SMA MILLIMETER OBSERVATIONS OF HOT MOLECULAR CORES

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Received 2013 September 14; accepted 2014 February 3; published 2014 April 15

ABSTRACT

We present Submillimeter Array observations in the 1.3 mm continuum and the CH3CN (12_K–11_K) line of 17 hot molecular cores associated with young high-mass stars. The angular resolution of the observations ranges from 1’0 to 4’0. The continuum observations reveal large (>3500 AU) dusty structures with gas masses from 7 to 375 \( M_\odot \), which probably surround multiple young stars. The CH3CN line emission is detected toward all the molecular cores at least up to the \( K = 6 \) component and is mostly associated with the emission peaks of the dusty objects. We used the multiple \( K \)-components of the CH3CN and both the rotational diagram method and a simultaneous synthetic local thermodynamic equilibrium model with the XCLASS program to estimate the temperatures and column densities of the cores. For all sources, we obtained reasonable fits from XCLASS by using a model that combines two components: an extended and warm envelope and a compact hot core of molecular gas, suggesting internal heating by recently formed massive stars. The rotational temperatures lie in the range of 40–132 K and 122–485 K for the extended and compact components, respectively. From the continuum and CH3CN results, we infer fractional abundances from \( 10^{-9} \) to \( 10^{-7} \) toward the compact inner components, which increase with the rotational temperature. Our results agree with a chemical scenario in which the CH3CN molecule is efficiently formed in the gas phase above 100–300 K, and its abundance increases with temperature.

Key words: ISM: molecules – stars: formation – stars: massive – stars: protostars – techniques: interferometric

Online-only material: color figures

1. INTRODUCTION

Massive stars (\( M > 8 \ M_\odot \)) are born inside of dense cores located in large and massive molecular clouds (e.g., Garay & Lizano 1999; Cesaroni 2005). These massive star-forming regions (MSFRs) have a substantial impact on the evolution of the interstellar medium (ISM) and make important contributions to its dynamics and chemistry. For example, molecular outflows, jets, stellar winds, and supernovae associated with MSFRs push into their surroundings, promoting additional star formation and mixing the ISM.

One of the first manifestations of massive star formation is the so-called hot molecular core phases (HMCs; Kurtz et al. 2000; Cesaroni 2005). This phase is characterized by molecular gas condensations at relatively high temperatures (>100 K) and high densities (\( \sim 10^9 \text{--} 10^8 \text{ cm}^{-3} \)), associated with a compact (<0.1 pc), luminous (>10^4 \( L_\odot \)), and massive (\( \sim 10\text{--}1000 \ M_\odot \)) molecular core.

HMCs show a forest of molecular lines, especially from organic species (e.g., Comito et al. 2005). Many of these molecules probably were formed on grain mantles during a previous cold phase, while others were produced by gas-phase reactions after “parents species” were evaporated from the grains by the strong radiation of embedded or nearby protostars (see Herbst & van Dishoeck 2009).

Both models and observations suggest that massive HMCs are collapsing and accreting mass onto a central source(s) at rates of \( 10^{-4}\text{--}10^{-3} \ M_\odot \text{ yr}^{-1} \) (Osorio et al. 2009b; Zapata et al. 2009). These intense mass accretion rates are high enough to prevent the development of an ionized region around the massive star(s) at least in the early stages (Osorio et al. 1999). Thus, HMCs probably precede ultracompact H II regions (UC H II; Kurtz et al. 2000; Wilner et al. 2001). Indeed, sub-arcsecond observations argue in favor of this scenario, particularly those showing embedded UC H II-regions, strong (sub)millimeter emission from dust condensations, or strong mid-IR emission from internal objects (e.g., Cesaroni et al. 2010, 2011).

In the above scenario, an HMC corresponds to the most internal clump of molecular material collapsing and probably feeding other structures and the massive stars inside (Cesaroni 2005; Wilner et al. 2001). However, recent sensitive high angular resolution observations suggest that the prototypical HMC, Orion BN/KL, may not follow this model. In this case, a close dynamical interaction of three young protostars produced an explosive flow and illuminated a preexisting dense clump, thus creating the HMC (Zapata et al. 2011; Goddi et al. 2011). Also, toward G34.26+0.15 (another prototypical HMC), Mookerjea et al. (2007) failed to find any embedded protostars within the hot core. The different nature of internally and externally heated HMC makes it important to distinguish between them.

With this in mind, we present a study using Submillimeter Array (SMA) archival observations of CH3CN (12_K–11_K) and 1.3 mm continuum emission, toward 17 MSFRs in the HMC stage. CH3CN (methyl cyanide) is frequently used as an effective thermometer and to estimate gas density toward HMCs (e.g., Araya et al. 2005a; Pankonin et al. 2001). Our main goal is to use the same molecular tracer toward a relatively large group of sources to study the innermost and hottest material, estimating densities, temperatures, masses, abundances, and the spatial distribution of the dust emission and CH3CN molecular gas.

In Section 2 we describe the archival observations presented in this study. In Section 3 we report the results and analysis of

3 The Submillimeter Array is a joint project between the Smithsonian Astrophysical Observatory and the Academia Sinica Institute of Astronomy and Astrophysics and is funded by the Smithsonian Institution and the Academia Sinica.
the millimeter continuum data and the molecular line emission. In Section 4 we comment briefly on each source, giving the physical characteristics from the literature and from our results. In Section 5 we discuss our results, first comparing the spatial distribution of the continuum emission and molecular emission, and then estimating the temperatures and densities of the regions.

In Table 2 we summarize the relevant information concerning positions, \( V_{\text{lsr}} \), distances, luminosities, and UC \( \text{H} \alpha \) regions are taken from the cited references.

Notes. Units of right ascension are hours, minutes, and seconds, and for declination are degrees, arcminutes, and arcseconds. Positions, \( V_{\text{lsr}} \), distances, luminosities, and UC \( \text{H} \alpha \) regions are taken from the cited references.

References. (1) Reid et al. 2014; (2) Rodríguez et al. 2008; (3) Franco-Hernández et al. 2009; (4) Fuñevez et al. 2004; (5) Leurini et al. 2011; (6) Purcell et al. 2006; (7) Longmore et al. 2011; (8) Sollins et al. 2005a; (9) Qin et al. 2008; (10) Pandian et al. 2008; (11) Cesaroni et al. 2010; (12) Zhang et al. 2007.

2. OBSERVATIONS AND DATA REDUCTION

We searched the literature for MSFRs in the HMC phase, based on previous detection of molecular species indicating warm and dense gas such as \( \text{CH}_3\text{CN}, \text{NH}_3, \text{and CH}_3\text{OH}. \) These molecules are commonly used to trace HMCs (e.g., Churchwell et al. 1990, 1992; Olmi et al. 1993; Kalenskii et al. 1997, 2000). We compiled a list of almost 60 objects, of which most are associated with UC \( \text{H} \alpha \) regions, strong (sub)millimeter emission, molecular outflows, or maser emission, i.e., they are young MSFRs. Then we searched in the SMA archive for observations that included the \( \text{CH}_3\text{CN} (12K-11K) \) transitions at \( \sim\)220.7 GHz. The intensity levels of the LSB in the visibility domain. All the line data were convolved source sizes were determined from two-dimensional Gaussian fits.

