SIGNATURES OF INFLOW MOTION IN CORES OF MASSIVE STAR FORMATION: POTENTIAL COLLAPSE CANDIDATES

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ABSTRACT

Using the IRAM 30 m telescope, a mapping survey in optically thick and thin lines was performed toward 46 high-mass-star-forming regions. The sample includes UC H II precursors and UC H II regions. Seventeen sources are found to show “blue profiles,” the expected signature of collapsing cores. The excess of sources with blue over red profiles \(\langle N_{\text{blue}} - N_{\text{red}} \rangle/N_{\text{total}}\) is 29% in the HCO\(^+\) \(J = 1\rightarrow 0\) line, with a probability of 0.6% that this is caused by random fluctuations. UC H II regions show a higher excess (58%) than UC H II precursors (17%), indicating that material is still accreted after the onset of the UC H II phase. Similar differences in the excess of blue profiles as a function of evolutionary state are not observed in low-mass-star-forming regions. Thus, if confirmed for high-mass-star-forming sites, this would point to a fundamental difference between low- and high-mass-star formation. Possible explanations are inadequate thermalization, stronger influence of outflows in massive early cores, larger gas reserves around massive stellar objects, or different trigger mechanisms between low- and high-mass-star formation.

Subject headings: ISM: kinematics and dynamics — ISM: molecules — radio lines: ISM — stars: formation

1. INTRODUCTION

Inflow motion is a fundamental phenomenon during stellar formation. Although the search for inflow is usually more difficult than that for outflow, studies of inflow have made great progress since the 1990s. In low-mass-star-forming regions, inflow motions were detected at different evolutionary stages, including Class –1, Class 0, and Class I cores (Zhou et al. 1993; Mardones et al. 1997; Lee et al. 1999; Gregersen et al. 2000; Evans 2003). Recently, a number of inflow candidates were found in high-mass-star-formation regions. Among a sample of 28 massive cores, 12 were found to show line profiles that peak at blueshifted velocities (hereafter “blue profiles”; see § 3.1), the expected signature of inflow (Wu & Evans 2003). Fuller et al. (2005, hereafter FWS05) detected such asymmetric profiles in 22 cores within a sample of 77 high-mass protostellar objects (HMPOs). Most recently, Wyrowski et al. (2006) detected nine sources with a blue profile in a sample of 12 ultracompact (UC) H II regions.

Variation of inflow motion with time is critical for high-mass-star formation. It has been indicated that when a protostar reaches \(>10\ M_\odot\) it can generate enough radiation pressure to halt spherical infall and inhibit its mass increase (Wolfire & Cassinelli 1987). Observationally, however, it is not yet clear how inflow is related to the evolution of massive (proto)stars. To study this problem, we have carried out a survey for a sample including both cores of UC H II regions and precursors of UC H II regions.

While previous surveys using single-point observations provided some statistical evidence for the occurrence of inflow within massive cores, blue profiles can also be caused by rotation. Therefore maps of the molecular environment are indispensable. Mapping also allows us to locate the center of the inflow and to identify cores that are simultaneously showing evidence for in- and outflow.

Therefore, we conducted a mapping survey including 46 high-mass-star-forming regions which were selected applying three criteria: (1) the sources must have been mapped in the submillimeter or millimeter wavelengths with continuum or spectroscopy; (2) signal-to-noise ratios should be \(>5\) at 350 \(\mu\)m (Mueller et al. 2002) and higher at other wavelengths; (3) there should be no other core within \(1''\) (Zinchenko et al. 1997; Hunter et al. 1998; Tieftrunk et al. 1998; Hatchell et al. 2000; Molinari et al. 2000; Beuther et al. 2002; Mueller et al. 2002). With respect to their stellar content, we can divide the sample into two different groups of targets: (1) Thirty-three sources lack 6 cm continuum emission and are precursors of UC H II regions or HMPOs (Molinari et al. 2000; Beuther et al. 2002). Among these, 30 host a luminous IRAS source. The remaining three are associated with IRAC (the InfraRed Array Camera on the Spitzer Space Telescope) point sources (W3-W and W3-SE) or do not host an IRAC source (18454-3). All 33 cores comprise “group I.” (2) Thirteen UC H II regions are assigned to “group II.” This letter presents a list of the identified collapse candidates and provides the statistics of blue excesses. Detailed properties of individual cores will be analyzed in a future paper.

