HIGH-RESOLUTION $\lambda = 1$ mm CARMA OBSERVATIONS OF LARGE MOLECULES IN ORION-KL

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ABSTRACT

We present high-resolution Combined Array for Research in Millimeter-Wave Astronomy (CARMA) $\lambda = 1$ mm observations of several molecular species toward Orion-KL. These are the highest spatial and spectral resolution 1 mm observations of these molecules to date. Our observations show that ethyl cyanide [C$_2$H$_5$CN] and vinyl cyanide [C$_2$H$_3$CN] originate from multiple cores near the Orion hot core and IRc7. In addition we show that dimethyl ether [(CH$_3$)$_2$O] and methyl formate [HCOOCH$_3$] originate from IRc5 and IRc6 and that acetone [(CH$_3$)$_2$CO] originates only from areas where both N-bearing and O-bearing species are present.

Subject headings: astrochemistry — ISM: individual (Orion-KL) — ISM: molecules — radio lines: ISM

Online material: color figures

1. INTRODUCTION

The Orion-KL region is the closest (~480 pc) site of massive star formation to us (Genzel et al. 1981). There are several cloud components (e.g., hot core, compact ridge, extended ridge, and plateau) which are associated with Orion-KL, each with different chemical and physical properties (e.g., Blake et al. 1987). The two most chemically interesting components, the hot core and compact ridge, are separated by only ~5800 AU. Large oxygen-bearing species (e.g., methyl formate [HCOOCH$_3$] and dimethyl ether [(CH$_3$)$_2$O]) have been observed primarily toward the compact ridge (e.g., Liu et al. 2002), while large nitrogen-bearing species (e.g., ethyl cyanide [C$_2$H$_5$CN]) are located toward the hot core (e.g., Blake et al. 1987).

The chemical pathways to most large detected interstellar molecules in hot molecular cores are not known or are poorly understood (e.g., Quan & Herbst 2007). The spatial location of a molecular species, in relation to the continuum, shocks, and other species, can give indications of its formation mechanism. In order to further our understanding of these formation mechanisms, we have conducted high-resolution observations of several large molecular species: acetone [(CH$_3$)$_2$CO], dimethyl ether [(CH$_3$)$_2$O], methyl formate [HCOOCH$_3$], ethyl cyanide [C$_2$H$_5$CN], methanol [CH$_3$OH], formic acid [HCOOH], acetaldehyde [CH$_3$CHO], and ethanol [C$_2$H$_5$OH].

While many of these molecular species have been observed at moderate resolution (e.g., Liu et al. 2002; Blake et al. 1996), (CH$_3$)$_2$CO has not. Its original detection in this source by Friedel et al. (2005) was with a rather large beam (~12'' x 9'') and indicated that its emission was not associated either with the hot core or compact ridge. In this paper we present the highest spectral resolution 1 mm observations of these molecular species to date.

2. OBSERVATIONS

The observations were taken in 2007 March with the Combined Array for Research in Millimeter-Wave Astronomy (CARMA). All data were acquired in two ~5 h long tracks [one for (CH$_3$)$_2$O, C$_2$H$_6$CN, (CH$_3$)$_2$CO, and the continuum and one for HCOOCH$_3$, CH$_3$OH, CH$_3$CHO, C$_2$H$_5$OH, and HCOOH] with nine antennas and a phase center of $(\alpha(2000.0) = 05^h35^m14.35^s$ and $\delta(2000.0) = -05^\circ22'35.0''$. The typical synthesized beam was $\sim 2.5''$ x 0.85'' (54 times higher resolution than the original acetone detection). The $u - v$ coverage of the observations gives projected baselines of 5.8–196.5 k $\lambda$ (7.5–255.5 m). Thus, any structure larger than ~16'' will be resolved out by the array. We compared our flux values to those of single-dish observations of Sutton et al. (1985) and determined that we are resolving out little flux (<15%) from most of the lines we observed. The only exception is the $J = 8_{1,8} - 7_{0,7}$ transition of CH$_3$OH, where we are resolving out ~90% of the flux.

The correlator for the first track was configured to have two 500 MHz wide windows for continuum and four 32 MHz windows for spectral lines (half in each sideband), while the correlator for the second track was configured to have six 32 MHz windows (three in each sideband). The spectral line windows had 63 channels with a spacing of 488 kHz (~0.64 km s$^{-1}$). Uranus was used as the flux density calibrator and 0530+135 was used to calibrate the antenna-based gains. The absolute amplitude calibration of 0530+135 from the flux density calibrator is accurate to within ~20%. The internal noise source and 0530+135 were used to correct the passbands of each window. The data were calibrated, continuum subtracted, and imaged using the MIRIAD software package (Sault et al. 1995).

3. RESULTS

Table 1 lists all the molecules that we searched for along with their parameters. Column (1) gives the molecular formula, column (2) gives the transition quantum numbers, column (3) gives the transition frequency in MHz, column (4) gives the upper state energy ($E_u$) in K, column (5) gives the line strength multiplied by the square of the relevant dipole moment ($S\mu^2$) in debyes$^2$, column (6) gives the synthesized beam size from the observations in arcseconds, column (7) gives the 1 $\sigma$ rms noise level from the associated spectral window in mJy beam$^{-1}$, column (8) gives the percentage of missing flux when compared to the single-dish observations of Sutton et al. (1985), and column (9) gives the literature reference for the molecular parameters. The table has been broken into two parts. The top section lists the transitions detected in narrowband windows, while the bottom section lists transitions detected in wideband windows.

