CANDIDATE ROTATING TOROIDS AROUND HIGH-MASS (PROTO)STARS

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ABSTRACT

Using the OVRO, Nobeyama, and IRAM millimeter arrays, we searched for “disk”-outflow systems in three high-mass (proto)star-forming regions: G16.59–0.05, G23.01–0.41, and G28.87+0.07. These were selected from a sample of NH₃ cores (Codella, Testi, & Cesaroni) associated with OH and H₂O maser emission (Foster & Caswell) and with no or very faint continuum emission. Our imaging of molecular line (including rotational transitions of CH₃CN) and 3 mm dust continuum emission revealed that these are compact (~0.06–0.13 pc), massive (~100–400 M☉), and hot (~100 K) molecular cores (HMCs) that are likely sites of high-mass star formation prior to the appearance of ultracompact H II regions. All three sources turn out to be associated with molecular outflows from ¹²CO and/or HCO⁺ J = 1–0 line imaging. In addition, velocity gradients of 10–100 km s⁻¹ pc⁻¹ in the innermost, densest regions of the G23.01–0.41 and G28.87+0.07 HMCs are identified along directions roughly perpendicular to the axes of the corresponding outflows. All the results suggest that these cores might be rotating about the outflow axis, although the contribution of rotation to gravitational equilibrium of the HMCs appears to be negligible. Our analysis indicates that the three HMCs are close to virial equilibrium due to turbulent pressure support. Comparison with other similar objects where rotating toroids have been identified so far shows that in our case rotation appears to be much less prominent; this can be explained by the combined effect of unfavorable projection, large distance, and limited angular resolution with the current interferometers.

Subject headings: ISM: evolution — ISM: individual (G16.59–0.05, G23.01–0.41, G28.87+0.07) — radio continuum: ISM — stars: early-type

1. INTRODUCTION

The role of disks in the formation process of low-mass stars (i.e., stars with masses ≤ 1 M☉) has been extensively studied in the last two decades through high angular resolution observations at various wavelengths. Images of such disks have been obtained in the optical (e.g., Burrows et al. 1996) and at millimeter wavelengths (e.g., Simon et al. 2000). The latter have demonstrated that the majority of the disks undergo Keplerian rotation. These findings are consistent with the fact that low-mass stars form through accretion, while (partial) conservation of angular momentum during the dynamical collapse produces a flattened and rotating structure at the center of the core.

What about high-mass (Mₖ ≥ 8 M☉) stars? In this case, formation through accretion faces the problem that stars more massive than ~8 M☉ reach the zero-age main sequence still deeply embedded in their parental cores (Palla & Stahler 1993). At this point radiation pressure from the newly formed early-type star can halt the infall, thus preventing further growth of the stellar mass. Various solutions have been proposed to solve this problem: (1) massive stars might form through merging of lower mass stars (Bonnell et al. 1998; Bonnell & Bate 2002; Bally & Zinnecker 2005); (2) sufficiently large accretion rates could allow the ram pressure of the infalling material to overcome the radiation pressure form the star (Behrend & Maeder 2001; McKee & Tan 2003; Bonnell et al. 2004); (3) nonspherical accretion could weaken the effect of radiation pressure by allowing part of the photons to escape through evacuated regions along the outflow axis and, at the same time, enhancing the ram pressure of the accreting material by focusing it through the disk plane (Yorke & Sonnhalter 2002; Krumholz et al. 2005, 2007).

An important test for discriminating between the different hypotheses is the presence of rotating, circumstellar disks, which would lend support to the third scenario depicted above. This can be determined by inspecting the velocity field of the innermost parts of molecular cores where young massive (proto)stars are believed to form. One possibility is to look for velocity gradients perpendicular to the direction of the larger scale outflows associated...
with such cores; this would suggest that one is observing rotation about the outflow axis. This technique has been adopted by us and other authors successfully inferring the existence of rotation in the gas enshrouding high-mass young stellar objects (YSOs) and leading to the discovery of circumstellar disklike structure or “toroids” in a limited number of cases (see Cesaroni et al. 2007 for a review on this topic).

The goal of the present study was to establish whether the presence of rotation is common in high-mass star-forming regions by observing three more objects, expected to be sites of deeply embedded OB (proto)stars. The ideal target for this type of study is hot molecular cores (HMCs), which are believed to be the cradles of massive stars (see, e.g., Kurtz et al. 2000; Cesaroni et al. 2007). Beside other studies, the one by Codella et al. (1997, hereafter CTC97), has proved successful in identifying the birthplaces of young massive stars as dense NH$_3$ cores associated with OH and H$_2$O maser emission. One of these HMCs (G24.78+0.08) has been the subject of a series of articles by us (Furuya et al. 2002; Cesaroni et al. 2003; Beltrán et al. 2004, 2005), which have shown that this is a unique object, characterized by the simultaneous presence of rotation, outflow, and infall toward a hypercompact H~II region ionized by an O9.5 star (Beltrán et al. 2006). With this in mind, we completed the study of the sources in CTC97 by observing three more objects in the same tracers used to investigate G24.78+0.08, which gives a total bandwidth of 1 GHz for the continuum and a velocity resolution of 5.5 km s$^{-1}$.

2. OBSERVATIONS AND DATA RETRIEVAL

2.1. Millimeter Array Observations

Aperture synthesis observations of molecular lines and continuum emission at 3 mm were carried out using the Owens Valley Radio Observatory (OVRO)$^1$ millimeter array toward G16.59$-0.05$ and G28.87$+0.07$, and the Nobeyama Millimeter Array (NMA) of the Nobeyama Radio Observatory$^2$ toward G23.01$-0.41$. We also carried out $^{12}$CO (1$-0$) line and millimeter continuum emission imaging with the Plateau de Bure Interferometer (PdBI) of the Institut de Radio Astronomie Millimétrique$^3$ (IRAM). The parameters for the continuum and molecular line observations are summarized in Tables 1 and 2, respectively.

TABLE 1

| Source | Telescope | Frequency (GHz) | Bandwidth$^a$ (GHz) | $\theta_{maj} \times \theta_{min}$ (arcsec) | P.A. (deg) | Image rms (mJy beam$^{-1}$) |
|--------|-----------|----------------|---------------------|---------------------------------|------------|--------------------------|
| G16.59$-0.05$ | OVRO | 90.6$^b$ | 3.5 | $2.31 \times 1.75$ | $-24$ | 0.50 |
| G28.87$+0.07$ | IRAM | 115.3$^c$ | 0.32 | $6.31 \times 4.10$ | $-167$ | 2.49 |
| G23.01$-0.41$ | NMA | 98.8$^d$ | 1.0 | $2.69 \times 1.93$ | $-14$ | 0.99 |
| | NMA | 110.0$^e$ | 1.0 | $2.40 \times 1.69$ | $-12$ | 1.35 |
| | IRAM | 115.3 | 3.5 | $5.50 \times 4.17$ | $-164$ | 1.90 |

$^a$ Effective bandwidth of line-free channels for obtaining continuum image.
$^b$ Center frequency of both side bands.
$^c$ Center frequency of each single side band.

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$^2$ Nobeyama Radio Observatory is a branch of the National Astronomical Observatory, operated by the Ministry of Education, Culture, Sports, Science and Technology, Japan.

$^3$ IRAM is supported by INSU/CNRS (France), MPG (Germany), and IGN (Spain).

The OVRO observations of G16.59$-0.05$ and G28.87$+0.07$ were carried out in the period from 2003 September to 2004 May in three array configurations (E, H, and UH). The shortest projected baseline length, i.e., the shadowing limit, is about 12.8 m. This makes our OVRO observations insensitive to structures more extended than 54$''$ corresponding to 1.2 and 1.9 pc at the distances of G16.59$-0.05$ and G28.87$+0.07$, respectively. We observed the CH$_3$CN (5$-4$) and N$_2$H$^+$ (1$-0$) lines in the upper sideband (USB) and the HCO$^+$ (1$-0$) line in the lower sideband (LSB). For the continuum emission, we simultaneously used the Continuum Correlator with an effective bandwidth of 4 GHz and the newly installed COBRA with 8 GHz bandwidth. We configured the digital correlator with 31 MHz bandwidth and 62 channels centered at 91979.970 MHz, in order to cover the $K = 0-3$ components of the CH$_3$CN (5$-4$) transition. We used 3C 273 and 3C 454.3 as passband calibrators and NRAO 530 and J1743$-038$ as phase and gain calibrators, respectively, for G16.59$-0.05$ and G28.87$+0.07$. The flux densities of NRAO 530 and J1743$-038$ were determined from observations of Uranus and Neptune. We estimate the uncertainty of flux calibrations to be 10%. The data were calibrated and edited using the MMA and MIRIAD packages. We constructed continuum images from the COBRA data by employing the multifrequency synthesis method.

2.1.2. NMA Observations

Our NMA observations toward G23.01$-0.41$ were carried out in the period from 2003 December to 2004 May with three array configurations (D, C, and AB). The largest detectable source size is 50$''$, corresponding to 2.6 pc at $d = 10.7$ kpc. We observed the CH$_3$CN (6$-5$), HNCO (5$-4$), $^{13}$CO (1$-0$), and C$^{18}$O (1$-0$) lines in the USB. For the continuum and line emission, except for CH$_3$CN, we employed the Ultra Wide Band Correlator (UWBC) with a 512 MHz bandwidth in each sideband; this configuration gives a total bandwidth of 1 GHz for the continuum and a velocity resolution of 5.5 km s$^{-1}$ for the lines. We used the FX correlator with 32 MHz bandwidth centered at 110374.0 MHz, thus covering the $K = 0-3$ components of the CH$_3$CN (6$-5$) transition.
We adopted 3C 273 as passband calibrator and J1743–038 as phase and gain calibrator. The flux densities of J1743–038 were bootstrapped from Uranus, and the uncertainty of the flux calibration is estimated to be 10%. We decided not to use the 13CO and C22 data taken with the C and AB configurations as these emissions are heavily resolved with the extended configurations. All the data were calibrated and edited using the UVPROC2 and MIRIAD packages.