3. RESULTS AND ANALYSIS

3.1. Millimeter Continuum Data

In Figure 1 we show the 1.3 mm continuum emission images overlaid with three \( K \) lines (\( K = 3, 5, \) and 7) of \( \text{CH}_3\text{CN} (12K-11K) \) emission toward the 17 HMCs. The intensity levels for the \( \text{CH}_3\text{CN} \) contours are given in Table 3 and the figure captions. Table 4 shows the corresponding continuum emission parameters, derived using line-free channels from the LSB. Using the task \texttt{imfit} in MIRIAD, we found the position of the peak, and the peak and integrated flux densities. The deconvolved source sizes were determined from two-dimensional Gaussian fits.

\[ \text{Ref s} \]

The Mir cookbook by Charlie Qi at http://www.cfa.harvard.edu/~cqi/mircook.html.
Table 2
Observational Parameters

| Source | Observation | Frequency Range (GHz) | Epoch | Gain | Flux (Jy) | Bandpass Calibrators | Spectral Resolution (MHz) | Bandpass Gain | Synthesized beam FWHM (arcsec) | P.A. (deg) | Published Data |
|--------|-------------|-----------------------|-------|------|-----------|----------------------|--------------------------|----------------|--------------------------------|------------|---------------|
| W3OH   | 2004 Oct 24 | 219.50–221.48         | 0.812 | 0359+509 | 1.41 | Uranus | 0102+584 | 219.42–221.07 | 0.812 | 3C273 | 0.97 | +69.1 | ... |
| W3TW   | 2004 Oct 24 | 219.50–221.48         | 0.812 | 0102+584 | 1.41 | Uranus | 0359+509 | 219.42–221.07 | 0.812 | 3C279 | 1.11 | +69.1 | ... |
| I16547 | 2006 Jun 06 | 219.21–221.19         | 0.812 | 3C273 | 0.82 | Uranus | 1745–290 | 2009 Jan 31 | 0.406 | 3C279 | 2.00 | +66.0 | ... |
| I17233 | 2007 Apr 10 | 219.45–221.43         | 0.406 | 3C454.3 | 1.22 | Uranus | 1626–298 | 2010 Apr 28 | 0.812 | 3C273 | 1.89 | +69.1 | ... |
| G5.89  | 2008 Apr 18 | 219.37–221.34         | 0.406 | 3C454.3 | 1.11 | Uranus | 1921–293 | 2008 Jun 21 | 0.406 | 3C454.3 | 1.93 | +69.1 | ... |
| G8.68  | 2008 Sep 17 | 220.28–222.27         | 0.406 | 3C454.3 | 1.11 | Uranus | 1911–201 | 2008 Jun 21 | 0.406 | 3C273 | 1.93 | +69.1 | ... |
| G10.47 | 2008 Jul 09 | 220.30–221.30         | 0.406 | 3C454.3 | 1.11 | Uranus | 1733–130 | 2008 Jul 09 | 0.406 | 3C454.3 | 2.00 | +66.0 | ... |
| G10.62 | 2009 Jan 31 | 220.32–222.30         | 0.406 | 3C454.3 | 1.11 | Uranus | 1911–201 | 2009 Apr 30 | 0.812 | 3C273 | 2.00 | +66.0 | ... |
| G23.01 | 2010 Apr 13 | 219.45–221.43         | 0.812 | 0359+509 | 1.89 | Uranus | 1733–130 | 2010 Apr 28 | 0.406 | 0359+509 | 2.00 | +66.0 | ... |
| G28.20 | 2007 Jul 09 | 220.30–221.30         | 0.406 | 3C454.3 | 1.89 | Uranus | 1911–201 | 2008 Jul 09 | 0.406 | 3C273 | 1.93 | +69.1 | ... |
| I18566 | 2007 Jul 09 | 220.30–221.30         | 0.812 | 0359+509 | 1.89 | Uranus | 1733–130 | 2008 Jul 09 | 0.406 | 3C454.3 | 1.93 | +69.1 | ... |
| G45.07 | 2007 Apr 13 | 220.30–221.30         | 0.812 | 0359+509 | 1.89 | Uranus | 1733–130 | 2008 Jul 09 | 0.406 | 3C273 | 1.93 | +69.1 | ... |
| G45.47 | 2008 Jun 30 | 219.15–221.13         | 0.406 | 3C454.3 | 1.89 | Uranus | 1925+211 | 2008 Jun 30 | 0.406 | 3C454.3 | 1.93 | +69.1 | ... |
| W51e2  | 2005 Sep 01 | 220.25–222.23         | 0.406 | 3C454.3 | 1.89 | Uranus | 1733–130 | 2005 Sep 01 | 0.406 | 3C454.3 | 1.93 | +69.1 | ... |
| W51e8  | 2005 Sep 01 | 220.25–222.23         | 0.406 | 3C454.3 | 1.89 | Uranus | 1733–130 | 2005 Sep 01 | 0.406 | 3C454.3 | 1.93 | +69.1 | ... |

Notes.
- We estimated bootstrapped flux for gain calibrators with an uncertainty of 15%–20%.
- A single sideband of 4 GHz bandwidth.

References. (1) Leurini et al. 2011; (2) Su et al. 2009; (3) Longmore et al. 2011; (4) Beuther et al. 2006; (5) Klaassen et al. 2009.

Since HMCs are chemically rich, the continuum emission may be contaminated by some molecular lines, particularly for extremely rich sources such as I17233, G10.62, G31.41, W51e2, and W51e8. Although we were careful to avoid any obvious contamination during the reduction process, we consider the peak and integrated fluxes as upper limits. Some HMCs show embedded or very nearby UC H II regions, and the 1.3 mm continuum emission may have contributions from both ionized gas emission and from the dust. To estimate the free–free contribution at 1.3 mm, we extrapolated the emission between 10 and 45 GHz reported in the literature, assuming optically thin emission, i.e., considering $S_v \propto \nu^{-0.1}$. For G45.07, G45.47, and W51e2, we choose $\sim 100$ GHz for extrapolation of the free–free emission because of their high turnover frequencies. In this way we derived the dust continuum emission for the HMCs, which ranges from 0.31 Jy for I18566 to 5.88 Jy for I17233. The measured fluxes and the contribution from thermal dust are presented in Table 4.

To estimate the gas mass and average column density, we follow Hildebrand (1983). Assuming optically thin dust emission and a constant gas-to-dust ratio, the gas mass is

$$M_{\text{gas}} = \frac{S_v D^2 R_d}{B_v(T_d) \kappa_v}$$

(1)

where $S_v$, $D$, $R_d$, $\kappa_v$, and $B_v(T_d)$ are the flux density, distance to the core, gas-to-dust ratio, the dust opacity per unit dust mass, and the Planck function at the dust temperature ($T_d$), respectively. Note that $\kappa_v$ ranges from 0.2 to 3.0 at 1.3 mm, depending on its scaled value with frequency as $\nu^\beta$, where $\beta$ is the dust emissivity index (e.g., Hunter et al. 2000; Henning et al. 1995). Following Ossenkopf & Henning (1994) and using $\beta = 1.5$, we obtain $\kappa_{1.3\, \text{mm}} = 0.74 \, \text{cm}^2 \, \text{g}^{-1}$, corresponding to a median grain size $a = 0.1 \, \mu\text{m}$ and a grain mass density $\rho_d = 3 \, \text{g} \, \text{cm}^{-3}$. Our value of $\kappa_v$ is very similar to other estimates toward HMCs (e.g., Hunter et al. 1999; Osorio et al. 2009).

In the Rayleigh–Jeans approximation, Equation (1) gives

$$M_{\text{gas}} = \frac{432.0 \, S_v}{\nu^2 \kappa_v}$$

(2)
Figure 1. SMA line-free continuum maps at 1.3 mm (color scale) and velocity-integrated emission (moment 0, contours) of CH$_3$CN (12K–11K) for $K = 3$ (red), $K = 5$ (green), and $K = 7$ (blue) lines. In all cases the contour levels have steps of 10% until 90% of the integrated emission shown in Table 3. For W3OH-H$_2$O, contour levels begin at 10% ($K = 3$), 20% ($K = 5$), and 50% ($K = 7$). For I16547, contour levels begin at 10% ($K = 3$), 20% ($K = 5$), and 50% ($K = 7$). For I17233, contour levels begin at 50% ($K = 3$, $K = 5$, and $K = 7$). For G5.89, we used the $K$ lines 3, 5, and 6 with contour levels beginning at 30%, 40%, and 40%, respectively. For G5.89, the yellow box marks the position of the Feldt’s star (Feldt et al. 2003), and circles with crosses show condensations with excess 870 μm emission reported by Hunter et al. (2008). For G8.68, contour levels begin at 20% ($K = 3$ and $K = 5$) and 50% ($K = 7$). For G10.47, contour levels begin at 20% ($K = 3$ and $K = 5$) and 40% ($K = 7$). In all cases a white dot marks the peak position of 1.3 mm continuum emission (Table 4), and the synthesized beam (Table 4) is shown at the bottom left. For G10.62, contour levels begin at 20% ($K = 3$, $K = 5$, and $K = 7$). For I18182, we used the $K$ lines 3, 5, and 6 with contour levels beginning at 50%. For G23.01, contour levels begin at 20% ($K = 3$, $K = 5$, and $K = 7$). For G28.20, contour levels begin at 20% ($K = 3$ and $K = 5$) and 40% ($K = 7$). For G31.41, contour levels begin at 40% ($K = 3$, $K = 5$, and $K = 7$). For I18566, contour levels begin at 20% ($K = 3$ and $K = 5$) and 40% ($K = 7$). For G45.07, contour levels begin at 20% ($K = 3$ and $K = 5$) and 30% ($K = 7$). For G45.47, contour levels begin at 20% ($K = 3$), 70% ($K = 5$), and 50% ($K = 7$). For G51.2, contour levels begin at 30% ($K = 3$ and $K = 5$) and 40% ($K = 7$). For W51e8, contour levels begin at 30% ($K = 3$) and 40% ($K = 5$ and $K = 7$).

