentum, and a factor of 2.7 higher energy. These results can be understood since the kinetic energy is scaled with the square of velocity, and therefore the low velocity outflow gas in the intermediate velocity range does not contribute to a lot of momentum and energy, as long as its mass is not very much higher than the high-velocity components. Thus we conclude that our estimates of the total energy and momentum feedback based on the high-velocity components is only accurate up to an order of magnitude. The estimated physical parameters of HCN outflow (Table 3) can be uncertain owing to the strong photodissociation. However, it is unlikely that the total molecular mass integrated in the line-of-sight of HCN outflow can be comparably high as the mass enclosed by the nearby hot toroid (\(~200\) M\(_\odot\)).

Based on this argument, we suggest the lower limit of the [12CO]/[H\(_2\)] abundance ratio in the HCN outflow to be 10\(^{-5}\). We expect the [12CO]/[H\(_2\)] abundance ratio in other outflow systems to be less biased from the typical value of 10\(^{-6}\).

\(^8\) This value provides the rough sense of the limit of our data. Physically, the outflow velocity is uncertain, which leads to uncertainties in the estimation of the outflow dynamical timescale.
We estimate the outflow mass, momentum, and energy in the entire blueshifted and the redshifted velocity range by integrating the flux in the whole field of view. For the blueshifted outflows, the total mass is about 6.2 $M_\odot$, the total line-of-sight momentum is 163 $M_\odot$ km s$^{-1}$, and the total energy is $6.6 \times 10^{46}$ erg. For the redshifted (also including the velocity range of 46.25–58.25 km s$^{-1}$) outflows, the total mass is about 4.4 $M_\odot$, the total line-of-sight momentum is 197 $M_\odot$ km s$^{-1}$, and the total energy is $3.2 \times 10^{46}$ erg. The estimated mass includes all entrained and shocked gas in the outflows which can be detected in $^{12}$CO emission. The dynamical timescale of these outflow systems has the order of $10^3$–$10^4$ years. In the blueshifted velocity range, the visually identified compact systems (B$_{1.4}$, HCN–B outflows) contribute 89% of the total outflow mass, 84% of the outflow momentum, and 72% of the outflow energy. However, in the redshifted velocity range, the visually identified compact systems (R$_{1.4}$ outflows) only contribute 31% of the total outflow mass, 20% of the outflow momentum, and 16% of the outflow energy. The total fractional contribution of the compact systems (R$_{1.4}$ outflows) in the redshifted velocity range can be explained by the significant contribution of the diffuse emission (Figure 9) in the velocity range of 8.75–46.25 km s$^{-1}$. Those diffuse emission can be contributed by both the foreground molecular emission and the diffuse molecular outflows, which are not distinguishable with the data we currently have. Additionally, the flux of the molecular outflows in the redshifted velocity range is also attenuated by the foreground absorption. Since the order of magnitudes of the total mass, momentum, and energy in the redshifted velocity range are still comparable with those in the blueshifted velocity range, we suggest that the contribution of the foreground emission is roughly compensated by the attenuation of the foreground absorption. Therefore, we accept the estimated total outflow mass, momentum, and energy in the redshifted velocity range without modeling and correcting for the foreground effect, and we argue that the relevant discussions are not seriously biased.

The total molecular mass in the region with CH$_3$OH detection (Figure 2) is about 1000–2000 $M_\odot$ (Liu et al. 2010a). Assuming that the majority of mass is moving with 2–4 km s$^{-1}$ absolute velocity (Liu et al. 2010a), the momentum and kinetic energy in this system has the order of magnitudes of 2000–8000 $M_\odot$ km s$^{-1}$ and (4–32) $\times 10^{46}$ erg. The mass of the outflows is about a few percent of the total molecular mass in this region. However, energy feedback from the outflows is comparable to the kinetic energy of the filament NE and G10–SW (see Section 3.1), and is a significant fraction of the total kinetic energy of the massive envelope. Note the system is marginally centrifugally supported (Liu et al. 2010a), and the gravitational potential energy has the same order of magnitude as the rotational kinetic energy. If the initial turbulence is induced by the global gravitational contraction, its kinetic energy should have the same order of magnitude as the gravitational potential energy, or less than that.

Our estimations of the outflow feedback parameters are based on the $^{12}$CO (2–1) flux. In the Orion 1S region ($\sim$450 pc from the Sun), the high resolution observation of the SiO (5–4) line unveils a cluster of molecular outflows, which are not detected in the $^{12}$CO emission (Zapata et al. 2006). Such kind of systems may be rare, and from that observation, have the dynamical ages of few hundreds of years, and have physical size scales of 460–2700 AU. Although our $^{12}$CO data achieve a factor of 2 lower rms noise level than the $^{12}$CO data reported in Zapata et al. (2006), the greater distance and hence more severe beam dilution makes those system non-detectable in G10.6–0.4 in $^{12}$CO. By assuming the LTE conditions, optically thin emission, a rotational temperature of 80 K, and an abundance ratio of [SiO]/[H$_2$] = $10^{-7}$, Zapata et al. (2006) estimated the total mass, momentum, and energy in those SiO outflows to be 1.155 $M_\odot$, 57.85 $M_\odot$ km s$^{-1}$, and 3.03 $\times 10^{46}$ ergs. However, as suggested by the authors, at least a factor of 50 enhancement of the SiO abundance with respect to the adopted value $10^{-7}$ is required to explain the non-detection of $^{12}$CO, implying that the real outflow mass, momentum, and energy can be a factor of 50 lower than the estimated values. If such kind of SiO outflow systems are rare either because of the short life time in the specific phase of weak $^{12}$CO emission, or because their formation requires unusual physical conditions, their feedback may not be as significant compared with the total outflow feedback estimated from the $^{12}$CO emission. With small size scale, the induced protostellar turbulence also dissipates faster.