2.1.3. PdBI Observations

Our 12CO (1–0) and 2.6 mm continuum observation toward the three HMCs were carried out with the IRAM five-antenna interferometer on Plateau de Bure in 1998 April and May. The D and C1 configurations were used, yielding a largest detectable angular scale of ~44″. The 82–116 GHz SIS receivers were tuned in SSB at the frequency of the 13CO (1–0) line, and the facility correlator was configured with a bandwidth of 40 MHz centered at the same frequency. Continuum emission has also been measured with two bandwidths of 160 MHz each. Line-free channels were averaged to produce a continuum image, which was then subtracted from the line data in the visibility plane. The flux densities of J1833–210 (1.7 Jy) and J1743–038 (3.0 Jy) were bootstrapped from 3C 273 whose flux density was assumed to be 16.7 Jy. We estimated an overall uncertainty on flux calibration of 20%. Data editing, calibrations, and image construction were done using the GILDAS software package developed at IRAM. Tables 1 and 2 summarize the observing parameters for the PdBI continuum and line imaging, respectively.

2.2. GLIMPSE and MSX Archive Data

We have retrieved infrared (IR) images at 21 μm from the Midcourse Space Experiment (MSX; Price et al. 2001) survey and at 8.0, 5.8, 4.5, and 3.6 μm from the Galactic Legacy Infrared Mid-Plane Survey (GLIMPSE) survey, making use of the Infrared Array Camera (IRAC) on board the Spitzer satellite. The calibrated data from the Spitzer Science Center were processed through the GLIMPSE pipeline reduction system (Benjamin et al. 2003; Whitney et al. 2004). All the infrared (IR) images were used without spatial smoothing; the pixel size is 6″ and ~1.2″ for the MSX and IRAC data, respectively.

3. RESULTS AND DISCUSSION

3.1. Continuum Emission

Figure 1 compares our 3 mm continuum emission maps to the IR images. The latter correspond to the MSX data at 21 μm and the GLIMPSE ones at the longest (8.0 μm) and shortest (3.6 μm) wavelengths. Here we do not show GLIMPSE images at 5.8 and 4.5 μm as they are basically similar to those at 8.0 and 3.6 μm. All three objects show intense, compact 3 mm continuum emission coincident with IR emission, although one must consider that the angular resolution of the MSX images is much worse than that of our interferometric maps. In the millimeter maps of G28.87+0.07, one can also see weaker 3 mm continuum sources located ~14″ to the north (hereafter G28.87+0.07 B and C; see Fig. 1b) and a 2.6 mm source ~10″ to the east (G28.87+0.07 D; same figure) of the main core found by CTC97. No other millimeter continuum emission is detected with S/N > 5 in our OVRO, NMA, and PdBI fields of view toward the three sources. Assuming that the flux density, $S_\text{cont}$, varies as $\propto \nu^{2+\beta}$ with $\beta = 1.5$ (Preibisch et al. 1993; Molinari et al. 2000), the expected flux of G28.87+0.07 B and C in the PdBI beam at 2.6 mm is below the sensitivity of our images (3.5 mJy corresponding to 2.2 σ). Similarly, assuming that G28.87+0.07 D matches the PdBI beam, this source is resolved by the OVRO beam, and its flux at 3.3 mm corresponds to only 1.4 σ of the OVRO continuum image, thus explaining why it is not detected.

The GLIMPSE images of G16.59–0.05 and G28.87+0.07 show IR emission from both the main cores and their surroundings. On the other hand, G23.01–0.41 seems rather isolated, although we may be missing weaker objects due to the large distance to the region. In the following we make no attempt to identify other IR sources beside the counterparts of those detected at millimeter wavelengths, because this would require an analysis that goes beyond the purposes of the present study. Note that no other millimeter sources with $S/N > 5$ are seen in the IRAC bands. We summarized the identified continuum sources in Table 3, where peak positions and effective radius ($R_{\text{eff}}$) of the millimeter continuum sources as well as their $S/N$ integrated inside the 5 σ level contours are given. Here the observed angular radius of the
source is computed from \((A/\pi)^{1/2}\), where \(A\) is the area enclosed by the 50\% contour level of the emission. Deconvolution assuming the source and the synthesized beam to be Gaussian is then applied, thus obtaining \(R_{\text{eff}}\), assuming that the emission has a Gaussian distribution. It should be noted that \(R_{\text{eff}}\) does not depend on the image noise levels. To estimate the core mass from the continuum flux the latter has been integrated all over the emitting region, namely, inside the corresponding 5 \(\sigma\) contour level. The fluxes of the IR counterparts are listed in Table 4.

3.1.2. Continuum Spectra and Core Masses Estimated from the 3 mm Flux Densities

Figure 2 shows the continuum spectra of the three HMCs, as from Tables 3 and 4. No contamination by free-free emission is expected to affect our 3 mm fluxes, as the upper limits obtained by CTC97 at 1.26 cm guarantee a maximum free-free flux of \(\simeq 1.4\) mJy at 3.0 mm, assuming optically thin emission. Establishing the origin of the IR emission requires a model fitting of
the spectral energy distribution (SED) that goes beyond the purpose of this study. We only note that a simple gray-body fit cannot consistently reproduce the SED from the millimeter to the near-IR regime. This suggests that the structure of the cores is rather complex, probably hosting a multiple stellar system such as the one seen in the G29.96–0.02 star-forming region; here recent subarcsecond resolution (1.8 AU resolution in linear scale) Submillimeter Array (SMA) imaging resolved the HMC (Maxia et al. 2001; Olmi et al. 2003) into six submillimeter continuum sources (Beuther et al. 2007). Although our angular resolutions in AU are 5–12 times worse, by analogy to the case of G29.96–0.02, we can argue that multiple sources are present in our cores, which might explain why the SEDs cannot be fitted with a simple gray-body fit. Furthermore, temperature gradients as well as optical depth effects and clumpiness should be taken into account to obtain a satisfactory fit. In particular, images with arcsecond resolution at wavelengths above 20 μm would be of great importance to obtain a precise estimate of the bolometric luminosity (and hence of the mass) of the embedded (proto)stars.

The 3 mm flux density in Table 3 can be used to estimate the mass of the cores (M_{dust}), under a few assumptions on the dust emissivity. More specifically, we use the Hildebrand (1983) relation \( M_{dust} = \left( \frac{S_{\nu} d^{2}}{\kappa_{\nu} B_{\nu}(T_{dust})} \right) \) with \( \kappa_{\nu} = 5.0 \times 10^{-22} (\nu/231 \text{ GHz})^{\beta} \text{ cm}^2 \text{ g}^{-1} \) and \( \beta = 1.5 \). When calculating \( M_{dust} \), we set \( T_{dust} \) equal to the rotational temperature obtained from the CH$_3$CN lines (see § 3.5.1), assuming that gas and dust are well coupled (e.g., Krügel & Walmsley 1984), a reasonable hypothesis at densities as high as those traced by the CH$_3$CN emission (typically >10$^{6}$–10$^{7}$ cm$^{-3}$).

The derived values of \( M_{dust} \) range from 95 to 380 M$_{\odot}$ (Table 5). Our three targets appear to fall in the mass range for “heavy” HMCs (≥100 M$_{\odot}$; Cesaroni et al. 2007). Cores that massive are likely to host multiple stars, as opposed to “light” HMCs (< a few 10 M$_{\odot}$), which appear to contain only single OB stars or binary systems (Cesaroni et al. 2007).

In G28.87+0.07 we have identified three additional weaker sources. Assuming that \( T_{dust} \) is equal to the excitation temperature of N$_2$H$^+$ (1–0) (see § 3.3.2 and Fig. 5c), we obtain \( M_{dust} \approx 7 M_{\odot} \) with \( T_{dust} = 46 \text{ K} \) for G28.87+0.07 D. The excitation temperature is estimated from the hyperfine structure analysis of mean spectra of the N$_2$H$^+$ emission toward a condensation hosting G28.87+0.07 D. If we assume that \( T_{dust} \approx 46 \text{ K} \) is valid for G28.87+0.07 B and C, we obtain \( M_{dust} \approx 29 M_{\odot} \) for G28.87+0.07 B and 28 M$_{\odot}$ for G28.87+0.07 C. These results suggest that the G28.87+0.07 HMC (\( M_{dust} \approx 100 M_{\odot} \); Table 5) is surrounded by less massive objects. Such a situation appears to be typical of high-mass star-forming regions, where embedded OB (proto)stars happen to be surrounded by less embedded, possibly more evolved, lower mass stars (Molinari et al. 1998; Fontani et al. 2004a, 2004b). Furthermore, because of the absence of free-free emission (CTC97), we argue that the G28.87+0.07 cluster is much younger than other clusters of massive YSOs, such as, for example, the cluster of ultracompact H ii regions in G19.61–0.23 (Furuya et al. 2005).