3.1. Continuum

We used two wideband (~500 MHz) windows to map the continuum of Orion-KL. Several molecular lines were detected in
the peak extending to the southwest from the hot core (hot core-SW).

Previously 1 mm array observations of this region by Blake et al.
(1995). Note that the emission from IRc6 is not a point source but
rather a rough shape around BN. There are also notable emission
peaks both to the southwest and west of IRc5 which are not
resolved. The elongation of the continuum is also closely aligned with known SiO outflows seen by Wright et al.
(2004) detected Migenes et al. (1989) indicate numerous clumps along the long
axis of the hot core. In addition, Beuther et al. (2004) detected several continuum peaks near the hot core at 865 \( \mu \)m, which we were not able to resolve. The elongation of the continuum is also closely aligned with known SiO outflows seen by Wright et al. (1995). Note that the emission from IRc6 is not a point source but rather a rough C shape around BN. There are also notable emission peaks both to the southwest and west of IRc5 which are not associated with known infrared sources.

### 3.2. Methanol [CH$_3$OH]

Two transitions of CH$_3$OH were detected in our narrowband windows. Figure 2a shows the channel map of the v_{LSR} = 5.5 km s$^{-1}$ emission of the lower energy (J = 8_{18} - 7_{07}) transition of CH$_3$OH. The CH$_3$OH map indicates some widespread emission, but has distinct concentrations near the hot core, IRc5, IRc7, and IRc6 (some are not seen in the map as they are at different velocities, but possibly most notable is the lack of emission from the compact ridge. There is also a notable emission peak extending to the southwest from the hot core (hot core-SW).

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### Table 1

| Molecule   | Quantum Numbers | Frequency (MHz) | \( E_u \) (K) | \( S_{\mu}^2 \) (debyes$^2$) | \( \theta_x \times \theta_y \) (arcsec) | rms Noise (mJy beam$^{-1}$) | Missing Flux (%) | Ref. |
|------------|-----------------|----------------|--------------|---------------------------|-------------------------------|--------------------------|-----------------|------|
| HCOOCH$_3$ | 20$_{19}$ - 19$_{18}$ A | 226778.764(10) | 120          | 51.4                      | 2.49 x 0.90                   | 185                      | \sim 15 1      |      |
| HCOOCH$_3$ | 20$_{19}$ - 19$_{18}$ E | 226773.152(9)  | 120          | 51.4                      | 2.49 x 0.90                   | 185                      | \sim 15 1      |      |
| (CH$_3$)$_2$O | 19$_{11}$ - 19$_{10}$ A | 231987.779(3)  | 81           | 16.9                      | 2.42 x 0.82                   | 252                      | \sim 10 2      |      |
| (CH$_3$)$_2$O | 19$_{11}$ - 19$_{10}$ E | 231987.856(3)  | 81           | 16.9                      | 2.42 x 0.82                   | 252                      | \sim 10 2      |      |
| C$_2$H$_5$CN | 27$_{03}$ - 26$_{02}$ | 231990.409(3)  | 157          | 399.4                     | 2.50 x 0.83                   | 252                      | \< 5 3        |      |
| C$_2$H$_5$CN | 19$_{02}$ - 18$_{01}$ | 227780.971(2)  | 150          | 365.4                     | 2.42 x 0.83                   | 179                      | \< 5 3        |      |
| (CH$_3$)$_2$CO | 23$_{03}$ - 22$_{02}$ A | 230170.265(20) | 135          | 22.4                      | 2.47 x 0.82                   | 196                      | e 4           |      |
| (CH$_3$)$_2$CO | 23$_{03}$ - 22$_{02}$ E | 230170.313(17) | 135          | 22.4                      | 2.47 x 0.82                   | 196                      | e 4           |      |
| (CH$_3$)$_2$CO | 23$_{03}$ - 22$_{02}$ EE | 230176.727(14) | 135          | 22.4                      | 2.47 x 0.82                   | 196                      | e 4           |      |
| CH$_3$OH | 19$_{13}$ - 19$_{12}$ | 229786.221(46) | 578          | 5.7                       | 2.43 x 0.88                   | 188                      | f 5           |      |
| HCOOH | 10$_{09}$ - 9$_{08}$ | 231505.705(23) | 64           | 19.3                      | 2.38 x 0.89                   | 279                      | g 3           |      |
| CH$_3$CHO | 11$_{11}$ - 10$_{10}$ | 229775.029(11) | 61           | 8.4                       | 2.45 x 0.88                   | 284                      | # 6           |      |
| C$_3$H$_5$OH | 12$_{08}$ - 11$_{07}$ | 226661.701(100) | 51          | 17.0                      | 2.47 x 0.90                   | 248                      | # 3           |      |

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* When compared with the results from Sutton et al. (1985).
* These (CH$_3$)$_2$O lines are blended.
* Calculations indicate that little or no flux is missing, but since the features are unresolved in our observations and source sizes cannot be determined, the values are upper limits.
* These (CH$_3$)$_2$CO lines are blended.
* Not detected by Sutton et al. (1985).
* The full line was not detected in our observations, so no comparison could be made.
* This line was not detected in our observations, so no comparison could be made.
* Since this line was spectrally unresolved, no comparison can be made.

References.—(1) Oosterling et al. 1999; (2) Groner et al. 1998; (3) Pickett et al. 1998; (4) Groner et al. 2002; (5) Xu & Lovas 1997; (6) Lovas 2004.

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2 Some sources are not labeled as they are too close together, namely IRc2 and radio source I, near the hot core.