\[ \frac{N_{\text{H}_2}}{\text{cm}^{-2}} = \frac{2.35 \times 10^{16}}{\theta^2} \left[ \frac{S_{\nu}}{\text{Jy}} \right] \left[ \frac{T}{K} \right]^{-1}, \]

where $\theta$ is the source size in radians, and we used the common gas-to-dust ratio of 100. At the high densities of HMCs, dust and gas are probably well coupled through collisions, and we can assume that they are in thermal equilibrium (Kaufman et al. 1998). Thus, we used the high temperatures derived from the CH$_3$CN (see Section 3.3) to obtain $M_{\text{gas}}$ and $N_{\text{H}_2}$. These values, obtained from the estimated 1.3 mm dust emission, are presented in Table 4.

We caution that the calculated values for the mass and column density are sensitive to both the dust emissivity index and the temperature assumed for each region. For example, decreasing $\beta$ to 1.0 (while keeping the same temperature) lowers the results by a factor of ~3.3. Also, we note that distance uncertainties may be significant for some sources. For other sources (i.e., W3OH/TW, G5.89, G10.47, G10.62, I18182, G23.01, G45.07, and the...
W51 region) trigonometric parallaxes have been measured (Reid et al. 2009, 2014); these distances are more accurate.

3.2. Molecular Line Emission

We detected many molecular lines toward the 17 HMCs, but the strength of each species and transition detected varies from source to source. We used the SPLATALOGUE Web site to identify by eye the main lines in the LSB spectra, which are mostly dominated by species such as $^{13}$CO and C$^{18}$O plus CH$_3$CN. Other species frequently detected were SO, SO$_2$, H$_{13}$CO, CS, and HNCO.

In Figure 3 we show the spectrum for each source, obtained from the integrated emission over the region of gas traced by the $K=3$ line, which traces gas at $\sim$247 K. For six sources, I17233, G10.47, G10.62, G31.41, W51e2, and W51e8, we detected $K=8$ lines with $E_u = 525$ K (see Table 5). The $K=9$ line is blended with the $^{13}$CO(2–1) line at $\sim$220.4 GHz, making its detection ambiguous.

A complete line identification and chemical analysis is beyond the scope of this work. Nevertheless, we note that there is substantial chemical differentiation in some sources, including pairs of objects as closely spaced as W3TW–W3OH or W51e2–W51e8. These differences have been explained as being due to different physical conditions in each region, different chemical composition of ice mantles on dust grains, or different ages of HMCs (e.g., Herbst & van Dishoeck 2009).

In Table 5 we present the results from the fit of Gaussian profiles to each CH$_3$CN $K$-component detected. We used the CLASS software package to estimate the line width ($\Delta V$), the...
integrated intensity (∫ T dν), and the LSR velocity (V_{LSR}) for each line. We show in Table 5 the average K-component values for ΔV and V_{LSR} toward each HMC.

3.3. Temperature and Density of the CH$_3$CN Gas

CH$_3$CN is considered to be a good tracer of warm–hot and high-density gas (e.g., Araya et al. 2005a). Its symmetric-top molecular structure works as a rotor, emitting in multiple $K$ levels within a specific $J$ transition, all within a narrow bandwidth (~0.2 GHz). This spectral characteristic is very useful in order to avoid certain systematic errors that occur when comparing lines of very different frequencies. The $K$ levels are radiatively decoupled and are populated only through collisions (Solomon et al. 1971), thus the rotational temperature of CH$_3$CN is close to the kinetic temperature of the gas.

If we assume local thermodynamic equilibrium (LTE) and optically thin gas, CH$_3$CN is an excellent tracer of kinetic

| Sources          | CH$_3$CN Transitions |
|------------------|-----------------------|
|                  | $K = 3$ (Jybeam$^{-1}$ km s$^{-1}$) | $K = 5$ (Jybeam$^{-1}$ km s$^{-1}$) | $K = 7^a$ (Jybeam$^{-1}$ km s$^{-1}$) |
| W3OH and TW      | 29.1                  | 17.4                  | 3.9                  |
| I16547           | 6.2                   | 4.8                   | 2.5                   |
| I17233           | 224.7                 | 206.6                 | 78.6                  |
| G5.89            | 5.8                   | 2.5                   | 1.8$^a$               |
| G8.68            | 7.6                   | 4.2                   | 1.4                   |
| G10.47           | 63.1                  | 100.6                 | 45.4                  |
| G10.62           | 33.6                  | 19.1                  | 6.2                   |
| I18182           | 11.8                  | 6.5                   | 8.0$^a$               |
| G23.01           | 18.7                  | 11.3                  | 3.5                   |
| G28.20N          | 13.9                  | 8.9                   | 2.5                   |
| G31.41           | 32.8                  | 31.1                  | 11.8                  |
| I18566           | 7.3                   | 4.7                   | 1.3                   |
| G45.07           | 10.8                  | 4.2                   | 1.6                   |
| G45.47           | 3.5                   | 0.6                   | 0.9                   |
| W51e2 and W51e8  | 34.6                  | 26.6                  | 13.0                  |

Note. $^a$ For G5.89−0.37 and I18182 we present the line $K = 6$. 
temperature using methods such as RDs (Linke et al. 1979; Turner 1991), population diagrams (PDs; Goldsmith & Langer 1999; Araya et al. 2005a), and simultaneous fitting of multiple lines in a spectrum (Comito et al. 2005; Schilke et al. 1999). In general, no background radiation is considered, and in the RD and PD methods, uniform temperature and density are assumed. Following the procedure outlined in Turner (1991) and Araya et al. (2005a), one obtains the linear equation \( \ln(N/H) = \ln(N/\text{H}_2) + A + B \), where the slope is \(-1/T_{\text{rot}}\) and the intercept. The left-hand side of this equation contains the column density per statistical weight of the molecular weight and represents the integrated intensity per statistical weight. In this way, plotting the natural logarithm of \( N/\text{H}_2 \) versus \( T_{\text{rot}} \) of each K level of CH$_2$CN and calculating the best linear fit, \( T_{\text{rot}} \), and \( N/\text{H}_2 \) can be inferred. In thermodynamic equilibrium the rotational temperature closely approximates the kinematic temperature of the gas.

As a first approximation, we estimated the column density and rotational temperature by means of the RD method. These diagrams are shown in Figure 2, and the results of the linear fits are listed in Table 6. The error bars come from the integrated intensity errors in the fitting to each K-transition with CLASS and are shown in Table 5.

In the case of mildly optically thick lines, RDs underestimate the upper level column density and overestimate the rotational temperatures. To first order, problems in these estimations can
be overcome by using the PD method, which accounts for optical depth and the source filling factor as proposed in Goldsmith & Langer (1999). Finally, in the RDs method we assumed one region with a single temperature $T_{\text{rot}}$.