### Table 3

**Properties of 3 mm Continuum Emission**

| SOURCE           | \( d^a \) (kpc) | \( \nu \) (GHz) | R.A. (J2000.0) | Decl. (J2000.0) | \( R_{eff}^b \) (pc) | \( S_{\nu}^c \) (mJy) |
|------------------|-----------------|----------------|---------------|----------------|----------------------|------------------------|
| G16.59–0.05……….. | 4.7             | 92.0           | 18 21 09.06   | –14 31 47.9    | 0.033                | 37.5 ± 7.5             |
| G28.87+0.07……….. | 7.4             | 92.0           | 18 43 46.25   | –03 35 29.9    | 0.029                | 11.3 ± 2.3             |
| G28.87+0.07 B……….. | 92.0           |             | 18 43 46.19   | –03 35 12.9    | 0.033                | 1.7 ± 0.3              |
| G28.87+0.07 C……….. | 92.0           |             | 18 43 46.31   | –03 35 15.4    | -0.01                | 1.5 ± 0.4              |
| G28.87+0.07 D……….. | 115.3          |             | 18 43 47.09   | –03 35 32.0    | 0.030^d              | 0.80 ± 0.2             |
| G23.01–0.41……….. | 10.7            | 98.8          | 18 34 40.29   | –09 00 38.1    | 0.068                | 27.8 ± 5.6             |
|                  |                 |               | 110.0         | –09 00 38.6    | 0.055                | 31.6 ± 6.3             |
|                  |                 |               | 115.3         | –09 00 38.2    | 0.103                | 33.9 ± 6.8             |

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

### Table 4

**Flux Densities of the Three HMCs at Infrared Wavelengths**

| SOURCE           | \( S \) (Jy) | \( S \) (Jy) | \( S \) (Jy) | \( S \) (Jy) | \( S \) (Jy) | \( S \) (Jy) | \( S \) (Jy) | \( S \) (Jy) | \( S \) (Jy) | \( S \) (Jy) |
|------------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|
|                  | Note         | Note         | Note         | Note         | Note         | Note         | Note         | Note         | Note         | Note         |
| G16.59–0.05……….. | 7.7          | 1.2          | 1.8          | 1.2          | 4.1          | 1.2          | 2.4          | 1.2          | 6.8E–2       | 2.4          | 3.3E–2       | 2.4          | 1.4E–2       | 2.4          | ...          | 5            |
| G28.87+0.07……….. | 14.7         | 1.2          | 6.8          | 1.2          | 5.1          | 1.2          | 2.8          | 1.2          | 1.3          | 2.4          | 8.0E–1       | 2.4          | 4.0E–1       | 2.4          | 6.0E–2       | 2.4          |
| G23.01–0.41……….. | 4.4          | 1.2          | <0.51        | 1.6          | <0.86        | 1.6          | <0.20        | 1.6          | 1.1E–1       | 2.4          | 1.1E–1       | 2.4          | 6.3E–2       | 2.4          | 1.0E–2       | 2.4          |

Notes.—(1) MSX data; (2) integrated inside the 50% level contour of the data; (3) contaminated with the nearby source(s); (4) GLIMPSE data; (5) impossible to define a point source (see Fig. 1); (6) 3 σ upper limit. See § 3.1.2 for the details.
Finally, in order to estimate the CH$_3$CN abundance in the cores (see § 3.5.2), we have calculated the mean molecular hydrogen column density, $\langle N(\text{H}_2) \rangle$, over the cores. To make the comparison between continuum and CH$_3$CN emission as consistent as possible, we reconstructed the 3 mm images by fixing the beam sizes to those of the CH$_3$CN images (Table 2). We subsequently integrated the continuum flux over the region enclosed by the 5$\sigma$ level contours. In Table 5 we summarize the calculated mean column densities ($\langle N(\text{H}_2) \rangle$) that are $(3-4) \times 10^{23}$ cm$^{-2}$, implying optical depths on the order of $10^{-3}$, consistent with our assumption that the dust emission is optically thin at 3 mm.

### 3.2. Spectral Line Profiles toward the Cores

Figure 3 shows the line spectra at the peak positions of each integrated intensity map, in units of brightness temperature in the synthesized beam ($T_{\text{syn}}$). For the CH$_3$CN emission, we show the $K = 3$ component, as this is not blended with the other $K$-ladder lines.

**G16.59−0.05**—The $^{12}$CO and HCO$^+$ peak spectra present deep “absorption” features around the systemic velocity, the latter being estimated from the CH$_3$CN lines (see § 3.5.1). Most likely this is not due to real self-absorption but to the fact that emission at low velocities arises from extended regions resolved out by the interferometer, as found in the case of G24.78+0.08 (see Cesaroni et al. 2003). However, only single-dish mapping of the regions under study in the same lines can establish the nature of such absorption.

The $^{12}$CO spectrum shows prominent high-velocity wings on both sides of the line, indicating the presence of a molecular outflow. In order to adopt suitable velocity ranges for the outflow lobes traced by the $^{12}$CO emission, we define terminal ($V_t$) and boundary ($V_b$) velocities: $V_t$ is the most blue- and redshifted LSR

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**TABLE 5**

| Source          | $M_\text{dust}$ ($M_\odot$) | $\langle N(\text{H}_2) \rangle$ ($\times 10^{23}$ cm$^{-2}$) |
|-----------------|----------------------------|--------------------------------------------------|
| G16.59−0.05     | 95 ± 6                     | 3.0 ± 0.9                                         |
| G28.87+0.07     | 100 ± 7                    | 4.2 ± 1.3                                         |
| G23.01−0.41     | 380 ± 22                   | 3.6 ± 1.1                                         |

*Note:* See § 3.1.2 for the details.

*a* Mass of the core estimated from the 3 mm continuum flux density shown in Table 3. We assumed that $T_{\text{dust}}$ is equal to $T_{\text{rot}}$ of CH$_3$CN emission (Table 9).

*b* Mean H$_2$ column density calculated over the area encompassing the emission inside the 5$\sigma$ contour.
velocity where the wing emission drops below the 1.5 σ level and $V_L$’s are the velocities where the intensity of the CH$_3$CN $K = 3$ line falls below 1.5 σ (see Fig. 4 legend for the $V_L$ and $V_H$ values).

**G28.87+0.08.**—The $^{13}$CO and HCO$^+$ (1–0) spectra toward G28.87+0.07 are very similar to each other in the sense that the emission around $V_{sys}$ is almost missing, and the blueshifted wing is barely detected, whereas prominent redshifted emission is seen. The CH$_3$CN $K = 3$ emission peaks around $V_{LSR} \approx 103$ km s$^{-1}$, where the $^{13}$CO and HCO$^+$ spectra present a sharp edge. Also in this case, as for G16.59–0.05, we argue that the spectral profiles of the $^{12}$CO and HCO$^+$ lines may suffer due to missing short spacing in our interferometric observations.

**G23.01–0.41.**—The profile of the $^{12}$CO line toward G23.01–0.41 presents a redshifted wing much more prominent than the blue one, while the emission close to $V_{sys}$ is strongly depressed. On the other hand, the lines of the lower density tracers $^{13}$CO and C$^{18}$O present well-defined peaks, although the velocity resolutions are poor. The peak LSR velocities of the $^{13}$CO and C$^{18}$O emission shifted slightly toward the blue with respect to the peak velocity of CH$_3$CN, which we have assumed as representative of the bulk material.

### 3.3. Maps of the Molecular Line Emission

#### 3.3.1. G16.59–0.06

Figure 4 compares maps of molecular line and continuum emission in G16.59–0.05. Figure 4a shows an overlay of the $^{12}$CO wing emission on the 3 mm continuum emission. The wing emission is integrated over the velocity ranges between $V_L$ and $V_H$ for both the blue and red lobes (§3.2). The G16.59–0.05 outflow map shows a clear bipolarity along a line with P.A. $\approx 135^\circ$. We define the outflow axis as the line connecting the peaks of the blue lobe and 3 mm continuum map. The blue lobe shows a remarkable structure with a large opening angle of $\approx 180^\circ$, whereas the red lobe is much more collimated. Interestingly, both lobes have a large aspect ratio (>1), defined as the ratio between the width and the length of the lobe. Moreover, the two lobes have a rather large spatial overlap, also coinciding with the position of the 3 mm continuum emission. Such a geometry indicates that the inclination angle of the outflow axis with respect to the line of sight—albeit difficult to quantify precisely—must be rather small.

In Figure 4d, we see that, while the distributions of CH$_3$CN (5–4) $K = 0 + 1$ and NH$_3$ (3, 3) emission agree well with each other, the peak position of the 3.3 mm source is displaced by $\approx 1.4''$ to the northwest of the CH$_3$CN peak. We also verified that the peak positions of the $K = 2$ and 3 emission agree with that of the $K = 0 + 1$ emission. Note that the 3.3 mm continuum and CH$_3$CN visibilities shared the same calibrators as they were observed simultaneously (§2.1.1), and that the peak positions of the 3.3 and 2.6 mm continuum sources (see Table 3), measured, respectively, with OVRO and PdBI, agree with each other within the errors. These facts indicate that the positional displacement between the CH$_3$CN and 3 mm continuum emission is real (see §3.6 for a discussion). One cannot rule out the possibility that such a displacement is due to optical depth effects, although this seems unlikely as line emission peaks at the same position for all species (NH$_3$ and CH$_3$CN), and the CH$_3$CN opacity quite low ($\leq 2$; described in §3.5.1). Observation of higher excitation CH$_3$CN lines might help by shedding light on this issue. The peak position of the more extended HCO$^+$ emission agrees with those of NH$_3$ and CH$_3$CN, suggesting that the HCO$^+$ (1–0) line also traces the HMC. On the other hand, the N$_2$H$^+$ emission has a totally different morphology from the other molecules, in the sense that it has a fairly extended structure and its peak position differs from both those of the other lines and that of the 3 mm continuum. The N$_2$H$^+$ emission is more extended than the HCO$^+$ emission, suggesting that it might be associated not only with the HMC, but also with the other sources seen in the IR images (Fig. 1a).

To estimate the column density of the region, we analyzed the HCO$^+$ and N$_2$H$^+$ data in the following fashion. The mean column density of a linear rigid rotor is calculated from equation (A1) of Scoville et al. (1986). Since we do not have measurements of the optical depth ($\tau$) and excitation temperature ($T_{ex}$) of the HCO$^+$ line, we assumed that the HCO$^+$ emission is optically thin and...
estimated the column density for two extreme values $T_{\text{ex}}$: a minimum $T_{\text{ex}}$, obtained from the line peak $T_{\text{SB}}$ (32.8 K from Fig. 3a) and a maximum $T_{\text{ex}}$, from $T_{\text{rot}}$ of the CH$_3$CN emission (130 K; described in § 3.5.1). Correspondingly, the mean HCO$^+$ column density over a region enclosed by its 5 $\sigma$ contour level is $N_{\text{HCO}^+} \simeq 6.3 \times 10^{14}$ cm$^{-2}$ and $2.1 \times 10^{10}$ cm$^{-2}$. For the fractional abundance, $X$(HCO$^+$), we assume a value of $10^{-9}$ (see, e.g., van Dishoeck et al. 1993). Under this assumption, the mass traced by the HCO$^+$ (1–0) line ($M_{\text{LTE}}$) ranges from 440 to 1500 $M_\odot$ (Table 6). We stress that these estimates are to be taken as lower limits, as part of the line emission close to the systemic velocity is resolved out in our interferometric maps.

