HIGH-RESOLUTION OBSERVATIONS OF MOLECULAR LINES TOWARD THE HOT CORE G28.20–0.04N

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ABSTRACT

We present the results from arcsecond resolution observations of various line transitions at 1.3 mm toward hypercompact H II region G28.20–0.04N. With the SMA data, we have detected and mapped the transitions in the CH3CN, CO, 13CO, SO2, OCS, and CH3OH molecular lines as well as the radio recombination line H30α. The observations and analysis indicate a hot core associated with G28.20–0.04N. The outflow and possible rotation are detected in this region.

Subject headings: H II regions — ISM: individual (G28.20–0.04N) — ISM: kinematics and dynamics — ISM: molecules — radio lines: ISM — stars: formation

1. INTRODUCTION

The scenario of massive star formation remains unclear and has been observationally challenging because of large distances, clustered formation environments, and shorter evolutionary timescales of massive stars. Ultracompact H II (UCHII) regions are considered signposts of massive star formation, but do not represent the earliest stage of the massive star forming process (e.g., Churchwell 2002). Hot molecular cores are defined as compact (≤0.1 pc), dense (≥107 cm−3), and warm (≥100 K) molecular cloud cores (Kurtz et al. 2000). The observations from various wavelengths have suggested that hot cores are the sites for massive star formation, and that they represent the early phase of the evolution prior to UCHII regions (Cesaroni et al. 1994; Hofner et al. 1996; Kurtz et al. 2000; Gibb et al. 2000, 2004; Churchwell 2002). So far only 20 or so hot cores from high-resolution observations have been reported in the literature. The observations of hot cores are important for understanding the evolutionary sequence and physical conditions of massive star formation. Hypercompact H II (HCHII) regions have smaller sizes and higher densities compared with UCHII regions, and they probably correspond to a transition phase from hot cores to UCHII regions.

The HCHII region G28.20–0.04N at a distance of 5.7 kpc has been observed at radio and millimeter wavelengths (Fish et al. 2003; Sollins et al. 2005; Sewilo et al. 2004, 2008; Keto et al. 2008). Masers, rotation, inflow, and outflow in G28.20–0.04N have been revealed from observations of molecular and radio recombination lines at centimeter wavelengths (Argon et al. 2000; Menten 1991; Sollins et al. 2005; Sewilo et al. 2008). However, the star formation environment and physical conditions of the hot core in this region are still poorly understood.

Due to the compact and dense nature of hot cores, high angular resolution observations using molecular lines with high critical densities and excitation temperatures at (sub)millimeter wavelengths are crucial to uncovering the physical conditions and kinematics in G28.20–0.04N. In this Letter, we present the Submillimeter Array (SMA) observations of molecular lines at 1.3 mm toward the hot core in G28.20–0.04N.

2. DATA

The data are from SMA archive. Observations toward G28.20–0.04N were carried out with the SMA in 2005 September, at 220 GHz (lower sideband) and 230 GHz (upper sideband) with a frequency resolution of 0.4125 MHz and an angular resolution of 1″. The mean system temperature was 100 K. In the database, QSO 3c454.3 and Uranus were observed for bandpass and flux-density calibrations. QSOs 1743–038 and 1911–201 were also observed for the antenna-based gain corrections. The calibration and imaging were done in Miriad. Multiple lines were detected in both sidebands. Using the task UVLIN in Miriad, the continuum level was determined by a linear fitting to the line-free channels. Then, the calibrated (u, v) data were separated for two output (u, v) data sets: the continuum and the continuum-subtracted spectral lines. In order to improve sensitivity, we smoothed the H30α, CO, and 13CO lines to 2 km s−1 velocity resolution, and smoothed the rest of the lines to 1 km s−1 velocity resolution. Self-calibration was performed to the continuum data. The gain solutions from the continuum were applied to the line data. The synthesized beam size of the continuum and line images with robust weighting was approximately 1.3″ × 0.8″ (P.A. = −89.6°).

3. RESULTS

The molecular lines were identified using the CDMS and JPL databases (Müller et al. 2005; Pickett et al. 1998), and the data by Sutton et al. (1985) and Nummelin et al. (1998). The molecular lines CH3CN, CO, 13CO, SO2, OCS, and CH3OH and the radio recombination line H30α were detected and identified from the lower and upper sidebands of the SMA observations. Table 1 lists the parameters of the detected molecular transitions.