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Fig. 1.—Continuum of Orion-KL at 231 GHz. Known infrared and radio sources are denoted with plus signs and labeled. Contour levels are $\pm 3\sigma, \pm 5\sigma$, etc., where the $1\sigma$ rms noise level is 11.3 mJy beam$^{-1}$. The synthesized beam is in the bottom left corner.

Fig. 2.—Map and spectra of CH$_3$OH. (a) Map of the $J = 8_{1,8} - 7_{0,7}, v_{\text{LSR}} = 5.5$ km s$^{-1}$ emission overlaid on gray-scale continuum. Contours are $\pm 3\sigma, \pm 5\sigma$, etc., ($\sigma = 0.268$ Jy beam$^{-1}$). The synthesized beam is in the bottom left corner of the map, and plus signs denote the same sources as in the continuum map (see Fig. 1). (b) Spectra toward IRc5. Dashed lines mark $v_{\text{LSR}} = 7.6$ and 9.6 km s$^{-1}$. Error bar denotes 1$\sigma$ rms noise level. (c) Spectra toward IRc6. (d) Spectra toward hot core. (e) Spectra toward IRc7.
that corresponds to weak continuum emission. Convolving our results with a 29" beam and comparing them to those from Sutton et al. (1985) indicates that we are resolving out a large percentage of flux ~90% from this transition.

Figures 2b–2e show the spectra toward IRC5, IRC6, the hot core, and IRC7, respectively. The highly asymmetric line profile of the IRC5 spectra indicates that CH$_3$OH may be self-absorbing near 9 km s$^{-1}$ along this line of sight, while the IRC6 spectra peak at the same velocity as the IRC5 absorption. Both the hot core and IRC7 spectra show possible absorption features near 7.6 km s$^{-1}$.

Fits to the spectral lines are given in Table 2. Column (1) lists the molecule, and column (2) lists the source. Column (3) gives the figure number for the spectra. Columns (4), (5), and (6) list the fit parameters: intensity in Jy beam$^{-1}$, $v_{\text{LSR}}$ in km s$^{-1}$, and FWHM in km s$^{-1}$, respectively. Columns (7) and (9) list the calculated opacity at the line center for assumed lower and upper rotation temperatures, respectively (see §§ 4.2 and 4.3). Columns (8) and (10) list the total column density for the assumed lower and upper rotation temperatures, respectively, in cm$^{-2}$ (see § 4.3). The fits to the spectra are $\chi^2$ Gaussian fits and only those lines for which we have a full spectral profile have been fit.

We did not set out to detect the second narrowband CH$_3$OH transition, but it was fortuitously at the edge of one of our spectral windows. Unfortunately, we did not observe the entire line of this higher energy ($J = 19_{5,15} - 20_{4,16}$) CH$_3$OH transition. We

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|c|c|c|c|c|}
\hline
Molecule & Source & Fig. & $I^a$ (Jy beam$^{-1}$) & $v_{\text{LSR}}$ (km s$^{-1}$) & $\Delta v$ (km s$^{-1}$) & $\tau$ & $N_T$ (cm$^{-2}$) & $\tau$ & $N_T$ (cm$^{-2}$) \\
\hline
CH$_3$CN & IRC7 & 6b & 2.5(2) & 4.9(1) & 2.8(2) & 0.36(4) & 3.2(4) & 10$^{16}$ & 0.13(1) & 1.9(3) \\
& IRC7 & 6b & 0.8(2) & 3.9(8) & 11.6(11) & 0.10(3) & 3.7(10) & 10$^{17}$ & 0.04(1) & 2.4(6) \\
& Hot Core & 4c & 3.8(4)$^b$ & 5.1(2) & 6.3(1) & 0.74(4) & 1.5(1) & 10$^{17}$ & 0.21(1) & 7.0(3) \\
(CH$_3$)$_2$O & IRC6 & 4b & 1.8(4)$^b$ & 7.1(1) & 1.54(1) & 0.63(20) & 9.0(3) & 10$^{17}$ & 0.35(10) & 1.3(5) \\
& IRC6 & 4b & 2.8(3) & 9.1(4) & 6.0(6) & 1.29(28) & 7.4(13) & 10$^{18}$ & 0.62(9) & 9.3(14) \\
& IRC5 & 4c & 3.4(4) & 7.6(1) & 1.1(2) & 1.77(65) & 1.9(6) & 10$^{18}$ & 0.78(15) & 2.1(5) \\
& IRC5 & 4c & 0.9(3) & 8.1(6) & 2.5(14) & 0.25(10) & 6.0(40) & 10$^{17}$ & 0.16(6) & 9.6(6) \\
HCOOCH$_3$ & IRC6 & 5b & 0.5(1) & 7.7(4) & 3.3(8) & 0.13(3) & 3.1(10) & 10$^{16}$ & 0.08(2) & 4.6(15) \\
& IRC5 & 5c & 3.7(3) & 7.5(0) & 1.3(1) & 2.11(7) & 2.0(5) & 10$^{17}$ & 0.83(11) & 1.8(2) \\
& IRC5 & 5c & 2.4(4) & 9.3(0) & 0.9(1) & 0.84(23) & 3.6(8) & 10$^{17}$ & 0.45(10) & 4.4(9) \\
CH$_3$OH & IRC5 & 2b & 4.1(5) & 7.8(2) & 6.6(6) & 4.37(1030) & 1.5(33) & 10$^{18}$ & 1.00(22) & 9.2(17) \\
& IRC5 & 2b & 4.1(5) & 8.1(6) & 1.43(3) & 0.82(22) & 5.9(32) & 10$^{16}$ & 0.44(10) & 8.6(46) \\
& IRC6 & 2e & 2.3(4) & 7.1(2) & 1.47(7) & 0.82(22) & 5.9(32) & 10$^{16}$ & 0.44(10) & 8.6(46) \\
& IRC6 & 2e & 5.0(4) & 8.7(2) & 0.66(3) & 0.82(22) & 5.9(32) & 10$^{16}$ & 0.44(10) & 8.6(46) \\
& IRC6 & 2e & 1.5(3) & 10.3(2) & 1.3(4) & 0.45(12) & 3.1(11) & 10$^{16}$ & 0.26(6) & 4.8(18) \\
& Hot Core & 2d & 2.8(2) & 5.6(2) & 5.5(4) & 0.42(4) & 7.4(8) & 10$^{17}$ & 0.13(1) & 4.7(5) \\
& Hot Core & 2d & 4.1(3) & 7.8(2) & 6.6(6) & 4.37(1030) & 1.5(33) & 10$^{18}$ & 1.00(22) & 9.2(17) \\
(CH$_3$)$_2$CO & IRC7 & 9b & 1.3(2)$^b$ & 8.0(2) & 2.4(4) & 0.37(6) & 3.2(7) & 10$^{17}$ & 0.23(3) & 5.5(12) \\
& IRC7 & 9b & 0.7(2)$^b$ & 5.3(4) & 2.4(10) & 0.18(5) & 1.6(8) & 10$^{17}$ & 0.12(3) & 2.8(14) \\
& Hot Core-SW & 9c & 1.7(2)$^b$ & 7.7(2) & 2.1(4) & 0.75(15) & 5.7(13) & 10$^{17}$ & 0.38(6) & 8.1(18) \\
& Hot Core-SW & 9c & 0.4(2)$^b$ & 5.3(8) & 2.5(6) & 0.14(7) & 1.3(7) & 10$^{17}$ & 0.08(4) & 2.1(11) \\
\hline
\end{tabular}
\end{table}