### 3.3. The Diagnostics of Interaction Signatures

While the interaction and shock signatures typically have velocity of a few km s$^{-1}$ from the systematic velocity, in massive cluster-forming regions, the CO isotopologue emission is extremely complicated in such velocity range, and is hard to robustly image in interferometric observations. The diagnostics of the interaction signatures are therefore relying on the observations of various tracers. In the following sections, we introduce the observed features in CH$_3$OH, HCN, and SiO, as the diagnostics in G10.6–0.4. The interaction signatures identified from the CH$_3$OH emissions are cross compared with the velocity dispersion map of the $^{12}$CO (2–1) emission in the intermediate velocity range, to demonstrate the robustness of the diagnostics. In addition, we compare the identified interaction signatures with the 1.3 mm continuum image, which is regraded as a reliable tracer of dense molecular cores.

#### 3.3.1. The Broad CH$_3$OH Emission

G10.6–0.4. By comparing the velocity integrated $^{12}$CO emission with the velocity integrated CH$_3$OH emission, we see the association of the molecular outflows with the dense envelope. With the terminal velocity of a few tens of kilometers per second, these molecular outflows can strongly shock the ambient dense gas in the envelope. A variety of molecules are then released from the dust grain, and their abundances in the gas phase can be dramatically enhanced. We diagnose the interactions between the molecular outflows and the ambient gas from the broad CH$_3$OH 5(0, 5)–4(0, 4) A$^+$ emissions. The CH$_3$OH molecule is considered to be one of the early-type molecules, and is abundant in the dense protostellar core. In addition, its abundance can be further shock enhanced by one or two orders of magnitude (Bachiller et al. 2001). The selected transition has the lowest upper-level-energy (34.65 K) among all observed CH$_3$OH lines, so that the excitation is least sensitive to the stellar heating.

Figure 3 shows a sample pv diagram of the CH$_3$OH 5(0, 5)–4(0, 4) A$^+$ transition. From this figure, we see two dominant signatures with distinguishable characteristics: the dense rotating envelope and the broad interaction signature. The dense envelope covers the angular scale of $\sim$20$''$, and is characterized by high brightness and steep increase of brightness. The interaction signature, as indicated by the red arrow, is faint and is spatially localized, but covers a much larger velocity range.
This broad and faint emission can be understood as the outflow wing component in the spectrum. More pv diagrams of the interaction signatures are discussed in Appendix B. Qualitatively, one can observe that, in the same range of angular offset, the envelope and the interaction signature roughly occupy the same area (in units of arcseconds × km s⁻¹) in the pv diagram, which is naturally explained by their difference in line width. However, the envelope is sketched by significantly more contours, which means that the area between two contour levels is much smaller.

The difference between the dense envelope and the interaction signature leads to a large contrast if we compare the velocity integrated flux between two significant contour levels, for example, the 3rd σ and the 6th σ significance levels (σ₃₆ hereafter). Between these two contour levels, the interaction signatures contribute significantly more to σ₃₆ than the dense envelope, although having lower total integrated flux. This property can be utilized to indicate the spatial distribution of the interaction signatures. Figure 5 shows the σ₃₆ map of the CH₃OH 5(0, 5)−4(0, 4) A+ transition together with the locations of the water maser sources and the locations of the 1.3 cm free–free emission peaks. From Figure 5 we see that this analysis is quite successful. The 0.1 pc scale hot toroid (Liu et al. 2010a, 2010b) which has the highest brightness temperature, cannot be seen in this map. Instead, we see significant local components (indicated by boxes) closely associated with the compact ¹²CO emission (for example, the B₂, R₁, R₃ outflows, and B₆ outflow), which are the most likely sources to induce the interaction signatures. We note that the CH₃OH emission is only significantly detected in the velocity range of −13 km s⁻¹ < vₜₜ < 10 km s⁻¹ while the blueshifted and the redshifted ¹²CO emissions are defined outside this velocity range. The consistency in their spatial distributions also indicates that the broad CH₃OH emission is indeed related to the high-velocity molecular outflows. We also evaluate the velocity dispersion of the emission between the
3rd $\sigma$ and the 6th $\sigma$ significance levels (Figure 6). The result consistently shows large velocity dispersion closely associated with the interaction signatures. Both Figure 5 and Figure 6 show that the interaction signature around the B6 outflow has an elongated distribution parallel to the global rotational axis of the dense envelope (Liu et al. 2010a, 2010b), and may be associated with an UC H$\beta$ region, indicated by a star symbol (Liu et al. 2010b). Whether that signature is related to the bipolar molecular outflow or is pushed by the bipolar expansion of the ionized gas can be studied in future high resolution observations. The interaction signature indicated by the orange box corresponds to the interaction signature shown in the sample pv diagram (Figure 3). The corresponding $^{12}$CO emission may be in the intermediate velocity range, and as shown in Figure 5, is elongated in the southeast–northwest direction. It can also be visually identified in the channel map (Figure 10) as compact components in the velocity range of 3.5–8.0 km s$^{-1}$.

