1. INTRODUCTION

Although molecular outflows have been commonly identified around both low- and high-mass young stellar objects (YSOs; e.g., Bachiller & Tafalla 1999; Arce et al. 2007), it is not clear how the bulk of the outflowing gas is accelerated. Past observations show that molecular outflows can often be divided into two components—the “classical” less-collimated component with low velocity and the highly collimated component with extremely high velocity (50–150 km s$^{-1}$, hereafter EHV). Bachiller & Tafalla (1999); Hirano et al. (2006); Palau et al. (2006). Exploring the physical conditions of the EHV molecular gas in detail will be helpful for clarifying its role in star formation processes.

The massive star-forming region G5.89−0.39 (hereafter G5.89) is associated with energetic CO outflows with velocities up to $\pm 70$ km s$^{-1}$ from its systemic velocity. Among the highest gas velocities that have been detected in molecular outflows (e.g., Choi et al. 1993). G5.89 also harbors a shell-like ultracompact (UC) H$\textsc{ii}$ region powered by a young O-type star (hereafter Feldt’s star) visible in the near-IR (Wood et al. 2012). The integrated high-velocity (\(\gtrsim 45\) km s$^{-1}$) CO emission reveals at least three blueshifted lobes and two redshifted lobes. These lobes belong to two outflows, one oriented N–S, the other NW–SE. The NW–SE outflow is likely identical to the previously detected Br$\gamma$ outflow. Furthermore, these outflow lobes all clearly show a Hubble-like kinematic structure. For the first time, we estimate the temperature of the outflowing gas as a function of velocity with large velocity gradient calculations. Our results reveal a clear increasing trend of temperature with gas velocity. The observational features of the extremely high velocity gas associated with G5.89−0.39 qualitatively favor the jet-driven bow shock model.

Key words: H$\textsc{ii}$ regions – ISM: individual objects (G5.89−0.39) – ISM: jets and outflows

Online-only material: color figures

2. OBSERVATIONS AND DATA REDUCTION

The observations were carried out with SMA on 2008 April 17 and May 2 in the 230 GHz band, and on 2006 July 27 and September 10 in the 345 GHz band. The phase center was R.A. $= 18^h00^m30.32$ (J2000) and decl. $=-24^o04’00”50$ (J2000). In the 230 GHz band, CO (2−1) was observed with seven antennas in the compact configuration, which resulted in projected baselines ranging from about 9 m to 120 m (7 to 90 k$\lambda$). For the CO (3−2) observations in the 345 GHz band also with seven antennas in the compact configuration, the projected baselines ranged from about 9 m to 70 m (10 to 80 k$\lambda$). The half-power width of the SMA primary beam was $\sim 51”$ at 230 GHz and $\sim 34”$ at 345 GHz. The total available double-sideband bandwidth was 4 GHz. The spectral resolutions of 230 GHz and 345 GHz observations were 0.41 MHz (0.53 km s$^{-1}$) and 0.81 MHz (0.71 km s$^{-1}$), respectively. See Ho et al. (2004) for more complete specifications of the SMA.
Figure 1. Channel maps of G5.89−0.39 in CO (2–1) emission at high velocity. The local standard of rest (LSR) velocity of each channel’s center is indicated in the upper right corner of each panel. The LSR velocity of the system is about +9.0 km s\(^{-1}\). Solid contours are at 4, 10, 20, 40, 60, 100, 150, 250, 350, and 450 × σ, and dotted contours indicate −4, −10, −20, −40, and −60 × σ, where σ = 11 mJy beam\(^{-1}\). The dotted circle shown in the first panel represents the primary beam of the SMA observations. The synthesized beam is shown in the lower left corner of the first panel. The asterisk represents the position of the H\(^{\text{ii}}\) region powering star, i.e., Feldt’s star (Feldt et al. 2003).