A more sophisticated approach is to simultaneously fit multiple lines as outlined by Comito et al. (2005) and Schilke et al. (1999). Their XCLASS program\(^7\) generates a synthetic spectrum for multiple molecular species, assuming multiple emission regions, all assumed to be in LTE. Also, XCLASS accounts for line blends and optical depth. For each emission region the program requires inputs for the source size, column density, rotation temperature, line width, and velocity offset from the $V_{\text{LSR}}$. XCLASS uses the CDMS and JPL spectral line database (Pickett et al. 1998; Müller et al. 2005, 2001) for line identification. (See Comito et al. 2005, for details of the procedure).

To form the synthetic spectra, we model each source as two distinct emission regions: one extended and warm, with relatively low density, and the other compact and hot, with high

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\(^7\) [http://www.astro.uni-koeln.de/projects/schilke/XCLASS](http://www.astro.uni-koeln.de/projects/schilke/XCLASS)
density. The size of the regions is degenerate with temperature and column density, depending on the optical depth (see Equations (6) and (7) of Comito et al. 2005). To avoid this degeneracy, the size of the extended component was fixed, and we varied the compact component size from 0.5 to 0.25 the size of the extended component. We fixed the offset from $V_{LSR}$ as estimated directly from the observed spectrum (Table 5).

We probed the parameter space with temperatures between 100 K and 500 K for the compact component and from 50 K to 150 K for the extended component. For the column density, we probed $10^{14}$--$10^{15}$ cm$^{-2}$ for the compact component and $10^{12}$--$10^{15}$ cm$^{-2}$ for the extended component. The best fit of the synthetic to the observed spectrum was determined by a χ$^2$ analysis. As we approached a better fit, we used step sizes of 1 K in temperature and $10^{-2}$ cm$^{-2}$ in column density. For ΔV we probed steps of ±2, ±1, and 0 km s$^{-1}$ from a near value to the observed average (Table 5). Most of the sources showed a better fit when we used larger line widths for the compact component than for the extended one. In order to estimate errors, we modeled new synthetic spectra perturbing separately temperatures and column densities until we measured an underestimation and overestimation in 20% of the brightness density.
temperature for the $K = 2$ transition (20% is the estimated upper limit flux uncertainty of observations), since such a line is mostly optically thin and not blended by other lines.

In Table 6 we present the final fit values, and in Figures 3 we show the observed and synthetic spectra, respectively. All HMCs showed reasonable fits with observations using the two-component model.

### 3.4. Virial Masses

Virial mass, $M_{\text{vir}}$, can be estimated by using the line width and source size. Assuming a power law density distribution with index $p = 1.5$ in a spherical core, we use the expression $M_{\text{vir}} = 0.40 \, d \theta_{\text{CH}_3\text{CN}} \Delta V^2$, where $d$ is the distance, $\theta_{\text{CH}_3\text{CN}}$ is the angular diameter, and $\Delta V$ is the line width, in kpc, arcseconds, and km s$^{-1}$, respectively (see Equation (1) of Beltrán et al. 2004; MacLaren et al. 1988). This is the central mass assuming that the core has gravitationally bound motion. For $\Delta V$ we used the average line width from the observed spectrum (Column 3 in Table 5), and for the source size we used the extended component from the XCLASS analysis (Table 6).

In the last column of Table 6 we present the calculated $M_{\text{vir}}$, which ranges from 60 to 473 $M_{\odot}$, with a median of 209 $M_{\odot}$.

We note that most of the $M_{\text{vir}}$ values are greater than $M_{\text{gas}}$. This imbalance would still hold even if we used the smaller source size of the compact component to calculate $M_{\text{vir}}$. We caution that many of the HMCs probably are not in dynamical equilibrium owing to complicated kinematics, multiple star forming sites, and large rotating structures such as toroids and disks. Also, large optical depths, outflowing gas, and systematic velocity gradients will increase the line width and thus the virial mass.

### 4. Comments on Individual Sources

In this section we comment the main properties of each source on the basis of previous observations and describe the results obtained in this work.

W3OH is a well-known shell UC H II region harboring OB stars at about 2.0 kpc, rich in OH and CH$_3$OH maser emission associated with ionized gas and weak molecular lines (Wink et al. 1994; Wilner et al. 1995). We measure a 1.3 mm flux density of $\sim$3.85 Jy, similar to reported values at different wavelengths: 3.5 Jy at 3 mm (Wilner et al. 1995) and 3.4 and 3.6 Jy at 1.4 and 2.8 mm, respectively (Chen et al. 2006). This is consistent with a large contribution of free–free emission and minimal dust emission. We estimated a gas mass of $\sim$19 $M_{\odot}$.
and a column density of $3.3 \times 10^{24}$ cm$^{-2}$. From interferometric observations of CH$_3$CN (5–4), Wink et al. (1994) estimated a rotation temperature of $90 \pm 40$ K. From the LTE analysis using XCLASS, we calculated rotation temperatures between 68 and 122 K; consistent with the results of Wink et al. (1994). Notably, W3OH shows the lowest temperature in our survey. CH$_3$CN column densities of $3.3 \times 10^{15}$ and $7.5 \times 10^{13}$ cm$^{-2}$ were estimated for the compact and extended regions. We estimated a CH$_3$CN abundance of $\sim 2 \times 10^{-9}$.

W3TW is a young source, resolved into three components by Wyrowski et al. (1999b), associated with strong dust and molecular emission at (sub)millimeter wavelengths. Using BIMA observations, Chen et al. (2006) report continuum flux densities of 1.38 and 0.22 Jy at 1.4 and 2.8 mm, respectively. Our higher estimate of 2.67 Jy at 1.3 mm may result from our lower angular resolution. Chen et al. (2006) found a protobinary system with a mass of $\sim 22 M_\odot$ for the pair. Using an LTE model for the CH$_3$CN (12$K$–11$K$) emission, they found rotation temperatures of 200 K and 182 K for sources A and C, respectively. Our data cannot resolve these two sources. From the 1.3 mm dust emission, we estimate a gas mass of $12.4 M_\odot$ and an H$_2$ column density of $1.2 \times 10^{24}$ cm$^{-2}$. Using XCLASS, we estimate temperatures of 108 and 367 K for the extended and compact components. We find a CH$_3$CN abundance of $3.2 \times 10^{-8}$.

I16547 is an MSFR with a central source of $\sim 30 M_\odot$. It hosts a thermal radio jet, outflowing gas, knots of shocked gas, and H$_2$O masers (Garay et al. 2003; Franco-Hernández et al. 2009). Although the 1.3 mm continuum emission is extended toward the west, it is dominated by a core of emission with the central source (see Figure 1). Our continuum analysis ($S_\text{dust} \sim 1.57 Jy$) estimates a gas mass of $\sim 20 M_\odot$ toward the eastern core. The CH$_3$CN (12$K$–11$K$) analysis shows kinetic temperatures from

Figure 3. (Continued)
78 to 272 K with XCLASS and \( \sim 245 \) K using RDs. The molecular emission from \( K = 3, 5, 7 \) lines is detected mainly toward the eastern region, coincident with the 1.3 mm continuum peak. We estimated CH3CN column densities of \( 2.1 \times 10^{16} \) and \( 8.8 \times 10^{13} \) cm\(^{-2} \) for the compact and extended regions, respectively, and a fractional abundance of \( 4.5 \times 10^{-8} \) toward the compact component.

\( \text{I} \) shows maser emission in OH (Fish et al. 2005), CH3OH (Walsh et al. 1998), and H2O (Zapata et al. 2008), and multiple outflows from several HC H\( \text{II} \) regions (Leurini et al. 2009; Zapata et al. 2008). Large-scale movement of NH\(_3\) gas suggests a rotating core (Beuther et al. 2009). However, SMA observations of CH3CN (12\( K \)−11\( K \)) reported by Leurini et al. (2011) show that this molecular tracer is probably influenced by molecular outflows. Leurini et al. (2011) used XCLASS with a two-component model similar to ours and report temperatures of 200 K and 50–70 K for the compact and extended components, respectively. Our higher values of 346 K and 132 K result from using smaller component sizes in the modeled spectrum. We estimated a CH3CN abundance of \( \sim 2 \times 10^{-7} \).