In the $f_{36}$ analysis, especially, the velocity dispersion map (Figure 6) unveils a population of interaction signatures, which lie close to the plane of the densest flattened molecular gas (Liu et al. 2010a, 2010b). Those interaction signatures show locality and relatively low-outflow velocities. We suggest that they are less likely due to the interaction of the wind emanated from the OB cluster embedded in the hot toroid, but rather associated with local sites of star formation. This result provides important indication that local star formation plays important roles in the feedback of kinetic energy to the dense molecular gas.

**Cross Comparison with $^{12}$CO Emission in the Intermediate Velocity Range.** In this section, we cross compare the broad CH$_3$OH 5(0, 5)–4(0, 4) A+ emission (Figures 5 and 6) with the broad $^{12}$CO emission in the intermediate velocity range (Figure 4). From the velocity dispersion map of the intermediate velocity $^{12}$CO emission (Figure 4, right), one can see two extended broad line regions, which are associated with two UC H$\beta$ regions (H$\beta$–M: R.A. = 18$^{h}$10$^{m}$28.683, decl. = −19°55’49’’07; H$\beta$–NW: R.A. = 18$^{h}$10$^{m}$27.435, decl. = −19°55’44’’67) are marked by green stars. Cross symbols mark the water maser detections (Hofner & Churchwell 1996). The relative positional accuracy of the maser data is about 0’’1, which is much smaller than the size of the crosses.

(A color version of this figure is available in the online journal.)
The distribution of the broad 12CO emission around H ii–NW agrees well with the interaction signature traced by the f_{36} of the CH3OH 5(0, 5)–4(0, 4) A+ transition (Figure 5). The morphology can be explained by the expansional motion of the molecular/ionized gas confined by the dense gas, which has a flattened distribution in the global plane of rotation (Liu et al. 2010a, 2010b). The broad 12CO emission around H ii–M does not have a CH3OH 5(0, 5)–4(0, 4) A+ emission counterpart, which can be explained by the lower optical depth around this specific region.

In addition to those two extended broad 12CO emission regions, we visually identify five very compact (1″–2″) broad 12CO emission signatures, for which the mean velocities also have significant contrasts with the ambient gas. Those regions are marked by circles in Figure 4, and are also marked in the leftmost panel of Figure 5. The central coordinates of these five circles are: (1) R.A. = 18°10′28″.7, decl. = −19°55′42″.18, (2) R.A. = 18°10′29″.088, decl. = −19°55′46″.28, (3) R.A. = 18°10′29″.059, decl. = −19°55′52″.78, (4) R.A. = 18°10′29″.349, decl. = −19°55′7″.18, and (5) R.A. = 18°10′28″.868, decl. = −19°55′56″.58, respectively (see also the channel maps in Figure 10). Two of them (1 and 2) are closely associated with water maser sources. The eastmost one (4) is associated with a faint peak of the CH3OH 5(0, 5)–4(0, 4) A+ transition, which is marked by the yellow box in Figure 5. A faint f_{36} peak of the CH3OH 5(0, 5)–4(0, 4) A+ transition is detected around 3, and similarly with 5. These five signatures marked by circles look compact even from the 12CO (2−1) transition, which is very easy to excite. It provides the indication that they are associated with active local dynamics. Since their mean velocities are offset from the systemic velocity of their ambient gas by a few km s^{-1}, we hypothesize that those signatures are the molecular gas in the local dense cores pushed by the protostellar outflows. Without the comparison with results from the outflow tracers, it is extremely difficult to recognize these interaction signatures from the 12CO (2−1) maps, and it is even more difficult to robustly interpret them when they are recognized.

We note that the missing flux and the high optical depth of the foreground gas can artificially enhance the measured velocity dispersion. However, the broad 12CO emission regions mentioned in this section have much smaller angular size scales (<20″) than the maximum detectable angular scale of our SMA subcompact–array data (~40″), and should not be severely affected by missing flux. If the missing flux artificially enhances the measured velocity dispersion at large scale, the contrast between the measured velocity dispersion of the broad 12CO emission regions and the measured velocity dispersion of the envelope is reduced. The contrast in velocity dispersion should be higher in reality, which means the identified broad emission signatures are robust. Therefore, we think that the missing flux does not have a significant impact on our discussions in this section. The high optical depth of the foreground gas trims structures for all angular size scales, however, only for the emissions redder than the systemic velocity of ~3 km s^{-1}. The mean velocities in those extended and compact broad 12CO emission regions are apparently redder than the mean velocity of the ambient gas. If the high-velocity dispersion is an artifact caused by the high optical depth of the foreground gas, we expect to detect a bluer mean velocity.

Comparison with 1.3 mm Continuum Emissions. In massive cluster-forming regions, flux in 1.3 mm continuum emission is dominantly contributed by the thermal dust emission, and the free–free continuum emission from UC H ii regions (Keto et al. 2008). To see the relation between those broad 12CO interaction signatures with the dense molecular gas, we mark the locations of those broad 12CO interaction signatures (as well as the locations of the 22 GHz water masers) on the 1.3 mm continuum image (Figure 1).