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

For the 345 GHz band observations, the flux calibrator was Uranus and the bandpass calibrators were Uranus (July 27 and September 10), Callisto (July 27), and 3C279 (September 10). The nearby compact radio sources 1626−298 (S ∼ 2.2 Jy in July 27 and 1.8 Jy in September 10) and 1924−292 (S ∼ 3.4 Jy in July 27 and 2.9 Jy in September 10) served as complex gain calibrators. See Su et al. (2009) for the calibration information of the 230 GHz band observations. For both 230 GHz and 345 GHz band observations, the absolute flux density scales were estimated to have an uncertainty of ∼20%. We calibrated the data using the MIR software package adapted for SMA from the software package developed originally for the OVRO MMA (Scoville et al. 1993). We made maps using the MIRIAD package (Sault et al. 1995). With robust weighting, the synthesized beam size was about 3.2 × 2.4 at P.A. of 40.8 for the CO (2−1) maps and about 3′0 × 2′0 at P.A. of 13:5 for the CO (3−2) maps. We smoothed our data to 2.0 km s\(^{-1}\) resolution for the analysis presented below. The rms noise level in a 2.0 km s\(^{-1}\) velocity bin is ∼35 mJy beam\(^{-1}\) (∼0.10 K) at 230 GHz and ∼90 mJy beam\(^{-1}\) (∼0.15 K) at 345 GHz.

3. CO (2–1) & (3–2) EMISSIONS

Figure 1 shows channel maps of the blueshifted and redshifted CO (2−1) emissions associated with G5.89. For display purposes, we have smoothed the channel maps to a velocity resolution of 20.0 km s\(^{-1}\). The spatial distributions of CO (2−1) and (3−2) agree with each other very well, and the velocity extents of the CO (2−1) and (3−2) outflows are comparable. Emissions are detected to velocities \(v_{\text{flow}}\) ≈ 80 km s\(^{-1}\) in the redshifted lobes and \(v_{\text{flow}}\) ≈ 160 km s\(^{-1}\) in the blueshifted lobes, where \(v_{\text{flow}}\) = \(V_{\text{flow}} - V_{\text{lsr}}\) with \(V_{\text{flow}}\) being the apparent outflow velocity and \(V_{\text{lsr}}\) (= +9.0 km s\(^{-1}\)) the systemic velocity of G5.89. The EHV line wing detected here is significantly broader than that reported by single-dish observations (e.g., Choi et al. 1993). The difference is due to the relatively poor sensitivities...
of single-dish observations. The structure of the CO gas with \( v_{\text{flow}} \lesssim 40 \) km s\(^{-1}\) is extended and complex. Due to the lack of short-spacing data to recover the extended structure filtered out by our SMA observations, in Figure 1 the low-velocity components are excluded.

The left and right panels of Figure 2 show the integrated blueshifted and redshifted emissions of CO (2–1) and (3–2), respectively. For both transitions, the emissions are integrated over the line wing, with 50 \( \lesssim v_{\text{flow}} \lesssim 162 \) km s\(^{-1}\) for the blueshifted gas and 42 \( \lesssim v_{\text{flow}} \lesssim 80 \) km s\(^{-1}\) for the redshifted gas. In the left panel, the overlaid color scales represent the free–free emission at 2 cm (Tang et al. 2009), filled triangles are the near-IR H\(_2\) knots from Puga et al. (2006), filled square is the NH\(_3\) maser from Hunter et al. (2008), open circles are Class I methanol maser positions (components 1 and 2 from Kurtz et al. 2004) and open squares are positions of water masers (components 1 and 3 from Hofner & Churchwell 1996). In each panel, the crosses mark the position of the submillimeter-millimeter dust components reported by Hunter et al. (2008), the asterisk marks the position of Feldt’s star (Feldt et al. 2003), and the filled circle labels the Br\(\gamma\) outflow center (Puga et al. 2006). The synthesized beam is shown in the lower left corner. The two black lines represent the axes of the position–velocity diagrams plotted in Figure 3. In the left panel, contours are 4, 10, 20, 40, 80, 120, 200, and 240 \( \times \sigma\), where \( \sigma = 0.53\) and 0.31 Jy beam\(^{-1}\) km s\(^{-1}\), respectively, for the blue- and redshifted components. In the right panel, contours are 4, 10, 20, 40, 80, 120, and 200 \( \times \sigma\), where \( \sigma = 1.36\) and 0.80 Jy beam\(^{-1}\) km s\(^{-1}\), respectively, for the blueshifted and redshifted components.