\( \text{G5.89} \) is a shell-type UC H\( \text{II} \) region probably ionized by an O5 star offset \( \sim 1'0 \) from the H\( \text{II} \) region (Feldt’s star; Feldt et al. 2003). Also present are strong molecular outflows, maser activity, five (sub)millimeter dust emission sources, and little molecular line emission (Hunter et al. 2008; Sollins et al. 2004). The locations of the five dusty objects are indicated in Figure 1. The molecular gas appears to form a cavity that encircles the ionized gas. Intriguingly, the peak position of the 1.3 mm continuum emission, the CH3CN (12\( K \)−11\( K \)) emission, and Feldt’s star do not coincide. However, most of the continuum emission probably comes from the free–free process, instead of thermal dust. The \( K = 3 \) line emission structure is much more extended than the continuum, while the \( K = 5 \) and 6 lines trace hotter gas to the northeast of Feldt’s star and the 1.3 mm emission. The CH3CN spectrum of G5.89 does not show emission in \( K \) lines \( \geq 6 \). Su et al. (2009) originally reported the SMA CH3CN (12\( K \)−11\( K \)) data. They found a decreasing temperature structure from 150 to 40 K with respect to the position of Feldt’s star. Using the same SMA data, we estimated temperatures of 165 and 40 K for the compact and extended components. We find a fractional abundance of \( 3.6 \times 10^{-9} \) toward the compact component.

\( \text{G8.68} \) is associated with the MSFR IRAS 18032–2137. Also, H\(_2\)O, Class II CH3OH, and OH maser emission, strong millimeter continuum emission, but no centimeter continuum compact sources or free–free emission are detected (Longmore et al. 2011). Infall profiles traced with HCO\(^+\), HNC, and \(^{13}\)CO at 3 mm (Purcell et al. 2006) and strong SiO indicative of shocks are detected (Harju et al. 1998). From the 1.3 mm continuum analysis, Longmore et al. (2011) estimated a mass of \( \sim 21 M_\odot \) and an H\(_2\) column density of at least \( 10^{24} \) cm\(^{-2} \), assuming dust temperatures of 100–200 K. Using the same data as Longmore et al. (2011) but assuming a higher temperature of 281 K, corresponding to the compact component, we estimate a mass of \( 14 M_\odot \) and a column density of \( 10^{23} \) cm\(^{-2} \). From the CH3CN data, Longmore et al. (2011) estimated a 200 K upper limit for the rotation temperature and \( 10^{16} \) cm\(^{-2} \) for the column density. We obtain column densities of \( 4.2 \times 10^{15} \) and \( 1.9 \times 10^{14} \) cm\(^{-2} \) for the compact and extended components, respectively. We estimate a CH3CN abundance of \( \sim 4 \times 10^{-8} \), which is consistent with the result of Longmore et al. (2011).

\( \text{G10.47} \) is one of the brightest HMCs and nursery of several OB stars. This source shows four UC H\( \text{II} \) regions embedded in the hot gas traced by NH\(_3\), CH3CN and many other complex molecules (Olmi et al. 1996; Cesaroni et al. 1998; Hatchell et al. 1998; Wyrowski et al. 1999a; Rolffs et al. 2011). There is strong millimeter continuum emission toward two of the UC H\( \text{II} \) regions. We adopt a distance of 8.5 kpc (Reid et al. 2014). Olmi et al. (1996), using 30 m plus PdBI merged observations of CH3CN (6–5), obtained rotation temperatures of 240 and 180 K for separate spectra of a core and extended components, respectively. They obtained CH3CN column densities of \( 6.0 \times 10^{16} \) and \( 3.6 \times 10^{15} \) cm\(^{-2} \) toward these regions. Using the NH\(_3\) (4, 4) line, Cesaroni et al. (1998) estimated kinetic temperatures of 250–400 K toward the central regions. We estimate rotation temperatures of 408 and 82 K, and CH3CN column densities of \( 5.1 \times 10^{17} \) and \( 4.1 \times 10^{14} \) cm\(^{-2} \), for the compact and extended components, respectively. From the 1.3 mm continuum emission, G10.47 shows the largest gas mass in our survey, \( \sim 375 M_\odot \). We find a CH3CN abundance of \( 7.6 \times 10^{-8} \).

G10.62 is a well-studied MSFR and associated with a UC H\( \text{II} \) region, H\(_2\)O and OH maser emission, and multiple molecular lines, including CH3CN (Keto et al. 1987; 1988; Sollins & Ho 2005; Sollins et al. 2005b; Fish et al. 2005; Liu et al. 2011). From the thermal dust emission and adopting a distance of 5 kpc (Reid et al. 2014), we derived a mass of \( 116 M_\odot \) and \( N_{H_2} = 6.3 \times 10^{23} \) cm\(^{-2} \). Klaassen et al. (2009) and Beltrán et al. (2011) derived \( 136 M_\odot \) and 82.5\( M_\odot \) also using the 1.3 mm continuum with distances of 6 and 3.4 kpc, respectively. Our rotation temperatures estimated from the XCLASS program are 415 and 95 K for the compact and extended components, respectively; column densities were \( 6.7 \times 10^{10} \) and \( 3.0 \times 10^{14} \) cm\(^{-2} \). Beltrán et al. (2011) obtained a rotation temperature of 87 K and a column density of \( 2 \times 10^{13} \) cm\(^{-2} \) using vibrationally excited CH3CN and CH3CN transitions. Discrepancies with Beltrán et al. (2011) probably come from a different distance adopted for the source and the fact that we used optically thick lines in our XCLASS model and the rotational diagram. Klaassen et al. (2009), using only the CH3CN emission, derived a temperature of 323 ± 105 K and a column density of \( 1 \times 10^{15} \) cm\(^{-2} \). We find a CH3CN abundance of \( 1 \times 10^{-8} \). With the uncertainties, our results agree with Klaassen et al. (2009).

\( \text{I18182} \) shows OH, Class II CH3OH, and H\(_2\)O maser emission, weak centimeter continuum emission, and multiple molecular outflows (Walsh et al. 1998; Zapata et al. 2006; Beuther et al. 2006). High-density gas tracers (CH3CN, CH3OH, and HCOOCH\(_3\)) appear offset from the millimeter continuum peak, but they are associated with the outflows (Beuther et al. 2006). Beuther et al. (2006) found gas masses of 47.6 and 12.4\( M_\odot \) from the 1.3 mm continuum emission using dust temperatures of 43 and 150 K, respectively. They estimated H\(_2\) column densities of \( 5.7 \times 10^{23} \) and \( 1.5 \times 10^{23} \) cm\(^{-2} \) at the same temperatures. Their XCLASS analysis of the CH3CN (12\( K \)−11\( K \)) shows a rotation temperature of 150 K and a column density of \( 3.5 \times 10^{14} \) cm\(^{-2} \), using a single component model. With the same data and assuming a temperature of 219 K, we obtained a gas mass of \( \sim 21 M_\odot \) and an H\(_2\) column density of \( 3.3 \times 10^{15} \) cm\(^{-2} \). Assuming two components for the XCLASS analysis, we obtain rotation temperatures of 219 and 75 K and column densities of \( 7.3 \times 10^{15} \) and 8.2 \( \times 10^{13} \) cm\(^{-2} \). We estimated \( \chi_{\text{XCLASS}} = 2.1 \times 10^{-8} \).

\( \text{G23.01} \) is a relatively isolated MSFR showing complex OH, H\(_2\)O, and CH3OH Class II maser emission (Caswell & Haynes 1983; Forster & Caswell 1989; Polushkin & Val'Tts 2011) but no free–free emission. Masers are clustered within 2000 AU in a probable disk, from which an outflow emerges. A 1.3 cm
continuum source likely traces a thermal jet driving the massive CO outflow observed at large scales (Sanna et al. 2010). From the analysis of CH$_3$CN (6–5) transitions, Furuya et al. (2008) found a rotation temperature of $\sim$121 K and a column density of $4.6 \times 10^{14}$ cm$^{-2}$ by using the RD method. They found a gas mass of $\sim$380 $M_\odot$ and an H$_2$ column density of $3.6 \times 10^{23}$ cm$^{-2}$ from the 3 mm continuum emission. From the 1.3 mm dust continuum emission, we estimate a gas mass of $\sim$16 $M_\odot$ and an H$_2$ column density of $1.4 \times 10^{23}$ cm$^{-2}$. The difference in gas mass with (Furuya et al. 2008) probably comes from our smaller size source and higher temperature. With the XCLASS analysis, we calculate rotation temperatures of 237 and 58 K and CH$_3$CN column densities of $1.5 \times 10^{17}$ and $1.7 \times 10^{14}$ cm$^{-2}$, for the compact and extended components. We estimated a CH$_3$CN abundance of $1 \times 10^{-7}$.