From the 1.3 mm continuum image, we first see an abrupt increase of the 1.3 mm continuum flux in the middle, which suggests the distinct origins of the flux. We identify two UC H ii regions from high resolution centimeter continuum images (Keto et al. 1988; Guilloteau et al. 1988; Sollins et al. 2005; Liu et al. 2010a, 2010b), and mark their locations on the 1.3 mm continuum image. Those centimeter continuum emissions indicate that in the middle of the 1.3 mm continuum map, the free–free continuum emission from the UC H ii region contribute significantly. In the extended region, the 1.3 mm continuum emission is dominantly contributed by the thermal dust emission, except for a fainter UC H ii region in the northwest.

The thermal dust emission unveils abundant dense cores over a 0.5 pc region. Three dusty dense cores (R.A.:18°10′29″.064, decl.: −19°55′46″.2; R.A.:18°10′29″.035, decl.: −19°55′49″.7; R.A.:18°10′28″.975, decl.: −19°55′52″.5) are closely associated with the identified broad interaction signatures of 12CO outflows. The core at the northeast (R.A.:18°10′29″.064, decl.: −19°55′46″.2) is further associated with a water maser source (Hofner & Churchwell 1996). The associations with water maser sources and outflow signatures indicates that those dense cores are actively forming stars. This core shows a complicated geometry, which may be explained by hierarchical fragmentation. The dense core at R.A. = 18°10′28″.975 and decl. = −19°55′52″.5 is apparently elongated, and has internal structures, which may be explained by fragmentation, or can be observationally caused by blending.

Comparison with Low-mass Protostellar Outflows. From the observations of the CH3OH J = 2 transitions with upper-level-energy E_u of 4.64–12.2 K, Takakuwa et al. (2003) suggests that in the Class 0 low-mass protostar IRAM 04191+1522, the enhanced broad CH3OH emission trace the interactions between the protostellar outflow and its parent molecular core. Similar to what is observed in G10.6−0.4, the pv diagram of CH3OH in IRAM 04191+1522 shows the distinguishable interaction signature with the envelope component. The interaction signature in IRAM 04191+1522 have the size scale of ~0.03 pc, closely associated with the protostellar envelope. Observations in other nearby protostellar outflows (Bachiller et al. 1995, 1998, 2001; Garay et al. 1998) show the localized enhancement of the CH3OH abundance in the strongly shocked regions around 0.1 pc from the ejecting sources. This 0.03–0.1 pc size scale correspond to the angular scale of 1″–3″ at the distance of G10.6−0.4 (6 kpc), which is marginally resolved in our observations (Table 2), and this scale is small as compared with the size scale of the massive envelope traced by CH3OH (20″–30″).

Supposedly, these observed phenomena in nearby clouds and their interpretations can be extrapolated to the distant massive dense envelopes with higher temperature and high density. Then each of the detected broad CH3OH interaction signature may be associated with an independent ejecting protostar. The distribution of the observed broad CH3OH emission features in G10.6−0.4 suggests abundant star formation activities over the entire ~0.5 pc scale dense envelope. In G10.6−0.4, we already detected three UC H ii regions, indicating that multiple massive stars have already been formed. It is not surprising if
there are many massive or low-mass (proto-)stars, which are still in accretion phase and are ejecting the molecular outflows. We expect higher resolution observations in lower excitation CH$_3$OH to reveal more protostellar objects.

Note that the detection of the thermal radio jets is regarded as one of the most robust methods to identify protostellar objects in the accretion phase. However, in UC HII regions, the free–free emission around the embedded OB cluster has the flux of a few Jy, which is 3–4 orders of magnitude brighter than the typical flux of the thermal radio jets. The bright free–free emission associated with the OB cluster ionization can have complicated spatial distribution and geometry, which will confuse the detection of the thermal radio jets. The shock enhanced molecular emission potentially provides good complementary information in the diagnostic of star forming activities. From Figure 5, we see that a population of protostellar and stellar activities (four CH$_3$OH outflow interaction signatures as indicated by three boxes and one white circle, and two UC HII regions as indicated by stars) seem to have a coplanar distribution, suggesting a scenario of enhanced star formation in the rotationally flattened dense envelope. This scenario is supported by recent numerical hydrodynamical simulations (Peters et al. 2010).

Some protostellar and stellar activities seem to follow the filaments detected in the intermediate velocity 12CO emissions. Owing to the projection effect, we cannot robustly distinguish whether those activities are just distributed in the bulk of the envelope.

### 3.3.2. The HCN Outflow

The HCN outflow is characterized by the significantly higher HCN (3–2) flux. Among all outflow systems detected by $^{12}$CO, the HCN outflow is also the unique case where we detect the SiO (8–7) emission. The deconvolved size scale of the $^{12}$CO emission is about 2", and its location is close to the central 0.1 pc scale hot toroid. Figure 7 shows the velocity integrated maps of HCN (3–2), SiO (8–7), and the blueshifted $^{12}$CO, in the top and the middle panels, and shows the 3.6 cm continuum image in the bottom panel. From this figure we see the locally enhanced HCN emission, for which the location and geometry agree excellently with those of its $^{12}$CO counterpart. The distribution of the SiO emission is consistent with the $^{12}$CO and HCN emission. Subjected to the non–uniform uv coverage, the SiO (8–7) data have an elongated synthesized beam, and therefore the projected geometry of the emission and the peak location are poorly constrained.