Figure 2. Extremely high velocity molecular outflows of G5.89—0.39 in CO (2–1) (left) and (3–2) (right) imaged with SMA. For both transitions, the blueshifted and redshifted lobes are integrated over the line wing, with 50 \( \lesssim v_{\text{flow}} \lesssim 162 \) km s\(^{-1}\) for the blueshifted gas and 42 \( \lesssim v_{\text{flow}} \lesssim 80 \) km s\(^{-1}\) for the redshifted gas. In the left panel, the overlaid color scales represent the free–free emission at 2 cm (Tang et al. 2009), filled triangles are the near-IR H\(_2\) knots from Puga et al. (2006), filled square is the NH\(_3\) maser from Hunter et al. (2008), open circles are Class I methanol maser positions (components 1 and 2 from Kurtz et al. 2004) and open squares are positions of water masers (components 1 and 3 from Hofner & Churchwell 1996). In each panel, the crosses mark the position of the submillimeter-millimeter dust components reported by Hunter et al. (2008), the asterisk marks the position of Feldt’s star (Feldt et al. 2003), and the filled circle labels the Br\(\gamma\) outflow center (Puga et al. 2006). The synthesized beam is shown in the lower left corner. The two black lines represent the axes of the position–velocity diagrams plotted in Figure 3. In the left panel, contours are 4, 10, 20, 40, 80, 120, 200, and 240 \( \times \sigma\), where \( \sigma = 0.53\) and 0.31 Jy beam\(^{-1}\) km s\(^{-1}\), respectively, for the blue- and redshifted components. In the right panel, contours are 4, 10, 20, 40, 80, 120, and 200 \( \times \sigma\), where \( \sigma = 1.36\) and 0.80 Jy beam\(^{-1}\) km s\(^{-1}\), respectively, for the blueshifted and redshifted components.

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

4. LINE RATIOS AND EXCITATION CONDITIONS OF THE OUTFLOWING GAS

Given the fairly good signal-to-noise ratio of the CO emission detected toward G5.89 even at the EHV line wing, it is feasible to estimate the physical parameters with a relatively narrow velocity bin (10 km s\(^{-1}\)) and investigate their velocity dependence. Table 1 summarizes the observed CO (2–1) intensities (in brightness temperature scale) as well as the intensity ratios of CO (3–2) and (2–1) as a function of gas velocity for all the observed lobes.
**Figure 3.** Position–velocity diagram of G5.89−0.39 in CO (2–1) (contours) and (3–2) (grayscale) along the P.A. of 175° centered at SMA1 (left) and P.A. of 130° centered at SMA2 (right). In each panel, the horizontal line marks the LSR velocity of the system (i.e., +9.0 km s\(^{-1}\)), and the vertical line indicates the position of SMA1 (left) and SMA2 (right).

**Table 1.** Observed CO (2–1) Intensities and CO (3–2)/(2–1) Line Ratios of the Five Outflow Lobes

| LSR Outflow | Vel. Ranges (km s\(^{-1}\)) | 2–1\(^a\) (K) | Ratio\(^b\) | 2–1\(^a\) (K) | Ratio\(^b\) |
|-------------|-----------------------------|----------------|------------|----------------|------------|
| B-NW Lobe   | −160 to −150                | 0.21           | 0.62       | ...            | ...        |
| B-N Lobe    | −150 to −140                | 0.41           | 0.73       | ...            | ...        |
| B-S Lobe    | −140 to −130                | 0.40           | 0.59       | 0.10           | 1.50       |
|             | −130 to −120                | 0.80           | 0.59       | ...            | ...        |
|             | −120 to −110                | 1.89           | 0.72       | 0.28           | 0.61       |
|             | −110 to −100                | 1.49           | ...        | 1.21           | ...        |
|             | −100 to −90                 | 1.78           | 0.73       | 1.78           | 1.10       |
|             | −90 to −80                  | 2.04           | 0.78       | 2.29           | 1.07       |
|             | −80 to −70                  | 2.84           | 0.82       | 1.92           | 1.15       |
|             | −70 to −60                  | 3.99           | 0.94       | 2.14           | 1.13       |
|             | −60 to −50                  | 6.35           | 0.94       | 2.61           | 1.19       |
|             | −50 to −40                  | 11.08          | 0.87\(^c\) | 11.08          | 0.87\(^c\) |
|             | −40 to −30                  | 18.92          | 0.84\(^d\) | 18.92          | 0.84\(^d\) |