Combining the lower and upper sideband data, we made continuum image from line-free channels at 1.3 mm, as shown in Figure 1a. The rms (1σ) noise level is 0.003 Jy beam−1. The observations show an unresolved core peaked at R.A.(J2000.0) = 18h42m58s.120 (ΔR.A. = ±0.02″),
decl.(J2000.0) = −4°13′57.40″ (Δdecl. = ±0.02″) with a peak intensity of 0.67 ± 0.02 Jy beam$^{-1}$. The total flux density and deconvolved source size from the Gaussian fit are approximately 0.89 ± 0.03 Jy and 0.6′ × 0.2′ (P.A. = −10.1°), respectively. The thick contours in Figure 1a are the integrated intensity map of the radio recombination line H30α. The SMA observations show that the peak position of the continuum is consistent (within 0.03″) with that of the H30α line image in G28.20−0.04N. Most likely the continuum emission in this observation comes from free-free emission (see Fig. 10 of Keto et al. 2008).

The line images were constructed from the maps of the continuum-subtracted spectral channels. Figure 1b shows the integrated intensity contours of the CH$_3$CN (122–112) transition. The major axis of the line image is approximately 1.4″, corresponding to a projected linear size of <0.04 pc. In order to avoid the cancellation of the integrated intensities of the emission (positive values) and absorption (negative values) in the overlapping region along the line of sight, the emission and absorption in CO and 13CO were handled separately for the integrated intensity maps, as done by Qin et al. (2008). Figure 1c presents the integrated intensity map of the 13CO. The absorption against the continuum and the emission were observed as shown in Figure 1c. No absorption was evident in the H30α and CH$_3$CN lines. Away from the continuum, the absorption was not observed. Figure 2 presents the spectra of the molecular line transitions. The spectra were extracted from the channel maps at the peak positions of the line images. In Figure 2, the emission spectra have similar profiles, showing single emission peak with similar line center velocity and line width. Gaussian fits were performed on all the spectra. The peak intensity ($I_p$), full width at half-maximum ($ΔV$), and central line velocity ($V_{LSR}$) from the Gaussian fits are summarized in Table 1. The radial velocities range from 95 to 96 km s$^{-1}$ (except for the 13CO, CO, and H30α lines). Compared with the SO$_2$, OCS, CH$_3$OH, and CH$_3$CN lines, the 13CO line with lower excitation temperature shows both absorption and emission components. Absorption can be observed if the excitation temperature of gas in front of the background continuum is lower than the brightness temperature of the continuum. Absorption is also observed in the CO line.