2. OBSERVATIONS

The observations were performed with the IRAM 30 m telescope at Pico Veleta, Spain, from 2005 July 28 to August 1. Four receivers were used simultaneously, usually two at \(\lambda \sim 3\ mm\) and two at \(\lambda \sim 1.3\ mm\) (A/B configuration). For some sources, none of the four 3 and 1.3 mm lines were optically thin. In these cases the tracer lines were changed employing two receivers at \(\lambda \sim 2\ mm\) and the other two to cover the upper part of the 1.3 mm window (C/D configuration). The lines and corresponding beam sizes, efficiencies, and channel widths are given in Table 1. The channel spacing and the bandwidth are 78.125 kHz and 105 MHz, respectively. The weather was extremely good for summer conditions, allowing us to observe the HCO\(^+\) \(J = 3\rightarrow 2\) transition at 268 GHz and leading to 3 and 1.3 mm (2 and 1.2 mm) system temperatures of order 150 and 400 K (200 and 550 K) on a \(T_A^*\) scale. Pointing and cal-

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TABLE 1

| Number | Line          | Frequency (GHz) | HPBW (arcsec) | $\eta_{\text{obs}}$ | $\Delta V_{\text{exp}}$ (km s$^{-1}$) |
|--------|---------------|----------------|--------------|---------------------|-------------------------------------|
| 1      | HCO$^+$ (1−0) | 89.18852       | 27.6         | 0.77                | 0.263                               |
| 2      | HCO$^+$ (3−2) | 267.55763      | 9.2          | 0.45                | 0.112                               |
| 3      | CS (3−2)      | 146.96905      | 16.7         | 0.69                | 0.159                               |
| 4      | CS (5−4)      | 244.93361      | 10.0         | 0.49                | 0.122                               |
| 5      | NH$_3$ (1−0)  | 93.17378       | 26.4         | 0.77                | 0.251                               |
| 6      | C$^{18}$O (1−0) | 109.78218     | 22.4         | 0.75                | 0.213                               |
| 7      | C$^{18}$O (2−1) | 219.56033     | 11.2         | 0.55                | 0.207                               |
| 8      | C$^{18}$O (1−0) | 112.35298     | 21.9         | 0.74                | 0.209                               |
| 9      | C$^{18}$O (2−1) | 224.71437     | 10.9         | 0.54                | 0.133                               |
| 10     | C$^{12}$S (3−4) | 241.01618     | 10.2         | 0.50                | 0.122                               |

Notes.—HPBW, half-power beam width; $\eta_{\text{obs}}$, beam efficiency; $\Delta V_{\text{exp}}$, channel width.

3. RESULTS AND DISCUSSION

3.1. Blue-Profile Identification

For self-absorbed optically thick lines, the classical signature of inflow is a double-peaked profile with the blueshifted peak being stronger, or a line asymmetry with the peak skewed to the blue side, while optically thin lines should show a single-velocity component peaking at the line center.

Among the 46 cores observed, five (05490+2658, G31.41+0.31, 18454−3, 18454−4, 19266+1745) will be ignored because they show either too complex spectral profiles, inhibiting a detailed analysis, or a lack of optically thin lines. Estimates of optical depths were obtained from line ratios between different isotopomers of CO and CS and from the relative intensities of individual hyperfine components in the case of C$^{13}$O and NH$_3$. C$^{18}$O, C$^{13}$C, C$^{18}$S, and NH$_2$ tend to be optically thin, while CS is optically thick. HCO$^+$ opacities could not be estimated. However, the similarity of HCO$^+$ and CS line shapes (see § 3.2) as well as the results of Gregersen et al. (2000) and FWS05 clearly indicate that HCO$^+$ is also optically thick.

The 41 remaining sources were detected in at least one optically thick and one optically thin line. A blue profile caused by inflow motion with velocity $v \propto r^{-1/2}$ in a region with higher excitation temperature ($T_r$) inside requires $T_r(B)/T_r(R) > 1$. Here $r$ is the radius of the collapsing core (Zhou et al. 1993). $T_r(B)$ and $T_r(R)$ are the blue and red peak intensities of the optically thick line. We also define a dimensionless asymmetry parameter following Mardones et al. (1997), $\Delta V = (V_{\text{blue}} - V_{\text{thin}})/\Delta V_{\text{thin}}$. Here $V_{\text{blue}}$ is the peak velocity of the opaque line; $V_{\text{thin}}$ and $\Delta V_{\text{thin}}$ denote the peak velocity and width of the optically thin line. Only for $\Delta V < -0.25$ or $0.25 >$ is the line profile rated blue or red, respectively.