G28.20N is an HCN region showing H$_2$O, OH, and CH$_3$OH maser emission (Caswell & Vaille 1995; Argon et al. 2000). Rotation and probably infall motion of gas is detected with NH$_3$ (Solins et al. 2005a). From SMA observations of CH$_3$CN, Qin et al. (2008) estimated a rotation temperature of 300 K, a column density of $1.6 \times 10^{16}$ cm$^{-2}$, and a CH$_3$CN fractional abundance of $5 \times 10^{-6}$, by RDs. From the 1.3 mm dust continuum emission, we estimate a gas mass of $33 M_\odot$ and an H$_2$ column density of $7.7 \times 10^{24}$ cm$^{-2}$. Using the XCLASS program, we estimate rotation temperatures of 295 and 59 K and CH$_3$CN column densities of $6.2 \times 10^{16}$ and $2.4 \times 10^{16}$ cm$^{-2}$, for the compact and extended regions, and we calculate $X_{\text{CH}_3\text{CN}} = 8 \times 10^{-8}$.

G31.41 is a prototypical HMC imaged in multiple high-excitation molecular transitions such as NH$_3$ (4, 4), CH$_3$CN (6–5) and (12–11), CH$_3$OH, CH$_3$CCH, and others (Cesaroni et al. 1994; Araya et al. 2008; Hatchell et al. 1998). Cesaroni et al. (1994) detected CH$_3$CN (6–5), CH$_3$CNCN (6–5), and vibrationally excited CH$_3$CN (6–5), and estimated a rotation temperature of 200 K. Hatchell et al. (1998) observed CH$_3$CN (13–12) and (19–18) and report temperatures of 149 and 142 K, respectively, and a column density $>0.5 \times 10^{14}$ cm$^{-3}$. Olmi et al. (1996), using observations with the IRAM 30 m of several CH$_3$CN transitions, estimated a rotation temperature of $\sim$140 K and a column density of $2.3 \times 10^{17}$ cm$^{-2}$. Cesaroni et al. (1998) found kinetic temperatures of 250–400 K toward the cores, using the NH$_3$(4, 4) line. Recently, with two SMA configurations and IRAM 30 m observations of CH$_3$CN (12–11) and CH$_3$CNCN, Cesaroni et al. (2011) confirmed the existence of a velocity gradient, explaining it as a rotating toroid. Using only the compact SMA configuration data as Cesaroni et al. (2011), we obtain a gas mass $\sim$250 $M_\odot$ and an H$_2$ column density of $3.5 \times 10^{24}$ cm$^{-2}$. With the XCLASS analysis, we calculate rotational temperatures of 327 and 95 K and column densities of $1.5 \times 10^{17}$ and $9.1 \times 10^{13}$ cm$^{-2}$ for the compact and extended regions. We estimate a CH$_3$CN abundance of $4.2 \times 10^{-8}$.

I18566 shows H$_2$O, CH$_3$OH, and H$_2$CO maser emission, CS, an outflow traced by NH$_3$ and SiO, and weak emission at 3.6 cm and 2 cm, probably coming from an ionized jet (Zhang et al. 2007; Araya et al. 2005b; Beuther et al. 2002). This source harbors a 6 cm H$_2$CO maser that flared in 2002 (Araya et al. 2007), from 43 and 87 GHz continuum emission, Zhang et al. (2007) estimate a gas mass of $\sim70 M_\odot$ for the core. Also, they detected significant heating of the NH$_3$ gas (70 K) as a consequence of the outflow. From the 1.3 mm dust continuum, we estimate a gas mass of $\sim16 M_\odot$ and an H$_2$ column density of $1.1 \times 10^{21}$ cm$^{-2}$. Our XCLASS analysis gives rotation temperatures of 382 and 110 K and CH$_3$CN column densities of $7.1 \times 10^{15}$ and $5.1 \times 10^{13}$ cm$^{-2}$. We detected broad line widths for most of the CH$_3$CN-$K$ components, with an average FWHM of 8.2 km s$^{-1}$. We find a CH$_3$CN abundance of $6.4 \times 10^{-8}$.

G45.07 is a pair of spherical UC H$_2$ regions showing OH, H$_2$O, and CH$_3$OH maser emission. At least three continuum sources are observed in the mid-infrared (De Buizer et al. 2005). Hunter et al. (1997) observed CS and CO probably tracing an outflow; the H$_2$O masers are roughly in the same direction as the axis. From the 1.3 mm dust continuum emission, we estimate a gas mass of 172 $M_\odot$ and an H$_2$ column density of $2.7 \times 10^{24}$ cm$^{-2}$. The physical parameters obtained from XCLASS are 290 and 82 K and CH$_3$CN column densities of $5.4 \times 10^{15}$ and $4.1 \times 10^{14}$ cm$^{-2}$, for the compact and extended regions, respectively. We estimate a CH$_3$CN abundance of $1.9 \times 10^{-9}$.

G45.47 is an MSFR associated with an UC H$_2$ region, multiple molecular lines, and OH, H$_2$O, and CH$_3$OH maser emission (Cesaroni et al. 1992; Remijian et al. 2004a; Olmi et al. 1993). Olmi et al. (1993) detected CH$_3$CN (6–5), (8–7), and (12–11) transitions using the IRAM 30 m, and they estimated upper limits of 51 K for the rotation temperature and $2.5 \times 10^{13}$ cm$^{-2}$ for the column density. From NH$_3$(2, 2) and (4, 4), Hofner et al. (1999) estimated a rotation temperature of 59 K and a column density of $1.8 \times 10^{17}$ cm$^{-2}$. From the ammonia absorption, they suggested that molecular gas is infalling onto the UC H$_2$ region. From their molecular line surveys Hatchell et al. (1998) and Remijian et al. (2004a) report that G45.47 is line-poor; they do not see evidence for an HMC in this field. However, the UC H$_2$ region and relatively high luminosity ($\sim10^6 L_\odot$) suggest a more evolved MSFR. From the 1.3 mm dust continuum emission, we estimate a gas mass of $\sim44 M_\odot$ and an H$_2$ column density of $6.7 \times 10^{23}$ cm$^{-2}$. From the XCLASS analysis, we estimate rotation temperatures between 155 K and 65 K, column densities of $6.8 \times 10^{14}$ and $3.8 \times 10^{13}$ cm$^{-2}$, and $X_{\text{CH}_3\text{CN}} = 1 \times 10^{-9}$. Consistent with the molecular line surveys mentioned above, we find little molecular line emission from this source, compared with the rest of our sample.