Subsequently, we analyzed the N$_2$H$^+$ data because the hyperfine structure (HFS) of the transition allows an estimate of the

![Figure 4](image-url)

**Fig. 4.**—Maps of molecular lines and continuum emission for G16.59−0.05. (a) Overlays of the blue- and redshifted wing emission maps of $^{12}$CO (1−0) on the 3 mm continuum emission (gray scale), total integrated intensity maps of (b) HCO$^+$ (1−0) and (c) N$_2$H$^+$ (1−0) emission (gray scale plus contour), and (d) overlay of total maps of NH$_3$ (3, 3) (green contours; CTC97) on CH$_3$CN $K = 0$ and 1 line emission (gray scale). In (b−d), the thin blue and red contours indicate the 5 $\sigma$ levels of the blue- and redshifted $^{12}$CO (1−0) lobes shown in (a). All the contours, except for the $^{12}$CO start from the 3 $\sigma$ level with a 3 $\sigma$ step. The dashed contours correspond to −3 and −6 $\sigma$ levels for (b) HCO$^+$, (c) N$_2$H$^+$, and (d) CH$_3$CN. Contours for the $^{12}$CO outflow maps are drawn with 5, 10, 15, 20, and 40 $\sigma$ levels for the clarity of the plots. The rms noise levels of the images are 33, 19, 0.43, 0.10, 4.2, and 0.26 mJy beam$^{-1}$ for $^{12}$CO blueshifted, $^{12}$CO redshifted, 3 mm continuum, HCO$^+$, N$_2$H$^+$, NH$_3$, and CH$_3$CN maps, respectively. The solid line in (a) indicates the identified outflow axis. The central star in (b−d) marks the peak position of the 3 mm continuum emission. The blue- and redshifted $^{12}$CO (1−0) emission is integrated over the velocity ranges of 47.4 km s$^{-1}$ $\leq$ $V_{\text{LSR}}$ $\leq$ 54.0 km s$^{-1}$ and 63.4 km s$^{-1}$ $\leq$ $V_{\text{LSR}}$ $\leq$ 78.1 km s$^{-1}$, respectively. The HCO$^+$ (1−0) line is integrated over 53.3 km s$^{-1}$ $\leq$ $V_{\text{LSR}}$ $\leq$ 66.7 km s$^{-1}$. These velocity ranges are shown by the horizontal color bars under the spectra shown in Fig. 3a. For the N$_2$H$^+$ (1−0) emission, all the hyperfine emission detected in 49.4 km s$^{-1}$ $\leq$ $V_{\text{LSR}}$ $\leq$ 70.6 km s$^{-1}$ is integrated. The frequency range to obtain the CH$_3$CN $K = 0 + 1$ map is shown by a horizontal bar under the corresponding spectrum in Fig. 7. The ellipse at the lower corners in each panel shows the synthesized beam size (Tables 1 and 2).

**Table 6**

| Source          | Probe       | $R_{\text{eff}}$ (pc) | $M_{\text{LTE}}$ (M$_\odot$) |
|-----------------|-------------|-----------------------|--------------------------------|
| G16.59−0.05     | HCO$^+$ (1−0)| 0.070                 | 440−1500                       |
| G28.87+0.07     | N$_2$H$^+$ (1−0) | 0.15                   | 540                            |
| G23.01−0.41     | HCO$^+$ (1−0) | 0.12                   | 84−360                         |
|                 | $^{13}$CO (1−0) | 0.426               | $1 \times 10^4$               |
|                 | C$^{18}$O (1−0) | 0.174                | $2 \times 10^4$               |

*Note.—For details, see § 3.3.

* Effective radius; see § 3.1.1 for the definition.

b LTE-mass obtained by integrated the emission over the area enclosed by the 5 $\sigma$ level contours.
line optical depth (see, e.g., Benson et al. 1998; Caselli et al. 2002). The details of our $N_2H^+$ HFS analysis are described in Appendix B of Furuya et al. (2006). For this purpose, we used two spectra obtained by integrating the emission over the 5σ contour level of the 3 mm continuum emission and the integrated $N_2H^+$ line emission. Note that the $N_2H^+$ emission does not peak at the position of the 3 mm continuum source. For the first spectrum, our analysis gives $T_{\text{ex}} = 41 \pm 9$ K, total optical depth (corresponding to the sum of the optical depths of the seven hyperfine components) $\tau_{\text{tot}} = 0.28 \pm 0.03$, and intrinsic line width $\Delta v_{\text{int}} = 2.10 \pm 0.04$ km s$^{-1}$ toward the 3 mm source. From the second spectrum, we obtain $T_{\text{ex}} = 16 \pm 2$ K, $\tau_{\text{tot}} = 0.91$, and $\Delta v_{\text{int}} = 2.82 \pm 0.02$ km s$^{-1}$. Using equation (B7) of Furuya et al. (2006), we calculate a column density $N_{N_2H^+} = (7.8 \pm 1.5) \times 10^{13}$ cm$^{-2}$ toward the 3 mm continuum source and $(6.1 \pm 0.4) \times 10^{13}$ cm$^{-2}$ for the average spectrum. If we assume $X(N_2H^+) = 3 \times 10^{-10}$ suitable for high-mass star-forming regions (Womack et al. 1992), the mass estimate for the entire region is 540 $M_\odot$ (Table 6).

3.3.2. G28.87+0.06

The $^{12}$CO spectrum of G28.87+0.07 strongly suggests the presence of high-velocity outflowing gas (§ 3.2). However, the maps of the wing emission presented in Figure 5a do not seem to outline a clear bipolar structure with respect to the 3 mm source position. A prominent red lobe lies to the southwest, whereas the blue lobe shows an elongated structure aligned approximately east-west as well as a condensation to the northeast of the main

Fig. 5.—Maps of molecular lines and continuum emission for G28.87+0.07. All the contours and symbols are the same as those in Fig. 4. The rms noise levels of the images are 47, 24, 0.51, 0.13, 5.0, and 0.18 for $^{12}$CO blueshifted, $^{13}$CO redshifted, 3 mm continuum, HCO$^+$, $N_2H^+$, NH$_3$ (CTC97), and CH$_3$CN maps, respectively. The dashed contours correspond to the −3σ level for (b) HCO$^+$, (c) $N_2H^+$, and (d) CH$_3$CN. The blue- and redshifted $^{12}$CO (−0) emission, HCO$^+$, and $N_2H^+$ are integrated over the velocity ranges of $83:3 \lesssim V_{\text{LSR}} \lesssim 96.3$ km s$^{-1}$, $111.8 \lesssim V_{\text{LSR}} \lesssim 123.9$ km s$^{-1}$, $102.3 \lesssim V_{\text{LSR}} \lesssim 114.0$ km s$^{-1}$, and $95.0 \lesssim V_{\text{LSR}} \lesssim 111.1$ km s$^{-1}$, respectively (see also Fig. 3b). The star with the associated labels indicate the peak positions and names of the mm sources identified by us (see § 3.1.1 and Table 3). All the other symbols are the same as in Fig. 4.
core. If we assume that all the CO lobe is associated with an outflow powered by a source in the core, the observed morphology and velocity structure can be interpreted in two ways: (1) one outflow, with patchy emission from the lobes and with a large opening angle (close to 90°) around the axis denoted by the solid line in Figure 5a; (2) two outflows, well collimated along the axes represented by the dashed lines in the same figure. On the basis of the present data, it is impossible to discriminate between these two hypotheses. Given the existence of several sources in G28.87+0.07 (§ 3.1.1) and the fact that multiple outflows appear to be frequent in high-mass star-forming regions (see Beuther et al. 2002b, 2003, 2004), one cannot rule out the possibility that the blueshifted condensation to the northeast and some portion of the eastern blueshifted lobe are associated, respectively, with G28.87+0.07 B (and/or C) and D. However, for the sake of simplicity, in the following we consider only the two scenarios proposed above, which assume that it is the main G28.87+0.07 core to host the source(s) powering the outflow(s).

In G28.87+0.07, the peak positions of all tracers but N2H+ roughly coincide with the 3 mm continuum peak (Fig. 5d). Both the NH3 and CH3CN emission are compact, whereas the HCO+ emission is slightly elongated in the north-south direction (Fig. 5b). We believe that the HCO+ emission mostly arises from the HMC and not from the outflow lobes because its elongation is not parallel to any of the possible outflow axes and only very faint HCO+ line wings are detected (see Fig. 3b). As done for G16.59—0.05, we estimate $N_{\text{HCO+}}$ for the region enclosed by the 5 σ level contour assuming two extreme values for the excitation temperature. We obtain $N_{\text{HCO+}} = 3.9 \times 10^{14}$ cm$^{-2}$ for $T_{\text{ex}} = 96$ K, and $9.2 \times 10^{13}$ cm$^{-2}$ for $T_{\text{ex}} = 17$ K, yielding a mass range $M_{\text{LTE}} \simeq 84$–$360 \, M_{\odot}$ (Table 6). Here the maximum $T_{\text{ex}}$ is assumed equal to the value of $T_{\text{rot}}$ obtained from the CH3CN emission. On the other hand, the minimum $T_{\text{ex}}$ is taken equal to the peak $T_{\text{ex}}$ of the HCO+ spectrum [14.5 K from Fig. 3; $T_{\text{ex}} \simeq T_{\text{bg}}$ (HCO+) $+ T_{\text{bg}} = 17$ K, where $T_{\text{bg}}$ is the cosmic background temperature].

Independent of the value chosen, this estimate represents a lower limit because of the different UV coverages, beam dilutions, and optical depth effects. We stress that the estimated $N_{\text{HCO+}}$ varies only by a factor of 4.3 regardless of the large uncertainty on $T_{\text{ex}}$.