In Figure 8, we present the pv diagrams of HCN (3–2), SiO (8–7), and $^{12}$CO (2–1) around the HCN outflow, which are all cut in the R.A. direction. From both panels in this figure, we can clearly see the broad outflow signatures around the angular offset of $\sim$5". The HCN (3–2) emission and the $^{12}$CO emission consistently trace the outflow to the velocity of $\sim$25 km s$^{-1}$. Owing to the detection limit, the SiO pv diagram only traces the outflow in a limited velocity range. From the pv diagram, we see that SiO is also excited in the hot toroid, which is located 2"–3" east of the HCN outflow. Assuming the LTE conditions, optically thin emission, and the excitation temperature of 100 K, we estimate the total number of the SiO molecule in HCN outflow to be $\sim$1.5 x 10$^{18}$.

We apply the same assumptions to derive the total number of the HCN and the $^{12}$CO molecules in the HCN outflow. Adopting the galactic $^{12}$CO abundance (i.e., $[^{12}$CO]/[H$_2$] = $1 \times 10^{-4}$), we list the derived number and the implied abundance ratios in Table 4. In the galactic molecular clouds, the [HCN]/[$^{12}$CO] ratio ranges from $10^{-4}$ in the quiescent zone to $2.5 \times 10^{-3}$ in the hot core regions (Blake et al. 1987). The enhanced [HCN]/[H$_2$] ratio has also been reported in other (proto-)stellar outflows (e.g., IRAS 20126: 0.1–0.2 x 10$^{-7}$, Su et al. 2007; L1157: 5 x 10$^{-7}$, Jørgensen et al. 2004). In the HCN outflow, the value of [HCN]/[$^{12}$CO] in the blueshifted velocity range is consistent with an enhanced HCN abundance. If our assumption of $[^{12}$CO]/[H$_2$] ratio is valid, the value of [HCN]/[H$_2$] in the HCN outflow is in between the two referenced cases. Even if the assumed $[^{12}$CO]/[H$_2$] ratio is overestimated by a factor of 10 (see the
around the HCN outflow. The pv cut is centered at (R.A. = \(18^\text{h}10^\text{m}28^\text{s}\)) and (decl = \(-19^\circ55'49.07''\)), with position angle of 90°. The positive angular offset is defined in the east. Contours in the top panel represent the SiO (8—7) emission, start from 0.48 Jy beam\(^{-1}\) with 0.48 Jy beam\(^{-1}\) intervals. Contours in the bottom panel represent the HCN (3—2) emission and absorption; positive contours start from 0.72 Jy beam\(^{-1}\) with 0.72 Jy beam\(^{-1}\) intervals; negative contours start from \(-0.72\) Jy beam\(^{-1}\) with \(-0.72\) Jy beam\(^{-1}\) intervals. Before performing the pv cut, the SiO (8—7) image cube is Hanning smoothed by \(3.5\) km s\(^{-1}\) width to enhance the signal-to-noise ratio.

### Figure 8

pv diagrams of \(^{12}\)CO (2—1) (gray scale), SiO (8—7), and HCN (3—2) around the HCN outflow. The pv cut is centered at (R.A. = \(18^\text{h}10^\text{m}28.683^\text{s}\), decl = \(-19^\circ55'49.07''\)), with position angle of 90°. The positive angular offset is defined in the east. Contours in the top panel represent the SiO (8—7) emission, start from 0.48 Jy beam\(^{-1}\) with 0.48 Jy beam\(^{-1}\) intervals. Contours in the bottom panel represent the HCN (3—2) emission and absorption; positive contours start from 0.72 Jy beam\(^{-1}\) with 0.72 Jy beam\(^{-1}\) intervals; negative contours start from \(-0.72\) Jy beam\(^{-1}\) with \(-0.72\) Jy beam\(^{-1}\) intervals. Before performing the pv cut, the SiO (8—7) image cube is Hanning smoothed by \(3.5\) km s\(^{-1}\) width to enhance the signal-to-noise ratio.

### Notes

The derived total numbers of HCN and \(^{12}\)CO for entire velocity range is uncertain because in the intermediate velocity range, the optically thin assumption may not be valid, and the missing flux and the high optical depth of the foreground gas lead to the uncertainties in flux measurements.

### Table 4

The Derived HCN Abundance Ratio in the HCN Outflow (Section 3.3.2)

| Velocity Range               | \(n_{\text{HCN}}\) | \(n_{\text{12CO}}\) | \([\text{HCN}]/[\text{^{12}\text{CO}}]\) | \([\text{HCN}]/[\text{H}_2]\) |
|------------------------------|--------------------|---------------------|--------------------------------|------------------|
| Blueshifted \((-124.75 \text{ to } -15.25\) km s\(^{-1}\)) | \(2.4 \times 10^{10}\) | \(3.0 \times 10^{12}\) | \(0.8 \times 10^{-3}\) | \(0.8 \times 10^{-7}\) |
| All \((-124.75 \text{ to } -58.25\) km s\(^{-1}\))     | \(1.3 \times 10^{10}\) | \(2.9 \times 10^{11}\) | \(0.4 \times 10^{-3}\) | \(0.4 \times 10^{-7}\) |

### Discussions

The derived \([\text{HCN}]/[\text{H}_2]\) ratio in the HCN outflow is still higher than the reported typical value of \(\leq 7 \times 10^{-9}\) (Jørgensen et al. 2004). The HCN molecule is usually regarded as a dense gas tracer. Our results suggest, however, that the HCN emission can also be locally enhanced in outflows and shocks around the dense core, and therefore might not be a good tracer of the overall dynamics in massive cluster-forming regions.