W51e2 is an UC H$_2$ region associated with warm gas and H$_2$O, OH, NH$_3$, and CH$_3$OH maser emission (Gauvreau & Mulder 1987; Gauvreau et al. 1993; Zhang & Ho 1995, 1997; Zhang et al. 1998). From the 1.3 mm continuum analysis, Klaassen et al. (2009) estimated a gas mass of $140 M_\odot$ assuming a dust temperature of 400 K. They calculated from the CH$_3$CN a rotation temperature of 460 K and a column density of $2.1 \times 10^{16}$ cm$^{-2}$. Using the same data, we estimate a gas mass of 95 $M_\odot$ and a column density of $3.9 \times 10^{16}$ cm$^{-2}$. Differences probably come from our higher temperature for the dust emission. Using the RD method, Zhang et al. (1998) found a CH$_3$CN column density of $2.8 \times 10^{16}$ cm$^{-2}$ and rotation temperature of 140 K; they estimated a CH$_3$CN fractional abundance of $5 \times 10^{-10}$. From multiple CH$_3$CN transitions at 3 mm and 1 mm, and using an LTE model for each transition, Remijian et al. (2004b) estimated a rotation temperature of 153 K and column density of $3.8 \times 10^{16}$ cm$^{-2}$. They calculated an H$_2$ column density of $8.3 \times 10^{22}$ cm$^{-2}$ and a CH$_3$CN fractional abundance of $X_{\text{CH}_3\text{CN}} = 4.6 \times 10^{-7}$. With XCLASS, we estimate rotation temperatures of 458 and 118 K and CH$_3$CN column densities of $2.8 \times 10^{17}$ and $1.0 \times 10^{15}$ cm$^{-2}$, for the compact and extended components. We calculated $X_{\text{CH}_3\text{CN}} = 7 \times 10^{-9}$. The discrepancies with Remijian et al. (2004b) probably arise from differences in the methods used to estimate temperatures and H$_2$ and CH$_3$CN column densities. The much lower abundances
W51e8 is an MSFR located to the south of W51e2 and is associated with H$_2$O and OH maser emission and multiple molecular lines such as HCO$^+$, NH$_3$, and CH$_3$CN (Zhang & Ho 1997; Zhang et al. 1998). Observing with the Nobeyama Millimeter Array at 2 mm, Zhang et al. (1998) detected molecules such as CS, CH$_3$OCH$_3$, HCOOCH$_3$, and CH$_3$CN. From the latter, they estimated a rotation temperature of 130 K and a CH$_3$CN column density of $2.0 \times 10^{14}$ cm$^{-2}$. Klassen et al. (2009) estimated a dust-derived mass of 82 $M_\odot$, assuming an average temperature of 400 K. They estimated a rotation temperature of 350 K and a CH$_3$CN column density of $8 \times 10^{15}$ cm$^{-2}$ through RDs. With the same method, Remijan et al. (2004b, W51e1 in their nomenclature) estimated a rotation temperature of 123 K, a column density of $1.4 \times 10^{16}$, and fractional abundances of $1.3 \times 10^{-7}$. With the set of data at 1.3 mm of Klassen et al. (2009), we calculate an H$_2$ gas mass of $86 M_\odot$ and a column density of $5.8 \times 10^{24}$ cm$^{-2}$. Using the XCLASS program, we estimate rotation temperatures of 384 and 85 K and column densities of $1.8 \times 10^{24}$ and $1.8 \times 10^{14}$ cm$^{-2}$, for the compact and extended regions, respectively. For the compact component, we estimate $X_{\text{CH}_3\text{CN}}$ of $3.4 \times 10^{-8}$. As in the case of W51e2, the differences with Remijan et al. (2004b) come from the methods used to obtain the physical parameters.

5. DISCUSSION

5.1. Mass and Density from 1.3 mm Continuum

The gas masses estimated from the 1.3 mm emission range from 7 to 375 $M_\odot$, for and column densities from $1.0 \times 10^{23}$ to $6.7 \times 10^{24}$ cm$^{-2}$. The median value for the mass is 21 $M_\odot$, and for the column densities is $8 \times 10^{-3}$ cm$^{-2}$. Using the physical size of a deconvolved beam, we obtained H$_2$ number densities from $8 \times 10^5$ to $1.4 \times 10^8$ cm$^{-3}$, assuming that the gas is distributed uniformly.

Except for IRAS17233, all sources are more massive than $\sim 10 M_\odot$, which is commonly adopted as the lower limit for the gas mass of an HMC (Cesaroni 2005).

The size of the dusty structures goes from $\sim 3500$ to 20500 AU (0.017 to 0.10 pc). In general, the dust-emission structures shown in Figure 1 have sizes, gas masses, and column densities that are similar to other HMCs (e.g., Beltrán et al. 2011).

From Table 4 we see that the estimated thermal dust contribution to the total 1.3 mm flux ranges from 8% in G5.89 to $>98%$ in sources W3TW, I16547, I17233, G8.68, I18128, G23.01, G31.41, and I18566. The latter sources show a high fraction of dust emission because they have essentially no free–free emission from ionized gas. Since even this sub-group has luminosities $>10^4 L_\odot$ (corresponding to an early B-type star), we would expect a more substantial amount of ionization. Possible reasons for the lack of such ionization include young sources in early evolutionary stages, very high mass accretion rates, or the presence of a stellar cluster whose luminosity is dominated by late-B-type stars. Sources such as G10.47, G31.41, G45.07, G45.47, and W51e2 clearly show UC H II regions embedded in the dusty molecular gas, indicating much higher levels of ionization.

One of the implicit assumptions in Equations (2) and (3) is that the gas and dust are well-coupled. As a test, we calculate the gas-dust relaxation time, $t_{gd}$. We follow Chen et al. (2006), who estimated the timescale necessary for thermal coupling of the dust and gas, and obtained $t_{gd} = 2.5 \times 10^6/\eta H_{\text{in}}$, in seconds, where $\eta H$ is the number density of H nuclei in cm$^{-3}$. For the values of $\eta H$, in Table 4, the gas-dust relaxation time ranges from 3 to 500 yr. Thus, $t_{gd}$ is much shorter than the expected HMC lifetime.

With respect to the LTE condition, the CH$_3$CN critical density is $\sim 10^6$ cm$^{-3}$ for the $J_{\text{upper}} = 12$ transition (Wang et al. 2010). We therefore conclude that the LTE approximation is valid and the rotation temperature of CH$_3$CN can be taken as the kinematic temperature of the H$_2$ gas.

5.2. Spatial Distribution with Respect to the CH$_3$CN

In Figure 1 we compare the spatial distribution of the 1.3 mm continuum emission with the velocity-integrated emission (moment 0) of $K$ lines 3, 5, and 7 of CH$_3$CN. These $K$-components trace kinetic temperatures of 133 K, 247 K, and 418 K, respectively. For G5.89 and I18182 we use the $K$ lines 3, 5, and 6 because of the lack of $K = 7$ emission.

At the resolution and sensitivity of our data, the 1.3 mm continuum emission and the hot CH$_3$CN emission coincide closely and have similar spatial extents for most of the sources. Notably, G5.89 has a more complicated morphology.

The close spatial coincidence between dust and molecular gas can be explained if embedded protostars are heating the dust grains, thus evaporating the ice mantles, and subsequent gas-phase chemical reactions produce species such as CH$_3$CN. This scenario has been observed toward HMCs, especially with nitrogen-bearing molecules (e.g., Qin et al. 2010). In Section 5.4 we will explore various scenarios to explain the molecular abundances.

We note that the displacement of some CH$_3$CN lines from the continuum peak for sources such G5.89, G10.47, G28.20N, and G45.47 (see Figure 1) could be due to factors such as multiple star forming points, unresolved continuum sources, or molecular gas heated externally. Since higher-$K$ transitions should be excited in denser, hotter, and probably more compact regions, clumpy cores, with different physical conditions, are an alternative explanation for the displacements. Sub-arcsecond observations will be necessary to test these alternative explanations.

5.3. Temperature, Density, and Virial Mass

The CH$_3$CN analysis, using the rotational diagrams and XCLASS, indicates high temperatures and densities for all sources. However, from Figure 2, large deviations are clearly seen to the linear fit for some of the $K = 3, 6$ lines, toward sources such IRAS17233, G10.47, G10.62, G31.41, IRAS16547, and IRAS18566; this indicates that these lines are optically thick and hence there is probably a mixture of optically thin and thick lines in our spectra. This occurs because the $K = 0, 3, 6, \ldots$ ladders are doubly degenerate compared with the $K = 1, 2, 4, 5, \ldots$ ladders. Thus the former lines will have higher optical depths than the latter. As we mention below, the homogeneous assumption of the RD method probably is inadequate.

Moreover, Figure 3 shows similar brightness temperatures of low $K$-ladders ($K = 0–4$), including the $K = 3$ line, toward some sources (e.g., IRAS17233, G28.20N, G10.47, G31.41, W51e2, and W51e8). This confirms that these lines are optically thick.

We find good agreement between the observed spectra and the synthetic models using XCLASS, with a two-component...
model. This result, along with the close coincidence between the molecular gas and dust emission, suggest that most of the HMCs are internally heated.