It is interesting that the N2H+ emission in G28.87+0.07 cannot be seen toward the center of the main core, where instead NH3 emission is detected (CTC97). The distribution of the N2H+ emission is very patchy, and several condensations are seen close to the edge of the 12CO outflow lobes (Fig. 5c). The eastern N2H+ condensation seems to be host G28.87+0.07 D, although the N2H+ peak position does not agree with the millimeter peaks. In fact, none of the N2H+ condensations matches the 3 mm source positions, which may indicate a low N2H+ abundance in these cores, as suggested by Womack et al. (1992), who argue that N2H+ is likely to be destroyed in regions of very high density ($n_{\text{H}} > 10^6$ cm$^{-3}$) and high temperature ($T_k > 200$ K). Alternatively, one might speculate that N2H+ could trace the borders of a region evacuated by the outflow. However, our fit to the N2H+ lines gives LSR velocities of $\sim$103 km s$^{-1}$ for these condensations, namely, too similar to the $V_{\text{sys}}$ to be typical of gas participating in the outflow motion.

### 3.3.3. G23.01—0.41

We have seen that the red wing of the 12$^1$CO spectrum toward G23.01—0.41 is more prominent than the blue wing (Fig. 3c). Figure 6a presents an overlay of the high-velocity 12$^1$CO emission map on the 3 mm continuum image; Figures 6b and 6d show, respectively, such overlay maps for the 13$^1$CO and HNCO wing emissions. To obtain these maps, we integrated high-velocity emissions between the $V_{\text{sys}}$ and $V_{\text{sys}}$ for each wing (see § 3.2 for their definitions). In order to maintain consistency in selecting velocity ranges for the three lines as much as possible, we integrated the blueshifted 12$^1$CO emission up to $V_{\text{LSR}} = 49.9$ km s$^{-1}$ beyond the $V_{\text{sys}}$ (blue) of 64.6 km s$^{-1}$, which is the first LSR velocity where the blueshifted wing drops below the 1.5 σ level (see Fig. 3c). The resultant velocity ranges for the blueshifted gas are almost the same for the three tracers, while velocity interval for the 12$^1$CO red wing is approximately twice those for the redshifted 13$^1$CO and HNCO emission.

In Figure 6a, a clear bipolar structure is seen with the bright redshifted lobe lying to the southwest and the blueshifted lobes to the northeast and southwest. In addition, a faint redshifted emission is found to the northeast of the 3 mm continuum peak. The velocity structure traced by the 13$^1$CO and HNCO seems to reconcile with that of the 12$^1$CO line in the sense that the bright blueshifted gas lies to the southwest of the 3 mm source, although the HNCO does not show blueshifted gas to the northeast. We also point out that a fainter redshifted HNCO condensation is seen to the northeast, whose position matches the northeastern 12$^1$CO redshifted lobe. In addition, one can see that the redshifted gas outlined by the 13$^1$CO is basically the same as the 12$^1$CO; both emissions show their peaks to the south of the 3 mm source and elongated toward southeast and northeast.

As in the case of G28.87+0.07 (see § 3.3.2), the above picture of the high-velocity wings may be interpreted either with the existence of two distinct outflows or with the fact that the outflow axis is sufficiently close to the plane of the sky to allow the observation of both blue- and redshifted gas in each lobe. In the former hypothesis, one of the two putative (proto)stars drives the northeastern blueshifted lobe as well as the southwestern redshifted one, and the other (proto)star drives the remaining two lobes. If this is the case, each (proto)star is driving a pair of outflow lobes whose masses (hence, momentum rates; see Table 7) differ significantly, which seems not to be reasonable. In conclusion, we prefer the single outflow hypothesis with the following two supporting reasons: (1) the high-velocity gas maps outlined by the 13$^1$CO and HNCO do not contradict with the velocity structure traced by the 12$^1$CO; neither the 13$^1$CO nor HNCO maps supports the presence of two outflows, and (2) we identified only a 3 mm continuum source toward the center of the HMC (§ 3.1.1). We thus adopt the solid line in Figure 6a as the outflow axis. This line passes across the 3 mm peak position and as close as possible to the peak positions of the blue- and redshifted HNCO lobes.

In Figures 6b and 6c we show maps of the 13$^1$CO and C$^{18}$O bulk emission integrated over a velocity range shown by the green bars in Figure 3c. These arise from a region 10 times larger than the HMC traced by higher density tracers such as CH3CN. In addition, the emission appears to peak a few arcseconds to the south of the HMC, which may be explained if the 13$^1$CO and C$^{18}$O lines are partially thick, thus hiding the densest part of the molecular cloud. To confirm this hypothesis, we have estimated the optical depth of the 13$^1$CO and C$^{18}$O gas from the ratio of the two isotopomers, assuming a relative abundance of 5.5%.

Note that our estimate is not affected by uncertainties due to relative calibration errors or different UV sampling, because the two lines were observed simultaneously (§ 2.1.1). Although the opacity estimate turns out to vary slightly across the line, depending on the velocity (from <1 to 3.4), we conclude that a mean value of $\tau_{\text{13CO}}(1-0) = 2$ is appropriate for our purposes. This indicates that the optical depth of the 13$^1$CO (1–0) line may be sufficiently high to prevent the detection of the HMC. On the other hand, C$^{18}$O should be less affected by this problem. In fact, a tail of
C\(^{18}\)O (1–0) bulk emission is seen in Figure 6c toward the position of the HMC, although the main peak is still shifted to the south. This may also be the effect of low angular resolution, which privileges regions with larger beam-averaged column density with respect to those (like the HMC) with enhanced volume and source-averaged column density.

We thus obtain mean column densities of \(4.2 \times 10^{17} \text{ cm}^{-2}\) for \(^{13}\)CO and \(7.1 \times 10^{17} \text{ cm}^{-2}\) for \(^{18}\)O, over the regions enclosed by the corresponding 5 \(\sigma\) contour level, which imply \(M_{\text{LTE}}\) of \(1 \times 10^4 \, M_\odot\) for \(^{13}\)CO and \(2 \times 10^4 \, M_\odot\) for \(^{18}\)O (see Table 6). Here we assume the same \(T_{\text{ex}}\) for both \(^{13}\)CO and \(^{18}\)O and make it equal to the peak \(T_{\text{mb}}\) of the \(^{13}\)CO emission [10.3 K from Fig. 3; \(T_{\text{ex}} \approx T_{\text{mb}}\) for \(^{13}\)CO plus \(T_{\text{bg}} = 13\) K]. Despite the lack of zero-spacing information in these interferometric maps, masses like these compare well to those measured in similar objects with single-dish telescopes (e.g., G24.78+0.08; Cesaroni et al. 2003).

Lastly, in Figure 6d we show the map of the CH\(_3\)CN emission integrated over the blue and red bars in Figure 3c. One can see that the shape of the HMC traced by this and the NH\(_3\) line (Fig. 6b), as well as the 3 mm continuum (Fig. 6a), is slightly elongated perpendicularly to the outflow axis. It is thus tempting to speculate that one is observing a disklike structure rotating about that axis. We discuss this issue in § 3.6.

3.4. Physical Properties of the Molecular Outflows

In order to calculate the outflow properties, we used the \(^{12}\)CO wing emission maps shown in Figures 4–6. For G28.87+0.07, where multiple outflows might be present (see § 3.3.2), we
Indeed, we have estimated the optical depth in the 12CO line wings (and turn around to order of 10 for all sources. Since molecular outflows appear to be momentum-driven (e.g., Cabrit & Bertout 1992), the momentum rate $F_{\text{co}} = M_{\text{lobe}} v_{\text{flow}}/l_{\text{lobe}}$ may be taken as an indicator of the strength of the outflow and hence of the mass and luminosity of the YSO powering it. The G16.59–0.05 outflow has $F_{\text{co}} \approx 3 M_{\odot} \text{km s}^{-1} \text{yr}^{-1}$, whereas for G28.87+0.07 and G23.01–0.41 $F_{\text{co}}$ are an order of magnitude higher. Values like these are typical of YSOs with luminosities of $\sim 10^3 L_{\odot}$ (see Fig. 5 of Richer et al. 2000 and Fig. 4 of Beuther et al. 2002a), confirming that we are indeed dealing with early B (proto)stars.

These findings are not affected if one takes into account the unknown inclination angle $i$, here defined as the angle between the outflow axis and the line of sight. In fact, $t_d$, $M_{\text{flow}}$, and $F_{\text{co}}$ are proportional to $\cos^2 i$, $\sin i$, and $i/\cos^2 i$, respectively. Thus, assuming as extreme values $i = 20^\circ$ and $i = 70^\circ$, the corrections for the three quantities above are 2.7–0.36, 0.36–2.7, and 0.39–8, respectively. In conclusion, for all reasonable inclination angles, the parameters listed in Table 7 might need a correction by less than an order of magnitude, thus leaving our conclusions unaffected.

3.5. Temperature, Column Density, and CH$_3$CN Abundance of Cores

3.5.1. Rotational Temperature and Column Density of the CH$_3$CN Lines

Symmetric top molecules like CH$_3$CN are ideal probes to measure the gas kinetic temperature, because different $K$ components belonging to the same $J + 1 \rightarrow J$ transition are mainly excited by collisions and spread over a few 10 MHz and can be observed simultaneously in the same bandwidth (hence, suffering less calibration errors). In addition, for densities typical of HMCs ($>10^6\text{ cm}^{-3}$) the rotational temperature, $T_{\text{rot}}$, obtained from $K$ line ratios turns out to be very close to the kinetic temperature of the H$_2$ gas. One can thus obtain reliable estimates of the temperature and column density of the region where CH$_3$CN is detected through the rotation diagram method (Hollis 1982; Loren & Mundy 1984; Churchwell et al. 1992).

Since optical depth effects may affect the reliability of rotation diagrams, we have attempted to fit the $K$ components of CH$_3$CN with a simple LTE fit, taking into account also the line opacity, as performed in, for example, Olmi et al. (1993). The results indicate that the optical depth is less than $\sim 2$, sufficiently low to allow usage of the rotation diagram method in our cases.