Among all detected high-velocity outflows, the HCN outflow does not have specifically higher linear momentum or energy. The uniqueness in the excitation of SiO (8—7) may be explained by the heating of the central OB cluster, or be explained by the molecular gas erupted from the hot toroid with shock enhanced SiO abundance. Some hints can be seen from the 3.6 cm continuum image (Figure 7, bottom panel), which shows an elongated emission feature around the location of the HCN outflow. Whether the elongated 3.6 cm emission feature is physically associated with the HCN outflow or is just a projection effect can be examined by future ALMA observations of molecular lines and the hydrogen recombination lines.

We note that a few more elongated/filamentary features\(^9\) are resolved in the previous 1.3 cm free–free continuum observation (Sollins et al. 2005). Those elongated/filamentary features have lengths of \(\sim 1''\) (0.03 pc) and width of \(\leq 0.1''\) (0.003 pc). The physical properties and the formation mechanism of those elongated features are still uncertain. Suppose those elongated/filamentary features of 1.3 cm free–free continuum emission are ionized gas which are undergoing thermal diffusion with velocity of 10 km s\(^{-1}\), the \(\leq 0.003\) pc widths imply that their age is no more than 300 years. If all those elongated/filamentary features can also be explained by ionized outflows, the velocities of the outflows can be estimated by

\[
\frac{\text{length}}{\text{age}} = \frac{0.03\text{ pc}}{300\text{ years}} \sim 100\text{ km s}^{-1}.
\]

This outflow velocity is consistent with the measurement in hydrogen recombination line (line-of-sight velocity 60 km s\(^{-1}\), Keto & Wood 2006), although the ionized outflow is not explicitly resolved in the image. The higher brightness of those elongated/filamentary features than the ambient regions may suggest that those outflows are originally ejected in molecular form with a much higher density, and then ionized by the stellar radiation. The molecular counterparts of those ionized outflows are not necessarily detected, especially in the bipolar direction, if stellar ionization is important. We suggest that the central OB cluster may accrete the molecular gas of very compact/clumpy structures (see the NH\(_3\) opacity results; Sollins & Ho 2005), which can survive the stellar ionization. The molecular gas can then approach individual O-type stars to the distance of \(\sim 10\) AU, and be centrifugally accelerated to the outflow velocity. Small scale accretion disks may exist around the O-type stars.

\(^{9}\) Not the arc shaped structures isolated from the free–free emission peak.
However, they are not detectable with the current instruments owing to the beam dilution.

4. DISCUSSIONS

In G10.6−0.4, previously we estimated the scalar momentum feedback from the stellar wind and from the ionized gas pressure to be of $10^2$–$10^3 M_\odot \, \text{km s}^{-1}$ (Liu et al. 2010b). From the $^{12}$CO data presented in this paper, we conclude that the total momentum feedback from the protostellar outflows has the same order of magnitude. However, these feedback mechanisms can still play very different roles in the massive cluster forming regions, owing to their differences in physical properties.

The stellar wind is an isotropic feedback mechanism. By comparing the resulting star formation efficiency in numerical hydrodynamical simulations, Nakamura & Li (2007) suggested that the spherical wind cannot propagate efficiently in dense gas. The feedback from such mechanisms is trapped in small size scale, where the induced turbulence is quickly dissipated. Therefore the energy feedback from the spherical wind supports the cloud less efficiently. The protostellar outflow is ejected from objects embedded in the local overdensities. Its momentum, however, is typically collimated in a small solid angle, which makes it penetrate the dense gas easily and can produce large scale disturbance. The induced protostellar turbulence potentially replenishes the dissipated initial turbulence in large scale, and plays the role of regulating the cloud contraction and the star formation efficiency.

From numerical simulations, Mac Low (1999) suggested the characteristic timescale of turbulence dissipation $t_d$ and the free-fall timescale $t_{ff}$ have the relation

$$t_d = \left( \frac{3.9 \lambda_d}{M_{\text{rms}} \lambda_J} \right) t_{ff},$$

(1)

where $\lambda_d$ is the driving scale of the turbulence, $\lambda_J$ is the Jeans length, and $M_{\text{rms}}$ is the rms Mach number of the turbulence. Assuming a total mass of $1000$–$2000 M_\odot$ is enclosed in the $0.5$ pc scale envelope, the global free-fall timescale is about $10^5$ years. If the averaged gas temperature is $30$–$50$ K, the Jeans length is about $0.1$ pc. The typical value of $M_{\text{rms}}$ can be $5$–$10^{10}$. Assuming the main driving source of the turbulence is the compact (proto-)stellar outflows, the value of $\lambda_d$ can be estimated by the physical size scale of the observed outflow systems, which is about $0.06$ pc ($2''$). Therefore, the characteristic timescale $t_d$ in G10.6−0.4 is about $0.23$–$0.47$ times $t_{ff}$, which is about a few times $10^5$ years. Among the outflow systems detected in G10.6−0.4, the maximum outflow dynamical timescale is about $10^4$ years, which is smaller than $t_d$. The estimations of outflow energy in Section 3.2 suggests that the energy injection from the protostellar turbulence is capable of balancing the turbulence energy dissipation in the relevant timescale.