We consider the two-component model to be more realistic than a single homogeneous structure. The reality is probably even more complex; Cesaroni et al. (2010, 2011), for example, report sub-arcsecond observations that indicate gradients in both temperature and density. We note that the two-component model overestimate the $K = 3$ line for some sources, suggesting that even this model is too simplistic.

We summarize our results from the XCLASS program as follows. For the extended component, the temperature ranges from 40 to 132 K, with an average of 85 K and a median of 82 K; the mean size is 0.10 pc; and the average column density $N_{\text{CH}_3\text{CN}} = 2.4 \times 10^{14} \, \text{cm}^{-2}$, with a median of $1.7 \times 10^{14} \, \text{cm}^{-2}$. For the compact component, the temperature ranges from 122 to 485 K, with an average of 303 K and a median of 295 K; the mean size is 0.02 pc; and the average column density $N_{\text{CH}_3\text{CN}} = 8.5 \times 10^{16} \, \text{cm}^{-2}$, with a median of $2.2 \times 10^{16} \, \text{cm}^{-2}$.

In Tables 4 and 6 we present $M_{\text{gas}}$ and $M_{\text{vir}}$, which provide information about the stability and structure of the HMCs. The ratio of the virial mass to gas mass, $M_{\text{vir}} / M_{\text{gas}}$, is greater than unity for all sources but G10.47 (see Figure 4). The ratio ranges from 29.6 to 1.1, with an average of 8.3. This suggests that the cores are not in virial equilibrium and a traditional interpretation of this result is that the HMCs are expanding, since $E_k > 2E_g$. However, another interpretation is that these cores are still collapsing, as suggested by recent models of molecular cloud formation and evolution (see Ballesteros-Paredes et al. 2011). This possibility will be explored in a future work.

5.4. Fractional Abundances

Adopting the H$_2$ column densities from the 1.3 mm continuum emission, we find CH$_3$CN abundances, $X_{\text{CH}_3\text{CN}}$, from $\sim 1 \times 10^{-9}$ to $\sim 2 \times 10^{-7}$ toward the hot inner components. These results span a range of fractional abundances that agree with other estimates toward HMCs, such as the Orion hot core with $10^{-10} - 10^{-8}$ (Wilner et al. 1994), G20.08N with $5 \times 10^{-9}$ to $2 \times 10^{-8}$ (Galván-Madrid et al. 2009), Sgr B2(N) with $\sim 3 \times 10^{-8}$ (Nummelin et al. 2000), and W51e8 and W51e2 with $1.3 \times 10^{-7}$ and $4.6 \times 10^{-7}$, respectively (Remijan et al. 2004b).

At the high dust temperatures of the compact components ($T > 122$ K), most of the organic molecules are probably evaporated from the grain mantles and incorporated into the gas phase (Herbst & van Dishoeck 2009). Moreover, these temperatures are high enough to form many new organic species by chemical reactions—if the chemical timescales are short enough. For any given molecular species, one can ask if it was formed (1) in a dense, cold gas phase prior to any protostellar object, (2) on the grains by surface reactions, or (3) in gas phase processes after evaporation (see the review by Herbst & van Dishoeck 2009). In the case of CH$_3$CN, all three of these scenarios have been studied using both chemical models and observations (e.g., MacDonald & Habing 1995; Ohishi & Kaifu 1998; Rodgers & Charney 2001; Wang et al. 2010).

Observations toward cold dense gas show CH$_3$CN abundances of $\sim 10^{-10}$ (Ohishi & Kaifu 1998), i.e., substantially lower than the abundances that we find. Thus, the scenario in which CH$_3$CN is formed in a cold gas phase, then adsorbed by dust grains and released by heating from young protostars, appears not to contribute to the high abundances observed toward these HMCs.

Alternatively, the formation of CH$_3$CN on grain surfaces and/or in the hot gas after evaporation of “parent” species represent better possibilities. The former process tends to underestimate the final abundances (e.g., Caselli et al. 1993), while the chain of mantle–surface–gas reactions yields good agreement with HMC abundances at times $> 10^5$ yr (e.g., Hasegawa & Herbst 1993). Moreover, if we consider the grain-surface process as the main path to form CH$_3$CN, the abundances toward the inner regions of all HMCs should be very similar, because the high temperatures would sublimate most of the ice on the dust (e.g., Viti et al. 2004; Herbst & van Dishoeck 2009).

Chemical models suggest that CH$_3$CN is synthesized from NH$_3$ and HCN, once the ammonia is released from ice mantles, and via the ion–molecule reaction of CH$_3$ + HCN and the radiative association reaction of CH$_3$ with CN (Charnley et al. 1992). The process occurs once the dusty regions reach temperatures $> 100$ K (e.g., Rodgers & Charney 2001; Herbst & van Dishoeck 2009). Moreover, at temperatures $> 300$ K the environment is optimal to form CH$_3$CN from the parent nitrogenated species HCN and NH$_3$ (Rodgers & Charney 2001). For example, Doty et al. (2002) found that the HCN abundance increases with temperature, and at $T > 200$ the formation of HCN proceeds quickly. This temperature dependence in the reactions of N-bearing molecules, including HCN and CH$_3$CN, has been observed in other chemical models and HMCs (Rodgers & Charney 2001).

In Figure 5 we plot $X_{\text{CH}_3\text{CN}}$ versus rotation temperature estimated for the compact components with XCLASS, and our RD results. Uncertainties of the hot components from XCLASS program were used to estimate uncertainties in gas masses and column densities from the continuum emission. We observe that fractional abundances increase with higher temperatures. This result can be understood with the chemical scenario in which CH$_3$CN molecules mainly form in a hot gas phase and its production is optimized at higher temperatures. A similar dependence between CH$_3$CN abundance and temperature was detected toward Orion-KL and the Compact Ridge (Wilner et al. 1994; Wang et al. 2010). High angular resolution, multi-species molecular line observations with ALMA would pro-
components of CH$_3$CN (12$K$–11$K$). Some spectra showed emission up to the $K = 8$ component, which traces gas at $\sim$525 K.

On the basis of these emission lines we estimated rotational temperatures, column densities, and fractional abundances, using both RDs and the XCLASS program that generates synthetic spectra. From the RD method, we find temperatures from 90 to 500 K and column densities from $2.5 \times 10^{13}$ to $2.5 \times 10^{16}$ cm$^{-2}$. With XCLASS, we find temperatures from 40 to 132 K and column densities from $1.6 \times 10^{13}$ to $1.0 \times 10^{15}$ cm$^{-2}$ for the extended component, and temperatures from 122 to 485 K and column densities from $6.8 \times 10^{14}$ to $5.1 \times 10^{17}$ cm$^{-2}$ for the compact component.

We used the rotation temperatures estimated with XCLASS to derive the gas mass from the 1.3 mm continuum. With the multiple $K$ lines of CH$_3$CN we find a good fit between observed and synthetic spectra for the two-component XCLASS model; this result, and a close spatial coincidence between the molecular gas and the continuum emission, suggest that most of these HMCs are internally heated. Sub-arcsecond observations are necessary to explore their structure in greater detail.

The fractional abundance of CH$_3$CN toward the hot inner regions shows a marked increase with temperature. This can be understood if we consider that CH$_3$CN molecules form in the hot gas phase when parent N-bearing species, such as NH$_3$, are evaporated from grain mantles.

This work has received partial support from grants UNAM/DGAPA project IN101310 to S.K. and CONACYT fellowship to V.H.-H. V.H.-H. thanks Roberto Galván-Madrid for comments and helpful discussion. We thank the anonymous referee for comments and suggestions that significantly improved the manuscript.

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We studied 17 HMCs in the CH$_3$CN (12$K$–11$K$) lines and the 1.3 mm continuum. The sources were observed with the SMA at $\sim$220 GHz, with either the compact or extended configuration. From the 1.3 mm continuum, we detected dusty structures with physical sizes of 0.01–0.1 pc, gas masses of 7–375 $M_\odot$, and column densities of 0.1–6.7 $\times$ 10$^{24}$ cm$^{-2}$. The continuum emission coming from dust ranges from 8% to 98% of the total flux.

All 17 sources show multiple molecular lines but different molecular richness. All sources show five or more $K$-