### Table 7: Parameters of Molecular Outflows

| Source        | Lobe     | $M_{\text{lobe}}$ ($M_\odot$) | $t_d$ (yr) | $M_{\text{flow}}$ ($M_\odot$ yr$^{-1}$) | $F_{\text{co}}$ ($M_\odot$ km s$^{-1}$ yr$^{-1}$) |
|---------------|----------|-------------------------------|------------|----------------------------------------|-------------------------------------------------|
| G16.59–0.05   | Blue     | 21 ± 11                       | 2.7 × 10$^4$ | (2 ± 1) × 10$^{-4}$                  | (9 ± 5) × 10$^{-3}$                               |
|               | Red      | 7 ± 4                         | 1.4 × 10$^4$ | (2 ± 1) × 10$^{-4}$                  | (9 ± 5) × 10$^{-3}$                               |
| G28.87+0.07   | Blue     | 25 ± 12                       | 2.6 × 10$^4$ | (2 ± 1) × 10$^{-4}$                  | (2 ± 1) × 10$^{-2}$                               |
|               | Red      | 90 ± 30                       | 3.1 × 10$^4$ | (2 ± 1) × 10$^{-3}$                  | (5 ± 3) × 10$^{-2}$                               |
| G23.01–0.41   | Blue SW  | 17 ± 12                       | 2.5 × 10$^4$ | (9 ± 7) × 10$^{-4}$                  | (2.5 ± 1.5) × 10$^{-2}$                           |
|               | Blue NE  | 14 ± 10                       | 2.8 × 10$^4$ | (6 ± 3) × 10$^{-4}$                  | (1.9 ± 1.2) × 10$^{-2}$                           |
|               | Red SW   | 140 ± 70                      | 3.4 × 10$^4$ | (4 ± 3) × 10$^{-3}$                  | (1.3 ± 0.7) × 10$^{-1}$                           |
|               | Red NE   | 4 ± 3                         | 3.4 × 10$^4$ | (1.2 ± 0.7) × 10$^{-1}$              | (3.5 ± 3.0) × 10$^{-1}$                           |

Note.—Outflow characteristic estimated from the $^{12}$CO (1–0) data; see §3.4. All the errors are considered only for the $T_{\text{ex}}$ uncertainty.

* $M_{\text{lobe}}$ — Outflow lobe mass.
* $t_d$ — Dynamical timescale.
* $M_{\text{flow}}$ — Outflow mass loss rate.
* $F_{\text{co}}$ — Outflow momentum flux.

Consider only the most prominent lobes, as these represent the dominant contribution to the mechanical luminosity and momentum rate of the outflow system. A caveat to this approach is that the secondary outflow might be weak because it is heavily resolved in our interferometric maps. In other words, one cannot rule out the possibility that better UV sampling at short spacing could reveal a stronger, better defined outflow pattern. Only single-dish mapping of these regions may shed light on this issue.

The outflow parameters are calculated as follows. We integrated the outflow lobe emission encompassing the 5σ level contours to calculate the mass of molecular hydrogen constituting the lobes ($M_{\text{lobe}}$), assuming that the wing emission is optically thin. Indeed, we have estimated the optical depth in the $^{12}$CO line wings for G23.01–0.41, for which $^{13}$CO data are available. We first reconstructed the NMA $^{13}$CO data with the same CLEAN beam as the PdBI $^{12}$CO data and then smoothed the latter to the same spectral resolution as the former. From the ratio between the $^{12}$CO and $^{13}$CO line profiles we computed the optical depth for the blue ($47.2 \text{ km s}^{-1} \leq V_{\text{LSR}} \leq 69.0 \text{ km s}^{-1}$) and red ($79.9 \text{ km s}^{-1} \leq V_{\text{LSR}} \leq 96.2 \text{ km s}^{-1}$) wings, which are, respectively, 0.70 ± 0.2 and 1.1 ± 0.5. This indicates that the correction due to optical depth effects for the outflow mass and the relevant parameters is very small, a factor of $\sim 1.5$. Given the similarity in the source properties, we assumed that the wing emission is also optically thin in G16.59–0.05 and G28.87+0.07 and used the same approach as for G23.01–0.41.

To calculate the outflow parameters, as a lower limit for $T_{\text{ex}}$ we adopted the maximum $T_{\text{ex}}$ observed in all low-density tracers ($\text{CO}$ and HCO$^+$; see Fig. 3), namely, $T_{\text{ex}} = 35 \text{ K}$ for G16.59–0.05, $31 \text{ K}$ for G28.87+0.07, and $15 \text{ K}$ for G23.01–0.41. Subsequently we calculated the kinematical properties of the flow (see Table 7) such as the dynamical timescale ($t_d$), mass-loss rate ($M_{\text{flow}}$), and momentum rate ($F_{\text{co}}$). The uncertainty on $T_{\text{ex}}$ reflects into a 40%–70% uncertainty on $M_{\text{lobe}}$.

One can estimate the outflow velocity from the terminal velocity of the CO spectra and the systemic velocity as $V_{\text{flow}} = |V_t - V_{\text{sys}}|$. The dynamical timescale is then given by $t_d = l_{\text{lobe}}/V_{\text{flow}}$, where the lobe length $l_{\text{lobe}}$ is defined as the maximum extent of the lobe measured from the 3 mm continuum peak. In all cases $t_d$ lies in the range $(1-3) \times 10^4 \text{ yr}$. Note that this estimate of $t_d$ is to be taken as a lower limit because the lobe could be extended beyond our field of view.

The mass-loss rate, $M_{\text{flow}}$, was estimated from the ratio $M_{\text{lobe}}/l_d$ and turns out to be on the order of $10^{-4}$ to $10^{-3} M_\odot \text{ yr}^{-1}$ for all
To derive mean values of $T_{\text{rot}}$ and $N_{\text{CH}_3\text{CN}}$ over the cores using rotation diagrams, we analyzed the mean spectra in Figure 7 obtained by averaging the emission over the regions inside the 5 $\sigma$ contour level of the $K = 0 + 1$ emission map. Assuming that all $K$-components trace the same gas, we performed multiple-Gaussian fitting of the lines, forcing their widths to be identical and their separations in frequency to be equal to the laboratory values. Hence, the free parameters of the fit are the line intensities, the FWHM of the lines, and the LSR velocity of one $K$-component, arbitrarily chosen. Tables 8 and 9 summarize the fitting results, where $V_{\text{sys}}$ is the best-fit LSR velocity. The line intensities were used to make rotation diagrams from which we obtained an estimate of $T_{\text{rot}}$ and $N_{\text{CH}_3\text{CN}}$. Note that our analysis is restricted to use the line intensities were used to make rotation diagrams from which we obtained an estimate of $T_{\text{rot}}$ and $N_{\text{CH}_3\text{CN}}$. Table 9 gives the obtained values of $T_{\text{rot}}$ and $N_{\text{CH}_3\text{CN}}$ for the three HMCs.

The three HMCs have comparable mean $N_{\text{CH}_3\text{CN}}$, spanning the range $(3-7) \times 10^{14}$ cm$^{-2}$ (Table 9), close to the values obtained from interferometric measurements in similar objects (e.g., G24.78+0.08; Beltrán et al. 2005). The mean values of $T_{\text{rot}}$ in G16.59$-0.05$ and G23.01$-0.41$ (120–130 K) are likely to be higher than that of G28.87$+0.07$ (93 K), although our $T_{\text{rot}}$ estimates have rather large errors. In G28.87$+0.07$ both the temperature estimated from NH$_3$ (see Table 9) and the $T_{ab}$ of the CH$_3$CN lines ($\sim 5$ K for $K = 0 + 1$) are 2 times smaller than in the other two sources ($\sim 10$ K), suggesting that CH$_3$CN gas should be colder than in G16.59$-0.05$ and G23.01$-0.41$.

In Table 9, one can notice that the mean $T_{\text{rot}}$ are a factor of 2 higher than the NH$_3$ kinetic temperature ($T_k$) derived from the VLA observations (CTC97). One possible explanation for this discrepancy is that optical depth effects in the CH$_3$CN lines may cause an overestimate of $T_{\text{rot}}$. It is also worth pointing out that the low-energy NH$_3$ transitions observed by CTC97 may be affected by more extended emission (and hence colder gas) than those obtained through the CH$_3$CN lines, as suggested in Olmi et al. (1993). In fact, these authors demonstrate that the two “thermometers,” CH$_3$CN and NH$_3$, are in reasonable agreement for $T \lesssim 50$ K, but for higher temperature the $T_{\text{rot}}$ estimated from CH$_3$CN tends to exceed that from NH$_3$. However, one should keep in mind that the relationship of Olmi et al. (1993) is based on single-dish observations with 6–8 times larger beam sizes than our interferometric measurements and might hence be affected by material extended over larger regions than those imaged by us.

### 3.5.2. Fractional Abundance of CH$_3$CN Molecules in the Cores

We have attempted an estimate of the fractional abundance of CH$_3$CN ($X_{\text{CH}_3\text{CN}}$) from the ratio between the mean $N_{\text{CH}_3\text{CN}}$ (Table 9) and $\langle N(\text{H}_2) \rangle$ calculated in § 3.1.2. Table 9 gives the resultant $X_{\text{CH}_3\text{CN}}$. We stress that the 3 mm emission from the three HMCs is dominated by thermal dust emission (§ 3.1.2). Note that the CH$_3$CN line and 3 mm continuum emission show fairly similar spatial distributions (see panels a and d in Figs. 9–11). It is also worth pointing out that the errors on $X_{\text{CH}_3\text{CN}}$ take into account only uncertainties on the flux calibration (§§ 2.1.1 and 2.1.2). One

### TABLE 8

RESULTS OF CH$_3$CN SPECTRA ANALYSIS

| SOURCE          | TRANSITION | $V_{\text{LSR}}$$^a$ (km s$^{-1}$) | $\Delta v$$^b$ (km s$^{-1}$) | $\int T_{\text{adv}}$ (K km s$^{-1}$) | $K = 0$ | 1 | 2 | 3 |
|-----------------|------------|----------------------------------|------------------------------|-------------------------------------|---------|---|---|---|
| G16.59$-0.05$   | $J = 5-4$  | 59.9 ± 0.2                       | 5.6 ± 0.2                    | 20.5 ± 1.2                          | 14.1 ± 1.2 | 10.5 ± 1.1 | 13.7 ± 1.1 |
| G28.87$+0.07$   | $J = 5-4$  | 103.5 ± 0.3                      | 9.1 ± 0.4                    | 12.9 ± 1.4                          | 11.5 ± 1.5 | 7.8 ± 0.9  | 7.7 ± 0.9  |
| G23.01$-0.41$   | $J = 6-5$  | 77.4 ± 0.1                       | 8.3 ± 0.2                    | 16.2 ± 0.8                          | 16.7 ± 0.8 | 15.0 ± 0.6 | 13.8 ± 0.6 |

$^a$ Centroid velocity from the multiple-Gaussian profile fitting. We adopted the $V_{\text{LSR}}$ in the third column as the $V_{\text{sys}}$ of the HMCs.