### Table 1: Molecular Line Parameters

| Molecule | Transition | Frequency (MHz) | $E_J$ (K) | $I_p$ (Jy beam$^{-1}$) | $ΔV$ (km s$^{-1}$) | $V_{LSR}$ (km s$^{-1}$) | Channel rms (Jy beam$^{-1}$) |
|----------|------------|----------------|-----------|------------------------|-----------------|------------------------|---------------------------|
| CO       | 2−1       | 230538.00      | 17        | −0.2 ± 0.07            | 9.9 ± 3.0       | 79.9 ± 1.3             | 0.07                      |
|          |           |                | ...       | −0.3 ± 0.07            | 10.3 ± 4.5      | 94.1 ± 1.6             | ...                       |
|          |           |                | ...       | 0.28 ± 0.09            | 7.1 ± 2.1       | 103.1 ± 1.3            | ...                       |
| 13CO     | 2−1       | 220398.68      | 16        | −0.29 ± 0.05           | 4.8 ± 0.8       | 77.1 ± 0.4             | 0.05                      |
| SO$_2$   | 11$_{11}$−10$_{10}$ | 221965.21   | 60        | 0.3 ± 0.05             | 6.3 ± 0.9       | 104.3 ± 0.4            | ...                       |
| CH$_3$OH | 10$_{0}$−9$_{0}$ | 231281.10   | 166       | 0.3 ± 0.07             | 4.6 ± 0.8       | 95.5 ± 0.3             | 0.07                      |
| CH$_3$CN | 12$_{2}$−11$_{1}$ | 220747.26   | 69        | 1.1 ± 0.08             | 3.8 ± 0.3       | 95.1 ± 0.1             | 0.08                      |
|          | 12$_{2}$−11$_{1}$ | 220743.01   | 76        | 1.2 ± 0.08             | 4.9 ± 0.4       | 95.0 ± 0.1             | 0.08                      |
|          | 12$_{2}$−11$_{1}$ | 220730.26   | 97        | 0.9 ± 0.08             | 4.1 ± 0.3       | 95.3 ± 0.1             | 0.08                      |
|          | 12$_{2}$−11$_{1}$ | 220709.02   | 133       | 1.0 ± 0.08             | 4.2 ± 0.3       | 95.4 ± 0.1             | 0.08                      |
|          | 12$_{2}$−11$_{1}$ | 220679.29   | 183       | 0.6 ± 0.08             | 4.8 ± 0.5       | 95.4 ± 0.2             | 0.08                      |
|          | 12$_{2}$−11$_{1}$ | 220641.09   | 247       | 0.7 ± 0.07             | 3.9 ± 0.3       | 95.3 ± 0.1             | 0.07                      |
|          | 12$_{2}$−11$_{1}$ | 220594.43   | 325       | 0.6 ± 0.08             | 3.3 ± 0.4       | 95.8 ± 0.2             | 0.08                      |
| H30α     |           | 231900.96     | ...       | 0.9 ± 0.2              | 20.9 ± 0.6      | 92.5 ± 0.2             | 0.06                      |

$^a$ Negative values of the intensity ($I_p$) in the CO and 13CO spectra indicate the absorption. Positive values indicate the emission.

$^b$ The two CH$_3$CN transitions (12$_{2}$−11$_{1}$) and (12$_{2}$−11$_{1}$) were blended.

$^c$ H30α line parameters are cited from the paper by Keto et al. (2008).

4. DISCUSSIONS

4.1. Hot Core

Methyl cyanide (CH$_3$CN) has been proved as an ideal probe to determine the kinetic temperature and column density of molecular gas (e.g., Remijan et al. 2004). Seven K-components of the CH$_3$CN ($J = 12−11$) transition were detected by the SMA observations. From the integrated intensities, in the limits of optically thin and local thermodynamic equilibrium (LTE), the rotation temperature and column density are estimated using a rotation temperature diagram (Goldsmith & Langer 1999; Liu et al. 2002). Figure 3 shows the rotation temperature diagram. A linear least-squares fit is performed toward the seven CH$_3$CN transitions. The derived rotation temperature and beam-averaged column density are 308 ± 22 K and (1.6 ± 0.3) × 10$^{16}$ cm$^{-2}$, respectively. In the Orion molecular cloud, the CH$_3$CN transitions were only detected in the hot core and the compact ridge, giving fractional abundances relative to H$_2$ of 7.8 × 10$^{-9}$ and 3.2 × 10$^{-10}$, respectively (Blake et al. 1987). Taking source size of 0.04 pc and the fractional abundance in the Orion cloud, we inferred the H$_2$ density of >10$^7$ cm$^{-3}$ in G28.20−0.04N. The relatively higher gas temperature (308 ± 22 K), H$_2$ density (>10$^7$ cm$^{-3}$), and smaller size (<0.04 pc) indicate a hot core in this region.