\textsuperscript{a} All uncertainties listed are 2 $\sigma$; an uncertainty of zero means there are not enough significant figures to display its true value.

\textsuperscript{b} Low temperature for hot core/IRC7 is 150 K, for all other sources is 100 K.

\textsuperscript{c} High temperature for hot core/IRC7 is 500 K, for all other sources is 150 K.

\textsuperscript{d} The $I_0$ for blend of all torsional states.

\textsuperscript{e} Quantities are for both A and E torsional states, as they are assumed to have equal populations.

\textsuperscript{f} Opacity and column density not calculated for absorption components.

\textsuperscript{g} Opacity calculation gave negative values, likely due to an assumed rotation temperature that is too low.

\textsuperscript{h} The $I_0$ for EE torsional state only; for other states $I_0$ ($A$ = 0.5$I_0$ (EE), $I_0$ ($E$) = $I_0$ (AE) = 0.25$I_0$ (EE)).

Fig. 3.—Map of CH$_3$OH $J_19_{5,15} - 20_{4,16}$ emission overlaid on gray-scale continuum. Contours are 3, 5, 7, and 10 times 0.188 Jy beam$^{-1}$. The synthesized beam is in the bottom left corner of the map, and plus signs denote the same sources as in the continuum map (see Fig. 1).
present a map of its emission at a $v_{\text{LSR}}$ of 5.4 km s$^{-1}$ in Figure 3. The emission is restricted to the hot core region and shows a slight extension to the southwest, similar to that of the other CH$_3$OH transition.

### 3.3. Dimethyl Ether [(CH$_3$)$_2$O]

(CH$_3$)$_2$O is a typical large O-bearing species and has been associated with the compact ridge (e.g., Liu et al. 2002). Figure 4 shows the (CH$_3$)$_2$O map at a $v_{\text{LSR}}$ of 7.6 km s$^{-1}$. There is clearly some extended emission as indicated by the large negative contours. There is significant emission from IRc6 with a notable hole near Orion-BN and in regions near IRc5. As with CH$_3$OH there is no notable emission from the compact ridge itself. There is also some emission from the hot core-SW. This emission is similar to that seen by Beuther et al. (2005) at 865 μm; however, they do not see the C shape around BN, but rather see more pointlike emission from IRc6. This may be explained by the factor of ~2 difference in $E_u$ between the observed transitions. Figures 4b and 4c show the (CH$_3$)$_2$O spectra from IRc6 and IRc5, respectively, and Table 2 shows the fits to the spectra. The IRc6 emission is best fit by two Gaussians, one narrow, the other wide. The wide absorption feature, near 0 km s$^{-1}$, seen in both spectra are due to the sidelobes of the C$_2$H$_5$CN ($J = 27_{0.27}-26_{0.26}$) emission from the hot core.
3.4. Methyl Formate \([\text{HCOOCH}_3]\)

Similar to \((\text{CH}_3)_2\text{O}\), HCOOCH$_3$ has traditionally been associated with the compact ridge. Both the \(A\) and \(E\) torsional states of the HCOOCH$_3$ \(J = 201_{10}-19_{11}\) transition were detected. Figure 5a shows the \(V_{\text{LSR}} = 7.6 \text{ km s}^{-1}\) map of the \(A\) torsional state. Unlike \((\text{CH}_3)_2\text{O}\), the strongest emission from HCOOCH$_3$ comes from the IRc5 region and not IRc6. In addition, there is some emission from the hot core-SW and no detectable emission from the compact ridge. As with \((\text{CH}_3)_2\text{O}\), there are some notable differences between our map and that observed by Beuther et al. (2005), especially the low level of emission we observe toward IRc6. This difference may be explained by the large (near 3 factor) difference in \(E_a\) of the observed transitions or by our single channel maps versus their velocity-integrated maps. The peak in the northeast of our map is most likely from sidelobes that were not completely removed. Figures 6b and 6c show the HCOOCH$_3$ spectra toward IRc6 and IRc5, respectively. The velocity scale is in reference to the \(A\) torsional state transition. The IRc5 emission appears to have two peaks at \(7.6\) and \(9.3 \text{ km s}^{-1}\).