$^b$ Line width in FWHM.

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**FIG. 7.**—Mean CH$_3$CN spectra integrated over the 5 $\sigma$ level areas of the three HMCs in flux density ($S_\nu$) scale; $J = 5-4$ for G16.59$-0.05$ and G28.87$+0.07$, and $J = 6-5$ for G23.01$-0.41$. The vertical bars above the spectra indicate the rest frequency of the $K$ rotational ladder emission. The horizontal bars under $K = 0$ and 1 emission indicate frequency ranges to obtain the integrated intensity maps in panel d of Figs. 4–6.
can see that \( X_{\text{CH}_3\text{CN}} \) lies in the range \((0.7 - 2) \times 10^{-9}\), marginally lower than the values quoted for the well-known HMC in Orion \((5 \times 10^{-9}; \text{see van Dishoeck et al. 1993})\).

### 3.6. Velocity Structure and Stability of the CH\(_3\)CN Cores

Our results demonstrate that the ammonia cores imaged by CTC97 are indeed compact \((\approx 0.1 \text{ pc})\), dense \((\approx 10^6 \text{ cm}^{-3})\), and hot \((\approx 10^2 \text{ K})\) molecular cores. This strengthens the idea that high-mass (proto)stars—whose presence is suggested by the presence of H\(_2\)O and OH masers (Forster & Caswell 1989)—are embedded in such massive \((\approx 10^2 M_{\odot})\) HMCs. In the case of G23.01−0.41, we also find evidence of a large-scale clump seen in two CO isotopomers enshrouding the HMC, which is consistent with the findings of other authors (see, e.g., Fontani et al. 2002 and references therein) in similar objects. In this section we wish to perform a more detailed analysis of the HMC structure.

### Table 9

**Summary of Methyl Cyanide RD Analysis**

| Source          | \( R_{\text{ef}} \)^a  (pc) | \( T_{\text{rot}} \) (CH\(_3\)CN) | \( T_i \) (NH\(_3\)) | \( N_{\text{CH}_3\text{CN}} \)^c (cm\(^{-2}\)) | \( X_{\text{CH}_3\text{CN}} \)^d (\( \times 10^{-9}\)) |
|-----------------|-------------------------------|---------------------------------|----------------|---------------------------------|------------------|
| G16.59−0.05     | 0.029                         | 130\(^{+16}_{-13}\)           | 54             | 6.9\(^{+29}_{-15}\) \times 10^{14} | 20 \pm 7            |
| G28.87+0.07     | 0.042                         | 93\(^{+11}_{-12}\)            | 37             | 3.1\(^{+13}_{-10}\) \times 10^{14} | 7 \pm 2            |
| G23.01−0.41     | 0.065                         | 121\(^{+17}_{-13}\)           | 58             | 4.6\(^{+0.9}_{-0.8}\) \times 10^{14} | 13 \pm 4            |

**Note.** For details, see §§ 3.5.1 and 3.5.2.

^a Effective radius for the CH\(_3\)CN \( K = 0 + 1 \) emitting region; see § 3.1.1 for the definition.

^b Rotational temperature for CH\(_3\)CN (§ 3.5.1) and kinetic temperature for NH\(_3\) (CTC97).

^c Total column density of CH\(_3\)CN.

^d Fractional abundance of CH\(_3\)CN obtained from comparisons with the mean \( \langle N(\text{H}_2) \rangle \) in Table 5.
by focusing on the velocity field of the gas, with the purpose of studying the HMC stability and infer the possible presence of rotation.

To gain insight into the velocity field of the gas, we used the same approach as Beltrán et al. (2004); i.e., we determined the velocity in each point of the region where CH$_3$CN is detected, by fitting the CH$_3$CN spectrum in such points with the method described in § 3.5.1. In this way we also obtained the CH$_3$CN line width ($\Delta v_{\text{int}}$) in each point of the map; this is the FWHM after deconvolution of the instrumental resolution (Table 2). In this process, we have considered only those points for which the intensity of the $K = 3$ line was above $5\sigma$. The results are shown in Table 10 and Figures 9–11. It should also be noted that the regions over which the CH$_3$CN velocity could be determined are only barely resolved, being comparable to the synthesized beam width.

**G16.59–0.06.**—The velocity field map of G16.59–0.05 (Fig. 9a) shows a gradient approximately along a line with P.A. $\approx 45^\circ$, roughly perpendicular to the outflow axis. The most blueshifted gas lies at the center, while the most redshifted is seen to the northeast and southwest, close to the border of the region. A map of the line width is shown in Figure 9b and appears to have no correlation with the velocity map.

It would be surprising if the velocity gradient in this core were related to the CO outflow shown in Figure 4, because the two are inconsistent both geometrically and kinematically. On the other hand, it is difficult to believe that the CH$_3$CN velocity is tracing rotation, since in this case the most blue- and redshifted gas should be found at the opposite extremes of the gradient. Furthermore, the velocity gradient corresponds to 1.2 km s$^{-1}$ over 2400 AU, which implies an equilibrium mass of 0.2 $M_\odot$, much less than the mass of the HMC.

We believe, however, that the presence of rotation about the outflow axis cannot be ruled out on the basis of our observations. In fact, the outflow appears to be close to pole-on, which would make the component along the line of sight of the rotation velocity very small and hence difficult to measure.

For a better understanding of the origin of the velocity gradient, one should also explain the positional displacement between

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**TABLE 10**

**PROPERTIES OF THE CENTRAL REGIONS OF THE THREE HMC**

| Source      | $M_{\text{vir}}$ | $\Delta v_{\text{int}}$ | $V_{\text{rot}}$ | $T_{\text{e}}$ | $M_{\text{K}}$ | $M_{\text{C}}$ |
|-------------|-----------------|-----------------|-----------------|-------------|--------------|--------------|
| G16.59–0.05 | 95 ± 6          | 5.4 ± 0.3       | 180 ± 15        | ...         | ...          | ...          |
| G28.87+0.07 | 100 ± 7         | 9.1 ± 0.4       | 780 ± 78        | $\pm 0.5$   | 3 ± 2        | 55 ± 3       |
| G23.01–0.41 | 380 ± 22        | 8.6 ± 0.2       | 1100 ± 40       | $\pm 0.6$   | 8 ± 3        | 340 ± 20     |

**Note.**—For details, see § 3.6.

* From Table 5.

* Intrinsic velocity width ($\Delta v_{\text{int}}$) in FWHM after deconvolving the instrumental velocity resolution (Table 2), where $\Delta v_{\text{int}}$ is measured over the region enclosed by the 50% level contour of the emission. Here contributions of thermal gas motions are 0.38, 0.32, and 0.37 km s$^{-1}$ for G16.59–0.05, G28.87+0.07, and G23.01–0.41, respectively, when we assume that kinematical temperature ($T_{\text{e}}$) of the gas is equal to the mean $T_{\text{rot}}$ in Table 9.

* Virial mass over the CH$_3$CN $K = 0 + 1$ emission. We adopted $R_{\text{vir}}$ in Table 9 for calculating $M_{\text{vir}}$.

* Rotation velocity assuming that the velocity gradient is produced by rotation of the core.

* Core mass calculated from the 3 mm continuum flux density over the region enclosed by the 5 $\sigma$ level contour of the CH$_3$CN.

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**Fig. 9.—** (a) Isovelocity and (b) intrinsic velocity width ($\Delta v_{\text{int}}$) maps obtained from the multiple Gaussian line-profile fitting to the CH$_3$CN emission toward the central portion of the G16.59–0.05 HMC. These maps are presented inside the 5 $\sigma$ level contour (inner solid contour) of the $K = 3$ total maps; the outer solid contour indicates the 5 $\sigma$ level of the $K = 0 + 1$ map. The dashed thin contours show the positive contour for the $K = 0 + 1$ map in Fig. 4. Systemic velocity ($V_{\text{sys}}$) of the HMC is $V_{\text{LSR}} = 59.8$ km s$^{-1}$ (Table 8), and thermal line width at $T_e = T_{\text{rot}} = 130$ K is 0.38 km s$^{-1}$.
the 3 mm and CH$_3$CN peaks. We propose two hypotheses for follow-up studies:

1. The continuum and CH$_3$CN emission might arise from two distinct YSOs, the former deeply embedded in a relatively cold, massive core, the latter associated with hot gas, possibly distributed in a rotating ring, similar to those seen around binary systems in low-mass stars (e.g., GG Tau; Guilloteau et al. 1999); the lack of gas and dust at the center of the ring would explain why the continuum emission from the CH$_3$CN peak is faint.

2. If the newly formed stars lie close to the surface of the core, this might cause a peak in the CH$_3$CN abundance close to the stars themselves and far from the core center, where the dust column density—and hence the millimeter continuum emission—peaks. In this scenario, the 3 mm peak could represent a high-mass protostar, while the CH$_3$CN peak would correspond to a relatively more evolved OB star.

$G28.87+0.08$.—The velocity map of the $G28.87+0.07$ core (Fig. 10a) displays a clear gradient from southeast to northwest plus a less prominent one from northeast to southwest. It is worth reminding that the 3 $\sigma$ contour levels of the 2.6 mm continuum (Fig. 1b) and CH$_3$CN $K = 0 + 1$ emission (Fig. 5d) are slightly elongated in a direction roughly perpendicular to the outflows ($\S$ 3.3.2). Such an elongation is consistent with a flattened circumstellar toroid.

The interpretation of the isovelocity map is complicated by the fact that the number of possible outflows and their structure is unclear in this region (see $\S$ 3.3.2). However, there are a few points worth of consideration:

1. The velocity gradients seen in CH$_3$CN are inconsistent with the outflow velocity—no matter whether the one- or two-outflow hypothesis is correct—because the redshifted CH$_3$CN gas is located approximately to the east-southeast of the core, whereas the redshifted CO emission is found to the west-southwest.