| LSR Outflow | Vel. Ranges (km s\(^{-1}\)) | 2–1\(^a\) (K) | Ratio\(^b\) | 2–1\(^a\) (K) | Ratio\(^b\) |
|-------------|-----------------------------|----------------|------------|----------------|------------|
| R-N Lobe    | 40 to 50                    | 20.08\(^e\)   | 0.87\(^e\) | ...            | ...        |
| R-S Lobe    | 50 to 60                    | 13.16          | 1.01       | ...            | ...        |
|             | 60 to 70                    | 6.75           | 1.10       | 2.23           | 0.56       |
|             | 70 to 80                    | 3.73           | 1.05       | ...            | ...        |
|             | 80 to 90                    | 0.72           | 0.80       | ...            | ...        |

**Notes.**

\(^a\) Measured at the peak position of the CO (2–1) map.

\(^b\) 3–2/2–1 measured at the peak position of the CO (2–1) map.

\(^c\) Including R-N lobe and R-S lobe.

\(^d\) CO (3–2) blended with \(^{34}\)SO\(_2\), which can also be discerned from Figure 3.

\(^e\) Including B-NW lobe and B-N lobe.

\(^f\) Including B-NW, B-N, and B-S lobes.
For a proper comparison, both CO (2–1) and (3–2) maps were reconstructed with a clean beam of 3′′ in order to match the resolutions. For each velocity bin, furthermore, we simply report the value calculated from the CO (2–1) peak toward each lobe rather than the value averaged over entire lobe to avoid the difficulty of emission separation from various lobes, in particular, at relatively low-velocity channels. We emphasize that for each outflow lobe, the peak positions of CO (2–1) and (3–2) in various velocity bins agree very well with each other, with both median and mean offsets of ~0.25″, and no systematic offsets can be discerned. Consequently we do not expect any systematic bias for the physical conditions estimated afterward. As listed in Table 1, most deduced line ratios are in the range of 0.6–1.2.

To estimate the physical conditions of the outflowing gas, we performed the LVG analysis with the code written by L. G. Mundy and implemented as part of the MIRIAD package (Sault et al. 1995). We assumed the canonical CO fractional abundance of 10^{-4} and a velocity gradient of 1000 km s^{-1} pc^{-1} as estimated from the Hubble-like Kinematic structure (in Figure 3). Figure 4 shows the gas temperature estimated from the LVG calculations versus gas velocity. The plot exhibits a clear increasing trend of gas temperature with outflow velocity. Such a trend can be discerned toward all the lobes, although the trend of the B-N lobe is less clear. In the case of B-NW lobe, there appears to be a temperature jump at outflow velocities of ~150 km s^{-1}, with gas temperature ranging from 1200 to 1800 K for \( v_{\text{flow}} \gtrsim 150 \text{ km s}^{-1} \) and ~150 K for \( v_{\text{flow}} \lesssim 150 \text{ km s}^{-1} \). The estimated temperature of the above highest velocity bins in the B-NW lobe will be reduced to 400–500 K hence eliminating the above-mentioned temperature jump if the assumed CO fractional abundance is lowered by a factor of two. The occurrence of abundance reduction may be attributed to partial dissociation or even ionization of CO molecules under high-excitation conditions.