3.5. Ethyl Cyanide \([\text{C}_2\text{H}_5\text{CN}]\)

\(\text{C}_2\text{H}_5\text{CN}\) is a typical large N-bearing species and has been associated with the hot core for many years (e.g., Blake et al. 1987). Blake et al. (1996) and Beuther et al. (2005) showed an extension in \(\text{C}_2\text{H}_5\text{CN}\) emission toward IRc7. The map of \(\text{C}_2\text{H}_5\text{CN}\ \(J = 253_{22}-241_{21}\) emission (shown in Fig. 6a) clearly resolves this second component for the first time. It also shows an extended ridge of emission running northeast–southwest along the hot core and in the direction of known outflows. In addition, there is a peak of emission to the north of the hot core, a region which has no detected continuum emission. The emission from IRc7 may be coming from two (or more) partially resolved sources. Figures 6b and 6c show the \(\text{C}_2\text{H}_5\text{CN}\) spectra toward IRc7 and the hot core, respectively. The \(\text{C}_2\text{H}_5\text{CN}\) spectra from IRc7 were best fit by two Gaussians, one narrow and one wide, while the hot core spectra were best fit by a single Gaussian. The second line \((V_{\text{LSR}} = -9.5 \text{ km s}^{-1}\) in the hot core spectra may be a \(U\) line (unidentified) or it may be a velocity component of \(\text{C}_2\text{H}_5\text{CN}\). This line does not have a large spatial distribution and is confined to the southwest corner of the hot core. The other transition of \(\text{C}_2\text{H}_5\text{CN}\) we observed \((J = 27_{0.27}-26_{0.26})\) maps nearly identically to this transition.

One notable feature of the \(\text{C}_2\text{H}_5\text{CN}\) emission is a strong peak at \(V_{\text{LSR}} \approx 12 \text{ km s}^{-1}\) just south of IRc6. Figure 7a shows the channel map of this emission and Figures 7b and 7c show the spectra from near the hot core and IRc6, respectively. There is no notable continuum associated with this emission and nothing else like it appears in any of the other transitions we observed.

While there is no notable velocity gradient along the ridge of the hot core, there are some velocity gradients across the hot core which was not completely removed. Figures 8b and 8c show the \(\text{C}_2\text{H}_5\text{CN}\) spectra toward IRc7 and IRc5, respectively. The velocity scale is in reference to the \(A\) torsional state transition. The IRc5 emission appears to have two peaks at \(7.6\) and \(9.3 \text{ km s}^{-1}\).

3.6. Acetone \([(\text{CH}_3)_2\text{CO}]\)

\((\text{CH}_3)_2\text{CO}\), while a large O-bearing species, does not map like any of the other molecules we observed. Figure 9a shows a map of the \((\text{CH}_3)_2\text{CO}\) emission. Two distinct emission features are seen: one at hot core-SW, the other near IRc7. Figures 9b and 9c
Fig. 7.—Map of C$_2$H$_5$CN at a $v_{LSR}$ of 12 km s$^{-1}$. (a) Contours are the same as in Fig. 6. Note the emission south of IRc6. (b) Spectra toward the emission peak south of the hot core. (c) Spectra toward the emission peak near IRc6.

Fig. 8.—Position-velocity diagram of C$_2$H$_5$CN. The inset is a zoom in on the hot core/IRc7 emission, at a $v_{LSR}$ of 5 km s$^{-1}$, shown in Fig. 6. The line denotes the $p$-$v$ cut, and the plus signs denotes its center [$\alpha(2000.0) = 05^h35^m14.4^s$, $\delta(2000.0) = 5^\circ22'31.5''$]. The abscissa of the diagram is offset arcseconds from the $p$-$v$ center, and the ordinate is $v_{LSR}$ in km s$^{-1}$. Labels indicate the position of the hot core and IRc7 along with the potential U line. The contours are the same as those in Fig. 6.
show the spectra toward IRc7 and the hot core, respectively, and Table 2 lists the parameters of the spectral fits. All three spectral features (AE/EA, EE, and AA) are seen at both positions. Both spectra are best fit by two velocity components, ~5 and ~8 km s\(^{-1}\), typical \(v_{\text{LSR}}\) values for the hot core and compact ridge. This is the largest known molecule that shows both velocity components, which are co-spatial at our resolution. Unlike \(\text{C}_2\text{H}_3\text{CN}\) there are no velocity gradients in any of the \((\text{CH}_3)_2\text{CO}\) emission.

3.7. Formic Acid \([\text{HCOOH}\), Acetaldehyde \([\text{CH}_3\text{CHO}\),
and Ethanol \([\text{C}_2\text{H}_5\text{OH}\)]

The HCOOH, \(\text{CH}_3\text{CHO}\), and \(\text{C}_2\text{H}_5\text{OH}\) transitions listed in Table 1 were not detected above their respective 3 \(\sigma\) detection limits. This may be due to these molecules having a generally extended emission and, thus, being resolved out by the array, or the transitions we observed were not favorable, or both.