2. If a single outflow is present, its axis (Fig. 10a, solid line) runs perpendicular to the most prominent CH$_3$CN gradient.

3. If instead two outflows are present, neither of these would be orthogonal to either CH$_3$CN velocity gradient.

Assuming that the CH$_3$CN emission is tracing a core rotating about the axis outlined by a poorly collimated CO outflow, the single-outflow hypothesis in $\S$ 3.3.2 seems preferable to the double-outflow scenario. Additional evidence in favor of this scenario is given by the line width map of Figure 10b, which shows that significant line broadening, by $\sim$2 km s$^{-1}$, occurs from the core center to the border, just along the outflow axis.

The CH$_3$CN velocity gradient corresponds to a change of $\pm 1.1$ km s$^{-1}$ over $\pm 1.1 \times 10^4$ AU. If this is due to rotation, the dynamical mass ($M_{\text{dyn}} = \frac{R_{\text{rot}}^2}{G} V_{\text{rot}}^2$) required to balance centrifugal and gravitational forces is equal to $3 \pm 2 M_\odot$ (Table 10). This is an order of magnitude smaller than the mass of the core estimated from 3 mm continuum flux ($M_{\text{core}} \approx 55 M_\odot$; Table 10), over the region where the rotation velocity is measured, and 2 orders of magnitude less than the virial mass ($M_{\text{vir}} \approx R_{\text{vir}}^2 \Delta V_{\text{vir}}^2 / G \approx 1100 M_\odot$; Table 10) obtained for the same region. This fact strongly suggests that even though rotation may be present in the HMC, its contribution to gravitational equilibrium is negligible.

What does support the core against gravitational collapse? Here we should recall that the $\Delta V_{\text{vir}}$ map of Figure 10b does not show a well-defined increase of the velocity width toward the core center, as one sees, instead, in similar objects—for example, G 31.41+0.31 and G24.78+0.08 (Beltrán et al. 2005; see their Figs. 9 and 23). Therefore, our data do not provide any evidence for infall motions toward the core center, so that infall is unlikely to contribute to line broadening. A more likely explanation for the observed line width is that of turbulent motions of the core gas, as turbulence is believed to play a dominant role on the evolution of the core and the star formation process in its interiors (e.g., McKee & Tan 2003).

$G23.01-0.41$.—The G23.01−0.41 core is significantly elongated in the southeast-northwest direction (see Fig. 6d; P.A. $\approx 160^\circ$), namely, perpendicular to the outflow axis, as one can see in the NH$_3$, CH$_3$CN, and 3.3 mm continuum maps in Figure 6. In the same figure, one can appreciate that the C$^{18}$O(1−0) line also presents a tail of emission in the same direction, extending toward the position of the 3 mm continuum peak. All the results strongly suggest that one could be observing a flattened structure rotating about the outflow axis. To shed light on this issue, as already done for the other two sources, we plot in Figure 11a the velocity field of the CH$_3$CN core. Regardless of some scatter, the velocity appears to increase quite steadily along the major axis of the HMC, as expected in case of rotation about the outflow axis.
(Fig 11a, solid line). The velocity shift amounts to 1.1 km s\(^{-1}\) over 2.6 \(\times 10^4\) AU.

Unlike the velocity, the line width increases from northeast to southwest, roughly along the outflow axis. This suggests that to some extent the CH\(_3CN\) emitting gas might also participate in the expansion. This fact could explain why the most blue- and redshifted CH\(_3CN\) emission is observed, respectively, to the north and south of the HMC, although the main velocity trend lies along the southeast-northwest direction. We conclude, that, albeit slightly affected by the outflow, the CH\(_3CN\) line emission from the HMC is mostly tracing rotation.

As already done for G28.87+0.07, we have estimated the mass needed for rotational support of the core. This is \(M_{\text{dyn}} \approx 8 \pm 3 \ M_\odot\), 2 orders of magnitude smaller than the HMC mass \(M_{\text{HMC}} \approx 340 \ M_\odot\) (Table 10). Instead, the virial mass is 5 times larger than the core mass, demonstrating that for G28.87+0.07, as well as for G23.01−0.41, the dominant contribution to core equilibrium is not coming from rotation but from turbulence.

3.7. Comparison with the Other CH\(_3CN\) Cores and Future Considerations

As discussed in § 3.6, we believe that we have found significant evidence of rotation in two of three cores, while in the third object detection of rotation might be hindered by projection effects (rotation axis almost parallel to the line of sight). In any case, rotational motions are undoubtedly less prominent in these two cores than in those (G24.78+0.08 and G31.41+0.31) studied by Beltrán et al. (2004, 2005). Given the low number statistics, it is impossible to draw any conclusion out of this result. However, one cannot rule out the possibility that this is an observational effect. The distance to G23.01−0.41 is 1.4 times larger than that of G24.78 and G31.41, while the angular resolution of our observations is at least 2 times worse than that of the PdBI observations by Beltrán et al. (2004, 2005). Therefore, not only are our observations less sensitive to velocity gradients, but this makes it also more difficult to disentangle the contribution by distinct toroid-outflow systems overlapping in the same region—especially when multiple sources are present as in the case of G28.87+0.07.

In conclusion, we believe that better angular and spectral resolutions are needed to make any search for rotating disks/toroids successful.

Notwithstanding these caveats, it is worth stressing that the mere existence of rotation in two of the HMCs studied by us, albeit insufficient to guarantee support against gravitational forces, is an important clue for the process of high-mass star formation. In addition, one cannot rule out the possibility that, on smaller scales than those imaged by us, conservation of angular momentum might speed up the rotation and thus attain centrifugal equilibrium in a circumstellar disk. This condition will be attained for radii satisfying the relation

\[
R_{eq} = R_{eff} \left( \frac{M_{\text{dyn}}}{M_{\text{HMC}}^{2/3}} \right)^{1/(4-p)}
\]

whose derivation is given in the Appendix. A minimum value of \(R_{eq}\) can be obtained for \(p = 2.5\) (see, e.g., Fontani et al. 2002), which gives \(R_{eq}/R_{eff} \approx 6 \times 10^{-3}\) and \(5 \times 10^{-3}\) for G28.87+0.07 and G23.01−0.41, respectively. Regions like these need sub-arcsecond angular resolution and a higher density tracer than CH\(_3CN\) to be investigated.

4. CONCLUSIONS

Using the OVRO, Nobeyama, and IRAM-PdB millimeter interferometers, we carried out an intensive search for rotating toroids toward the massive YSOs in G16.59−0.05, G28.87+0.07, and G23.01−0.41 which exhibit no or faint free-free emission (CTC97). Our observations revealed that these objects are embedded in HMCs with masses of 95−380 \(M_\odot\) and temperatures of 93−130 K, making the cores typical sites of high-mass (proto)star formation. All three objects harbored in the HMCs are driving powerful (\(F_{\text{co}} \approx 10^{-3}\) to \(10^{-2}\) \(M_\odot\) km s\(^{-1}\) yr\(^{-1}\) CO outflows. However, the nature of the outflows in G28.87+0.07 and G23.01−0.41 is unclear; the origin of high-velocity wing emission may be attributed to either single or double outflow(s). Such ambiguity made the interpretation of velocity gradients, identified through CH\(_3CN\) K-ladder line analysis, existing in the innermost densest part of the G28.87+0.07 and G23.01−0.41 HMCs fairly difficult. The velocity gradients are almost perpendicular to their molecular outflow axes, suggesting the presence of rotating, flattened structures. However, the corresponding dynamical masses are an order of magnitude smaller than the masses derived from 3 mm dust continuum emission, which indicates turbulent
pressure as the dominant support of the HMCs. No conclusion could be reached for the third source, G16.59−0.05, as the putative rotation axis appears to lie close to the line of sight, thus making the detection of the rotation velocity very difficult for projection effects. Further higher resolution imaging will allow us to establish the presence of rotation on more solid ground.

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APPENDIX

CENTRIFUGAL RADIUS

Here we calculate an expression of the radius at which the centrifugal equilibrium can be attained inside a rotating, spherically symmetric core. The hypothesis is that the rotation velocity $V_{\text{rot}}$ observed at radius $R_{\text{eff}}$ is not sufficient to sustain the core against gravitational forces, thus allowing contraction and speed up of the gas in the core until centrifugal equilibrium is attained. If this occurs at radius $R_{\text{eq}}$ with velocity $V_{\text{eq}}$, conservation of angular momentum per unit mass gives the following relation:

$$V_{\text{eq}} R_{\text{eq}} = V_{\text{rot}} R_{\text{eff}}, \quad (A1)$$

while the equilibrium condition turns into

$$\frac{V^2_{\text{eq}}}{R_{\text{eq}}} = \frac{G M(R_{\text{eq}})}{R_{\text{eq}}}. \quad (A2)$$

The mass $M(R)$ contained inside radius $R$ depends on the dependence of the gas volume density $n$ on the radius. Assuming that $n$ varies with $R^{-p}$, one obtains $M(R) \propto R^{3-p}$. Therefore, we can write the following relation:

$$M(R_{\text{eq}}) = M(R_{\text{eff}}) \left( \frac{R_{\text{eq}}}{R_{\text{eff}}} \right)^{3-p}, \quad (A3)$$

where $M(R_{\text{eff}}) = M_{\text{dust}}^{K=3}$ measured by us from the mm continuum emission.

Substituting $V_{\text{eq}}$ from equation (A1) and $M(R_{\text{eq}})$ from equation (A3) into equation (A2), and replacing $V_{\text{rot}}$ with $M_{\text{dyn}}$ from the definition, we find

$$M_{\text{dyn}} = \frac{R_{\text{eff}} V^2_{\text{rot}}}{G}, \quad (A4)$$

one consequently obtains the expression of $R_{\text{eq}}$ as a function of measurable quantities:

$$R_{\text{eq}} = R_{\text{eff}} \left( \frac{M_{\text{dyn}}}{M_{\text{dust}}^{K=3}} \right)^{[1/(4-p)]}. \quad (A5)$$

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