Our sources (Table 2) discriminate among five main types of line shapes: (1) cores with lines showing a “blue profile” (in the following denoted with B); (2) cores with lines showing

TABLE 2

| Source Name | $\alpha$ (J2000.0) | $\delta$ (J2000.0) | $D'$ (kpc) | Profile$^a$ | Ref. |
|-------------|--------------------|--------------------|------------|-------------|------|
| W3-W        | 02 25 32.4         | +62 06 01          | 1.95       | B           | 1    |
| W3-C$^4$    | 02 25 39.5         | +62 05 51          | 2.3        | B           | 1    |
| W3-S$^5$    | 02 25 41.4         | +62 04 11          | 2.3        | B           | 1    |
| 05358+3543$^3$ | 05 39 10.4        | +35 45 19          | 1.8        | BRS         | 3, 7 |
| 05490+2658$^4$ | 05 52 12.9        | +26 59 33          | 2.1        | ...         | 3, 7 |
| G10.47+0.03$^5$ | 18 08 38.2        | -19 51 50          | 5.8        | B           | 10   |
| G12.42+0.50$^5$ | 18 10 51.8        | -17 55 56          | 2.1        | B           | 2    |
| G12.89+0.49$^5$ | 18 11 51.3        | -17 31 29          | 3.5        | BRL         | 2, 3, 9 |
| G13.87+0.28$^5$ | 18 14 35.4        | -16 45 37          | 4.4        | S?          | 10   |
| 18144−1725NW$^6$ | 18 17 23.8       | -17 22 09          | 4.33       | R           | 5    |
| 18182−1433$^3$ | 18 21 07.9        | -14 31 53          | 4.5        | B           | 3, 7 |
| G19.61$^7$  | 18 27 37.9         | -11 56 07          | 4.0        | S?          | 2    |
| 18286−1152$^8$ | 18 29 14.3        | -11 50 26          | 3.5        | R           | 3, 7 |
| 18306−0835$^9$ | 18 33 21.8        | -08 33 38          | 4.9        | R           | 3, 7 |
| G24.49−0.04$^8$ | 18 36 05.3        | -07 31 23          | 3.5        | B           | 2, 11 |
| 18337−0743NE$^8$ | 18 36 45.9       | -07 39 20          | 4.0        | BRL         | 3    |
| 18355−0650$^{*}$ | 18 38 14.2        | -06 47 47          | 4.2        | B           | 8    |
| 18372−0541$^5$ | 18 39 56.0        | -05 48 19          | 4.8        | B           | 3, 7 |
| 18385−0512E$^6$ | 18 41 13.3        | -05 09 06          | 2.0        | R           | 3, 7 |
| G31.41+0.31$^1$ | 18 47 34.7        | -01 12 46          | 7.9        | ...         | 10   |
| 18453−3$^3$ | 18 47 55.9         | -01 53 56          | 5.6        | ...         | 3, 7 |
| 18454−d$^a$ | 18 48 01.4         | -01 52 37          | 5.6        | ...         | 3, 7 |
| 18470−0044$^a$ | 18 49 36.7        | +00 41 05          | 8.2        | R           | 3, 7 |

Notes.—$^{*}$ Indices I and II attached to the source names denote groups I and II, respectively (see § 1); the asterisk (*) denotes the optically thin line as quoted from X. Luo & Y. Wu (2007, in preparation).

References.—(1) Tieftrunk et al. 1998; (2) Mueller et al. 2002; (3) Beuther et al. 2002 and references therein; (4) Zinchenko et al. 1997; (5) Molinari et al. 2000; (6) Hunter et al. 1998; (7) Srividyan et al. 2002; (8) Wu et al. 2006 and references therein; (9) Hughes & MacLeod 1994; (10) Hatchell et al. 2000; (11) Lockman 1989.
3.2. Collapse Candidates and Their Profile “Excess”

With the criteria outlined in § 3.1, 17 inflow candidates are identified (see Table 2). Ten belong to group I and seven are part of group II. To provide a typical example, Figure 1 shows the infall signature of the group I core W3-SE. Figure 1a displays the HCO$^+$ (1–0) spectra, showing the angular size of the core. Figure 1b shows a number of profiles toward the central position. The HCO$^+$ (1–0) and (3–2) lines as well as the CS(3–2) transition show the blue asymmetry. For the HCO$^+$ (1–0) line this is also demonstrated in the position-velocity (P-V) diagram of Figure 1c. For comparison, Figure 1d shows a P-V diagram of the optically thin transition C$^{18}$O(1–0) emission.