We provide rough estimations for the total protostellar mass from a fiducial momentum ejection efficiency $I_{\text{total}} = P_\ast M_\ast$, where $I_{\text{total}}$ is the total ejected scalar momentum, $M_\ast$ is the total stellar mass, and $P_\ast$ is a proportional factor. Following Nakamura & Li (2007), we adopt $P_\ast = 50 \text{ km s}^{-1}$. In G10.6−0.4, the projected scalar momentum in the blueshifted and the redshifted velocity ranges is $273 M_\odot \, \text{km s}^{-1}$, which leads to $f_{\text{los}} M_\ast = 5.45 M_\odot$, where $f_{\text{los}}$ is the ratio of the scalar momentum contributed by the line-of-sight velocity component to the total scalar momentum. Statistically the value of $f_{\text{los}}$ can
Figure 10. Channel maps of the $^{12}$CO (2$\rightarrow$1) line. Solid contours start from 0.7 Jy beam$^{-1}$ (11.2 K) with 0.7 Jy beam$^{-1}$ intervals; dashed contours start from $-0.7$ Jy beam$^{-1}$ with $-0.7$ Jy beam$^{-1}$ intervals. Five visually identified regions with broad-line emissions are marked by circles. The colors of the circles are just for better contrast in presentation and do not have physical meaning. The coordinates of the circles can be referenced in Section 3.3. Five visually identified regions with broad-line emissions are marked by circles (see also Figure 4).

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

be estimated by

$$\frac{\int_0^\frac{\pi}{2} \sin\theta d\theta d\phi}{\int_0^\frac{\pi}{2} 1 d\theta d\phi} \simeq 0.637,$$

assuming the inclination angle of the outflows are uniformly randomly distributed. Given the 1000–2000 $M_\odot$ total molecular mass in the envelope, the star formation efficiency (SFE) in the past $10^7$ years is about 0.42%–0.86%. Assuming a uniform star formation rate in the time domain, the SFE in one free-fall timescale is of the order of a few percent. This estimated SFE is comparable to the SFE in the simulations of Nakamura & Li (2007), consistently suggesting the cloud contraction is self-regulated by the local star formation. High-resolution observations of the thermal dust emission to statistically study the prestellar and protostellar cores will further improve the constraint on the efficiency of the outflow feedback. The number of the young stellar objects (YSOs) can be statistically estimated by dividing $M_*$ by the averaged protostellar mass $\bar{m}$. The fiducial value of $\bar{m}$ based on the Scalo (1986) initial mass function (IMF) is $0.5 M_\odot$. In G10.6$-0.4$, the value of $\bar{m}$ can be biased by the evolutionary stage, and potentially by the observational selection bias where we only pick up the systems with powerful molecular outflows. Assuming the
Figure 11. Channel maps of the $^{12}$CO (2−1) line. Solid contours start from 0.09 Jy beam$^{-1}$ with 0.09 Jy beam$^{-1}$ intervals; dashed contours start from $-0.09$ Jy beam$^{-1}$ with $-0.09$ Jy beam$^{-1}$ intervals.

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

Figure 12. Channel maps of the $^{12}$CO (2−1) line. We bin per ten 1.5 km s$^{-1}$ velocity channels into one 15 km s$^{-1}$ velocity channel. Solid contours start from 0.03 Jy beam$^{-1}$ with 0.03 Jy beam$^{-1}$ intervals; dashed contours start from $-0.03$ Jy beam$^{-1}$ with $-0.03$ Jy beam$^{-1}$ intervals.

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

detected outflows are associated with YSOs, which on average have $\sim 1 M_\odot$ stellar mass, the number of the YSOs can be estimated by $M_*/1.0 = 8.56$. The surface density of these YSOs in the $\sim 0.5$ pc region is therefore $\sim 8.56/(0.5^2) \sim 34$ pc$^{-2}$. The derived YSO surface density should be treated as a lower limit since our observations do not trace protostellar objects which have weak or no outflows.

Alternatively, we can assume that each of the compact high-velocity outflows (R1−4, B1−6, HCN) is associated with one protostellar objects. Considering also the non-identified outflow
systems in the intermediate velocity range, there can be ~10 protostellar objects in total in the observed region. If we estimate the averaged mass of each protostellar object by $1 \, M_\odot$, our observational results suggest that an order of ~10 $M_\odot$ molecular gas are converted into (proto-)stellar objects in ~10^4 years. The system potentially evolves into a stellar cluster with an order of 10^2 stars in a few $t_{ff}$.

The ionized gas only propagates in low density regions, which have low recombination rates. However, our previous studies (Liu et al. 2010b) suggest that the thermal pressure of the ionized gas is capable of driving the large scale (a few times of 0.1 pc) coherent motions, such as the expansion motions of the ionized cavities or the bubble walls. The absolute velocity of such kind of motion is about a few km s^{-1}, and which
is smaller than the thermal sound speed of the ionized gas ($\sim$10 km s$^{-1}$). The efficiency of converting the kinetic energy in such an expansional motion to the large scale turbulence energy has to be investigated in theoretical studies.