3.8. Lines Detected in Wideband Windows

Several molecular transitions were strong enough to detect in our wideband windows (~500 MHz bandwidth, ~41.3 km s\(^{-1}\) resolution). Ten of the 12 transitions from six molecules detected in the wideband channels are listed in the lower part of Table 1. Figure 10 shows the channel maps of the transitions. The 1 \(\sigma\) rms noise level for all maps in this figure is 29 mJy beam\(^{-1}\). Note that all maps in this figure are one channel wide and cover all the velocity components of the transition.

Figure 10a shows the OCS \(J = 19\rightarrow18\) emission. There are notable peaks and valleys all throughout the region, indicating widespread features that are resolved out by the array, in addition to the smaller scale structures that are seen. For such a low-temperature transition from a simple molecule, this is not a surprising result. Figure 10b shows the \(\text{CH}_3\text{OH}\) \(J = 10_{2,9} - 9_{1,6}\) transition. The emission is very similar to that of the CH\(_3\)OH \(J = 8_{1,8} - 7_{0,7}\) transition.

\(3\) The other two transitions are from HCOOCH\(_3\) and were also detected in the narrow spectral windows.

Figure 10c shows the HCOOCH\(_3\) \(J = 20_{2,19} - 19_{2,18}\) \(A\) and \(E\) emission, which maps in a manner very similar to the \(J = 20_{1,19} - 19_{1,18}\) \(A\) and \(E\) emission, with the exception that these HCOOCH\(_3\) transitions have a strong peak near IRc6, which may indicate contamination from another species in the wideband channel or may be due to velocity averaging (similar to that of Beuther et al. 2005). Figures 10d–10f show the \(1\) \(J = 25_{0,25} - 24_{0,24}\) and \(22_{0,22}\) and \(1\) \(J = 25_{0,25} - 24_{0,24}\) transitions of vinyl cyanide \([\text{C}_2\text{H}_5\text{CN}\), respectively. These are the only transitions of \(\text{C}_2\text{H}_5\text{CN}\) detected, and all are from vibrationally excited states. They map in a manner very similar to the \(\text{C}_2\text{H}_5\text{CN}\) transitions, having strong emission from the hot core region and IRc7. One notable difference is that the \(\text{C}_2\text{H}_5\text{CN}\) emission shows two emission peaks in IRc7, while \(\text{C}_2\text{H}_5\text{CN}\) only hints at two spatially blended components. These two components have peaks at \(\alpha(2000.0) = 05^{h}35^{m}14.333^{s}\), \(\delta(2000.0) = -05^{\circ}22^{\prime}31.5^{\prime\prime}\) and \(\alpha(2000.0) = 05^{h}35^{m}14.239^{s}\), \(\delta(2000.0) = -05^{\circ}22^{\prime}31.1^{\prime\prime}\).

Figure 10g shows the \(J = 26_{1,25} - 25_{1,24}\) transition of \(\text{C}_2\text{H}_5\text{CN}\). While this transition maps in a manner similar to the other detected \(\text{C}_2\text{H}_5\text{CN}\) transitions, there is one significant difference. The emission near IRc6 seen here is not detected in any other \(\text{C}_2\text{H}_5\text{CN}\) transitions. This may be due to contamination from weaker lines of O-bearing species (several \(\text{CH}_3\text{CHO}\) transitions fell within the same channel). Lastly, Figure 10h shows the \(J = 5 - 4\) transitions of \(^{13}\text{CS}\). The map shows strong emission from the hot core, IRc7, and IRc6 and weaker emission from IRc5 and the hot core-SW.

4. DISCUSSION

4.1. Sources

4.1.1. Hot Core and IRc7

As can be seen from the maps of \(\text{C}_2\text{H}_5\text{CN}\) and \(\text{C}_2\text{H}_3\text{CN}\), when observed under high spatial resolution, molecules that traditionally have been associated with the hot core have multiple strong components: one or two sources associated with IRc7 and a string of components associated with the hot core.

The spectral line fits to the hot core features (listed in Table 2) show a common ~5.2 km s\(^{-1}\) velocity component (the canonical
The spectral line fits to the IRc6 features have a common component near 7.4 km s$^{-1}$ (a typical rest velocity for compact ridge species). However, the two O-bearing species detected toward the hot core/hot core-SW, CH$_3$OH and (CH$_3$)$_2$CO, have a second, narrower component near 7.5 km s$^{-1}$ (a typical rest velocity for compact ridge species). How this second component is associated with the hot core is unclear; although since the CH$_3$OH line is in absorption, it is likely that this component is from gas along the line of sight.

The spectral line fits to the IRc7 features have fewer commonalities. The C$_2$H$_5$CN spectrum is best fit by a pair of Gaussians at $\sim$4 and $\sim$5 km s$^{-1}$, both with distinctly different line widths. The O-bearing species in IRc7 also have two components: one near 5.1 km s$^{-1}$, the other near 7.5 km s$^{-1}$. The latter velocity component is in absorption in CH$_3$OH, indicating that it is cooler and may be between us and IRc7. The C$_2$H$_3$CN maps give a strong indication of multiple cores which may have differing velocities. However, they are unresolved in all other lines, so future observations will be needed to study these further.

4.1.2. Compact Ridge, IRc6, and IRc5

The spectral line fits to all the IRc6 features have a common component near 7.4 km s$^{-1}$. In addition, (CH$_3$)$_2$O and CH$_3$OH have secondary velocity components at $\sim$9–10 km s$^{-1}$. As none of the CH$_3$OH components are in absorption, it is likely that all velocity components are warmer. It is also evident in the maps that there are multiple unresolved components in IRc6, each of which may have a slightly different $v_{LSR}$. Comparing our maps with those presented by Beuther et al. (2005) indicates that the structure that is observed in IRc6 may be more dependent on the
$E_u$ of the transition observed than it is for any of the other sources. This indicates that IRC6 may be at a notably different temperature or have distinctly different physical conditions than the other regions.