The quantity “excess” as defined by Mardones et al. (1997) is $E = (N_B - N_R)/N_T$, where $N_B$ and $N_R$ mark the numbers of sources with blue and red profiles. $N_T$ is the total number of sources. For our survey the excess was calculated for the two HCO$^+$ transitions and the CS(3–2) line. Figure 2 shows the log $[T_B/\sigma(B)/T_R^\alpha(R)]$ and $\delta V$ (see § 3.1) distributions of the three individual lines. Statistical results are given in Table 3. The observed excess derived from the HCO$^+$ (1–0) and (3–2) lines is 0.29 and 0.11, respectively. Both are larger than those obtained by FWS05 for the same lines (0.15 and 0.04). For the CS transition we obtain 0.29. To evaluate the statistical significance of the determined values, we conducted the binomial test (see FWS05 and references therein). Probabilities that the excesses are a product of a random distribution are given in the last column of Table 3. These are 0.006 and 0.01 for HCO$^+$ (1–0) and CS(3–2), respectively. Apparently, both lines are sensitive tracers of potential inflow motion.

To evaluate differences between the two classes of cores (I and II; see § 1) with respect to the excess, we used the HCO$^+$ (1–0) line, which was mapped in the largest number of sources. The results listed in the lower part of Table 3 include 16 sources with profiles of type B. The excesses observed for groups I and II are 0.17 and 0.58, respectively. Twenty of our 46 sources overlap with those of FWS05. Among them are 19 group I sources (out of 33), but only one source is from group II (out of 13). Our study includes various CO and CS lines. We also made maps. Thus we can view the common objects from a different perspective and can check
TABLE 3

| Line/Source | $N_p$ | $N_r$ | $N_t$ | $E$  | $p$  |
|-------------|-------|-------|-------|-----|-----|
| HCO$^{+}$'–1) | 16    | 4     | 41    | 0.29| 0.006 |
| HCO$^{+}$'–3) | 8     | 5     | 28    | 0.11| 0.29  |
| CS(3–2)     | 9     | 1     | 28    | 0.29| 0.01  |

Notes.—$N_p$, number of blue profiles; $N_r$, number of red profiles; $N_t$, total number of observed sources; $E$, excess; $p$, statistical likelihood that the result is caused by random fluctuations (see § 3.2). Note that only 15 of the 17 inflow candidates show blue profiles in the HCO$^{+}$'–0) line. The other two are identified by their CS(3–2) and HCO$^{+}$'(3–2) spectra. One of the 16 HCO$^{+}$'–0) blue profiles is a BRL source (see § 3.1).

We have carried out a mapping survey toward 46 molecular cores associated with massive-star formation. Seventeen collapse candidates were identified. Among them are 10 UC HII precursors and 7 UC HII regions. Overall, statistical results indicate a predominance of blue over red profiles which is surprisingly similar to that obtained toward cores forming low-mass stars. Among high-mass-star-forming sites, the probability of detecting blue profiles seems to depend on evolutionary stage and increases from UC HII precursors to UC HII regions. Toward low-mass-star-forming sites, however, this effect is not observed, suggesting a more fundamental difference in the way stellar masses are assembled. Larger line surveys and more detailed maps in various molecular transitions are needed to improve statistical evidence in order to confirm or to reject this potentially important finding.

4. OUTLOOK

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how far the choice of different molecular transitions and the presence of maps is leading to contradictions with previously published results. Differences are indeed significant. For eight of the 19 overlapping type I cores we obtain different line asymmetry classifications, emphasizing the need for detailed maps. Nevertheless, the overall difference in the HCO$^{+}$'–0) excess is negligible (0.17 vs. 0.15).

To summarize, both data sets indicate that the HCO$^{+}$'–1) excess is low for UC HII precursors. For UC HII regions, our results and those of Wyrowski et al. (2006) suggest that the excess is larger and more significant. From the binomial test results and those of Wyrowski et al. (2006) suggest that the increase of inflow (Vorobyov & Basu 2005). However, high-mass stars form in giant molecular clouds and their inflow motions are not easily halted by the exhaustion of molecular gas before most of it is dispelled. (4) In low-mass cores, star formation may be spontaneous. In high-mass cores, collapse may be triggered by extrinsic disturbances and the collapse may take more time to develop.

With respect to potential selection effects, we used the same criteria to identify the targets of the two separate groups of sources. Since this study is based on a limited number of sources, more data quantifying the blue excess as a function of evolutionary stage would be highly desirable.

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