Following Gibb et al. (2000), we adopt 3 × 10$^{24}$ cm$^{-2}$ as a typical H$_2$ column density. Using this value, we calculate a fractional abundance of CH$_3$CN relative to H$_2$ of 5 × 10$^{-9}$. The derived abundance is close to that in the Orion hot core (Blake et al. 1987). The derived rotation temperature agrees (within 2 σ of the least-squares fit) with the value of 280 K estimated by the NH$_3$ lines (Sollins et al. 2005). The similar gas temperatures derived from the CH$_3$CN and NH$_3$ lines suggest a close relationship between the two N-containing species. The gas-phase chemistry likely dominates the pathways to produce CH$_3$CN (Rodgers & Charnley 2001), in which NH$_3$ evaporates from grain surfaces and CH$_3$CN is then formed via gas-phase reactions at high temperatures. Based on the high temperature (300 K) gas-phase chemical model (Rodgers & Charnley 2001), if NH$_3$ is injected for the chemical reactions, the derived fractional abundance of the CH$_3$CN of 5 × 10$^{-9}$ corresponds to a timescale of 1.5 × 10$^{5}$ yr which is in good agreement with those (1.9 × 10$^{7}$−5.7 × 10$^{5}$ yr) ob-
Fig. 1.—Continuum and spectral images. (a) The continuum (thin contours) is superimposed on the H30α radio recombination line image (thick contours). The synthesized beam is 1.3″ × 0.8″, P.A. = −89.6° (lower right corner). The rms (1 σ) noise level of the continuum is 0.003 Jy beam −1. The contours are 4, 4, 8, 16, 32, 64, 128, 190, and 220 Jy beam −1. The cross symbol indicates the peak position of the continuum source. The contours of the H30α integrated intensity are 1.24, 1.24, 3.68, 6.13, 8.58, 11.03, 13.48, 15.93, 18.38, 20.83, and 23.28 Jy beam km s −1. (b) The CH3CN (12 −11) integrated intensity contours. The levels are 0.74, 0.74, 1.23, 1.72, 2.21, 2.70, 3.19, 3.68, 4.17, and 4.66 Jy beam −1 km s −1. (c) The 13CO (2 −1) integrated intensity contours. The levels are −2, −1.8, −1.6, −1.4, −1.2, −1, −0.8, −0.6, 1, 1.3, 1.6, 1.9, 2.2, 2.5, 2.8, and 3.1 Jy beam −1 km s −1; the positive and negative values indicate the emission and absorption, respectively.

Fig. 2.—Molecular spectra averaged over one beam. The solid and dashed curves are the observed spectra and the Gaussian fitting to the spectra, respectively. (a–f) Various K components in the CH3CN (12−11) transition. (g–j) OCS (19−18), CH3OH (10−9), CO (2−1), and 13CO (2−1) transitions, respectively. The spectra are Hanning smoothed for better signal-to-noise ratios. Negative and positive values of the intensity in the CO and 13CO spectrum indicate absorption and emission, respectively.

For the 13CO absorption component in Figure 1c, the derived optical depth of the line peak is 0.57 by use of the line-to-continuum ratio (see eq. [1] of Qin et al. 2008). The intensity of 1 Jy beam −1 in this observation corresponds to a brightness temperature of 26 K under the Rayleigh-Jeans approximation. Given the beam filling factors of the line and continuum of 0.5, the upper limit of the excitation temperature in the 13CO line is 35 K (see eq. [5] of Qin et al. 2008). Assuming the gas is in LTE and the emission component (with integrated flux density of 9.1 Jy beam −1 km s −1) is optically thin with abundances of [CO]/[13CO] = 89 and [CO]/[H2] = 1 × 10 −4, the H2 column densities of observed in other hot cores (Kurtz et al. 2000). The CH3CN, SO2, OCS, and CH3OH spectra have similar radial velocities and line widths, suggesting that the N-bearing, O-bearing, and S-bearing molecules probably originated from the hot core.

4.2. Kinematics
the absorption and emission components are \( \sim 4.6 \times 10^{22} \) and \( 6.8 \times 10^{22} \) cm\(^{-2} \), respectively. The major axes of the absorption and emission components are approximately 0.025 and 0.04 pc. The estimated H\( \text{I} \) densities and masses are \( 5.9 \times 10^5 \) cm\(^{-3} \), 1.5 \( M_\odot \) and \( 5.5 \times 10^5 \) cm\(^{-3} \), 1.9 \( M_\odot \) for the absorption and emission components, respectively. Compared with the rotation temperature and H\( \text{I} \) density traced by CH\( \text{3CN} \) lines, the lower excitation temperature and H\( \text{I} \) densities suggest that the \( ^{13}\text{CO} \) is located outside of the hot molecular core. The average rotation temperature diagram for the observed CH\( \text{3CN} \) transitions. The linear least-squares fit (solid line) gives a rotation temperature of 308 ± 22 K. The vertical bars indicate the errors of ln \( (N/\varpi) \) transferred from the integrated intensities.