As with IRC6, IRC5 has two distinct velocity components (one near 7.6 km s$^{-1}$, the other near 8.5 km s$^{-1}$) for all transitions observed toward this source. The CH$_3$OH transition is in absorption, indicating that it may be between IRC5 and us. As with our other sources, IRC5 appears to have at least two partially resolved components, which may be the sources of the different velocity components. As no transitions of larger molecules were detected toward the compact ridge, it is likely that many molecules typically associated with the compact ridge, via their $v_{LSR}$, may actually be in IRC5 instead. One exception that we know of is HCOOH. Observations comparing the spatial distribution of (CH$_3$)$_2$O and HCOOH by Liu et al. (2002) show that HCOOH may be associated with the compact ridge as, its emission is to the southeast of that of (CH$_3$)$_2$O and appears to be on top of the compact ridge.

4.2. Rotation Temperature Estimation

As we did not detect enough transitions of any one molecule to construct a reasonable rotation-temperature diagram, we assume a range of temperatures for the different molecular species. From the 3 mm spectral line survey of D. N. Friedel et al. (in preparation), we use temperatures of 100–150 K for O-bearing (compact ridge) species and 200–500 K for N-bearing (hot core) species. Note that for (CH$_3$)$_2$CO we assume a temperature range of the other O-bearing species, as its original detection gave rotation temperature of $\sim$176 K, notably below the range from the hot core.

4.3. Opacity and Column Densities

High optical depth (τ > 1) can greatly reduce the observed intensity of a spectral line. From Rohlfis & Wilson (2000), the opacity at the line center can be calculated from

$$\tau = -\ln \left[ 1 - \frac{T_{MB}}{J(T_r) - J(2.73 \text{ K}) - T_C} \right],$$

(1)

where $T_{MB} = T_b/\eta_M$ is the main beam brightness temperature of the line and $\eta_M$ is the corrected main beam efficiency; $J(T)$ is defined as (Rohlfis & Wilson 2000)

$$J(T) = \frac{h\nu}{k} \left( \frac{1}{e^{h\nu/kT} - 1} \right) \text{ K},$$

(2)

$J(2.73)$ is the cosmic microwave background, and $T_C$ is the continuum brightness temperature. For observations not done in a temperature scale, one can convert from jansky per beam to degrees kelvin using (Rohlfis & Wilson 2000)

$$T_{MB} = \frac{1.22I_0}{\eta_M B \theta_b^2 \nu^2} \times 10^6 \text{ K},$$

(3)

where $I_0$ is the peak intensity of the line in jansky per beam, $B$ is the beam filling factor (assumed to be 0.5, filling the beam, for all calculations here), $\theta_b$ and $\theta_b$ are the FWHM Gaussian synthesized beam axes in arcseconds, and $\nu$ is the transition frequency in gigahertz. For emission lines the optical depth correction factor, $C_{\tau}$, can then be calculated (Goldsmith & Langer 1999),

$$C_{\tau} = \frac{\tau}{1 - e^{-\tau}}.$$ 

(4)

This factor is then applied to the column density (eq. [5]). The opacities for the detected transitions are given in column (7) (low-temperature limit; 150 K for hot core/IRc7 and 100 K for all others) and column (9) (high-temperature limit; 500 K for hot core/IRc7 and 150 K for all others) of Table 2.

With the assumption of local thermodynamic equilibrium (LTE), to calculate the total beam averaged column density (\langle N_T \rangle) from a single transition for an array, we have (e.g., Friedel et al. 2005; Remijan et al. 2005)

$$\frac{N_u}{g_u} = \frac{2.04WC_r}{B_0\eta_bS_\mu^2\nu^5} \times 10^{20} \text{ cm}^{-2}$$

(5)

and

$$\langle N_T \rangle = \frac{N_u}{g_u} Q_{rv} e^{E_u/T_r},$$

(6)

where $W$ is the integrated line intensity in Jy beam$^{-1}$ km s$^{-1}$, $Q_{rv}$ is the rotational-vibrational partition function (Friedel et al. 2005; Widicus Weaver et al. 2005), $E_u$ is the upper state energy of the transition in degrees kelvin, $T_r$ is the rotational temperature in degrees kelvin, $S_\mu^2$ is the product of the line strength and the square of the relevant dipole moment in debye$^2$, $N_u/g_u$ is the upper state column density divided by its degeneracy (2 $J$ + 1), and $T_b$ is the total background continuum temperature. The column densities for each transition are given in column (8) (low-temperature limit; 150 K for hot core/IRc7 and 100 K for all others) and column (10) (high-temperature limit; 500 K for hot core/IRc7 and 150 K for all others) of Table 2.

From Table 2 it can be seen that most of our lines are fairly optically thin at our low-temperature limit. However, several transitions, notably those of O-bearing species, are optically thick. At our high-temperature limit it can be seen that more transitions are optically thin when compared to the low-temperature limit. In general, the column densities for all transitions are notably higher than those reported previously in the literature. The reasons for this are (1) we are resolving the sources and, thus, do not suffer from beam dilution and (2) we are accounting for the vibrational part of the partition function, which can increase $\langle N_T \rangle$ by factors of 5 or more.