A few factors may contribute to the uncertainty of the temperature estimates reported above. Given the flux calibration uncertainty of 20%, the gas temperature obtained with LVG calculations would vary by a factor of 10 or so. In Figure 4, we show with the blue-shaded area the 1σ temperature range when allowing flux variations up to 20% in the B-NW lobe. Although the temperature uncertainty appears fairly large, we emphasize that the general increasing trend of gas temperature with outflow velocity is indeed robust. For a given flux calibration error, the line ratios will be affected in the same way in all channels and render a simple temperature shift across all velocity bins. For the LVG calculations, variations in input parameters also lead to variations in the derived temperature by a similar factor and hence do not change the general increasing trend on temperature with gas velocity. For example, the derived temperature will decrease by about a factor of three if the adopted CO fractional abundance is reduced by half or the velocity gradient increases twice. Although variation in velocity gradient or CO abundance across the line wings could mimic the derived temperature trend with velocity, the Hubble-like kinematic feature shown in Figure 3 makes this confusion quite unlikely. A precise gas temperature estimate will require observations with better flux calibration. Alternatively, observations in higher transitions of CO will also help to constrain hot gas temperature.

5. THE ORIGIN OF THE EHV COMPONENTS AND THEIR CONNECTION TO THE GAS ACCELERATING PROCESSES

Observations have shown that the kinetic temperature of high-velocity molecular gas in outflows associated with YSOs can be as high as 100–1000 K. For example, the inner SiO knots in the HH211 jet have a temperature excess of 300–500 K (Hirano et al. 2006). In the case of extremely active molecular jets in L1448-MM, the kinetic temperature of the EHV bullets close to the YSO is estimated to be ~500 K (Nisini et al. 2007). Gas temperature estimated from near-IR H2 observations typically ranges from 1000 to 2500 K (Richer et al. 2000; Dionatos et al. 2010). Both hot H2 emission and warm SiO bullets are thought to trace shocked molecular gas. The broad velocity dispersions revealed from the kinematic structures of the EHV bullets further indicate...
their connections to (bow) shocks (Lee et al. 2001; Hirano et al. 2006; Su et al. 2007).

Could the heating of the EHV gas associated with G5.89 be dominated by shocks? Indeed, shock indicators have been detected around the highest velocity gas of the N-S and NW-SE outflows (Hofner & Churchwell 1996; Kurtz et al. 2004; Hunter et al. 2008; Puga et al. 2006). For example, as shown in Figure 2, the highest velocity gas in the R-N lobe is associated with masers of H$_2$O and Class I CH$_3$OH as well as H$_2$ knots (labeled as C1 and C2 by Puga et al. 2006). Furthermore, the positions of the highest velocity gas detected in the B-NW and B-S lobes coincide with the H$_2$ knots B and group A, respectively, very well. The highest velocity in the B-NW lobe is also associated with masers of NH$_3$ and Class I CH$_3$OH. The hot (about 150–1800 K) molecular gas in the highest velocity bins of the N–S and NW–SE outflows can be naturally interpreted as shock-heated gas, while the lack of velocity spread in the outflow tips (Figure 3) can be attributed to insufficient sensitivity.

It is expected that the outflow-driving process provides energetics to not only accelerate but also heat the (ambient) gas. Estimations made from a simple jet-driven bow shock model predict temperature rising with outflow velocity and distance from the driving source (Hatchell et al. 1999), while such trends are different from the predictions of other classes of models (Arce et al. 2007). Hatchell et al. (1999) further argued that compared with the molecular cooling mechanisms, the heating (as a consequence of acceleration) is sufficient to maintain outflowing gas temperature a few times higher than that of ambient materials. Since the Hubble-like kinematic structure can also be reproduced by the jet-driven bow shock model (Lee et al. 2001; Arce et al. 2007), all above-mentioned features of the EHV gas associated with G5.89 can be qualitatively interpreted by the jet-driven bow shock model. We note that most, if not all, available bow shock models have parameters typical of low-mass outflows. Models with physical conditions more similar to outflows from high-mass young stars will be necessary to make quantitative comparisons between observational results and model predictions. Observations with better sensitivities and spatial resolutions are also essential to search for the bow-shock signatures in both morphology and kinematics.

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