5. CONCLUSION

We present the arcsecond resolution interferometry observations of the $^{12}$CO (2–1) transition. From the distribution and the mass/momentum/energy of the detected high-velocity outflows, we discuss the role of the outflow feedback in the massive cluster formation region. Our main results are as follows.

1. We detect multiple high-velocity outflow components in the blueshifted and the redshifted velocity ranges, respectively. The total molecular mass in these outflow systems are about 10 $M_\odot$, and the total momentum and energy budgets are of the order of 10$^2$ $M_\odot$ km s$^{-1}$ and 10$^{47}$ erg, respectively.

2. No high-velocity bipolar molecular outflow parallel to the global rotational axis is directly detected around the central 0.1 pc hot toroid. However, we cannot rule out the possibility that it is photoionized.

3. The $^{12}$CO outflows are interacting with the dense molecular envelope, which can be diagnosed by the CH$_3$OH, HCN, and the SiO shock signatures.

4. From the distribution of the UC H II regions, we know that multiple massive stars have been formed in the 0.5 pc scale massive envelope, and not only formed in the central 0.1 pc hot toroid. From the association of high-velocity outflows with water maser sources, and with the interaction signatures detected in thermal molecular emission, we suggest that multiple protostellar objects with $\sim$10 $M_\odot$ have also been formed within 10$^4$ years. The star formation efficiency over one global free-fall timescale is of the order of a few percent.

5. We detect strongly enhanced HCN (3–2) emission in an outflow system near the hot toroid, and therefore suggest that HCN is not a good tracer for the global dynamics.

We will follow up the polarization observation to provide thorough discussions of the energetic relation in this source. We emphasize that the discussions and conclusions in this paper are relevant to the cluster forming regions with size scale of a parsec or a fraction of a parsec, and with mass of thousands of $M_\odot$. In less massive systems (with lower opacity), the radiative hydrodynamical simulations suggest that the heating by the stellar radiation efficiently suppress the star formation (Offner et al. 2009).

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Facilities: SMA

APPENDIX A

THE CHANNEL MAPS OF THE $^{12}$CO (2–1) AND THE HCN (3–2) LINES

We present the channel maps of the $^{12}$CO (2-1) line and the HCN (3-2) lines in this section. Figures 9, 10, 11, and 12 show the $^{12}$CO (2–1) line in the velocity channels of $-131.5$ km s$^{-1}$–77 km s$^{-1}$. Contour levels are adjusted according to the rms noise. We think the channel maps in the redshifted velocity channels ($9.5$ km s$^{-1}$–45.5 km s$^{-1}$) are contaminated by the contribution of the foreground molecular gas, and therefore show subparsec scale diffuse emission, which are not seen in the channel maps in the blueshifted velocity ranges ($-124.75$ to $-15.25$ km s$^{-1}$). The absorption line of $^{12}$CO (2–1) is also detected at the location of the free–free continuum peak (R.A.:18$^h$10$^m$29$^s$.89, decl.:$-19^\circ$55’49.0’’7), up to $v_{\text{abs}}$ $\sim$45 km s$^{-1}$. The H I absorption experiment (Caswell et al. 1975) consistently shows the foreground absorption up to $v_{\text{abs}}$ $\sim$45 km s$^{-1}$.

Figure 13 shows the channel maps of the HCN (3–2) line. We note the high consistency between the HCN and the $^{12}$CO channel maps. In the HCN (3–2) channel maps, the low velocity counterpart of outflow R$_3$ (see Section 3.1) may be visually identified in the velocity range of 7.5 km s$^{-1}$–12 km s$^{-1}$, and the low velocity counterparts of outflow B$_3$ and B$_5$ may be visually identified in the velocity range of $-10.5$ km s$^{-1}$ to $-15$ km s$^{-1}$; the HCN outflow can be seen in the same velocity range as covered by its $^{12}$CO emission.

APPENDIX B

THE POSITION–VELOCITY DIAGRAMS OF THE INTERACTION SIGNATURES

Figure 14 shows the pv diagrams of the CH$_3$OH 5(0, 5)–4(0, 4) A$^+$ transition, at the locations of three broad CH$_3$OH interaction signatures, and at the location of two
water maser sources. Those CH$_3$OH interaction signatures are visually identified from the $f_{36}$ maps (Section 3.3.1). The position angles of the pv cuts are chosen purposely to detect the broad line emissions and to avoid the confusion with nearby interaction signatures. These figures provide complementary information in the velocity space, which cannot be explicitly seen in the $f_{36}$ maps.

The first three panels in Figure 14 present the pv diagrams at three broad CH$_3$OH interaction signatures. From these panels, we see broad emissions features of $1''$–$2''$ angular sizescale around the zero angular offset. The last two panels in Figure 14 present the pv diagrams at two water maser sources, which are associated with high-velocity 12CO outflows (Section 3.1).

In panel (4), the broad emission signature can be seen around the angular offset of $0''$–$2''$; in panel (5), the broad emission signature can be seen around the angular offset of $1''$–$3''$.

The angular offset of $3''$ corresponds to the physical size scale of 0.09 pc. Suppose the water maser sources mark the exact location of the stellar object, the 0.09 pc separation of the interaction signature from the water maser source is consistent with the typical size scale of the molecular outflow.

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