Fig. 3.—Rotation temperature diagram for the observed CH\( \text{3CN} \) transitions. The linear least-squares fit (solid line) gives a rotation temperature of 308 ± 22 K. The vertical bars indicate the errors of ln \( (N/\varpi) \) transferred from the integrated intensities.

Fig. 4.—Position-velocity diagram cutting along NE-SW direction across the continuum peak. The diagram is constructed from the OCS transition. The contours are 0.19, 0.38, 0.56, 0.75, 0.94, and 1.13 Jy beam\(^{-1} \); the absorption and emission components are approximately 0.025 and 0.04 pc. The estimated H\( \text{I} \) densities and masses are \( 5.9 \times 10^5 \) cm\(^{-3} \), 1.5 \( M_\odot \) and \( 5.5 \times 10^5 \) cm\(^{-3} \), 1.9 \( M_\odot \) for the absorption and emission components, respectively. Compared with the rotation temperature and H\( \text{I} \) density traced by CH\( \text{3CN} \) lines, the lower excitation temperature and H\( \text{I} \) densities suggest that the \( ^{13}\text{CO} \) is located outside of the hot molecular core. The average rotation temperature diagram for the observed CH\( \text{3CN} \) transitions. The linear least-squares fit (solid line) gives a rotation temperature of 308 ± 22 K. The vertical bars indicate the errors of ln \( (N/\varpi) \) transferred from the integrated intensities.

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REFERENCES

Argon, A. L., Reid, M. J., & Menten, K. M. 2000, ApJS, 129, 159
Blake, G. A., et al. 1987, ApJ, 315, 621
Cesaroni, R., et al. 1994, A&A, 288, 903
Churchwell, E. 2002, ARA&A, 40, 27
Fish, V. L., Reid, M. J., Wilner, D. J., & Churchwell, E. 2003, ApJ, 587, 701
Gibb, E., Nummelin, A., Irvine, W. M., Whittet, D. C. B., & Bergman, P. 2000, ApJ, 545, 309
Gibb, E., Wyrowski, F., & Mundy, L. G. 2004, ApJ, 616, 301
Goldsmith, P. F., & Langer, W. D. 1999, ApJ, 517, 209
Hofner, P., et al. 1996, ApJ, 460, 359
Keto, E., Zhang, Q., & Kurtz, S. 2008, ApJ, 672, 423
Kurtz, S., et al. 2000, in Protostars and Planets IV, ed. V. Mannings, A. Boss, & S. Russell (Tucson: Univ. Arizona Press), 299
Liu, S.-Y., Girart, J. M., Remijian, A., & Snyder, L. E. 2002, ApJ, 576, 255
Menten, K. M. 1991, ApJ, 380, L75
Müller, H. S. P., et al. 2005, J. Mol. Struct., 742, 215
Nummelin, A., et al. 1998, ApJS, 117, 427
Pickett, H. M., et al. 1998, J. Quant. Spectrosc. Radiat. Transfer, 60, 883
Remijian, A., et al. 2004, ApJ, 606, 917
Rodgers, S. D., & Charnley, S. B. 2001, ApJ, 546, 324
Qin, S.-L., et al. 2008, ApJ, 677, 353
Sewilo, M., et al. 2004, ApJ, 605, 285
———. 2008, ApJ, 681, 350
Sollins, P. K., Zhang, Q., Keto, E., & Ho, P. T. P. 2005, ApJ, 631, 399
Sutton, E. C., et al. 1985, ApJS, 58, 341
———. 1991, ApJS, 77, 255

The position-velocity diagram across the peak of the continuum along the NE-SW direction is constructed from the OCS line (see Fig. 4). In Figure 4, the velocities of the two emission peaks are 95 and 97 km s\(^{-1} \) with 0.2\( \text{}\) separation, respectively, indicating a velocity gradient in NE-SW direction. Assuming a rotating motion along NE-SW with a rotation axis in the NW-SE direction (Sewilo et al. 2008) and an equilibrium between rotational and gravitational forces, the dynamical mass responsible for the rotation can be estimated by \( M = V^2 r/\varpi \), where \( V \) and \( r \) are the velocity difference and spatial separation of the emission peaks, respectively; \( G \) is the gravitational constant. The derived dynamical mass is 25 \( M_\odot \), which is consistent with the mass derived by Sewilo et al. (2008).