4.4. Implications for Astrochemistry

One of the big questions about the Orion-KL region is what is causing the O-N differentiation. One could argue that the O-N differentiation seen in Orion-KL is due to the differing dipole moments (and hence differing critical densities) of O- and N-bearing molecules (in general, N-bearing molecules have notably larger dipole moments). In order to investigate this possibility, we calculate the critical density for the C$_2$H$_2$CN and (CH$_3$)$_2$O transitions we detected. The critical densities, $n_{cr}$, can be calculated as (Tielens 2005)

$$n_{cr} = \frac{\sum_{J<\omega_n} A_{ul}}{\sum_{J<\omega_n} \gamma_{ul}},$$

(7)

where $A_{ul}$ is the Einstein $A$-coefficient of the transitions and $\gamma_{ul}$ is the collisional de-excitation rate coefficient. Since the quantum levels of the C$_2$H$_2$CN and (CH$_3$)$_2$O transitions are dominated by single radiative routes in and out, we can consider this to be a
two-level system and the summation collapses to single expressions; \( A_{ul} \) is defined as

\[
A_{ul} = \frac{64\pi^4}{3\hbar c^3} \frac{S\mu^2}{g_u},
\]

and we find for the observed transitions of \( \text{C}_2\text{H}_5\text{CN} \) \((J = 27_{17} - 26_{0,26}) \) and \( \text{(CH}_3\text{)}_2\text{O} \) \((J = 13_{0,13} - 12_{1,12}) \), \( A_{ul} = 9.8 \times 10^{-4} \) and \( 9.1 \times 10^{-5} \text{ s}^{-1} \), respectively. The de-excitation coefficient is defined as (Tielens 2005)

\[
\gamma_{ul} = \frac{4}{\pi} \left( \frac{\mu}{2kT} \right)^{3/2} \int_0^\infty \sigma_w(v) v^3 e^{-\frac{v^2}{2kT}} dv,
\]

where \( \mu \) is the reduced mass of the system and \( \sigma_w(v) \) is the collisional de-excitation cross section at the relative velocity \( v \). If we assume the geometrical cross section\(^4\) of each molecule \( \sigma_w(v) \approx 1.3 \times 10^{-15} \text{ cm}^2 \) for \( \text{C}_2\text{H}_5\text{CN} \) and \( \sigma_w(v) \approx 7.1 \times 10^{-16} \text{ cm}^2 \) for \( \text{(CH}_3\text{)}_2\text{O} \), the primary collision partner to be \( \text{H}_2 \), and temperatures of 200 and 100 K for \( \text{C}_2\text{H}_5\text{CN} \) and \( \text{(CH}_3\text{)}_2\text{O} \), respectively, then we find \( \gamma_{ul} = 1.9 \times 10^{-10} \text{ cm}^3 \text{ s}^{-1} \) for \( \text{C}_2\text{H}_5\text{CN} \) and \( \gamma_{ul} = 7.4 \times 10^{-11} \text{ cm}^3 \text{ s}^{-1} \) for \( \text{(CH}_3\text{)}_2\text{O} \). Using Equation (7) gives critical densities of \( 5.3 \times 10^6 \text{ cm}^{-3} \) for \( \text{C}_2\text{H}_5\text{CN} \) and \( 1.2 \times 10^6 \text{ cm}^{-3} \) for \( \text{(CH}_3\text{)}_2\text{O} \). This slight difference in critical densities is unlikely to be the cause of the differentiation.

Others have argued that the differentiation could be due to differences in the age of the regions, the O-bearing species are liberated off grain surfaces by shocks or form in gas-phase reactions in shocked region, while the N-bearing species take longer to form in gas-phase reactions (e.g., Blake et al. 1987). This argument fits well with what is suspected about the region; outflows from the older (N-bearing) hot core are impacting the ambient gas and dust, forming shocked regions where larger O-bearing species are most populous. However, our observations of \( \text{(CH}_3\text{)}_2\text{CO} \) show that this O-N differentiation is not as simple as it may seem. Figure 11 shows \( \text{C}_2\text{H}_5\text{CN} \) in gray contours, \( \text{(CH}_3\text{)}_2\text{O} \) as dashed contours, and \( \text{(CH}_3\text{)}_2\text{CO} \) as overlaid black contours (note that negative contours have been removed to reduce confusion). The \( \text{(CH}_3\text{)}_2\text{CO} \) emission only appears where both \( \text{C}_2\text{H}_5\text{CN} \) and \( \text{(CH}_3\text{)}_2\text{O} \) emission overlap, indicating grain surface formation from reactions with secondary products.

\(^4\) This assumption is valid, since the primary collision partner, \( \text{H}_2 \), has no permanent dipole moment, and all other interactions are very short range; thus, the collisional cross section will be dominated by the geometrical cross section.

\(^5\) Changing the assumed temperature will not affect the outcome much, as \( n_c \) will go as \( T^{-1/2} \) (higher temperature gives a lower \( n_c \)).

5. SUMMARY

We have conducted high-resolution \( \lambda = 1 \) mm observations of the Orion-KL region with the CARMA array. Our observations studied the continuum of the region as well as 11 molecular species. Of these 11 species, eight were detected, and we have presented their maps and spectra. These maps show that this region is more complex than previously thought. The large N-bearing species \( \text{C}_2\text{H}_5\text{CN} \) and \( \text{C}_2\text{H}_3\text{CN} \) originate from multiple cores near the Orion hot core and IRc7, while large O-bearing species \( \text{(CH}_3\text{)}_2\text{O} \) and \( \text{HCOOCH}_3 \) originate near IRc5 and IRc6, not the compact ridge, as had been assumed before. In addition, we see that \( \text{(CH}_3\text{)}_2\text{CO} \), unlike other large O-bearing species, does not originate from IRc5 or IRc6, but rather from the hot core-SW and IRc7, the only regions where both large N-bearing and O-bearing species are present.

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